JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, A11305, doi:10.1029/2005JA011124, 2005

East-west asymmetries of the equatorial electrojet 8.3 m type-2 echoes observed over Trivandrum and a possible explanation

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Received 8 March 2005; revised 30 July 2005; accepted 15 August 2005; published 11 November 2005.

[1] The east-west asymmetries in the spectral parameters of the type-2 echoes from the equatorial electrojet plasma irregularities observed using a 18 MHz radar from Trivandrum are presented. Observations show that the difference in signal strength, velocity, and spectral width of the type-2 echoes observed in the west and east beam are as high as 15 dB, 60 m s^{-1}, and 70 m s^{-1}, respectively. Further, the asymmetry in velocity increases with height, while the asymmetries in signal strength and spectral width decrease with height. While the velocity asymmetry is consistent with the past results, the asymmetries in signal strength and spectral width of the type-2 echoes are significant new results, not reported earlier. Finite vertical drift velocities of the irregularities, associated with the primary wave structures, are found to be responsible for the observed east-west velocity asymmetry. The asymmetries in signal strength and spectral width are attributed to the orientation of kilometer-scale plasma waves present in the equatorial electrojet. Finally, a unified picture is presented to show that the properties of the kilometer-scale waves are the ones that are responsible for all three asymmetries observed in the spectral parameters of the type-2 echoes.

Citation: Patra, A. K., D. Tiwari, C. V. Devasia, T. K. Pant, and R. Sridharan (2005), East-west asymmetries of the equatorial electrojet 8.3 m type-2 echoes observed over Trivandrum and a possible explanation, *J. Geophys. Res.*, *110*, A11305, doi:10.1029/2005JA011124.

1. Introduction

[2] The "east-west asymmetry" of the electrojet echoes refers to the observational difference of the radar echoes detected through the east and west beams pointed at identical look angles. The existence of asymmetry has been known for about 4 decades [*Bowles et al.*, 1963; *Cohen and Bowles*, 1967; *Balsley*, 1970; *Crochet et al.*, 1976; *Fejer et al.*, 1976; *Farley et al.*, 1978]. Two important asymmetries, which have been discussed much in the literature, are (1) signal strength asymmetry: type-1 echo strength observed in the west beam is stronger than that of the east and (2) velocity asymmetry: the velocities of the type-2 echoes observed in the west direction of the radar beam are more than that of the east.

[3] *Cohen and Bowles* [1967] showed that the signal strength observed during daytime by the west beam is more than that of the east beam. Later, *Farley et al.* [1978] showed that this observation is related to the type-1 echoes and the echo strength of upward propagating density irregularities are stronger and more common than the returns from downward propagating irregularities during the day, while the converse is true at night. Similar studies have also been made from Trivandrum using a 54.95 MHz radar [*Ravindran and KrishnaMurthy*, 1997]. They have shown that the type-1 echoes are stronger for upgoing waves as compared to the downgoing waves when observed by the vertical beam. When observed by oblique beams they are stronger in west beam as compared to that in the east. *Kudeki et al.* [1985] explained the up-down asymmetry of the type-1 echoes returned from the equatorial electrojet irregularities as due to the nonlinear development of the horizontally propagating large-scale primary waves.

[4] Using a 49.92 MHz radar from Jicamarca, *Balsley* [1970] showed that the velocities of the type-2 echoes observed by the west beam were 30–60% higher than that observed by the east beam. *Crochet et al.* [1976] found that while there was no such asymmetry in velocity in the 21.3 MHz radar observations from Sarh-Fort-Archambault in central Africa, there was large asymmetry in the 21.3 MHz and 14 MHz radar observations from Arta Djibuti in eastern Africa. The above observations, however, represented the average picture of the electrojet since the height

0148-0227/05/2005JA011124$09.00

Table 1. Radar Specifications and Important Parameters Used for the *E* Region Experiments

Parameter	Value
Frequency	18 MHz
Peak transmitter power	50 kW
Duty-cycle ratio (maximum)	2.5%
Average transmitter power used	250 W
Antenna	12 × 6 phased dipole array
Antenna gain	26.5 dB
Antenna beam-width (both way)	4.4° in zenith and 5° off-zenith
Beam orientations	zenith, and 30° off zenith due east and west
Pulse width	20 μs
Pulse repetition frequency	250 Hz
Number of FFT	256
Number of spectral averaging	16

resolution employed at that time was poor. More recently, a detailed study on the east-west velocity asymmetry, based on the 49.92 MHz radar observations from Pohnpei (6.96°N, 158.19°E, 0.7° magnetic dip) with 1 km range resolution, has been made by *Tsunoda and Ecklund* [2002]. They have shown that the vertical drifts of the electrojet irregularities are responsible for the observed difference.

