HF Doppler radar observations of vertical and zonal plasma drifts–Signature of a plasma velocity vortex in evening F-region

C V Sreehari\textsuperscript{1}, C Bhuvanendran\textsuperscript{2} & S R Prabhakaran Nayar\textsuperscript{1}

\textsuperscript{1}Department of Physics, University of Kerala, Trivandrum 695 581, Kerala, India
e-mail: srp@md2.vsnl.net.in
\textsuperscript{2}Department of Physics, Devaswom Board College, Sasthamcotta, Kollam 690 521, Kerala, India

Received 28 July 2005; revised 23 January 2006; accepted 14 April 2006

The simultaneous vertical and zonal plasma drift measurements using an HF Doppler radar system around March equinox of 1995 at the magnetic equatorial station, Trivandrum, India (8.33°N, 77°E, dip 0.4°N) are analyzed to evaluate the vector plasma drift at the F-region. It is found that the pre-reversal enhancement in vertical drift and the direction change of zonal drift from westward to eastward occur almost simultaneously. The velocity vector in the vertical-zonal plane, the resultant of vertical and zonal velocities, exhibits a gradual rotation in the evening time. The characteristics of velocity vector clearly promulgate the existence of a plasma velocity vortex in the equatorial F-region during post-sunset period.

Keywords: Equatorial ionosphere, HF Doppler radar, Vertical drift, Pre-reversal enhancement, Zonal drift, Plasma drift vortex

PACS No: 94.20.Ww

1 Introduction

The nearly horizontal geometry of geomagnetic field over magnetic equator causes unique electrodynamic phenomena in the equatorial E- and F-regions. Due to enhanced thermospheric zonal neutral wind (U) in the evening, polarization electric fields are formed through the $\mathbf{U} \times \mathbf{B}$ mechanism, which drive transverse $\mathbf{E} \times \mathbf{B}$ plasma drifts\textsuperscript{1}. The polarization electric field (E) will have a prominent vertical component and a small zonal component. The vertical electric field drives zonal plasma drift and zonal electric field drives vertical plasma drift, respectively. The vertical plasma drift exhibits an interesting phenomenon during the post-sunset period called the pre-reversal enhancement (PRE) – an upward enhancement of plasma drift after the sunset, followed by a gradual reversal to the downward direction after reaching a maximum. Correspondingly the electric field enhances in the eastward direction followed by a westward reversal after the PRE. This phenomenon can be explained in different ways – (i) due to mapping of an additional zonal electric field that is formed at the conjugate ionospheres along the sunset terminator;\textsuperscript{2} (ii) due to divergence of upward EEJ currents;\textsuperscript{3} (iii) due to curl-free nature of the equatorial electric fields\textsuperscript{1,4} and (iv) due to a longitudinal gradient in conductivity and absence of short circuiting effect of E-region\textsuperscript{5}. The zonal plasma drift changes its direction from westward to eastward around the time of PRE, which is associated with the turning of vertical polarization electric field from upwards to downwards.

A plasma drift velocity vortex in the zonal-vertical plane during the post-sunset period at equatorial latitudes was excellently imaged using Jicamarca incoherent scatter radar\textsuperscript{6}. Post-sunset height gradients (vertical shears) in F-region zonal plasma drifts inferred from earlier Barium cloud release and coherent backscatter radar experiments\textsuperscript{7-9} as well as the height gradients in F-region vertical plasma drifts\textsuperscript{10,11} also appear to be associated with the evening velocity vortex. From Jicamarca radar observations, the velocity vortex is centered about 250 km altitude and about 2000-3000 km east of the sunset terminator. Eccles \textit{et al.}\textsuperscript{12} also reported experimental and theoretical features of velocity vortex. Their data came from 150°-210° longitude sector measurements of San Marco D satellite. The observed vortex in $\mathbf{E} \times \mathbf{B}$ drifts implies a divergent post-sunset electric field structure at F-region heights, with electric field vectors pointing toward the core region of the velocity vortex from all directions on the zonal plane. This field geometry requires the presence of a negative space charge region in the core of the vortex\textsuperscript{6}. Modelling studies\textsuperscript{5,13} explaining the PRE favours the existence of a negative charge accumulation near the
sunset terminator. The post-sunset vortex seems to be the critical phenomenon existing in the evening F-region and all other mechanisms such as zonal drift direction change, PRE of vertical drift, evening spread-F, etc. occur due to it. So it is important to conduct studies related to equatorial electrodynamic drifts in the perspective of velocity vortex and the present work is aimed in this direction. The present paper deals with the investigation of the rotation of velocity vector around the sunset period using the observations made during February-April 1995. The rotation of the plasma drift vector is attributed to the presence of a plasma drift vortex existing over the sounding station.

