A study is made on the short period fluctuations in the equatorial electrojet parameters at the magnetic equatorial location of Trivandrum (8.5° N, 77° E; dip 0.5° N), during daytime for a number of magnetically quiet days, using coherent VHF backscatter radar observations in the altitude region of 90-115 km. For this study ΔH values at and off equatorial latitudes have also been used. The detailed analysis of radar and magnetometer data show the following: (a) Significant fluctuation amplitudes in the period range of 25-35 min are present in the radar observations at different range bins over and above the dominant diurnal pattern of the height invariant large scale E-W electric field ($E_y$). The same periods do manifest when the radar data products are divided into sub-intervals of 1-1.5 h. (b) Values of $H$ also indicate the same periods as that of radar observations. (c) A decrease in the amplitudes of the fluctuating components in $H$ is seen from equator to low latitudes. The implications of the observations in terms of the possible origin of the fluctuations are discussed.

**Keywords:** Equatorial electrojet; Short period fluctuations; Type I irregularities; Type II irregularities; Coherent radar

**PACS No:** 84.40 Xb; 94.20.–y

### 1 Introduction

In view of the important role played by electric fields in the electrodynamic interaction processes in the ionosphere, both the electric fields as well as their fluctuation amplitudes have been the subject of investigation for many a study. In the past researchers have examined the presence of fluctuating amplitudes with periods of the order of minutes and tens of minutes, superposed on the diurnal large-scale $E_y$ pattern and the seasonal and long-term variability in $E_y$ field. The E-W electric field $E_y$ is derived from the E-W electron drift velocity $V_{ey}$ that in turn is derived from the radar measured irregularity drift velocities. Reddy and Devasia\(^1\) have reported the occurrence of short period fluctuations in the period range of 20-30 min in $V_{ey}$ well correlated with the earth’s magnetic field variations. Somayajulu \textit{et al.}\(^2\) have presented experimental evidence that internal gravity waves could possibly produce observable fluctuations in the electric fields and currents in the electrojet region. Based on a study of the simultaneous observations of E-region irregularity drift velocities by VHF radar at 54.95 MHz and F-region vertical plasma drift by HF radar at 5.5 MHz at the same location of Trivandrum on quiet days. Viswanathan \textit{et al.}\(^3\) have reported on the nature of E- and F-region electric field fluctuations for equinoctial period.

VHF radar observations have been made on four days with a time resolution of 1 min and on several days with 5 min resolution. The experimental techniques, method of analysis and results obtained for two sample days are given in the following sections.

### 2 Experimental techniques and method of analysis

The detailed system characteristics of VHF backscatter radar at Trivandrum are given elsewhere (Reddy \textit{et al.}\(^4\)). It is a 54.95 MHz pulsed Doppler radar with a nominal peak power of 20 kW, pulse width of 20 μs and pulse repetition frequency (PRF) of 500 Hz for E-region studies. The radar antenna is directed westward at 60° elevation. For the radar geometry, negative (positive) Doppler shift corresponds to westward (eastward) drift of irregularities and electrons under the action of eastward (westward) electric field. The data recording and analysis procedure for VHF backscatter radar have been described in Reddy \textit{et al.}\(^4\). The parameters estimated from the radar Doppler spectra are the power (zeroth moment), mean Doppler frequency $\overline{f_D}$ (first moment) and the width of the spectrum (second moment). The value of $\overline{f_D}$ is a direct measure of the phase velocity of the scattering irregularities (Reddy \textit{et al.}\(^4\)), from which $V_{ey}$ and $E_y$ are determined under certain constraints. For condi-
tions like the presence or absence of Type I irregularities the estimation of $E_z$ and other parameters of interest in the ionosphere for varying levels of signal-to-noise ratio and the associated error budgets have been discussed by Reddy et al.\textsuperscript{4} and Viswanathan et al.\textsuperscript{5}

Radar observations conducted during daytime (5-6 h duration) at several altitudes for two magnetically quiet days (26 Dec. 1991 and 7 Jan. 1992) as evidenced by the geomagnetic indices are presented here. Values of $\Delta H$ at and off electrojet latitudes are also used for the study. Only quiet day observations are presented, in view of the fact that disturbance effects on the nature of the electric field and current variations are not considered for the present study. Winter solstice days with very little Type I contamination in the Doppler spectrum has been chosen for the present study, in order to ensure reliable estimates of the electric fields (Viswanathan et al.\textsuperscript{5}).

