Chapter 6
Analysis of post sunset F region vertical plasma drifts during counter electrojet (CEJ) days using multi frequency HF Doppler Radar

6.1 Introduction

It is well known that equatorial ionosphere is characterized by interesting features such as equatorial electrojet (EEJ), equatorial ionization anomaly (EIA), equatorial spread F (ESF) etc. All these are driven due to complex electrodynamical nature of the ionosphere. Several publications cover different aspects of the ionosphere at equatorial and low latitudes (Rastogi et al., 1972; Kelley and McClure, 1981; Raghavarao et al., 1988; Rastogi, 1989; Rastogi, 1990). The electrodynamics plays an important role in the equatorial/low latitude ionosphere.

In the ionospheric E-region, tidal winds drive currents during the daytime which, together with the magnetic field, cause the accumulation of positive and negative charges at the dawn and dusk terminators respectively, resulting in a strong eastward electric field along the magnetic equator. This gives rise to the Hall and Pederson currents, and Cowling (1933) showed that when a Hall current is restricted by the presence of boundaries, the effective (Cowling) conductivity parallel to the boundaries is significantly enhanced beyond the normal Pederson conductivity. It was later realized that the presence of low conducting layers above and below the E-region are sufficient to drive this Cowling conductivity near the magnetic equator, giving rise to the equatorial electrojet (EEJ) (see Forbes, 1981). Thus EEJ is the intense daytime eastward current that flows in the E-region of ionosphere in a narrow band of latitudes (± 30°) centered over the dip equator. The name ‘Equatorial Electrojet was given by Chapman (1951). The intense currents are because of the enhanced conductivity due to the vertical polarization field close to dip equator. During certain times, the
westward current flow during daytime due to the electric field reversals and is known as the counter electrojet (Gouin, 1962).

Equatorial electrojet which is generated by the eastward electric field also found to influence the sporadic E (Esq) layer over the magnetic equator. Associated with equatorial electrojet is the strong sporadic-E of transparent type. This is resulting from the scattering of radio waves from plasma density fluctuations. These types of fluctuations in plasma density arise due to the plasma instabilities that operate in the electrojet region. The highest frequency of Es-q is correlated with electrojet strength (Matsushita (1951)). During daytime counter electrojet events, when electric field reverses its polarity to westward, equatorial type of sporadic-E also disappears. Ionosonde data have been used extensively to study the occurrence features of the disappearance of equatorial Es. Away from magnetic equator sporadic-E is of flat type or blanketing type because of thin layers due to Ion convergence. During the counter electrojet event equatorial type of sporadic-E disappears and the electric field reveres to westward (Rastogi et al. 1971).This was measured from the spaced receiver drift measurements from Thumba near the magnetic equator. Rastogi (1974) studied in details about the occurrence of counter electrojet based on the geomagnetic field measurements in the electrojet regions in India and at other longitudes.

Strength of electrojet is found to influence many other parameters such as EIA, foF2 (critical frequency of F-layer) etc. For example EIA is suppressed during periods of counter electrojet. An example is described in Chapter 3 (section 3.4). foF2 is negatively correlated with the electrojet strength near magnetic equator where as it is positively correlated near anomaly peak.

Based on ground observatory data there have been many studies of EEJ (Arora et al., 1993; Doumouya et al., 1998) which further study its day to day and seasonal variability, longitudinal and local time structure, counter-electrojet, etc. A new generation of satellite magnetic data provides a longitudinal and temporal coverage of the EEJ previously unattainable with ground based observations alone.