[5] In this paper we present observations on additional east-west asymmetries of the electrojet plasma irregularities observed using a 18 MHz radar located at Trivandrum (8.5°N, 77°E, dip latitude 0.5°N), India. We show, for the first time, that the echo strength and spectral width of the type-2 echoes observed by the west beam are more than that of the east. These observations provide additional information on the east-west asymmetry to the existing knowledge of velocity asymmetry of the type-2 echoes. As far as the type-2 echoes are concerned, while the asymmetry in velocity can be understood considering the role of nonzero vertical velocity, the asymmetries in signal strength and spectral width need to be accounted for. We show that the zonally propagating primary gradient drift waves, which are responsible for the up-down/east-west asymmetry of the type-1 echoes, are also responsible for the observed features of the type-2 echoes presented here.

2. Experiment Description and Data

[6] The observations presented here were made using a 18 MHz radar located at Thumba Equatorial Rocket Launching Station (TERLS), Trivandrum. The radar system, described by *Janardhanan et al.* [2001], is operated with a peak power-aperture product of 5×10^8 W m^2. The antenna system is a 12 × 6 dipole array with its larger arm aligned in the magnetic east-west direction. At present, the antenna array is phased to form the beam at three look angles: zenith, 30° off-zenith due east and 30° off-zenith due west. In the east-west plane, the two-way half power beam width is 4.4° for zenith beam and 5° for off-zenith beam. In the north-south direction it is basically decided by the aspect sensitivity of the irregularities [*Kudeki and Farley*, 1989] and therefore is very small (∼0.5°).

[7] The observations were made over 8 days from 16 to 25 May 2002 using the three-beam configuration (30°E, 30°W, and zenith beams) presently available in the radar system. The radar specifications and other important parameters used for this study are given in Table 1. Data were collected online in the form of Doppler power spectrum and processed off-line to get signal-to-noise ratio (SNR), mean Doppler velocity, and spectral width. It may be mentioned that while the height resolution is 3 km (corresponding to the pulse length of 20 μs) for the zenith beam, it is poorer for the off zenith beam. On the basis of the beam width and the tilt angle used, theoretically, it turns out to be 7.5 km. However, if relative contributions from the top and bottom edges of the beam are considered, it may turn out to be ∼5 km.

3. Observations

[8] Figures 1a–1c show SNR, mean Doppler velocity, and spectral width, respectively, as a function of height and time observed using the west and east beam on 25 May 2002. It is clear that the observed SNR in the west beam is higher than that observed in the east beam. The difference is observed to be as high as 8 dB with the maximum difference being at 93 km. It may be noticed that the difference decreases with height. The velocity observed in the west beam is higher than that of the east beam and the difference is found to be as high as 30 m s^{-1}. The difference in velocity is found to increase with height and is maximum at 105 km. Spectral width is observed to be higher in the west beam than in the east beam. The difference is found to be as high as 50 m s^{-1} occurring at 93 km and it decreases to a value close to zero at 105 km.

[9] In all 8 days of observations, we found that these asymmetries are regular features. To show the general features, mean and standard deviation of the differences in the three spectral parameters observed by the west and east beam as a function of height and time are shown in Figures 2a–2c. These statistics clearly show that the east-west asymmetry is present in all the three spectral parameters of the type-2 echoes. While the difference in SNR, velocity, and spectral width could be as high as 15 dB, 60 m s^{-1}, and 70 m s^{-1}, respectively, the mean differences are found to be in the ranges of 3–9 dB, 10–25 m s^{-1}, and 10–35 m s^{-1}, respectively. The height variations are quite similar to that shown in Figure 1. Much larger fluctuations in spectral width observed at 93 km as compared to other heights may be due to the effect of low SNR on the estimation of spectral width observed in the east beam as compared to that in the west beam.

[10] To verify that the vertical velocities are responsible for the observed east-west velocity asymmetry, the velocities measured by the vertical beam are presented in Figure 3 as scatterplot. It clearly shows that the velocities are upward at higher altitudes with values reaching as high as 60 m s^{-1}. At lower altitudes, the velocities are close to zero. These values are quite similar to that observed by *Tsunoda and Ecklund* [2002].