2 Measurement techniques and evaluation of plasma drifts

The simultaneous zonal and vertical plasma drift data were recorded using a 5.5 MHz HF Doppler radar13-17 located at Trivandrum (8.33°N, 77°E, dip 0.4°N). The HF Doppler radar system consists of a high frequency pulse transmitter, three phase coherent receivers with quadrature detection, a frequency synthesizer with stability better than one part in 107 and transmitting and receiving antennas. The transmitter radio frequency, the receiver injection frequencies and the modulation and gate pulses are all derived from the same master frequency synthesizer. The system is therefore phase coherent. The RF signal from frequency synthesizer with a pulse width of 100 μs and a pulse repetition frequency (PRF) of 50 Hz is fed to the input of the transmitter, in which it undergoes various stages of amplification. The final output is a pulse with a peak power of about 3 kW, which is fed to the transmitting antenna. The transmitting antenna is a three-element folded dipole at a height of λ/4 from the ground. The balanced RF output of the transmitter is fed to the antenna by an open parallel wire feeder of impedance 600 Ω.

The vertically transmitted pulse signal gets reflected back from the ionosphere and is received by half-wave dipole antennas, situated at the corners of a right-angled triangle with antenna spacing of 100 m. The received signal is fed to phase-coherent receivers through coaxial cables from the antenna. The received signal is generally Doppler shifted and has a frequency of 5.5 MHz ± fD, where fD is the Doppler frequency. The receiver comprises a conventional mixer and IF amplifier. The IF signal in the receiver is phase compared against the two-phase quadrature signals derived from the frequency synthesizer in two separate phase detectors. The two quadrature channels of each receiver are identified as $A \cos \phi$ and $A \sin \phi$ components, where $A$ and $\phi$ are the instantaneous amplitude and phase of the received signals. The output of the two-phase detectors is separately amplified and band limited before sampling and holding the Doppler signal for amplitude recording.

The Doppler frequency signal is sampled at the rate of 1024 samples per second using a digital data acquisition system and is then recorded on a computer. The four input channels of the data acquisition system are used to sample the output of the three receivers (sine channels) and are recorded along with the cosine channel of the central antenna. The vertical and horizontal motions of the ionosphere are estimated from the Doppler data recorded in the computer, and the virtual height of the ionosphere is directly read from a gate delay counter.

From the 1024 digital values obtained for each channel in one minute, the spectra of the Doppler signal are evaluated using Fast Fourier Transform (FFT). The mean Doppler frequency is obtained by

$$\bar{f}_D = \frac{\int fP(f)df}{\int P(f)df}$$

The spectral analysis gives 1024 frequency and power values. The mean Doppler frequency is the one corresponding to the peak power, from which the magnitude and sense of direction of vertical drift is found out. Here $P(f)$ denotes arbitrary Fourier power values corresponding to each frequency $f$ in the power spectrum. The vertical plasma drift ($V_z$) for operating wavelength $\lambda$ is obtained as

$$V_z = \frac{-\bar{f}_D \times \lambda}{2}$$

For the measurement of the zonal drift, we made the observation using the spaced receiver antennas. Using the conventional similar fade method of Mitra18, the horizontal speed and direction of the plasma drifts are derived. Finding the time delay between the signals received at the central and west antenna by cross-correlation method, estimation of zonal drift have been carried out. The signals from antennas are recorded in digital files, which contain 1024 samples for one minute. Then the cross-correlation between the central and west antenna signals is carried out by taking 128 points from each set. The time delay corresponding to maximum correlation coefficient is identified and from this
value, while the zonal components of the plasma drift velocity is calculated every one minute.

While doing the cross-correlation with 128 points, the value of correlation coefficient needs be greater than 0.25 to obtain 99% significance. To obtain reliable estimates of the zonal drift, data sets with correlation coefficient less than 0.25 were discarded. Due to this omission, data gaps are present intermittently in zonal drift measurement. The zonal drift values are averaged over half-an-hour intervals, so as to remove the problem of data gaps. The vertical plasma drift values with one-minute resolution are also averaged over each half-an-hour to compare with the zonal drift. The uncertainty in vertical drift estimation is very small (~ 0.25 ms$^{-1}$) and it arises from the sampling rate of the Doppler signal. The uncertainty in zonal drift estimation comes from the computation of the time delay. The expected error in the zonal drift is variable, depending on the range of zonal drift value. For the present study, the zonal drift ranges between 65.6 and 15.8 ms$^{-1}$ and the corresponding uncertainties ranges between 5.47 and 0.287 ms$^{-1}$.

