Chapter 6

Multitechnique observation of equatorial irregularities and effect of magnetic storm on the generation of ESF

6.1 Introduction

The dynamics of the plasma bubbles is one of the important aspects of the phenomenon of Equatorial Spread F (ESF). Since its discovery more than a half-century ago [Booker and Wells, 1938], considerable experimental and theoretical investigations have been undertaken towards an understanding of Equatorial Spread F (ESF) phenomena [Fejer & Kelly, 1980; Kelly, 1989; Fejer, 1996]. Data gathered from early ionosonde measurements, radar backscatter and in situ rocket probes have fostered a good general understanding of important ESF processes and computer models continue to supplement analytic and empirical findings [Fejer and Kelley, 1980].

The evolution of ESF irregularities, leading to a wide range of scale sizes, seems to involve the operation of a hierarchy of processes [Ossakow, 1981]. Experimental [Kelley et al., 1976; Woodman and La Hoz, 1976; McClure et al., 1977] and numerical simulation studies [Scannapieco and Ossakow, 1976] of the nighttime equatorial F region have given evidence for rising bubbles (plasma density depletions). That the rising plume so indeed represents plasma bubbles has been confirmed through evidence from combination of radar, rocket and satellite observations [Tsunoda, 1980; Rino et al., 1981; Tsunoda et al., 1982]. The bubbles so generated steepen on their top, get polarized, and rise to the topside of the ionosphere through enhanced electrodynamic drift [Ossakow and Chaturvedi, 1978; Anderson and Haerendel, 1979].

Studies of ESF using the 50 MHz radar at the Jicamarca observatory near Lima, Peru have been carried out since the sixties [Farely et al., 1970; Woodman & LaHoz, 1976; Kelly et al., 1986; Hysell et al., 1990; Farely & Hysell, 1996]. The plumes observed on the radar Range-Time-Intensity (RTI) maps have been interpreted in terms of plasma bubbles generated in the post sunset bottomside F region. From Altair radar maps at Kwajalein, Tsunoda & White [1981] first reported that the bottomside F layer is indeed altitude modulated, and the altitude modulation actually leads to the large-scale characteristics of equatorial backscatter plumes. Coordinated study of equatorial scintillation, in situ and radar observation of nighttime F region
irregularities were done by Basu et al. [1980]. In the early evening hours saturated VHF and UHF scintillation and 3 dB fluctuations at 1.5 GHz are obtained in association with strong 50 MHz radar backscatter, implying near simultaneous (~min) excitation of large scale (~km to 100m) and 3 m irregularities.

Rastogi and Aarons [1980] attributed the seasonal variations of the occurrence of ESF at different longitudes to the time delays between the sunset and reversal of the ionospheric electric fields. Raghava Rao et al. [1992] studied the effect of vertical winds on Rayleigh-Taylor growth rates and reported that downward wind pushing the F-region into lower altitudes of higher recombination rates that does not favor the Rayleigh-Taylor growth rate, while an upward wind acts in a way such that it lifts the ionization to the higher altitudes favoring the Rayleigh Taylor instability growth. Chandra et al. [1997] operated digital ionosonde, scintillation recording system and Langmuir probe carried by a RH-560 rocket during Spread-F condition from SHAR (14° N dip), a low latitude station in India and reported that the virtual height of the F layer (h'F), rose to higher altitudes (~400 km) on Spread-F days than non spread F days (~300-320 km). It has also been reported that the electric field reversal occurred around 1930 LT on Spread-F days and around 1900 LT on days without spread F. The upward vertical drift velocities exceeded 50m/sec on spread F days. Rao et al. [1997] made a study on radar observations of updrafting and downdrafting plasma depletions associated with the ESF at Gadanki, Tirupati. Hysell [2000] made an overview and synthesis of plasma irregularities in ESF and reported that three varieties of irregularities occur, all produced by ionospheric interchange instabilities. Type-I and type-II irregularities exist on magnetic flux tubes controlled by the E region and F region dynamo respectively, whereas type-III irregularities are due to very strong polarization electric fields. Patra et al. [2005] made simultaneous observations of equatorial Spread-F irregularities with an 18 MHz radar from Trivandrum and a 53 MHz radar from Gadanki and found that the irregularities occurred at both the locations nearly at the same time.

The effect of geomagnetic storms on the equatorial and low latitude ionosphere in the context of development/ inhibition of ESF is an important Space Weather concern and a subject of much current research interest. The Dst ring current index, which is the average global variation of the low latitude H component of geomagnetic disturbances is taken to be the definitive representation of geomagnetic storms.
A geomagnetic storm is said to be intense if minimum Dst < -100nT; Bz < -10nT for at least 3 hours. It is moderate if minimum Dst < -50nT; Bz < -5nT for at least 2 hours. The storm is weak if minimum Dst < -30nT; Bz < -3nT for at least 1 hour [Gonzalez et al., 1994].

The Auroral Electrojet (AE) index is designed to provide a global, quantitative measure of auroral zone magnetic activity produced by enhanced ionospheric currents flowing below and within the auroral oval. Ideally, it is the total range of deviation at an instant of time from quiet day values of the horizontal magnetic field (H) around the auroral oval. Martinis et al., [2005] showed that the development (or inhibition) of equatorial irregularities during magnetically active periods can be understood using the AE-parameterized Fejer-Scherliess model [Fejer and Scherliess, 1997] for disturbance vertical drift versus storm time and local time.