[11] Among these, new and interesting observations are the asymmetries observed in SNR and spectral width. We

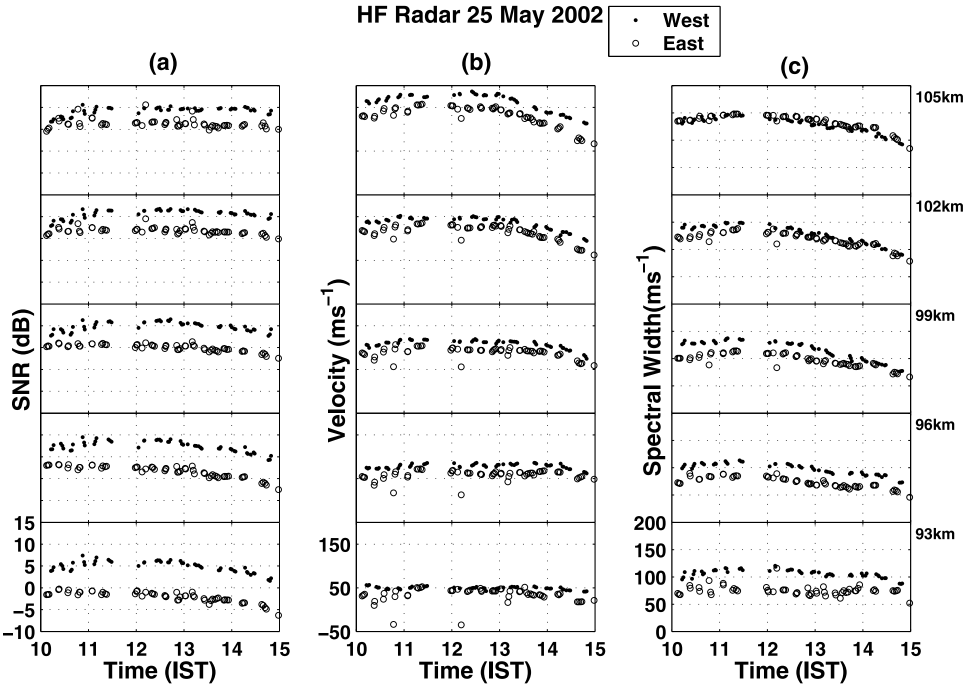

Figure 1. Height and time variations of (a) signal-to-noise ratio (SNR), (b) velocity, and (c) spectral width observed on 25 May 2002. Star and circle represent observations corresponding to west and east beam, respectively.

plot the time-averaged mean and standard deviation in the difference (west minus east) of SNR and spectral width as a function of height in Figures 4a and 4b, respectively. Data during 1100–1400 LT only have been used to compute these. As can be seen, the mean values in SNR difference is found to decrease from 6.5 dB at 93 km to 3 dB at 105 km and spectral width from 35 m s^{-1} at 93 km to nearly zero at 105 km. The standard