The $\bar{f}_D$ values at each altitude are subjected to a running mean window of 45 min (corresponding to 9-point moving average window, with each point being obtained at 5 min interval) as the periods of interest are found to be much less than 45 min. The residual $\bar{f}_D$ values are then obtained by subtracting the trend from the individual values. This procedure is carried out for detrending the basic diurnal variations, so as to extract the shorter time scale perturbations in Doppler values. The resulting $\delta \bar{f}_D$ values are then Fourier analysed, to determine the dominant periods and their amplitudes. The $\Delta H$ values at Trivandrum (TRV – dip 0.5 °N), Annamalainagar (ANGR – dip 7 °N), both electrojet stations and Alibag (ALB – dip 25 °N), an off electrojet station, have also been used for the present study. The observed residual $\Delta H$ values $[\delta(\Delta H)]$ are obtained for the stations considered by the same method as outlined above for $\bar{f}_D$ values.

3 Computation of $\delta(\Delta H)$

Corresponding to the dominant period present in $\delta \bar{f}_D$ values, the fluctuating components in the vertical polarization electric field $E_z$ ($\delta E_z$) are determined at different altitudes. The $\delta(\Delta H)$ values are then computed as $[\delta(\Delta H)]_c$, considering the appropriate mobilities of electrons and ions (Banks and Kockarts\textsuperscript{8}), the neutral densities and temperatures from the neutral atmospheric model of Jacchia\textsuperscript{7} along with the average electron density ($N_e$) profile for quiet days. The $N_e$ values used for the calculations are based on rocket borne Langmuir probe measurements at Trivandrum, compiled by Subbaraya et al.\textsuperscript{3}

The $\delta E_z$ value is given as

$$\delta E_z = \lambda \left( \delta \bar{f}_D \right) \left( 1 + \alpha \right) B$$

where $\lambda$ is the radar wavelength, $\alpha = \nu_e/\omega_{i0e}$ and $B$ the earth’s magnetic field. Value of $B$ is taken as $3.9 \times 10^{-5}$ T for Trivandrum. The terms $\nu_e$ and $\omega_{i0e}$ are the collision and gyro frequencies of ions and electrons. Also

$$\delta[j(h)] = (\delta E_z) K_2 N_e$$

where $K_2$ is the Hall mobility, $N_e$ the electron density and $j(h)$ the current density at an altitude $h$. Here $\delta$ represents the residual value of any parameter considered. Again

$$\delta J = \sum \{ \delta[j(h)] \}$$

where $J$ is the altitude integrated current density. The limits of summation from $h_1$ to $h_2$ are considered only for the altitudes of VHF radar signal returns (95-115 km). The value of $\delta E_z$ is deduced at different altitudes for the dominant period of interest present in the $\delta \bar{f}_D$ values (obtained by Fourier analysis) for the whole daytime. Profile of $N_e$ used for the computations is its average value for noontime.

By computing $\delta J$, using the radar observations, $[\delta(\Delta H)]_c$ values are obtained under certain assumptions as follows. Generally, $\Delta H$ observed at a point on the ground is not only due to the overhead currents, but also due to the currents flowing over a latitudinal belt of a few degrees on either side of the overhead point, in addition to induced currents. The latitudinal distribution of $J$ as obtained in the numerical calculations by Devasia\textsuperscript{9} is taken for the computation. Assuming that the shape of the latitudinal profile of $J$ does not vary with time of the day or between different days, the values at different latitudes are computed. In addition, here it is also assumed that $\delta J$ follows the same latitudinal distribution as $J$. Thus the value of $\delta J$ is computed first for Trivandrum and then for other latitudes in steps of 0.1° using the latitude profile. Using the latitudinal distribution of $J$ thus obtained, Biot-Savart law is used to compute $\delta(\Delta H)$ due to currents in the ionosphere (external), i.e., $\Delta H_{ext}$. Generally, the $\Delta H$ variations observed at the ground are the sum of $\Delta H_{ext}$ and $\Delta H_{int}$ (internal due to currents induced by the jet in the earth). Making use of the
known value of \((H_{int}/H_{ext})\) for Trivandrum as 0.39 (Sampath and Sastry\textsuperscript{10}), \(\Delta H\) is found to be equal to 1.39 \(\Delta H_{ext}\). So for the fluctuating components

\[
\delta[\Delta H] = 1.39 \, \delta(\Delta H)_{ext}
\]

(4)

These values are then compared with the observed residual values \([\delta(\Delta H)]_o\) obtained using magnetograms.