During magnetically disturbed periods, the electric fields, plasma drifts and the onset of plasma instabilities in the equatorial F region exhibit complex variations as compared to their quiet day patterns [Basu et al., 1996; Fejer et al., 1999]. The occurrence of large electric field and current disturbances during and after geomagnetically disturbed periods arise from the variable nature of coupling between high and low latitudes which has been thought of in terms of two basic mechanisms, solar wind magnetospheric dynamo [Spiro et al., 1988] and the ionospheric disturbance dynamo [Blanc and Richmond, 1980]. Magnetospheric dynamo converts solar wind energy into electromagnetic energy in the magnetosphere through a reconnection process between the solar wind and earth’s magnetic field. This reconnection is favored when the direction of Interplanetary Magnetic Field (IMF) is southward and opposed when the direction of IMF is northward. The magnetosphere intercepts the solar wind voltage and a prompt penetration of electric field is caused by rapid changes in Polar Cap Potential (Φpc) that produce sudden Region 1 current (higher latitude current system in auroral region) variations. Region 2 currents (lower latitude current system in auroral zone) can’t change at the same rate and there is an “undershielding” condition whereby the high latitude electric field can penetrate to lower latitude [Kelly et al., 1979; Fejer and Scherliess, 1997; Kikuchi et al., 2000]. In addition to these sudden perturbations, longer lasting (timescales of a few hours) middle- and low-latitude electrodynamic disturbances with a polarity opposite to the quite time pattern at all local times and with high amplitudes also in the midnight-dawn sector [Sastri, 1988; Scherliess and Fejer, 1997] often occur from a few to
several hours after large enhancements in the high-latitude currents [Fejer et al., 1983; Fejer, 1986]. These electric field perturbations are most probably associated with ionospheric disturbance dynamo effects produced by enhanced energy deposition into the auroral ionosphere during geomagnetically active periods [Blanc and Richmond, 1980]. The local time dependence of the polarity and amplitude of electric field perturbations due to these two processes, in fact, determines the favorable or unfavorable conditions for the development of ESF irregularities at any given location.

The significant changes in the key ionospheric F-layer parameters, such as the critical frequency of the F2-layer (foF2), the virtual height of the F-layer (h'F), the peak height of the F2-layer (hmF2), the maximum electron density of the F2-layer (NmF2), and the Total Electron Content (TEC) and in the ground based magnetometer records associated with magnetic storms have been reported on both a regional and a global basis [Rajaram et al., 1971; Batista et al., 1991; Yeh et al., 1992; Walker and Wong, 1993; Sojka et al., 1994; Sobral et al., 2001; Afraimovich et al., 2002; Las’tovicka, 2002; Blagoveshchensky et al., 2003, Hazra et al., 2010]. The Prompt Penetrating (under-shielded) Electric Field (PPEF) of eastward polarity can cause large uplift of the day- and evening-side ionosphere resulting in large increase of the TEC as measured by GPS receivers [Tsurutani et al., 2004; Maruyama et al., 2004; Lin et al., 2005a, 2005b]. During such storms the Equatorial Ionization Anomaly (EIA) can expand poleward with the ionization crests displaced to midlatitudes [Mannucci et al., 2005; Abdu, 1997]. At low latitudes the eastward Prompt Penetration Electric Field (PPEF) has maximum intensity in the dusk sector [Richmond et al., 2003; Fejer and Scherliess, 1998; Abdu et al., 2007], where the Pre Reversal Enhancement (PRE) of zonal electric field arising from the F layer dynamo is normally active. Large uplift of the evening F layer can cause the instability growth by Rayleigh-Taylor mechanism leading to the development or intensification of the ESF [Abdu et al., 2003; Sastri et al., 1997].

During magnetic storm the energy enters the storm time ionosphere at auroral and polar cap latitudes in the form of particle precipitation and Poynting flux [Knipp et al., 2005] and is mostly transferred to the thermosphere via ion-neutral collisions. The thermospheric energy, Eth which is derived from pAv (where pAv is the global average stormtime density) consists of two sources, solar ultraviolet radiation (Eth_{UV}) and the solarwind (Eth_{SW}). Responses of Eth_{SW} to interplanetary driven dissipative system suggest that the thermosphere can be described by the equation dEth_{SW}/dt = α_{VS} (Eth
\( \varepsilon_{VS} \), where \( \varepsilon_{VS} \) represents the unshielded Volland-Stern electric field in the inner magnetosphere determined from Advanced Composition Explorer (ACE); \( \alpha \) and \( t \) are coupling and relaxation constants. A survey of provisional Dst and \( \varepsilon_{VS} \) traces over the 5.5 years (1999 - mid 2005) shows that [Burke et al., 2007] all sustained excursions of \( \varepsilon_{VS} \) above quiet time levels of 0.22 ± 0.08 mV/m are closely tied to the main phase of storms. In every instance \( \varepsilon_{VS} \) returned to background at or near the beginning of the recovery phase. It is also shown that \( I_{VS} = \int \varepsilon_{VS} \, dt \) is highly correlated with Dst during the main-phase of the storms which have minimum Dst ≤ -100 nT. It is shown from November 10, 2004 storm that [Burke et al., 2010] \( E_{sw} \) is three times the ring-current energy (\( E_{RC} \)) and signatures of equatorward propagating disturbances were detected in neutral density profiles.