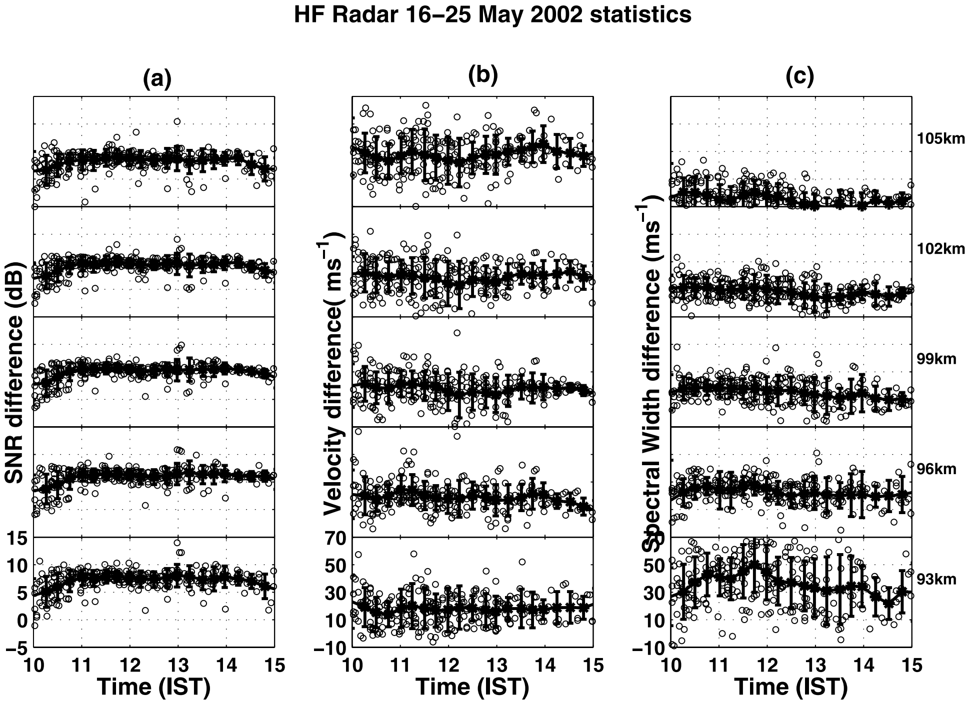

Figure 2. Scatterplot of (a) SNR difference, (b) velocity difference, and (c) spectral Width difference as a function of height and time observed during 16–25 May 2002. The mean and standard deviations are also shown. The differences represent the parameters observed in west minus east.

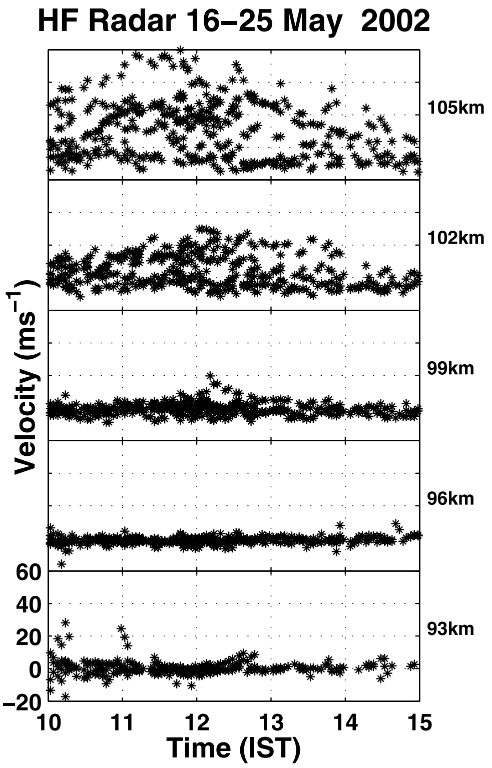

Figure 3. Scatterplot of vertical drifts observed during 16–25 May 2002 as a function of height and time.

deviations in SNR difference and spectral width difference are as high as 2.5 dB and 20 m s^{-1}, respectively.

4. Discussion

[12] There are three observations that are of interest and need proper explanation. They are (1) SNR, velocity, and spectral width observed in the west beam are more than that of the east, (2) the asymmetry in velocity increases with height, and (3) the asymmetries in both SNR and spectral width decrease with height.

[13] Signal strength asymmetry of the electrojet type-1 echoes have been known for many years [*Bowles et al.*, 1963; *Cohen and Bowles*, 1967; *Fejer et al.*, 1976; *Farley et al.*, 1978], but the same for the type-2 was not known. As far as the velocity asymmetry is concerned, we provide an additional feature in what we show the height variation in this asymmetry. The observations, which have not at all been talked about, are the asymmetries in SNR and spectral width associated with the type-2 echoes. A more important aspect is the way the asymmetries in SNR and spectral width as a function of height decrease and go hand in hand. Perhaps one expects this result in a turbulent situation, but this also needs proper investigation if we are to fully understand the asymmetries that are so built in to the electrojet. It may be noted that while velocity asymmetry increases with height, the SNR and spectral width asymmetries decrease with height. This implies that the two asymmetries are manifested differently. We first address the velocity asymmetry and then the other two asymmetries of the type-2 echoes seen in our observations.

4.1. Velocity Asymmetry

[14] During daytime, in normal conditions, zonal and vertical electric fields are eastward and upward, respectively. The upward electric field causes westward electron drift. This drift in conjunction with positive electron density gradient, associated with the lower part of the *E* region, can make the lower part of the *E* region unstable through gradient drift instability. The plasma waves generated propagate westward. Once these irregularities grow, secondary irregularities get generated subsequently and are observed in all directions. Using radar backscatter from these small-scale irregularities, the large-scale features of the electrojet have been studied. In normal condition, the Doppler velocities observed during daytime are westward. Further, the vertical phase velocities of the irregularities are dominantly upward during daytime, although both upward and downward velocities have been observed [*Farley et al.*, 1994]. Recent observations made by *Tsunoda and Ecklund* [2002] also show that the vertical drifts are upward. For the type-2 echoes, since the mean Doppler velocity represents the line-of-sight phase velocity of the irregularities, it is possible to write radial velocity in terms of zonal and vertical components of the irregularity velocity. At the magnetic equator, neglecting neutral wind, we can write the radial velocity observed in the west and east beam looking at zenith angle θ as