3 Observation of vertical and zonal plasma drifts and their characteristics

The diurnal variation of the vertical and zonal plasma drifts presented in Fig.1 is based on the observations conducted for eight days—February 24, 25, 27, 28, March 23, 24, April 03 and 06 in 1995. The observation days include both magnetically quiet and active periods, with the magnetic activity index $A_p$ varying from 1 to 34. The F-region vertical drift velocity is found to have a typical pattern around the sunset period, as evident from the mean vertical drift of all the eight days shown by thick line in Fig. 1(a). The vertical motion of the equatorial ionosphere due to $\mathbf{E} \times \mathbf{B}$ drift is generally upward in daytime and downward in nighttime. The vertical drift reaches a maximum upward value after sunset. After reaching the maximum, the magnitude of vertical plasma drift slowly decreases and then reverses its direction and in general remains downward in the midnight period. At dusk, the upward drift velocity increases for 1 to 2 hours prior to the drift reversal. This is called the evening enhancement, or pre-reversal enhancement (PRE), of the equatorial ionospheric zonal electric field. 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.

The variation of the mean of zonal drift velocities observed on all eight days is shown as a thick line in Fig. 1(b) along with daily zonal drifts. The pattern shows that the zonal drift is westward during the
afternoon and eastward during the night with a transition occurring between 1815 and 1900 hrs LT. As seen from Fig. 1(b), the afternoon westward drift is almost constant with a mean velocity of about 27 m/s. The nighttime eastward drift increases to a broad mean maximum of about 60 m/s occurring between 2130 and 2300 hrs LT. The variations shown for each individual day shows that the maximum nighttime eastward velocity varies from 60 to 80 m/s.

It is observed that, on all the days, the maximum of pre-reversal enhancement almost coincides with the time of reversal of the zonal drift from westward to eastward. This is evident from Fig. 1, comparing the mean values of vertical and zonal drifts. The data resolution for the vertical and zonal drifts is 30 min. When individual days are taken, the PRE peak and zonal drift reversal falls within the same 30 min interval. Moreover, for six days, out of the eight days presented in this work, there is excellent coincidence between the zonal drift reversal and PRE. For the other two days, the zonal drift reversal takes place relatively earlier. For one of these two days (March 23, 1995) the zonal drift reversal takes place relatively earlier at 1730 hrs LT. Here, the vertical drift reaches a value of 14 m/s and it slightly increases to reach a maximum of 16 ms$^{-1}$ at 1800 hrs LT, i.e. this day the PRE maximum is almost constant over the period 1730-1815 hrs LT sector and it coincides with the zonal drift reversal. On the other day (25 Feb., 1995), the zonal drift reverses at 1800 hrs LT; there is a simultaneous PRE maximum of 20 ms$^{-1}$. The latest zonal drift reversal time is 1900 LT and this coincides with a maximum PRE with 31.9 ms$^{-1}$ in the top panel. The drift velocity discussed does not correspond to a fixed height, but to a gradually varying height as seen in Fig. 1. Accordingly to this observation, the mean observation height is raised from an altitude of about 320 km to about 395 km during the PRE period and then drifts down to an altitude of below 300 km after 2300 hrs LT. The coincidence between vertical drift maximum and zonal drift reversal, and the variation in reflection height have significant effect while interpreting the behaviour of zonal and vertical plasma drifts as signature of a velocity vortex.