The study of storm-time patterns of equatorial ionospheric electric fields and their effects on the spatial distribution of plasma density and the onset of plasma instabilities that cause VHF/UHF/L-band scintillations is a subject [Fejer et al., 1999; Basu Su et al., 2001a, Basu S et al., 2001b] of much current research interest in the context of Space Weather. Basu Su et al. [2001a] and Basu S et al. [2001b, 2005] have reported that there is an abrupt onset of VHF and L-band scintillations due to the prompt penetration of high latitude electric fields (eastward) into low latitudes, in the longitude sector for which the early evening period corresponds to the time of rapid decrease (50 nT/h or larger) in the Sym-H/Dst index. Huang et al. [2002] have shown that the rate of change of Sym-H/Dst index is larger than -5 nT / hr, for duration of more than 2 h would trigger the development of irregularities, possibly due to the penetration of high-latitude electric fields.

There are several reports on the geomagnetic control over the occurrence of scintillations at equatorial and low latitudes [Aaron et al., 1980; Rastogi et al., 1981; Aaron and DasGupta, 1984; DasGupta et al., 1985; Dabas et al., 1989; Aaron, 1991; Chandra et al., 1995; Kumar and Gwal, 2000; Basu et al., 2002]. Sastri et al., [2002] discussed the response of equatorial ionosphere in the Indian Sector (midnight) to the severe magnetic storm of July15, 2000. Near simultaneous formation of ionospheric plasma density structures at middle and equatorial latitudes during the intense magnetic storms of October 29–31, 2003, July 15, 2000, and March 30–31, 2001 is investigated by Basu S. et al. [2005]. Huang et al. [2005, 2006] have shown that the penetration of electric field into the low latitude ionosphere without shielding
continued for many hours as long as the magnetic activity continues to intensify and the IMF Bz remains southward.

The main objective of this chapter is multitechnique observation of equatorial irregularities for geomagnetically quiet and disturbed days using Gadanki radar data, GPS and Geostationary scintillation data, DMSP ion density and Trivandrum ionosonde data. Apart from probing the regions of Mesosphere, Stratosphere and Troposphere Gadanki radar is also used for coherent backscatter study of the ionospheric irregularities above 90km. All radar data used for the analysis in this chapter are the backscattered data where Bragg’s matching condition is satisfied. Those days are selected for analysis when scintillations are observed from Kolkata in the geostationary VHF link or both in VHF and L-band links during the equinoxes of 1998-2004. In 1998 there are 52 days in the two equinoxes when scintillations are observed in both VHF and L-band or only at VHF band. Similarly in 1999 there are 72 days when scintillations are observed at both bands or only at VHF band. In 2000, 2001 and 2002 these figures are 100 days, 118 days and 102 days respectively. In 2003 and 2004 the scintillation data are available for 48 and 25 days. Out of these days NARL backscatter data are available only for 18 and 9 days in the equinoxes of 1998 and 1999. No backscatter data are available for 2000 and 2001. Again in 2002, 2003 and 2004 the radar data are available for 6, 6 and 7 days respectively. From the common days of NARL backscattered and scintillation data of Kolkata, there were geomagnetic storms on 2 days in 1998, 2 days in 2002 and 1 day in 2004. The operating frequency of Gadanki radar is 53 MHz i.e its wavelength is approximately 6 meter. The radar can detect the irregularities of scale sizes of half the wavelength of the transmitting signal which is 3 meter. The days when a plume is observed at Gadanki, the GPS satellite signals are examined at the common ionospheric volume probed by the radar beam and the GPS satellite. Since GPS satellites orbit the earth at 20,200 km at different look angles, the corresponding subionospheric points at 350 km height even from Kolkata may sometimes be close to the NARL north beam and collocated observation is possible. These records are combined with the observations of Trivandrum ionosonde, DMSP (Defense Meteorological Satellite Program) ion density, and geostationary satellite scintillation data from Kolkata for the magnetically quiet days as well as for the disturbed days. There is a good correspondence except on few occasions which can be explained in terms of longitudinally localized generation and drift of the irregularities. Figures 6.1(a
& b) show the locations of Tirupati, Kolkata and 350 km subionospheric points of the two geostationary satellites FLEETSATCOM and INMARSAT on the Indian map and in polar plot.

6.2 Multitechnique observation of equatorial irregularities during geomagnetically quiet days

(a) March 18, 1998

Range-Time-Intensity (RTI) maps of March 18, 1998 which represents backscattered intensity as a function of altitude and time, is shown in Figure 6.2 where color bars denote signal to noise ratio (SNR) in decibels (dB). The figure shows the series of plume-like structures from 19:10 IST [IST = UT + 5:30] to 22:50 IST. Four distinct plume structures with intensities modulated in time can be found. The first plume extends from 277km to 590km around 19:50 IST. The second plume of near vertical structure was observed at about 20:50 IST at an altitude of about 298km and reached a height of about 555km. The third plume is observed around 22 IST and extends from 235km to 530km. The fourth and less intense small plume is observed at 00:04 IST from 256 to 386 km height. A plume in the RTI map is an indicator of a
deep plasma depletion rising up through the F peak under the influence of well
developed irregularities which are thought to be generated by interchange or
generalized Rayleigh–Taylor instability. The tilt of the plume could be explained by a
sheared drift in the ionosphere when the east-west drift is faster at lower altitudes than
at higher ones [Woodman and Lahoz, 1976]. The hourly values of Dst index is plotted
in Figure 6.3 which shows that there is no magnetic storm on this day.

