Multi-frequency HF Doppler radar observations of vertical plasma drift—Preliminary results

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A multi-frequency HF Doppler radar system suitable for ionospheric F-region vertical drift studies has been installed at the magnetic equatorial station, Trivandrum, India (8.33° N, 77° E, dip 0.4° N). The speciality of the system is the usage of three frequencies (2.5 MHz, 3.5 MHz and 4.5 MHz) in a nearly simultaneous manner, which gives F-region vertical plasma drifts at three successively higher altitudes over the sounding station. The radar is mainly used to study the nocturnal vertical drift characteristics such as pre-reversal enhancement, onset of spread-F, short-period fluctuations, etc. An equinoctial maximum in pre-reversal enhancement of vertical drift is noted. Characteristics of short-period fluctuations are studied. Preliminary results of multi-frequency sounding are presented.

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

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1 Introduction

The plasma drifts in equatorial F-region are driven by neutral winds in magnetic meridian direction and electric fields in the transverse directions. The vertical and zonal F-region plasma drifts are produced by the zonal and vertical electric fields, respectively. In the equatorial ionosphere, where the intensity of the geomagnetic field varies significantly with longitude, an electric field of 1 mV/m corresponds to F-region plasma drift of about 30-40 m/s. Electric fields from both tidal wind driven E-region dynamo and thermospheric wind driven F-region dynamo play important role in the electrodynamics of low-latitude F-region. At the geomagnetic equator, since the field lines are nearly horizontal, the observed vertical plasma drift can be directly attributed to $E \times B$ effect due to the zonal electric field. The pre-reversal enhancement is a regular feature observed in the global equatorial F-region vertical plasma drift in the evening time and its study is one of the major goals of this work. The equatorial F-region zonal electric field is small and eastward in the afternoon. In the evening time, the eastward field increases and reaches a maximum value just after sunset and then decreases and reverses in direction to westward. Mainly, two theoretical suggestions have been put forward, after the studies of models, to explain the observed pre-reversal enhancement in zonal electric field. But Eccles remarked that these two may be only the supporting mechanisms and the basic physical thrust for the pre-reversal enhancement comes from the curl-free nature of vertical electric field as proposed by Rishbeth. In this context, Fesen et al. asserted that the pre-reversal enhancement remains poorly understood theoretically. Hence, it is very relevant to conduct experimental investigations during the sunset period in view of getting a clear-cut picture of the electric field behaviour.

Extensive studies on the equatorial ionospheric drifts and electric fields have been conducted using Jicamarca Incoherent Scatter Radar in Peru and from radio measurements over India and Brazil. Satellites like DE-2, AE-E and San Marco-D have also provided valuable data of plasma motion at the low latitude ionosphere. A detailed overview of the techniques and results can be obtained from a review by Fejer. A 5.5 MHz HF Doppler radar operated at the University of Kerala, Trivandrum, from 1982 to 1995, helped to understand many interesting features of ionospheric drifts. A new frequency
agile HF Doppler radar is now operational here from June 2003 onwards and first results obtained from this facility are presented in this paper.

2 System details

The important specifications for the radar system are given in Table 1 and a simplified block diagram is given in Fig. 1. The HF Doppler radar is a monostatic pulsed coherent HF Doppler radar capable of operation at three frequencies, viz. 2.5 MHz, 3.5 MHz and 4.5 MHz. The system can work both in single-frequency (any one frequency of the three) and in multi-frequency modes. The HF Doppler radar system was designed, assembled and installed at the University of Kerala. The transmitter, receivers and antenna systems were procured from M/s. Tomco Electronics, Australia. Assembling of systems, installation of antennas and radar, development of hardware and software for data acquisition and analysis were done in-house. For the vertical drift data, the time resolution for single frequency operation is one minute and it can be programmed to get higher resolution. For multi-frequency operation, there is a sequential switching scheme such that the system is operated in one frequency for one minute and after a delay of two minutes the next frequency is operated for one minute and so on. The two minutes delay in between data collections for two frequencies is required for changing the frequency settings. Thus, we are getting nearly simultaneous vertical drift data at two different heights with a time interval of two minutes. It is assumed that the ionospheric conditions change little within these two minutes.