The behaviour of vector plasma drift in the equatorial zonal-vertical (local time-height) plane in the evening time is shown in Fig. 2. The local time on the X-axis of the figure can be viewed to represent the east-west space in equatorial F-region for understanding the vector drift behaviour as manifestation of a velocity vortex. In such an interpretation, one hour increase along the horizontal axis corresponds to 15° longitude or ~ 1670 km eastward displacement. The mean values of zonal and vertical drifts with 30 min resolution on all the eight days were taken and are combined and plotted as a
velocity vector plot. The average standard deviations are 17 ms$^{-1}$ for the half-hourly zonal drifts and about 5 ms$^{-1}$ for the corresponding value of vertical drifts. Each velocity vector is the resultant of mean zonal and mean vertical drift velocity components of eight days and is fixed at the corresponding local time-height co-ordinates. The scale of vertical drift and zonal drift are marked on the figure. Each grid box in the figure has a dimension of 10 ms$^{-1}$ in the vertical direction and 100 ms$^{-1}$ in the zonal direction. So, from the size of the vectors, one can get an idea of the magnitude of vertical and zonal drifts. The magnitude of the velocity vector is given by $\sqrt{V_{\text{vertical}}^2 + V_{\text{zonal}}^2}$ and the direction of the vector is given by $\tan^{-1}(V_{\text{vertical}}/V_{\text{zonal}})$. The vectors slanting towards left side (from the vertical direction) contains westward zonal drift and the vectors slanting towards right side contains eastward zonal drift. The vectors pointing up represents upward vertical drift and vice versa.

From 1530 to 1800 hrs LT, the westward drift gradually decreases in magnitude and the upward vertical drift gradually increases in magnitude. Around 1830 hrs LT, i.e. some time around local sunset, the vertical drift reaches its maximum ($V_{\text{zp}}$ of PRE) and the zonal drift changes its direction from westward to eastward. Afterwards the vertical drift decreases, turns downward around 2000 hrs LT and sustains more or less downward throughout the night. The zonal drift moderately enhances and sustains consistently eastward throughout the night as seen from Fig. 2. The size of the arrow of each vector also denotes the magnitude of the zonal drift, i.e. the arrows become more and more wide as zonal drift increases. The overall behaviour of vertical and zonal drifts evident from Fig. 2 clearly reveals the existence of a velocity vortex over Indian peninsular region. The velocity vector in the vertical-zonal plane, the resultant of vertical and zonal velocities, exhibits a gradual rotation in the evening time, which is a clear signature of a plasma drift vortex existing at equatorial F-region during this time. The HF Doppler radar observation point in ionosphere traverses in time through a dome like path around the two-dimensional velocity vortex obtained from Jicamarca measurements$.^6$ The centre of the vortex occurs at a time when the vertical component of the plasma drift vanishes and the vector drift is purely eastward. From HF Doppler radar observations presented in Fig. 2, the vertical component of the plasma drift vanishes around 2000 hrs LT and the velocity vector rotate around this time. The centre of the velocity vortex is situated at this location. In other words, the centre of the vortex is situated nearly 2500 km east of the sunset terminator or about 1.5 h past the local sunset, which is around 1833 hrs LT.

4 Discussion

The equatorial F-region zonal and vertical plasma drifts are driven by the vertical and zonal electric fields respectively, which are coupled along the magnetic field lines to the conjugate E-region, away from the magnetic equator. The nighttime F-region electric fields are mainly governed by the F-region dynamo action driven by thermospheric zonal wind. With no shorting of the electric fields by the E-region in the evening, polarization electric fields will develop in the F-region by thermospheric zonal neutral wind, through the $\mathbf{U} \times \mathbf{B}$ mechanism. Then this polarization fields induce $\mathbf{E} \times \mathbf{B}$ drifts in F-region ionospheric plasma. At dusk, the upward drift velocity increases for 1-2 h prior to the drift reversal. This is established as due to the evening enhancement or pre-reversal enhancement of the equatorial zonal electric field, which is formed as a part of the vertical polarization electric field. A quantitative evaluation of the zonal wind control of the pre-reversal vertical drift enhancement was carried out using a numerical code developed by Batista et al.$^8$. Their results show a linear relation between the maximum amplitude of the pre-reversal vertical drift enhancement ($V_{\text{zp}}$) with the corresponding zonal wind values.