3 minute averaged Signal to Noise Ratio (SNR) is plotted against time with
increasing height in Figure 6.4 where four plume structures can be easily
distinguished. The downward drift of the F layer occurred after the layer rises to the
maximum height of 590km at about 19:50 IST. Again the layer starts to rise vertically
and reached a height of 555km. A sinusoidal variation of F layer base is found in the
second plume.

There have been a number of studies aimed at understanding the vertical motion of
the plasma bubbles associated with the ESF [Ott, 1978; Ossakow and Chaturvedi,
1978; Hudson, 1978; Anderson and Haerendel, 1979, Laakso et al., 1994]. It is shown
in Laakso et al., [1994] that as the background zonal electric field becomes westward,
the plasma in a depletion channel may assume a downdrafting motion at altitudes less
than about 400 km, while the flow remains upward at higher altitudes. The Height
Time Variations of the Doppler velocity transverse to the magnetic field in the
meridian plane for the same event is shown in Figure 6.5. Both updrafting and
downdrafting are found in the plume structures. The highest velocity encountered in
the upward first plume is 260 m/s at 19:40 IST. The highest downdrafting velocity
observed is 87 m/s in case of the third plume. The present observation showing
downdrafting up to a height of about 550 km clearly underlines the importance of the
flux tube integrated quantities in the assessment of plasma flow in the depletion
channels as pointed out by Anderson and Haerendel [1979].
Figure 6.2: The RTI map recorded by LST radar at Gadanki, Tirupati on March 13, 1998.
Figure 6.3: Dst variation on March 18, 1998

Figure 6.4: Height time variation of SNR from Gadanki, Tirupati on March 18, 1998.
Figure 6.5: Height time variation of Doppler velocity as measured by MST radar at Gadanki, Tirupati on March 18, 1998.

It is known that the spectral width of the backscattered signal is a measure of the strength of the irregularity. From the Height Time Spectral width plot (Figure 6.6) it is found that the spectral width is maximum at the height ranges 489km to 537km and varies between 148 to 156 m/sec for the first plume. The total area covered by the
curve at each height is also maximum within this height ranges i.e. the backscattered echo strength is maximum at these ionospheric heights. The height of the maximum spectral width for the second plume is less than that of the first plume. For the second plume the spectral width is highest at the level of 380-400 km. This implies that as the time progresses the F layer gradually descends.

Generation of equatorial irregularities over the magnetic equator in the post sunset hours is intimately related to the variation of height of the F-layer around sunset [Farley et al., 1970; Abdu et al., 1981]. It was established that a sharp rise of F-region altitude due to the pre-reversal enhancement of the eastward electric field is often followed by the generation of intense irregularities through Rayleigh-Taylor instability
mechanism. Ionosonde data from Trivandrum, a station situated close to the magnetic equator, has been utilized to calculate the vertical drift of the F-layer over the magnetic equator for this day to find out any relationship between the post sunset height rise of the F2 layer at Trivandrum with the plume structure at Gadanki. Figure 6.7 shows the variation of h'F with time. The h'F attains a maximum height 440km. Then the virtual height started to fall and showed an oscillatory nature. From the ionogram it is found that the Spread F was generated at 20:00 IST when the F layer attains its maximum value. The slope of h'F (dh'F /dt) is plotted against time and it is found from Figure 6.7 that the maximum rise velocity of F region attains 55.5 m/sec at 19:07 IST. Comparing Trivandrum ionosonde data and Gadanki backscatterd data it is found that at about 19:30 IST Spread F is observed by ionosonde, whereas the plumes at Gadanki (Figure 6.2) are developed at about 19:40 IST.

The DMSP ion density plots of F12 and F14 (Figure 6.8a and 6.8b) show bite outs in ion density at different longitudes. In the figures, longitude and time of the ion density bite out marked by red circle coincide with the plume at Gadanki. The ion density plot marked by green circle occurred in a different longitude sector. In Figure 6.8a ion density biteout near Gadanki longitude (middle panel of second row) is
observed where ambient level of ion density is $6 \times 10^4$ ions/cc. This value is quite high compared to the ion density at the longitude sectors where no bite outs are present. From the right panel of the first row, before the ion density depletion the ambient level of ion density is $2 \times 10^4$ ions/cc. This value is $4 \times 10^4$ ions/cc after the bite out shown in the right panel of the second row. Similarly in Figure 6.8(b), when the satellite crosses the magnetic equator at 1234 UT the ambient level of ion density is $4 \times 10^4$ ions/cc. It is raised to nearly $8 \times 10^4$ ions/cc when bite out are observed (shown by the red circle). Again it is dropped to nearly $5 \times 10^4$ ions/cc during the next pass when no bite out is observed.