The peak power of the transmitter is 5 kW and the maximum duty cycle is 1%. The transmitter is tuned for operation at 2.5 MHz, 3.5 MHz or 4.5 MHz by selecting appropriate output filter. The pulse width used is 20 μs and pulse repetition frequency (PRF) is 100 Hz. The pulse width and PRF are programmable and their values are limited only by the maximum duty cycle. A frequency synthesizer unit (FSU) produces the basic waveforms required for the transmitter and receiver. The synthesizer uses direct digital synthesis (DDS) technique of signal generation. This results in extremely low phase noise, comparable with the crystal clock that drives it, and excellent frequency and/or phase agility. Three DDS channels generate three output channels. The first channel is dedicated to drive transmitter, while the other two are local oscillator signals for driving receiver.

<table>
<thead>
<tr>
<th>Table 1—Radar specifications</th>
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<tr>
<td><strong>Type of radar:</strong></td>
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<tr>
<td><strong>Frequencies of operation:</strong></td>
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<tr>
<td><strong>Peak power output:</strong></td>
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<tr>
<td><strong>PRF:</strong></td>
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<tr>
<td><strong>Pulse width:</strong></td>
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<tr>
<td><strong>Antenna type:</strong></td>
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<td><strong>Receivers:</strong></td>
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<td><strong>A/D converter:</strong></td>
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<td><strong>Number of FFT points:</strong></td>
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<td><strong>Vertical drift data resolution:</strong></td>
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![Fig. 1—Block diagram of the multi-frequency HF Doppler radar system installed at University of Kerala](image-url)
The antenna subsystem includes two antennas—one for transmission and the other for reception. Each has a length of 60 m and is of three-element folded dipole type with proper loading at the centre and capable for wideband operation in the frequency range of 2-5 MHz. The antennas are horizontally stretched at a height of 20 m from the ground and are installed in a line parallel to magnetic meridian. There are balun-cum-antenna tuner units between radar and antennas, which perform two functions. First function is to provide a balun operation (balanced to unbalanced conversion) to correctly interface the 50 Ω coaxial cable from radar with 600 Ω ladder line feeder that goes vertically up to the antenna feed point. The second function is that they perform impedance matching to ensure that the impedance observed, looking into coaxial cable, is 50 Ω at each of the three operating frequencies. There are three separate L-C matching networks (for three operating frequencies) within both transmitting and receiving baluns. The antenna gets tuned to a desired frequency when the corresponding matching network is selected by a relay that is activated by a DC control signal coming from the radar superimposed on the coaxial cable.

The receiver is capable for quadrature detection of Doppler shifted echoes from ionosphere and has a number of sections, namely, RF gain strip including gain control, in-phase (I) and quadrature phase (Q) mixers, the baseband filters and limiters. The RF gain strip uses a distributed attenuator approach to give a total gain control range of 60 dB in 1 dB steps. It is arranged in such a way that it allows the system to maintain the best possible dynamic range at all gain settings. The output from the RF gain strip is fed to the pair of active mixers that are fed with in-phase and quadrature phase local oscillator signals of the selected frequency from FSU. The mixer outputs are fed to the post-detection filter sets where four bandwidths, namely, 80 kHz, 125 kHz, 160 kHz and 250 kHz, can be selected. These are baseband bandwidths and RF bandwidths are double these figures. The I and Q outputs from the receiver are passed to a signal conditioning circuit prior to digitization.

The trigger pulses for the transmitter are provided from a master pulse generator at the rate specified by the programmed PRF. The same pulses are used in the signal conditioning circuit to gate the pulsed Doppler echo obtained from the receiver. This is realized such that the rising edge of a pulse triggers the generation of a transmitter pulse of already programmed pulse width and the trailing edge of the pulse is made to gate the reflected echo from ionosphere. The gating pulse triggers a sampling circuit whose acquisition time is less than 10 μs. Then the pulsed Doppler echo is sampled and held for the inter-echo period. After the inter-pulse period, the transmitter trigger pulse again goes high and it will come to low state at a time when the next echo is obtained which will trigger another sampling. This process continues automatically giving a continuous Doppler frequency signal, which is fed to the A/D converter. The A/D converter digitizes the Doppler signal with a sampling rate of 34.133 s⁻¹ and stores in the hard disk of a PC. The time delay between the transmitter pulse and received echo is also recorded and the reflection height is calculated from that.