The errors in the computation of \(\Delta H\) have been discussed in Vikram Kumar \textit{et al.}\textsuperscript{11} Since only the fluctuating components are considered, the errors associated with base magnitudes of \(\Delta H\) and \(\overline{f_D}\) do not affect the fluctuations. Even small magnitudes of the fluctuating components are significant, as the larger period diurnal trend has been removed in the estimation of the fluctuations.

4 Results

The \(\delta f_D\) values are obtained for different altitudes in the range of 96-109 km for the two quiet days considered. Outside this altitude region, the radar signals are not present during daytime continuously, so as to facilitate the estimation of the dominant periods from the \((\delta f_D)\) values. In Figs 1-4 are shown samples of daytime variations of computed and residual \(f_D\) values on two quiet days of 26 Dec. 1991 \((A_p = 9)\) and 07 Jan. 1992 \((A_p = 8)\) in the altitude region of 101-109 km. The \(Y\)-axis scale on the left and right correspond to \(\overline{f_D}\) and \(\delta f_D\) values, respectively. In each panel the \(\overline{f_D}\) variations and the long period trend (dashed curve) are shown on the top and the \(\delta f_D\) variations are shown below that. It is seen that quasi-periodic fluctuations of significant amplitude are superposed over the normal large-scale diurnal variations of the eastward electric field. On these days, throughout the EEJ altitude region (95-110 km) observed by the radar, only Type II spectra (corresponding to gradient drift instability) and velocities less than the normally
expected E-region Type I velocities have been observed.

In Figs 1-4 a dominant period in the range of 25-35 min with significant fluctuation amplitude is seen for both the days. The residual values are subjected to Fourier analysis and the results are shown in Fig. 5. The top panel shows the dominant periods corresponding to the $\delta f_D$ variations on 26 Dec. 1991, while the bottom panel shows the same on 07 Jan. 1992. The altitude is given on the top right of each box. The dominant periods are in the range of 30-35 min for the two days as has been seen from Figs 1-4. The amplitudes of the dominant periods are typically of a few Hz range. The dominant amplitudes for different altitudes for the two days are shown in Table 1. The errors in the estimated amplitudes corresponding to the dominant period are found to be $\pm 0.45$ Hz. A cross-correlation analysis has been carried out for the Fourier spectra obtained at different altitudes. The correlation coefficients lie in the range 0.4-0.5 for 26 Dec. 1991, while they lie in the range of 0.3-0.4 for 7 Jan. 1992. The statistical significance of the estimated correlation coefficients is examined using the $t$-statistics of the distribution of correlation coefficients given as

$$T = r^{0.5} / (1 – r^2)^{0.5} \quad \ldots (5)$$

where, $f = (n – 2)$ corresponds to the degree of freedom with which the quantity is distributed as $t$, $n$ the number of data points and $r$ the correlation coefficient. The $t$-test shows that the correlation coefficients for the two days are highly significant (99% confidence level). It is to be noted that the correlation coefficients for the two days are relatively lower for 7 Jan. 1992 in comparison with 26 Dec. 1991. Further the cross-spectral correlation reveals that there is highest correlation at the frequencies corresponding to the dominant periods of interest in the present study.

Table 1 – Dominant amplitudes obtained from $\delta f_D$ values at different altitudes for the two days of study period

<table>
<thead>
<tr>
<th>Altitude, km</th>
<th>26 Dec. 1991</th>
<th>7 Jan. 1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>99</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>101</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>104</td>
<td>3.0</td>
<td>2.3</td>
</tr>
<tr>
<td>107</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>109</td>
<td>2.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Trivandrum and decreases correspondingly at Annamalainagar and Alibag. Figure 7 shows the same variations as Fig. 6 but for 7 Jan. 1992. The ΔH values at Annamalainagar are available only for the duration shown. The correlation between the three stations for this day is not so good.