The hourly polar plots of GPS satellites recorded at Kolkata during 14:00-18:00 UT on this day are given in Figure 6.9. The triangle denotes the 350 km subionospheric point of the north beam of MST radar at Gadanki, Tirupati which is orthogonal to the magnetic field line and the crosses represent the 350 km subionospheric point of FLEETSATCOM and INMARSAT from Kolkata. The different ranges of SI are denoted by different colors. It is observed that GPS Sv 1, Sv 23 and Sv 30 are nearly in the common ionospheric volume probed by MST radar beam and they show scintillation $>10$ dB in conjunction with the backscatter returns from 3 meter irregularities upto 1733 UT (2303 IST). The radar backscattered signals decay earlier than scintillation. The radar backscattered is caused by 3 meter irregularities, whereas amplitude scintillation is essentially caused by irregularities with the first Fresnel dimension (300-800m). In the initial stages the irregularities of 3 meters and 100s of kms coexist, but the smaller scale irregularities decay faster than the larger ones. The earlier disappearance of radar backscattered signal is an indication that a smaller scale irregularities (3 meter) have low power at late evening and early morning hours. Figure 6.10 shows the temporal variation of Scintillation Index (SI) for two geostationary satellites FLEETSATCOM and INMARSAT observed from Kolkata. Series of scintillation patches are found at FLEETSATCOM and INMARSAT, corresponding to the plumes observed by the radar at Gadanki (Figure 6.2). The 350 km field line over Kolkata maps up to about 700 km above the magnetic equator. Irregularities which are upwelled to 700 km and above will map down to latitudes of Gadanki and Kolkata, causing plumes at Gadanki radar and scintillations at Kolkata. Equatorial irregularities generated earlier at nearby longitudes at Trivandrum, may cross the propagation path of Gadanki Radar beam and FLEETSATCOM, INMARSAT links with some time delays.
Figure 6.8(a): Global picture of DMSP F12 ion density. The plot marked red showing the depletion in ion density in the Indian Longitude Sector. The equator crossing longitude shows that the satellite transit was close to Gadanki. The plot marked green shows the ion density bite out in a different longitude sector.
Figure 6.8(b): Global picture of DMSP F14 ion density. The plot marked red showing the depletion in ion density in the Indian Longitude Sector. The equator crossing longitude shows that the satellite transit was close to Gadanki. The plot marked green shows the ion density bite out in a different longitude sector.
Figure 6.9: Polar plot of GPS satellites from 14:00-18:00 UT observed from Kolkata for March 18, 1998. The different colored circles indicate different ranges of scintillation index in dB.
The onset time of plume at Gadanki and scintillation patches at Kolkata

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<tr>
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<th>Gadanki, Tirupati</th>
<th>Kolkata</th>
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<tbody>
<tr>
<td>First patch</td>
<td>19:40 IST</td>
<td>20:40 IST</td>
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<tr>
<td>Second patch</td>
<td>20:26 IST</td>
<td>21:36 IST</td>
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<tr>
<td>Third patch</td>
<td>21:58 IST</td>
<td>23:00 IST</td>
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Figure 6.10: Scintillation at FLEETSATCOM and INMARSAT links observed from Kolkata on March 18, 1998.
b) April 20, 1998

Another RTI map of April 20, 1998 is shown in Figure 6.11. Three plume structures are seen in the RTI map. The first vertical plume reaches its maximum height of nearly 416 km at 21:26 IST. Around 21:50 IST the second plume developed and reaches a height of about 402 km. It is observed that none of these plumes reached a height greater than 425 km.

The 3 minute averaged SNR for different heights of the ionosphere is plotted in Figure 6.12 where small plume structures are clearly distinguished. Figure 6.13 shows the height time variation of Doppler velocity. In all the plumes the downdraft is dominant and the maximum downward velocity is 32 m/sec. From the plot of height time variation of Doppler width (Figure 6.14) it is found that the width is maximum at the height of nearly 380 km. This implies that near this height of the ionosphere the ion density is maximum. Temporal variation of $h'\bar{f}$ observed from Trivandrum is shown in Figure 6.15 and it is found that the F layer rises to maximum 375 km at 20:30 IST. From the ionogram it is found that the ESF is developed at Trivandrum around 19:30 IST at about 337 km. Figure 6.16 shows the variation of $\frac{dh'\bar{f}}{dt}$ with time. The maximum velocity of the F layer is 24.4 m/sec at 18:52 IST.
Figure 6.12: Height Time Variation of SNR observed from Gadanki for April 20, 1998
Figure 6.13: Height time variation of Doppler velocity observed from Gadanki, Tirupati for April 20, 1998
Figure 6.14: Height time variation of Doppler width observed from Gadanki, Tirupati for April 20, 1998
From the polar plot (Figure 6.17) of GPS satellites it is found that during 14:00-15:00 UT Sv9 shows scintillations with SI > 20 dB. During this time no plume is found over Gadanki and the position of this satellite is far east of NARL north beam. The irregularity which causes scintillation in GPS Sv9 link may be generated in between Gadanki and Sv9 longitude, then drifted eastward and caused scintillations. During 15:00-16:00 UT there are collocated GPS passes near the north beam of radar. Satellite Sv1 shows scintillation with SI > 10 dB during this time when a plume is also observed in the RTI map (Figure 6.11). During 16:00-17:00 UT, Sv6 shows scintillation with SI > 20 dB due to the field alignment position of the satellite.

There are also collocated DMSP F12 (Figure 6.18a) and F14 (Figure 6.18b) passes on this day. It is found from Figure 6.18a and 6.18b that when DMSP F12 and F14 passed near the Gadanki longitude, no ion density bite out are observed though at the same time the radar detected plume structure. The ambient value of the ion density is also low in this longitude sector. But in the two preceding longitude sectors the ion
density is high. The ESF generated at magnetic equator, could not reach the height of DMSP transit (840 km) and DMSP satellites did not encounter any bite out in ion density.