As said earlier ionosphere is a dynamical system, in which its different layers exhibit drift motions. These are controlled by the electric fields from low latitude E region. since F region doesn’t have an electric field, because both ions and electrons
are magnetized and they are in gyrational motion. After sunrise the east-west component of electric field E (which has its origin in the global dynamo field) gets mapped to the F-region altitudes along the highly conducting geomagnetic field lines and causes the vertical $E \times B$ plasma drift through the interaction with the vertical component of the geomagnetic field and causes the development of EIA. The F-region plasma that is uplifted over the dip equator, by the process of the vertical $E \times B$ plasma drift, diffuses along the geomagnetic field lines resulting in depletion of plasma around the dip equator and accumulation of plasma away from the equator producing a double humped latitudinal distribution, known as EIA. Many workers have extensively studied plasma drifts using radar and satellite measurements (Fejer, 1997). Electric field of 1 mV/m corresponds to F-region plasma drifts of about 30 - 40 m/s.

Another interesting feature of F region plasma drift, the pre-reversal enhancement (PRE) which is discussed in detail in Chapter 5 (section 5.2).(Balan et al. (1992) and Woodman (1970) have studied the importance post sunset vertical plasma drift, as they appear to have a direct bearing on the occurrence of equatorial spread. The E-region changes can be observed with radar studies of the equatorial electrojet, while the F-region fields are observed via the motion of the F-layer in ionograms, HF Doppler radar and/or incoherent scatter measurements. Using incoherent scatter radar measurements at Jicamarca Radio Observatory (11.95°S, 76.87°W; magnetic dip 2°N) the equatorial ionosphere has been extensively studied by (Woodman, 1970; Fejer et al., 1979, 1985, 1989, 1991; Gonzales et al., 1983). In the Indian equatorial sector, Balan et al. (1992); Sreehari et al. (2006) made ionospheric drift observations with the HF Doppler radar system operate at University of kerala. Nayar and Sreehari (2004) have presented the characteristics and altitude dependence of vertical plasma drift during post-sunset hours using multi-frequency HF Doppler radar observations. Subbarao and Murthy (1994) have used coherent HF radar to study F-region vertical velocity during post-sunset period.

It is understood that vertical drift in the ionospheric F region is related to electric field variations in the E region. When the electric field is positive vertical plasma drift will shows upward enhancement and when it is negative drift will show downward excursion. In this context vertical drift variations during post sunset hours are analyzed in connection with the electric field variation in the day time.
In India, the relationships between the daytime EEJ, PRE strength and ESF onset have been extensively investigated. The virtual height of the bottom side F-layer (h’F) on ionograms and the $E \times B$ drift ($dh'F/dt$) during evening hours with the EEJ ground strength observed at 11:00 IST (Indian standard time, IST = UT + 5.5 h) in February 1980 and September and October 1989 are compared by Dabas et al. (2003). They found that the daytime EEJ ground strength and both the evening h0F and $E \times B$ drift show good, positive correlations. The highest h’F, ESF onset from 18:00 to 21:00 IST, and the integrated EEJ ground strength (IEEJ) from 07:00 to 17:00 IST in March for the period 2001 to 2005 is examined by Tulasi Ram et al. (2007). They found that the highest h’F, ESF onset, and IEEJ show good, positive correlations. The relationships they found can help in forecasting ESF onsets because the EEJ ground strength before sunset can be measured prior to ESF onsets. On the other hand, Haerendel and Eccles (1992) found, by performing calculations, that the dayside EEJ flows into the night side region and that the vertical divergent current of EEJ connects to the vertical F region dynamo current. Denardini et al. (2006) observationally verified the existence of the divergent current of EEJ. Thus, EEJ just before sunset could be connected to PRE.

Haerendel and Eccles (1992) studied the role of equatorial electrojet (EEJ) in the evening ionosphere. They suggested that the equatorial electric field in the evening sector results from a large current system setup by the effects of the F-region neutral wind dynamo and equatorial electrojet. This current is upward at the equator. The post-sunset current demand of the F-region dynamo is the driver of the electric field enhancements but current continuity in the underlying electrojet region is the primary cause of PRE. They proposed that zonal Cowling conductivity gradients in EEJ at sunset in combination with the current demands from the evening F-region dynamo may have a causal relationship with the PRE. The rapid drop in conductivity in the EEJ at sunset requires an enhanced zonal electric field to draw the current zonally to the nightside, where it then is diverted upward to meet the vertical current demands at the bottom of the F-region. However, the relationship between the CEJ, and PRE has not been observationally investigated using multi-frequency HF Radar instead of taking ($dh'F/dt$) by ionosonde as far as the authors are aware.
6.1.1 Data and Method of Analysis