$$\mathrm{V_{rW} = V_z\,Sin\,\theta + V_v\,Cos\,\theta}$$

$$\mathrm{V_{rE} = V_z\,Sin\,\theta - V_v\,Cos\,\theta,}$$

where $\mathrm{V_{rW}}$ and $\mathrm{V_{rE}}$ are the radial velocities measured by the west and east beam, respectively. $\mathrm{V_z}$ and $\mathrm{V_v}$ are zonal (positive westward) and vertical (positive upward) components of irregularity drift, respectively. The above equations clearly suggest that the observed velocity in the west beam will be more than that in the east. The difference in these two-beam measurements, in principle, can provide an estimate of the vertical drift $\mathrm{V_v}$ as

$$\mathrm{V_v = (V_{vW} - V_{rE})/2\;Cos\,\theta.}$$

Our observations show that the difference in the velocities measured by the two beams is as high as 60 m s^{-1}. In our experiments, θ = 30°. Accordingly, the vertical drift works out to be 36 m s^{-1}, which is quite consistent with the vertical drifts measured directly using the vertical beam. They are also consistent with the observations made recently by *Tsunoda and Ecklund* [2002]. A small discrepancy, however, can occur between the direct measurement of $\mathrm{V_v}$ using the vertical beam and the derived one from $\mathrm{V_{rW}}$ and $\mathrm{V_{rE}}$ due to the fact that the net vertical drift is smaller than the zonal drift and the derived vertical drift through vector decomposition could be different. Accordingly, observing larger irregularity drift in the west beam as compared to the east is consistent with basic understanding of the electrojet irregularity drifts during daytime.

[15] In general, while this appears to be true for the observations of the electrojet irregularities when measured using radars with beam width of 3–4°, the scenario could be

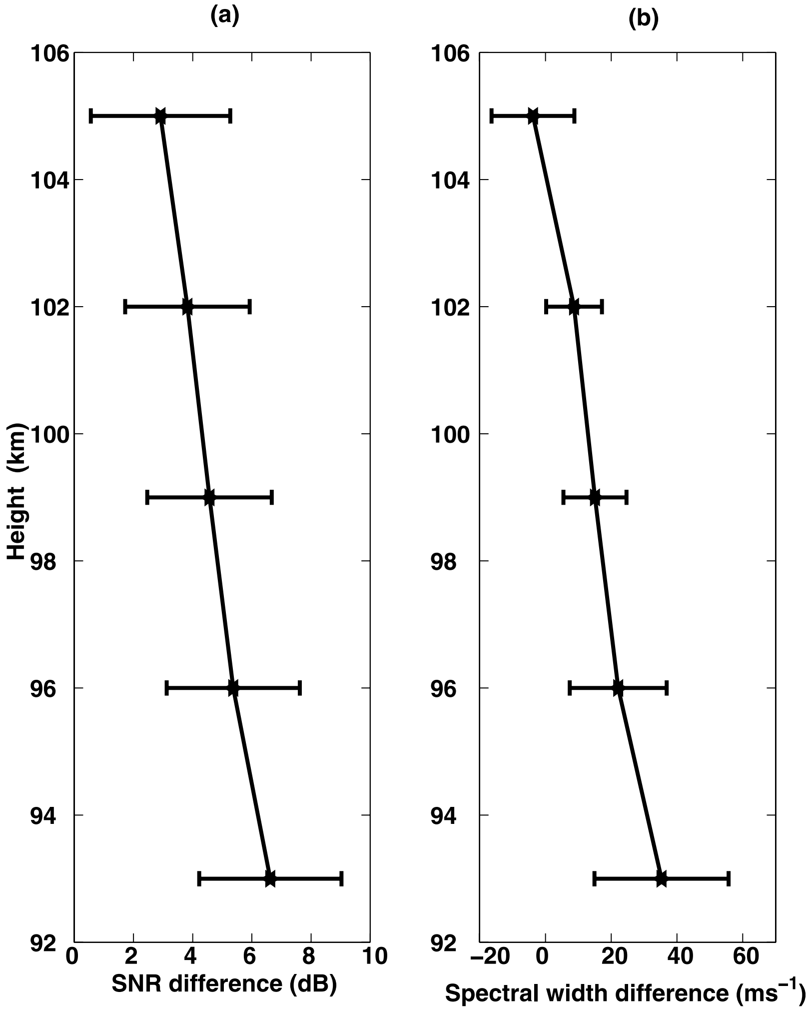

Figure 4. Time-averaged height variations of (a) SNR difference and (b) spectral width difference. Standard deviations are also shown.