From Kolkata, FLEETSATCOM and INMARSAT do not show any scintillations on this day. As the ESF at Gadanki is confined to a lower height, it does not map up to the height of the magnetic field line corresponding to FLEETSATCOM and INMARSAT subionospheric point. For this reason no scintillation is observed at Kolkata.
On Figure 6.17: Polar plot of GPS satellites from 14:00-18:00 UT observed from Kolkata for April 20, 1998. The different colored circles indicate different range of scintillation index in dB.
Figure 6.18a: Global picture of DMSP F12 ion density on April 20, 1998. The plot marked red shows the satellite is passing near the Gadanki longitude.
Figure 6.18b: Global picture of DMSP F14 ion density on April 20, 1998. The plot marked red shows the satellite is passing near the Gadanki longitude.
Figure 6.19 shows the RTI map of Gadanki radar on March 14, 2004. No ESF is found on this day but from Kolkata, INMARSAT and FLEETSATCOM satellite links show scintillations (Figure 6.23). Trivandram ionosonde data shows that the F region reaches its maximum height of 330 km (Figure 6.20) and the maximum vertical velocity of the F layer is found to be 25.7 m/sec (Figure 6.21). No ESF is seen on this day.
Figure 6.21: Variation of $\frac{dh'F}{dt}$ with time from Trivandrum ionogram data on March 14, 2004

Figure 6.22a: Polar plot of GPS satellites from 1330-1630 UT observed from Kolkata for March 14, 2004. The different coloured circles indicate different range of scintillation index in dB.
Figure 6.22a shows the polar plot of GPS satellites observed from Kolkata on the same day. During 1330-1430 UT, GPS Sv56 signal passes through the common ionospheric volume probed by the MST radar, but did not show any scintillations >10 dB. No plume was also recorded (Figure 6.19) by the radar in this time interval. There is also no ion density bite out during the DMSP F14 (Figure 6.22b) passes near the longitude of Gadanki radar. During 1430-1530 UT Sv15 encountered scintillations (Figure 6.22). Geostationary INMARSAT and FLEETSATCOM also show scintillations when the ray paths passes through the common ionospheric volume probed by GPS Sv 15. If the irregularities are generated over the magnetic equator in between the longitudes of Gadanki and Kolkata and move eastward, the plumes may not be observed by radar but from Kolkata scintillations are encountered in the GPS and Geostationary links. Two scintillation patches are found in the INMARSAT and FLEETSATCOM link of Figure 6.23 where there is a systematic time difference between the patches of INMARSAT and FLEETSATCOM. The onset time of scintillation for the first patch at INMARSAT link is 19:54 IST, whereas for the second patch it is 21:29 IST. The onset time at FLEETSATCOM link for the two patches are 19:56 and 21:38 IST. As INMARSAT is situated west of FLEETSATCOM, the time difference of INMARSAT and FLEETSATCOM scintillation indicates that the irregularities drift eastward. From the GAGAN GPS data of Kolkata it is found that Sv15 shows TEC (TOTAL ELECTRON CONTENT) bite out from 14:37 UT which matches with geostationary observations. The 1 minute TEC, corresponding S4 at GPS L1 and deviation of STEC from its 90 minute moving average in Sv15 link is shown in the Figures 6.24(a), 6.24(b) and 6.24(c) respectively. There are two TEC bite outs (Figure 6.24(a)) similar to the observation of two scintillation patches in the geostationary links. A periodic structure of TEC is found before the TEC bite out (Figure 6.24(c)) which is also discussed in Chapter 5.
Figure 6.22b: Global picture of DMSP F14 ion density on March 14, 2004. The plot marked red shows the satellite is passing near the Gadanki longitude.
Figure 6.23: Scintillation at INMARSAT and FLEETSATCOM link observed from Kolkata on March 14, 2004.
Figure 6.24(a): TEC bite out encountered at Sv15 link observed from Kolkata on March 14, 2004.

Figure 6.24(b): $S_4$ index at Sv15 recorded at Kolkata on March 14, 2004

Figure 6.24(c): STEC deviation from its 90 minute moving average for Sv15 recorded at Kolkata on March 14, 2004
6.3 Multitechnique observation of equatorial irregularities during a geomagnetically disturbed day

The Radar backscattered data of NARL during geomagnetically disturbed period is available for 5 cases. March 21, 1998 is one of them. The result of the analysis during this storm is given below.

**March 21, 1998**

Figure 6.25 shows the variation of IMF Bz, AE, Dst and dDst/dt indices during March 20-22, 1998. There is a Gradual Commencement (GC) type magnetic storm on March 21, 1998. ACE satellite measures IMF Bz at a distance of about 240 Re, where Re is the radius of earth. IMF Bz turned southward and reached southward component of -10 nT at 11:20 UT on March 21, 1998, reaches minimum of -15.5 nT at 13:00 UT and remained below -10 nT till 14:04 UT. Again it goes below -10 nT at 17:24 UT and remained below -10 nT till 18:04 UT. The solar wind is also measured by the ACE satellite. The time taken by the IMF change to travel from the satellite height to the magnetopause is calculated to be about 1 hour. At magnetopause the IMF change will be realized at (11:20+1:00=12:20) 12:20 UT. AE value exceeded 1000 nT at 16 UT and at the same time the minimum value of Dst reaches -85 nT. The dDst/dt attained a minimum value of -25 nT/hr at 14:30 UT on the same day.
Figure 6.25: Variation of IMF Bz, AE, Dst and dDst/dt during March 20-22, 1998
Figure 6.26: RTI map recorded at Gadanki, Titupati from MST radar for March 21, 1998.
Figure 6.26 shows the RTI map observed at Gadanki on March 21, 1998. No plume is generated during early evening hours. Later from 20:30 IST, ESF occurs at Gadanki (Figure 6.26), within 3 hours from the IMF Bz turning southward to a value below -10 nT reaching the magnetopause (12:20UT). The bottomside of the F layer height underwent nearly full cycle of a long period modulation from 20:30-22:00 IST followed by modulation of smaller periods up to 23:15 IST.