A few cases of counter electrojet events occurred during geomagnetically quiet days (Ap ≤ 20) of the moderate solar activity years 2004 and 2006, where simultaneous data are available, is used to analyze the behavior vertical drifts during such events. The HF Doppler Radar system having good temporal resolution developed at the University of Kerala is used for measuring vertical drift in the equatorial F region. The measurements have been carried out mainly during evening time. The system was operated at frequency 3.5 MHz to probe the bottom side of the F-region. Hourly values of the geomagnetic field (ΔH) at Trivandrum and at Alibag (18.7° N; 73° E; dip lat 13° N), a location outside the electrojet region, obtained from Indian Institute of Geomagnetism (IIG), Mumbai (India) is used to characterize the strength of EEJ on each day as given by the relationship, \( ΔH_{TIR} - ΔH_{ABG} \), where ΔH is calculated by subtracting the magnetic field values from the respective night level mean values. Ionosonde data is utilized to find dh'F/dt \( (V_d) \) and thereby comparing the \( V_d \) measurement with HF Radar. The total number of events is restricted due to the non availability of simultaneous HF Radar, Ionosonde and CEJ day.

6.1.2 Observations

In order to study the behavior of evening time vertical drifts during counter electrojet days five cases of fully developed CEJs during the years 2004 and 2006 have been looked into. Figure 6.1 (a-c) is the EEJ induced surface magnetic field values Radar measured drifts \( (V_d) \) and Ionosonde measured vertical drift \( (dh'/dt) \) during for the year 2004. In Figure 6.1 (a) January 8 and January 11 represents the counter electrojet days and February 24 and April 08 represents normal electrojet days. It is clear from the figure that during February 24 and April 08, EEJ shows an increasing trend from 06:00 IST and peaks around 10:00 IST with peak values of 69 nT and 74 nT respectively. There after it shows decreasing trend up to 16:30 IST and then the field recovers to its normal level. This represents a typical behavior of a normal electrojet day. However, on a CEJ day i.e., on January 08, magnetic field shows an increasing trend in the morning hours and reaches a maximum of 74 nT around 10:45 IST. After that it shows a decreasing trend and continues the trend with negative variations from 12:35 IST which is a clear cut indicative of the eastward
electric field reversal to westward i.e. the occurrence of CEJ. The field reversal maximizes to a value of -45 nT at around 14:00 IST and after that it recovered to its normal level at around 17:30 IST. Similarly, On January 11, the magnetic field increases to a maximum of 87 nT around 10:22 IST and after that shows a reversal at 13:00 IST and reaches a negative maximum of 48 nT at 15:30 IST.

In order to check the connection between the variability of E-region electric field and post sunset F region dynamics, vertical drift in the post sunset period (18:00 - 20:00 IST) has been analyzed and depicted in Figure 6.1 (b). During February 24, and April 08 a clear-cut post sunset enhancement or Pre-reversal enhancement (PRE) is seen in vertical drift with values of nearly 35 m/s and 27 m/s respectively around 19:00 IST. This is the typical behavior of vertical drift in the evening hours. However, during CEJ days this pattern is totally different. It is clear that the maximum value of drift never exceeds 30 m/s on CEJ days. Also PRE is found to be inhibited or weakened during the CEJ days. The interesting observation is that, in general the vertical drift shows a decreasing tendency and field reversal happens much earlier than that on normal electrojet days. On January 08, $V_d$ exhibits a decreasing pattern from 18:30 IST onwards whereas on January 11, $V_d$ decreases from 18:00 IST onwards.
Figure 6.1: (a-c) EEJ induced surface magnetic field values, Radar measured drifts ($V_d$) and Ionosonde measured vertical drift ($dh'F/dt$) during for the year 2004.