3 Observations of vertical plasma drift and data analysis

The recorded Doppler data are Fourier analyzed to get the prominent Doppler frequency ($f_D$) corresponding to up or down F-region movement. The vertical plasma drift velocity is calculated using the relation, $V_z = -(f_D \times \lambda)/2$, where $\lambda$ is the sounding wavelength. The Doppler spectra obtained from the radar system after Fourier analyses are shown in Fig. 2 for different situations, i.e. (a) when F-region drift is upwards, (b) when F-region drift is downwards and (c) during a spread-F event.

The Fourier analysis has a frequency resolution of 0.0042 Hz. The corresponding resolutions in the magnitude of vertical drift are 0.25 ms⁻¹, 0.18 ms⁻¹ and 0.14 ms⁻¹ for 2.5 MHz, 3.5 MHz and 4.5 MHz, respectively. The receiver, data acquisition hardware and software are accurately standardized after transmitting and recording the synthesized very low frequency signals. It is verified that any data acquisition error will induce a maximum frequency uncertainty of 0.005 Hz or 0.3 ms⁻¹ in terms of vertical drift.

The radar is recording vertical drift data in the evening-morning sector between 1700 hrs LT and 0800 hrs LT with 1 min data resolution. The measured drift velocity, in the strict sense, is apparent as it includes the contribution due to chemical loss induced by recombination reactions. This is to be considered because on some of the days, the reflection height is below 300 km where layer decay is prominent in the evening time. To account for the velocity due to chemical loss, a correction scheme was applied to the measured vertical drift. The major loss reactions in the lower F-layer are
and the loss coefficient (β) is given by, $\beta = k_1 n[O_2] + k_2 n[N_2]$ (Ref. 22). The rate coefficients $k_1$ and $k_2$ are calculated using the relations, $k_1 = 2 \times 10^{-11} (T_e/300)^{-1/2}$ and $k_2 = 7 \times 10^{-13}$ as given by Anderson and Rusch.23 The number densities of $O_2$ and $N_2$ and the neutral temperature $T_n$ are calculated using MSIS-86 model.24 Hari et al.25 have evaluated the electron density scale height at the F-region during evening hours using ionosonde at Trivandrum between 2.5 MHz and 3 MHz as 10 km. Similarly Ramesh and Sastri11 also assumed a scale height of 10 km at 4 MHz for explaining the seasonal variation in F-region vertical drifts. Though there is variation of scale height with altitude, since the present probing altitudes are closer within 30 km, the same scale height is assumed for all the altitudes. As no information about the seasonal and height variation of the scale height at the equatorial ionosphere is available at present, the scale height is taken as 10 km for all the three frequencies and for the entire period of investigation.

The velocity due to chemical loss $\beta H$ is calculated to be 1-2 m/s and is subtracted from the measured drift velocity to get the true electrodynamic vertical drift.

A coordinated observation of HF Doppler radar at the University of Kerala, Trivandrum, with ionosonde at Space Physics Laboratory, VSSC, Trivandrum, was conducted on 08-09 Oct. 2003 to standardize the results of HF Doppler observations. These observations gave similar results on the nature of vertical plasma drift at the equatorial F-region. Both the instruments were operated in single frequency mode at 3.5 MHz between 1800 hrs LT on 08 Oct. 2003 and 0800 hrs LT on 09 Oct. 2003. The ionograms (Fig. 3) obtained from the ionosonde were scaled and after taking 10 min running averages, the vertical velocity values were evaluated by taking the rate of change of the reflection height and compared with the vertical drift obtained from HF Doppler radar.