From the plot of Doppler velocity of the plume structure as shown in Figure 6.27 it is found that maximum upward drift velocity is 127 m/sec at 21:45 IST. The overall oscillatory pattern seems to drift downward with a speed of about 30 m/sec after 22:30 IST. Figure 6.28 shows the variation of 3 min averaged SNR with time at different heights.
The Spectral width (Figure 6.29) is above 100m/s from 333km to 352km at 21 IST and again it crosses 100m/s at 463km at about 22 IST. The total area covered by the plot is also maximum at 463 km. This indicates that the irregularity strength is maximum at this height. Simultaneous measurement of the apparent height of the bottomside of the F layer is also made using ionosonde at Trivandrum as shown in Figure 6.30a. The maximum height reached by the F layer is 490km at 20:30 IST. From the variation of dh'/dt with time (Figure 6.30b) it is found that maximum
upward velocity of the F layer is 44.4 m/sec at 19:52 IST after and the layer starts to descend afterwards.

Figure 5.29: Height time variation of Doppler width (m/sec) observed from Gadanki, on March 21, 1998.

Figure 6.30a: Variation of h'f with time from Trivandrum ionogram data on March 21, 1998.
The ion density plots of DMSP F12 (Figure 6.31) show strong ESF around the magnetic equator in the 61°E longitude sector at 1704 UT. This bite out occurred within few hours of the southward component of IMF Bz attaining (12:20 UT) a peak value and this time corresponds to the post-sunset local time of this longitude sector. There is no signature of ESF in other longitudes following the storm. The generation of other bite out during 1158 UT occurs well before the time of IMF Bz crossing -10 nT may not be related to magnetic storm.

Similarly, from Figure 6.32 it is found that F14 shows bite out in ion density on two longitude sectors. One is at 1118 UT in the 130°-145°E longitude sector and the other at 16:24 UT in 55°-68°E longitude sector. Development of first bite out before IMF Bz crossing -10 nT at the DMSP satellite height implies that, ESF development during post sunset local time in this longitude sector may be a part of a regular process not related to magnetic storm. But the second bite out at longitude range 55°-68°E occurs at 16:24 UT, after the southward component of the IMF Bz attains a peak value where post sunset period prevails. The eastward penetration electric field together with the enhanced prereversal upward drift in this longitude region may have caused very large upward drifts. The depleted region extends from about 15° S to 16° N around 62°E longitude and the ion density depletion is also of the order of 1 x 10^5/cc. The DMSP data indicate that the enhanced upward drift in this longitude sector must have lifted the ionosphere with plasma density bite out at the satellite altitude of 840 km over a wide magnetic latitude interval of almost 30°. No bite out during the DMSP passes is detected in the other longitude sectors following the storm, indicating inhibition of ESF activity at non dusk longitude sectors.
Figure 6.31: Global picture of DMSP F12 ion density on March 21, 1998. The plots marked green and red circle show the ion density bite outs before and after the magnetic storm.
Figure 6.32: Global picture of DMSP F14 ion density on March 21, 1998. The plots marked green and red circle show the ion density bite outs before and after the magnetic storm.
On the same day, the hourly polar plots of GPS satellites observed from Kolkata during 14:00-18:00 UT (UT+5:30 = IST) are shown in Figure 6.33. It is found that with the onset of ESF at Gadanki, Sv1 link experiences scintillations in excess of 10 dB from 16-18 UT when it is collocated with the north beam of the radar. From Kolkata scintillation is recorded at FLEETSATCOM (250 MHz) link also at 21:45 IST (Figure 6.34).

Figure 6.33: Polar plot of GPS satellites from 1400-1800 UT observed from Kolkata for March 21, 1998. The different coloured circles indicate different range of scintillation index in dB.

Figure 6.34: Scintillation at FLEETSATCOM link on March 21, 1998 observed from Kolkata.
6.4 Discussions

Simultaneous ionosonde and radar observations at Trivandrum and Gadanki help to understand the magnetic flux tube mapping of ESF associated plasma depletions. It is found that on March 18, 1998 the h'F height crosses 400 km at Trivandrum and the plumes are detected by radar from Gadanki. GPS satellites encounter scintillations in excess of 10 dB at the common ionospheric volume probed by the north beam of MST radar. DMSP satellites also show ion density bite outs over this longitude sector. The DMSP satellites orbit the earth at a height of 840 km. The ion density bite out in the DMSP passes implies that the irregularities reached this height. Then it maps down to the latitudes of 350 km subionospheric point of INMARSAT (1.5 GHz) and FLEETSATCOM (244 MHz) link observed from Kolkata and cause scintillations.