Table 2 shows the fluctuation magnitudes corresponding to the dominant periods determined from \[\delta(\Delta H)\] values at Trivandrum, Annamalainagar and Alibag. The \[\delta(\Delta H)_c\] values in Table 2 are computed based on the \[\delta f_D\] values as described in Eqs (1)-(4). The VHF radar observations are made at Trivandrum and hence the \[\delta(\Delta H)_c\] values in the table correspond to that location. The computed values are compared with the \[\delta(\Delta H)_o\] (obtained by Fourier analysing the observed fluctuations in \(\Delta H\)) at Trivandrum. It is seen from the table that the fluctuating component in the magnetic field corresponding to the dominant period decreases progressively from equator to low latitudes on both the days. The agreement between \[\delta(\Delta H)_o\] and \[\delta(\Delta H)_c\] values for Trivandrum is very good for 26 Dec. 1991, while the agreement is not so good for 7 Jan. 1992.

Figure 8 shows the altitude profile of \(\delta E_z\) for the two days corresponding to the dominant period. This is estimated based on the amplitude of the dominant period considering the data sets for the whole day using Eq. (1). The shape of \(\delta E_z\) is strikingly dissimilar on the two days studied. The estimated \(\delta E_z\) values are found to be in the range of 0.2-0.7 mV/m which is 5-10% of the normally expected \(E_z\) values of 2-10 mV/m at 104 km during the day. The shape of the \(\delta E_z\) profile is grossly similar to the normal \(E_z\) profile for December 1991, while for the other day it differs con-
siderably from the normal pattern of a monotonic increase and decrease on either side of the peak value.

Overall, it is seen that the fluctuation amplitudes are typically in the range of 5-10% over the background for Doppler spectral values and 2-5% over the background for $\Delta H$ values.

5 Discussion

In the past, certain studies have been made on the nature of the short period electric field fluctuations in the EEJ at the magnetic equator. Reddy and Devasia\(^1\) reported a dominant period of around 20-30 min on moderately disturbed days and a 20-30 min period on quiet days from an analysis of VHF backscatter radar observations monitored at a single altitude. These fluctuations were found to correlate with the magnetic field variations. Such fluctuations have been attributed to possible perturbations in electron drift velocity with respect to other charged species. It has been suggested that probably these fluctuations are of gravity wave origin.

Using radar observations and $\Delta H$ values, Reddy \textit{et al.}\(^{13}\) showed that most of the bay type disturbances and fluctuations with 20-30 min period in the EEJ have their origin in corresponding disturbances in the auroral dynamo region. Further, Reddy \textit{et al.}\(^{14}\) have examined the possibility that the short period fluctuations in the EEJ electric fields on quiet days may have their origin in corresponding global scale electric field fluctuations in the polar dynamo region.

Using simultaneous VHF radar (at 54.95 MHz) observations of E-region horizontal drift velocities corresponding to the peak altitude of the EEJ and HF (5.5 MHz) Doppler radar observations of F-region vertical plasma drifts, during daytime at 15 min interval on magnetically quiet days, during April, 1987 at Trivandrum, Viswanathan \textit{et al.}\(^3\) have reported that the dominant fluctuating components in 30-90 min range of E- and F-region electric fields are well correlated. The amplitudes are of the order of 15% over the long period diurnal background for the E-region and 25% for the F-region. From the observed spectral characteristics, medium scale gravity waves have been proposed as the possible source mechanism of these fluctuations. It is to be pointed out that in the above studies, neither the altitude variation of the fluctuating electric field components nor the associated $\delta H$ fluctuations have been examined. Moreover the observations presented in the present study correspond to the winter solstice period and the fluctuation amplitudes are found to be 5% or slightly above over the background, while Viswanathan \textit{et al.}\(^3\) have reported the E-region fluctuation amplitudes of 15% over background using data for the equinoctial period. This difference indicates the solar activity and seasonal dependence of the fluctuations.

Based on limited datasets in the evening hours at two altitude levels in the EEJ, in the presence of blanketing Es layers Somayajulu \textit{et al.}\(^2\) have presented experimental evidence of fluctuations in electric fields and currents probably due to internal gravity waves. All the earlier studies have been conducted for limited time periods and for one or two altitudes. The fluctuating components [$\delta(\Delta H)_f$] corresponding to the dominant period of interest deduced using the radar observations in the EEJ region have not previously been estimated for whole or part of daytime. In the present study [$\delta(\Delta H)_c$] values have been estimated and comparison has been made with the observed ($\Delta H$) fluctuations.