4 Characteristics of vertical plasma drift at the equatorial F-region

4.1 Day-to-day variations in vertical plasma drift

Typical post-sunset vertical drift profile obtained from the HF Doppler radar on 03-04 Mar., 2004 ($K_p = 3$) as a result of single frequency sounding at 3.5 MHz is shown in Fig. 4. The 30 min running averaged vertical drift data observed by HF Doppler radar presented in Fig. 4 (full line) reveal the general behaviour of the plasma drift at equatorial F-region during the post-sunset period. The curve with circles

![Fig. 2—Doppler spectra: (a) negative Doppler, (b) positive Doppler and (c) Doppler spectrum during spread-F.](image)

![Fig. 3—Sample of ionogram obtained when the ionosonde operated at a fixed frequency of 3.5 MHz.](image)
represents the vertical drift values for Trivandrum obtained by using the global equatorial vertical drift model of Scherliess and Fejer for the same day. The vertical plasma drift observed by HF Doppler radar exhibits deviations from the model calculation both during the pre-reversal and post-reversal periods. However, both the model calculation and observation exhibit the reversal of plasma drift direction at the same time. While the model calculation shows a peak vertical plasma drift value of 12 m/s, the observation shows a value of 22 m/s around 1830-1900 hrs LT. Similarly, during the post-reversal period, the vertical plasma drift exhibits a variety of oscillations in addition to the deviation in the average values of plasma drifts.

The magnitude of the peak value of vertical plasma drift, the time of reversal of the drift and the nature of fluctuations in the plasma drift exhibit day-to-day variations depending on a number of controlling parameters including the interplanetary electric field. The fluctuations observed in the plasma drift pattern may be associated with gravity waves, TIDs or interplanetary electric field fluctuations at the magnetopause.

4.2 Seasonal variation in vertical plasma drift

The seasonal variation of pre-reversal enhancement in zonal electric field is studied using vertical drift data of single frequency sounding at 3.5 MHz, which were recorded from June 2003 to March 2004. For this study, the maximum value of the vertical drift (Vzp) during the time of the pre-reversal enhancement is noted on all available days (70 days of data are used for this study). The seasonal variations of Vzp can be directly attributed to the variations of the strength of the F-region dynamo action with season. It is observed that as season advances from summer to equinox, the magnitude of Vzp increases. During summer the range of Vzp is 10-20 m s⁻¹ and this gradually increases to equinox where the range is 35-45 m s⁻¹. Again as one goes from equinox to winter, the peak value of vertical drift falls to lower values of the range 15-25 m s⁻¹. These results are evident from Fig. 5(a) that shows the seasonal variation of Vzp. The Vzp values in summer (June-August) and winter (November-January) solstices are almost in the same range, whereas both equinoxes (September-October and March-April) have high Vzp values. The data gap between 11 October and 11 November is due to non-operation of the radar. From autumnal equinox to winter Vzp has a descending trend. The peak values of plasma drift during post-sunset period exhibit a strong seasonal variation. The vertical drift at the F-region is generated by the dynamo mechanism operative at both E-region and F-region of the ionosphere. The peaking of the post-sunset enhancement in plasma...
drift during equinoxes is in agreement with the earlier observations\textsuperscript{11,18,19}. Figure 5(b) shows the seasonal variation of the time of occurrence of $V_{zp}$. Fifth degree polynomial fits are evaluated to the data sets and drawn on Fig. 5(b) to reveal the seasonal behaviour. These results are consistent with those reported from Trivandrum earlier\textsuperscript{27}. The time of occurrence of the peak in vertical plasma drift depends on the variation of the sunset time and the rate at which the E-region conductivity reduces. In addition to this, the interplanetary magnetic field condition and the geomagnetic activity also control both the magnitude of $V_{zp}$ and time of occurrence of the peak velocity. Similarly, the time of reversal of the vertical plasma drift direction also gets modified by the interplanetary and geomagnetic activity conditions apart from the F-region dynamo strength. The scattering of data points seen in Fig. 5 can be explained as due to the deviations in peak value of vertical plasma drift caused by the above-mentioned facts.