To confirm this aspect further, the $V_d$ obtained from the HF radar has been compared with $V_d$ derived using ionosonde ($dh'F/dt$) and the same is depicted in Figure 6.1c. It has been observed that the results obtained are consistent.

In order to check the consistency of this observation $V_d$ during more cases of CEJ days have been analyzed during the year 2006 also. It has been seen that the observation is found to be valid for the year 2006 too. Figure 6.2 (a) shows the time
variations of induced magnetic field at surface during five days considered in the year 2006. Among these days three days i.e., January 28, January 29 and January 30 are CEJ events while the other two days i.e., January 21 and January 22 are normal EEJ days. It is observed from the figure that on January 21 and January 22 EEJ shows typical EEJ pattern peaking around 12:30 IST with values 67 nT and 65 nT respectively. On the other hand, on CEJ days i.e., January 28, January 29 and January 30, the magnetic field shows typical pattern of CEJ with maximizing time 15:10 IST, 14:00 IST and 16:00 IST respectively. The magnetic field values on all these days recover to their normal level at around 17:00 IST.

Figure 6.2 (b) depicts the time variation of post sunset $V_d$ on these days. Here also it is clear that during normal electro jet days (January 21 and January 22), $V_d$ shows clear-cut signatures of PRE around 19:00 IST with maximum values of 30 m/s and 35 m/s respectively. However, as mentioned earlier during CEJ days this PRE is observed to be either weakened or totally inhibited. On January 28, $V_d$ shows a downward tendency from 18:00 IST onwards and reaches a negative maximum of 7 m/s around 19:15 IST. On January 29, it shows a downward trend from 18:20 IST and reaches a negative maximum around 19:45 IST. Similarly, on January 30 also $V_d$ exhibits a decreasing tendency from 1800 IST and reaches a negative maximum at around 19:30 IST. In general, on all the three CEJ events, $V_d$ never exceeds the value of 25 m/s. The same observation is found to be valid on Ionosonde measured drifts (figure 6.2 c). Here the ionogram traces were not available for January 22, so $dh'/dt$ cannot be plotted.
Figure 6.2: (a-c) EEJ induced surface magnetic field values, Radar measured drifts $(V_d)$ and Ionosonde measured vertical drift $(dh'/dt)$ during for the year 2006.

The inhibition of PRE during CEJ events is further evident from the evening time $h'F$ variation as depicted in Figure 6.3a and 6.3b. It is well evident from the figure that $h'F$ never exceeded above 260 km on CEJ days during both the years whereas on normal EEJ days it rises beyond 280 km.
It is to be mentioned here that, among the days analyzed in the year 2004, January 8 and February 24 were spread with occurrence time 19:30 IST. But the trend of $V_d$ for both these days can be understand much before the occurrence time of spread.

![Figure 6.3: $h'F$ variations for the years 2004 and 2005](image)

### 6.1.3 Discussion

A number of studies have been carried out on the electro dynamical drift of equatorial F region using different techniques. Neutral wind and the electric field are the two important parameters, which play important role in the dynamics of lower altitude ionosphere/thermosphere system. Normally post sunset vertical rift can be affected by many factors. The essential characteristics of the evening enhancement are known to be the result of the dynamo effect by F-region neutral winds and the effect of rapid changes in E-region electric conductivity at sunset. As is known, the F region dynamo will be active after sunset and the in-situ electric field in the F region will map to E region and enhances the eastward electric field at the dawn-dusk terminator. The combination of both E and F region electric field from low latitude again map to equatorial F region via highly conducting magnetic field lines and thereby causing PRE. Since EEJ is taken as a proxy for the strength of the electric field over the low latitude E region, one could see that the strength of EEJ is related to the strength of PRE. During the CEJ days eastward electric field responsible for PRE will be either weakened or reversed in its direction, which will suppress the mechanism of PRE.
Recently Sreeja et al., (2009) reported the relationship between the electric field variations and the PRE and its association with the occurrence of Equatorial Spread F (ESF). They found a good correlation between the maximum morning gradient in $\Delta H$ and $V_d$. The plausible mechanism given was, when the morning gradient in $\Delta H$ is high, the strength of EIA is also expected to show an enhancement due to the stronger E region electric field. The intensification of EIA reduces the plasma density over the magnetic equator (trough of EIA) through increased vertical $E \times B$ drift. The decrease in the plasma density over the magnetic equator reduces the ion drag on the neutrals and hence the zonal wind is enhanced prior to sunset. The enhanced anomaly will increase the F- to E-region flux tube integrated Pedersen conductivity (Crain et al., 1993 a). Both these changes in turn produce large eastward electric field and hence cause a large post sunset vertical drift of the F-layer.