The study brings out the presence of the dominant period of around 30 min in $\Delta H$ values at and off electrojet latitudes and in the $\delta f_D$ values at several altitudes in the EEJ with differing amplitudes. The observed and computed fluctuation amplitudes in $\Delta H$ for the dominant period at Trivandrum are found to be in excellent agreement (~2 nT) on 26 Dec. 1991, while it is not so good for 7 Jan. 1992. The errors in computing $\delta(\Delta H)$ are based on deduced $\delta f_D$ values. This is in addition to other assumptions involved, like average $N_e$ profiles and the shape of latitudinal distribution of current intensity $J$. The errors associated with $\overline{f_D}$ computation for good SNR values are to a maximum of $\pm 1$ Hz (for this study). Considering all these aspects the agreement seen on 26 Dec. 1991 is quite good. The shape of the $\delta E_z$ profile (from which $J$ is deduced for Trivandrum and which in turn is used for $\delta(\Delta H)$ computation on this day is similar to the normal $E_z$ profile. In contrast, the $\delta E_z$ profile on 7 Jan. 1992 is distinctly different and distorted.

The $\delta(\Delta H)$ amplitude falls off from Trivandrum (TRV) to Annamalainagar (ANGR) and decreases further towards Alibag (ALB) on both the days. This fall in amplitude of the fluctuations in $\Delta H$ from equator towards higher latitudes has been reported previously. In that study, the fluctuations in $\Delta H$ during three phases of a storm, viz. a quiet period prior to the storm, a duration during the onset of the storm and another during the recovery phase have been subjected to spectral analysis to estimate the dominant
periods and their amplitudes. Further the root mean square values of the disturbances in $\Delta H$ have been estimated for equator and some other latitudes. The ratio of the dominant amplitudes of the fluctuations at the equator to that at two mid-latitude stations of Sitka and Hartland are 3.33 and 5, respectively. This compares well the ratio of $\delta(\Delta H)_{\text{TRV}/\Delta H}^{\text{ALB}}$, which is 3.33 for 26 Dec. 1991 and 3.6 for 7 Jan. 1992. This has been attributed to a fall in amplitude as one moves from equator to other latitudes to the effect of quite time ring current, which peaks at equator and falls off to other latitudes. The term $\delta(\Delta H)$ being a function of Cowling conductivity (which falls off from equator to low latitudes) and $\delta E_y$ for any period of interest, the decreasing $[\delta(\Delta H)_o] \,$ for the period of $\sim 30 \,$ min from the equator to low latitudes may be attributed to the fall in the conductivity.

For 26 Dec. 1991, the time variations of $[\delta(\Delta H)_o] \,$ values at the three stations are well correlated as mentioned earlier. The correlation coefficient ($\rho$) is 0.61 (TRV-ALB), 0.65 (TRV-ANGR) and 0.86 (ANGR-ALB). The significantly higher correlation between ANGR and ALB could be due to the fact that these stations are outside the electrojet belt and consequently under the reduced influence of the EEJ than those stations within the jet itself. On the basis of the above it can be inferred that the $\Delta H$ values at a station like Kodaikanal (dip 3ºN, within the EEJ belt) would have shown a good correlation with TRV values. Similarly on 7 Jan. 1992, the correlation coefficient between ANGR and ALB is reasonably good (0.6), although ANGR data was available only for a few hours in the morning. The significant positive correlation again indicates that these stations are under reduced control of the electrojet. The correlation coefficient between different stations is lower in the case of 7 Jan. 1992, which indicates that other factors like wind fields may be modulating the electric field fluctuations on this day. The distorted $\delta E_y$ profile on this day also supports this argument. Medium scale gravity waves are known to be the source of medium scale electric field fluctuations (Anandarao et al., 1985; Anandarao and Raghavarao, 1996). The medium scale gravity wave associated winds tend to fall off towards equator from low latitudes (Hirota, 1985). The reduction in $[\delta(\Delta H)_o] \,$ from equator to low latitudes might be due to the combined effects of the fall in conductivity from equator to low latitudes and the increasing amplitude of the electric field fluctuations (from equator to low latitudes) modulated by gravity waves.

The study shows that electric field fluctuations even on magnetically quiet days in the same season exhibit different behaviour, indicating the large day-to-day variability in the factors affecting the fluctuations.

Acknowledgements

The authors have made use of the magnetograms obtained from Indian Institute of Geomagnetism, Mumbai. The authors gratefully acknowledge the useful discussion with colleagues at Space Physics Laboratory. The authors are thankful to the anonymous referees for their valuable comments.

References

10. Sampath S & Sastry T S G, Results from in situ measurements of ionospheric currents in the equatorial region, J Geomag Geoelectr (Japan), 31 (1979) 373.