4.3 Relation between vertical plasma drift and solar radio flux

The pre-reversal enhancement (PRE) depends on the level of solar activity indicated by the 10.7 cm solar radio flux. The variation of PRE with solar activity level is noticed even in short time intervals (within a week). The magnitude of $V_{zp}$ increases with 10.7 cm radio flux. Figure 6 depicts the vertical plasma drift profiles on three days in the same season in the year 2003 under different solar activity levels (23 Nov. 2003 with 178.2 sfu, 25 Nov. 2003 with 170.7 sfu and 12 Nov. 2003 with 98.7 sfu). The increase of PRE with solar activity can be due to the corresponding increases in the equatorial zonal wind and in the ratio of field-line integrated Pedersen conductivities in the F-region and E-regions\textsuperscript{19}.

4.4 Fluctuations in vertical plasma drift

On some days, it is found that the usual vertical drift profiles are superimposed with short period fluctuations. These fluctuations are separated out from the average vertical drift data and are Fourier analyzed. Periodicities in the range 7-30 min were obtained on various days. But most of the days were having fluctuations of period around 15-25 min. Vertical drift profile on 13 Dec. 2003, a day with systematic fluctuations, is shown in Fig. 7 along with the fluctuations in velocity and the corresponding power spectrum.

4.5 Multi-frequency observation of vertical plasma drift

The HF Doppler radar was also operated in multi-

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{fig6.png}
\caption{Vertical drift profiles on three days in the same season with solar flux values of 178.2 (dashed line), 170.7 (thin line) and 98.7 (thick line).}
\end{figure}
frequency mode on selected days. A multi-frequency sounding profile obtained on 03 Feb. 2004 is shown in Fig. 8. The radar operating at three fixed frequencies, viz. 2.5 MHz, 3.5 MHz and 4.5 MHz was used to study the vertical plasma drift variations at post-sunset period. To investigate the altitude dependence of vertical drift, the system was operated at all the three frequencies in a nearly simultaneous manner. Preliminary results show that vertical plasma motion is altitude dependent. The plasma drift was observed to decrease with sounding frequency and the reflecting altitude is found to increase with sounding frequency. From Fig. 8, it is noticed that during the pre-reversal period, the vertical plasma drift has a clear negative height gradient.

5 Discussion

Multi-frequency HF Doppler radar operated in both single and multi-frequency modes during June 2003-March 2004 is used to investigate the characteristics of vertical plasma drift during the evening hours. The vertical plasma drift variation at the post-sunset time is driven by the complex interaction of E-region and F-region dynamic processes. The F-region dynamo produces polarization electric fields, which are short-circuited during daytime by conjugate E-regions that are magnetically linked to the equatorial F-region. During the post-sunset period, due to reduced electrical conductivity of the E-region, the short-circuiting effect gets weakened and F-region polarization field develops, causing an enhancement in the F-region height and vertical drift. Late in the evening, thermospheric wind direction reverses, thereby reversing the plasma drift direction. At the magnetic equator, the observed vertical plasma drift is attributed to the combined effect of vertical electrodynamic effect and the vertical velocity due to the chemical loss arising from changes in the reflection height. The correction in the vertical drift due to chemical loss is evaluated assuming electron density scale height to be 10 km. Though the electron density scale height varies with season and altitude, at present no systematic evaluation of this variation is available. So, for the present work, the values of scale height for the three
The observed vertical plasma drift at the F-region altitudes are assumed to be the same, since the observed altitudes for the three probing frequencies 2.5 MHz, 3.5 MHz, and 4.5 MHz are within 10-30 km. The observed vertical plasma drift at the F-region altitude exhibits a wide variety of day-to-day and seasonal variations. The seasonal variations in the nature of the vertical drift are associated with the changes in the simultaneity of sunset at magnetically conjugate E-layers that are coupled to the equatorial F-region. The day-to-day variations in the vertical plasma drift may be associated with the level of solar activity, solar flux, solar wind, direction of interplanetary magnetic field, magnetic activity and variety of waves in the F-region.