Nevertheless there have not been any studies, which addressed the effect of counter Electrojet (CEJ) on post sunset F region electrodynamics. In this context, the present study brings out some new aspects of PRE and variations of $V_d$ during CEJ days. In contrast to EEJ days PRE on CEJ days are inhibited and $V_d$ shows a negative trend from post sunset hours. Due to various reasons including the operational difficulties, the simultaneous data from HF Radar, Ionosonde and the magnetometer were available only for a few days.

In the present study, the interesting aspect is that, even though the magnetic field came back to the normal level before the sunset, the PRE showed a clear-cut signature of the reversed electric field. As can be seen from the Figures, magnetic field on CEJ days comes to normal level around 17:00 IST, well before the PRE. Another interesting observation is that the occurrence time of the CEJ plays an important role in the inhibition of PRE, i.e. whenever the occurrence time of CEJ is delayed the PRE is totally inhibited or $V_d$ shows maximum downward drifts. A possible explanation for the observed result is as follows. Since the EEJ was weakened or even reversed in its direction on CEJ days the accumulation of charge particles in the dawn-dusk terminator is reduced. This in turn will reduce eastward electric field at the dawn-dusk terminator and thereby inhibit the PRE. Another possibility is the existence of the reversed field in the F-region due to the reversal of the zonal wind. Even though EEJ induced magnetic field recovers to normal level from 17:00 IST (Refer Figure 1a and 2a), it doesn’t mean that electric field is absent
at F-region. Eastward/Westward electric field will persist and that is responsible for PRE and $V_d$ variations. Over equatorial latitudes, any change in the east-west electric field will get reflected in the vertical drift driven by $E \times B$ mechanism. Among the days analyzed two days were spread (January 08 and February 24, 2004) with occurrence time 19:30 IST and 19:45 IST respectively. Therefore the estimation of $V_d$ after the occurrence of ESF on these days may not be accurate.

There are other mechanisms suggested for explaining the PRE. According to Haerendel and Eccles (1992) the fundamental driver of the PRE is the zonal neutral wind in the equatorial F-region, but the EEJ region is the source for the PRE. The authors proposed that zonal Cowling conductivity gradients in the EEJ at sunset in combination with the current demands from the evening F-region dynamo may have a casual relationship with PRE. Our results are in agreement with the mechanism proposed by them, i.e. when the electric field reverses to westward (CEJ) PRE is inhibited and $V_d$ how negative trend from post sunset hours. As mentioned earlier time of occurrence of maximum CEJ is also related to the minimizing time of $V_d$. Thus it is obvious that when the strength of CEJ comes earlier that is manifested later in the $V_d$ and vice versa.

6.1.4 Summary

The details of the observational results relating to the plausible linkage of the daytime CEJ related electric field variability’s with the vertical drift variations under magnetically quite conditions is presented in the work. The inhibition of PRE and the relation between CEJ maximizing time and $V_d$ minimizing time is also described in the present work. The interesting observation is that, even though the magnetic field came back to the normal level before the sunset, the PRE showed a clear-cut signature of the reversed electric field.