The F-region zonal plasma drift is generally westward during daytime and eastward during nighttime. Herrero et al.$^{20, 21}$ compared the equatorial zonal neutral wind measured by the WATS instrument on the DE-2 satellite during 1981 with the zonal ion drift measured by the ground based incoherent scatter radar data of Jicamarca. They observed that the zonal ion drifts show a similar behaviour with the zonal wind. They also found that at night, both the velocities almost coincide and a significant difference occurs only during daytime. Rishbeth$^1$ found that the ratio of the zonal ion drift to the zonal neutral wind is significantly smaller than 1.0 during daytime and closer to 1.0 at night. With no shorting of the F-region electric fields by the E-region, the F-region plasma drifts along with the thermospheric zonal wind and depending upon the extent of shorting, the plasma lags the zonal wind. Therefore the zonal drift observed during the post-sunset period presented in this work is similar in pattern to that of zonal neutral wind, since both have almost the same magnitudes during this time.
The gross pattern of the diurnal variation of zonal plasma drift observed in the March equinox of 1995 is similar to that observed earlier by Balan et al. The zonal drift measured at Trivandrum by Balan et al. was about 30 ms\(^{-1}\) westward in the noon and 110 ms\(^{-1}\) eastward at around 2100 and 2300 hrs LT, respectively when the solar radio flux index was 128. In the present estimation of zonal drift, under conditions of low solar activity (average solar flux \(\sim 75\)), the westward value is 27 ms\(^{-1}\) in the afternoon and the mean eastward velocity is about 55 ms\(^{-1}\) at night as seen from Fig. 1. Comparing the earlier observations of Balan et al. at Trivandrum with the present study, it is noticed that the mean eastward zonal wind velocity at night increases with the solar activity and the westward drift in the afternoon remains almost the same. Fejer et al., using Jicamarca data, also found that the daytime westward drift does not change with solar flux value but the nighttime eastward velocity increases linearly with solar flux at all seasons. The difference in the observed magnitudes of the eastward zonal drift at night between various studies can be attributed to the difference in the height ranges of observations. The height range of the observations of Balan et al. is 325-475 km in the PRE time and then falls to 300 km after 2300 hrs LT, which was made during high solar activity period. Whereas the corresponding height ranges of the present observations made during low solar activity are 320-395 km and 300 km, respectively.

The results of simultaneous observation of the F-region zonal and vertical plasma drifts in the equinox period presented in Figs 1 and 2 establish that there exists a relation between the enhancement of vertical drift and the reversal of zonal drift. From a simulation of the global atmospheric dynamo, Crain et al. have proposed a simple mechanism, by which a reversal of the zonal wind from eastward to westward in the F-region may produce enhanced zonal electric field. They have also shown that the enhancement of the zonal electric field is well correlated with the reversal of the zonal drift in the region, where the dominant dynamo driver exists. The entire characteristics of evening zonal and vertical drifts described in the present study can be attributed to the presence of a velocity vortex existing at the equatorial ionosphere.

The plasma drift vortex implies an evening F-region electric field, which is curl-free, but with a finite divergence. As long as there is no local time variation of magnetic field, electric field will remain curl-free. If one computes \(\nabla \times \mathbf{V}\) after substituting \(\mathbf{V} = \mathbf{E} \times \mathbf{B} / B^2\), it will be clear that \(\nabla \cdot \mathbf{E} \neq 0\), as there is a velocity vortex. This field geometry requires the presence of a negative space charge in the core region of the vortex and the electric field point inward to the centre of the vortex. The post-sunset charging of the bottomside F-region was also suggested by Rishbeth. Kudeki and Bhattacharyya remarked that if negative space charge accumulation to the east of the terminator was a consequence of the sunset, then the charged region would be constrained to follow the westward progression of the terminator, including a local time invariant pre-reversal enhancement and vortex structure in the ionosphere at all longitudes, as they have assumed in the interpretation of their drift maps. The present observations, though not as explicitly as Jicamarca results, confirms the presence of a plasma drift vortex centred around 2500 km to the east of the sunset terminator over Indian longitude sector. Thus, the similar occurrence of velocity vortex over South American and Indian longitudes emphasizes that the negative space charge accumulation is a consequence of sunset and the plasma drift vortex structure is a local time invariant ionospheric feature over all longitudes.

The evening characteristics of zonal and vertical plasma drifts that have been studied for several years can be viewed as manifestations of the spatial structure of the F-region plasma drift vortex. Also, many other phenomena like spread-F can be studied in the perspective of the plasma drift vortex. Jicamarca measurements clearly reveal that bottomside spread-F commences near the centre of the vortex. The observation of vertical and zonal plasma drifts at multiple heights at this site using the newly developed multi-frequency HF Doppler radar will give better picture of the structure of plasma drift vortex.

5 Conclusions

(i) Simultaneous observation of both vertical and zonal plasma drifts at the equatorial F-region show that the pre-reversal enhancement of the vertical plasma drift is well correlated with the reversal of the zonal drift.

(ii) The relation between vertical and zonal plasma drifts at the equatorial F-region and their time evolution are manifestations of the plasma drift vortex existing in that region.
Acknowledgements

The work was partially supported by Indian Space Research Organization (ISRO) through a project under its RESPOND program.

References