On April 20, 1998, maximum h'F was 375 km. The maximum plume height at Gadanki is about 400 km. No scintillation is recorded in geostationary L band and VHF satellite links from Kolkata on this day. As the F layer over the magnetic equator did not reach the necessary height of the magnetic lines linked with subionospheric points of FLEETSATCOM and INMARSAT, no scintillation is recorded from this station. The F12 and F14 DMSP satellite passes in the Indian longitude sectors during the evening hours also did not encounter any bite out of ion density as the irregularity did not reach to the satellite height.

On March 14, 2004 no ESF is recorded at Gadanki, but from Kolkata, scintillation is recorded at geostationary FLEETSATCOM and INMARSAT satellite links. It is found from the polar plot of GPS satellites observed from Kolkata that Sv15 shows scintillations in excess of 20 dB during 14:30-16:30 UT (20:00-21:00 IST). Geostationary INMARSAT and FLEETSATCOM also showed scintillation during 19:55-22:00 IST. Generation of irregularities may sometimes be very localized. Freshly generated irregularity in between the longitudes of Gadanki and Kolkata, may drift eastward, causing scintillations at Kolkata but no radar backscattered echoes at Gadanki.

Analyzing the available data of geomagnetically quiet days, Chi Square test is performed for the threshold values of h'F and upward velocity of the F layer at Trivandrum above which plume may be observed at Gadanki at a height greater than 550 km. Different threshold values of h'F height are chosen from 350 to 400 km and velocity of the F layer are selected from 25 to 35 m/sec. Chi Square test is performed...
for each set of threshold values and 4X2 contingency table is drawn. For 4X2 contingency table the degrees of freedom (df) is 3. Chi Square value is high when threshold values of h_F and dh/dt are chosen as 375km and 30m/sec, respectively. The computed values of Chi-Square (31.6) exceeded the value 16.2 in the table for df = 3 and level of significance p=0.001. Therefore, the null hypothesis (with a 0.1% probability of error) is rejected and the research hypothesis that if the height of the F layer (h_F) exceeds 375 km and the velocity of the layer is greater than 30 m/sec then there will be a possibility of detection of plume with Gadanki radar reaching a height greater than 550 km. If the maximum height of the plume at Gadanki exceeded 550 km, there will be a possibility of scintillations in geostationary satellite links (INMARSAT and FLEETSATCOM) observed from Kolkata.  

The results of other four geomagnetic storms’ analysis are summarized below.

March 25, 1998:  
On March 25, 1998 there is GC type magnetic storm. Most of the studies on geomagnetic storm related ESF based on SC type storms. The ESF observed on March 25, 1998 shows that during GC type storm also penetration electric field and disturbance dynamo may play roles similar to those of SC type storms. The minimum Dst was -56 nT at 17 UT and minimum value of dDst/dt was -17 nT/hr at 15:30 UT. IMF Bz reaches its minimum value of -8.071 nT at 14:08 UT. The time to reach the minimum southward turning of IMF Bz at the magnetopause is about 1 hour. Within 3 hours of IMF Bz reaches its minimum value a plume is observed at 21:30 IST (16 UT) by Gadanki radar. DMSP F12 and F14 also showed ion density bite outs at 1614 UT and 1534 UT near the Gadanki longitude sector. From Kolkata scintillation were observed in the geostationary VHF and L-band link with some time delay.

September 04, 2002:  
On this day minimum Dst was -109 nT at 6 UT and the minimum value of dDst/dt is -48 nT/hr at 3:30 UT. IMF Bz crosses -10 nT at 2:00 UT and remains below -10 nT till 4 UT. Irregularity generation is suppressed and no plume is observed at Gadanki on this night. No scintillations are also observed from Kolkata in any frequency band.

September 8, 2002:  
This storm is of Sudden Commencement (SC) type (16:36 UT on September 07, 2002). The minimum Dst was -181 nT at 01:00 UT on September 08 and minimum value of dDst/dt was -59 nT/hr on September 07, 2002 at 18:30 UT. There is no affect of storm on the generation of irregularities. Plumes are observed by
Gadanki radar and scintillation are also present in VHF and L-band links from Kolkata.

February 11, 2004:

On February 11, 2004 there is also a GC type magnetic storm. The minimum Dst was -109 nT at 18 UT and minimum value of dDst/dt was -28 nT/hr at 15:30 UT. IMF Bz crosses -10 nT at 12:00 UT and remains below -10 nT at 16:00 UT. The southward turning of IMF Bz reaches its minimum value of -12.4 nT at 14:00 UT. The time taken by the southward component of IMF Bz (-10 nT) to reach magnetopause is 58 min. The plume observed by Gadanki radar at 20:00 IST (14:30 UT) within 3 hours of southward turning of IMF Bz reached -10 nT (12:58 +3:00). DMSP F15 encounters bite out in ion density at 16:03 UT near the common volume of north beam of Gadanki radar. Scintillations are also observed in VHF and L-band from Kolkata.

It can be summarized that the southward turning of IMF Bz associated with decrease of Dst caused a penetration of eastward electric field into the equatorial ionosphere. IMF Bz at the magnetosphere boundary crosses -10 nT a few hours before Dst and dDst/dt attained its minimum value. Within 3 hours of the interplanetary magnetic field (IMF) Bz reaching the magnetopause with value less than -10 nT, ESF is generated in a narrow longitude zone where the local time is in the dusk sector. It may be concluded that the time of southward IMF Bz below -10 nT with a duration of 3 hours, could be a warning that for a GC storm also, there will a possibility of scintillations in the longitude sectors within 3 hours where post sunset time prevails.