In general, the time of occurrence and magnitude of pre-reversal enhancement and the time of reversal in vertical plasma drift direction are decided by sunset times at the magnetically conjugate E-layers. The comparison of the vertical plasma drift observed using HF Doppler radar at Trivandrum with values obtained using the global equatorial vertical drift model of Scherliess and Fejer as depicted in Fig. 4 reveals the differences between them. Though the pattern of vertical plasma drift evaluated by both the model and HF Doppler radar observations show the pre-reversal enhancement and reversal simultaneously, the magnitude of the pre-reversal enhancement is smaller by about 10 m/s in the model calculation. The peak value of the post-sunset enhancement exhibits a strong seasonal dependence as depicted in Fig. 5. At equinox, sunset occurs simultaneously at both the conjugate E-region points on the two hemispheres. At 1800-1900 hrs LT longitude sector, both conjugate E-regions of an equatorial station are undergoing a simultaneous electrical conductivity weakening. This will enhance the build-up of polarization fields to a maximum and hence the larger pre-reversal enhancement \((V_{zp})\) during equinox. At solstices, the summer hemispheric conjugate E-region point will be sunlit even after the local sunset at equator. Thus, during the solstices, conjugate E-regions at the northern or southern hemispheres will partially short-circuit the F-region polarization fields. Therefore, the short-circuiting will be effective even after local sunset at equatorial F-region and hence the pre-reversal enhancement peak \((V_{zp})\) will have lower values. Similarly, the weakening of E-region dynamo can be referred as a sharp longitudinal gradient in E-region conductivity near sunset. This longitudinal conductivity gradient will be affected by the value of magnetic declination angle, angle between sunset terminator and magnetic meridian and variations in thermospheric winds. The seasonal variation of any of these effects can be reflected in post-sunset ionospheric dynamos and in \(V_{zp}\) values. Apart from dependence of the seasonal variation in the pre-reversal enhancement on the sunset times of the conjugate E-layer, the magnitude of the pre-reversal enhancement depend on the solar activity level as depicted in Fig. 6. Due to the limitation in the availability of vertical plasma drift during active days, the study of this relation is restricted to a few days.

The characteristic features of the fluctuations in vertical drift suggest that medium scale gravity waves could be a potential source for the fluctuations. Acoustic gravity waves occur primarily in the neutral atmosphere and they can drive TIDs in the ionosphere. Medium scale TIDs (having horizontal speeds between 100 and 250 m/s) occurs more frequently than large-scale TIDs in the equatorial region. These medium-scale TIDs can induce zonal electric field fluctuations and this could be the reason for the vertical drift fluctuations having periods around 20 min. The Brunt-Vaisala period, which is of the order of 15 min, sets a lower bound on the periods of medium-scale TIDs at F-region levels. So periods shorter than this critical value may not be due to gravity waves in the F-region. But there can be a considerable shift in the period of a wave due to movement of the medium. The intrinsic period \(\tau\) of an atmospheric wave as seen by an observer moving with a horizontal wind speed \(U\) parallel to the horizontal trace velocity of the wave is related to the period \(\tau\) observed on the ground by \(\tau = \tau_W/(V_w-U)\), where \(V_w\) is the horizontal trace speed observed from the ground. Thus, a wave that appears to have shorter period may actually be a longer-period wave in the windy ionosphere. On some days, short period fluctuations with periods less than 15 min were observed in this study and these can be attributed to longer-period waves in the F-region, where thermospheric winds are quite strong.

Preliminary results of the multi-frequency observation of the vertical plasma drift at the equatorial station, Trivandrum, reveal the altitude dependence of the plasma drift. The plasma drifts observed using frequencies 2.5 MHz, 3.5 MHz, and 4.5 MHz reveal that the vertical drift decreases and the reflection altitude increases with the increase in frequency of operation. On an average, the vertical plasma drift gra-
dient is small and negative during the post-sunset period except a sharp reversal to positive gradient just before the reversal of the plasma drift from upward to downward direction. The diurnal and seasonal changes in the altitude gradient of the vertical plasma drift are to be carried out with longer period of observation.

6 Summary

The multi-frequency HF Doppler radar system at Trivandrum is an excellent facility to study the dynamics of low latitude F-region zonal electric field. A study of seasonal variation of the pre-reversal enhancement is carried out and an equinocial maximum in $V_T$ value is found out. The $V_T$ value is found to increase with solar activity. Short period fluctuations of periods around 20 min associated with vertical plasma drift are studied. The altitude gradient of the vertical plasma drift observed at the equatorial F-region ionosphere around the pre-reversal enhancement period is negative.

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References