very different when measured with radar of narrower beam width (about a degree; e.g., Jicamarca radar). This is expected due to the fact that for the Jicamarca radar the spatial averaging is less. In fact, it observes the type-2 velocities to be as high as 200 m s^{-1} when the electrojet is reasonably turbulent and the velocity changes from upward to downward and back with a timescale of few tens of seconds [*Farley et al.*, 1994; *Swartz and Farley*, 1994]. These large vertical velocities are believed to be the manifestation of large-scale gradient drift waves [*Kudeki et al.*, 1982]. Accordingly, we would expect the radial velocities observed by a narrow east/west beam to be more in either of the beams at any given time, not more in the west beam alone. Given the opportunity to probe the same volume by two radars having narrow beams looking from east and west, we would find that the difference observed by two conjugate beams is extremely high (as high as 200 m s^{-1}) and either of the beams may measure larger value at any given time. However, we also know that during daytime, there is a net asymmetry in the vertical drift itself: the occurrence and magnitude of upward motion being more than that of downward [*Farley et al.*, 1994]. Accordingly, most of the time, we expect to see the west beam observing higher velocities than the east. For a radar beam wider than that of Jicamarca, however, we will observe the spatially averaged vertical drift, which would be mostly upward, and hence the west beam will observe higher velocity than that of the east beam. This is consistent with the observations reported here and that reported by *Tsunoda and Ecklund* [2002].

[16] Finally, one point that deserves some discussion is the asymmetry as a function of height. In our observations, the asymmetry is seen to increase with height in general. Observed vertical velocities as a function of height also show quite similar feature. *Tsunoda and Ecklund* [2002] also have observed the vertical velocities to increase with height. *Farley et al.* [1994] have reported that large upward drifts are observed at higher altitudes as compared to lower altitudes. Since the zero-order electron drift is low at the low altitudes as compared to that at higher altitudes, the horizontally propagating primary waves at lower altitudes also have smaller velocities than that at higher altitudes. Accordingly, the vertically propagating secondary waves also will have smaller velocities at lower altitudes than that at higher altitudes. At lower altitudes, another factor that could reduce the phase velocity of the vertically propagating

waves is the increasing Ψ factor with decreasing height ($\Psi = \nu_e \nu_i / \Omega_e \Omega_i$, where ν_e and ν_i are the collision frequencies of the electrons and ions, respectively, with the neutrals, and Ω_e and Ω_i are the gyrofrequencies of electrons and ions, respectively). Hence the observations of vertical velocity and east-west asymmetry as a function of height are consistent with the expectation.

4.2. SNR and Spectral Width Asymmetries

[17] There are two aspects: (1) both SNR and spectral width observed in the west beam are more than that in the east beam and (2) the asymmetries decrease with height. *Ierkic et al.* [1980] made a detailed study on the zenith angle dependence of radar echo power of 3 m equatorial electrojet irregularities. They showed that the type-1 echoes are highly anisotropic in the plane perpendicular to the magnetic field with echo strength increasing with zenith angle and the type-2 echoes do not show such anisotropy. It may be mentioned that the east-west anisotropy in echo power of the type-2 echoes that is relevant to this discussion is 3–9 dB. We feel that much of this anisotropy was not captured in the earlier experiments of the electrojet irregularities due to large beam widths used in those experiments. For example, *Ierkic et al.* [1980] used east-west beam width of 25° for their study. Comparison of echo power observed in the east and west beam for a given range could be erroneous due to the fact that wide beam could see irregularities at different zenith angle and thus at different altitudes. We believe that the problem of east-west velocity asymmetry of the type-2 echoes also remained unresolved due to the problems related to wide beam measurements used earlier. In this context, it may be mentioned that observations made using a 50 MHz radar from Sao Luis, Brazil also show asymmetry in the type-2 echo strength: SNR in the 30° west beam being more than that in the 30° east beam (M. A. Abdu, personal communication, 2002). It may be mentioned that the beam width of both the radars is ~5°, which is better than that used in the earlier studies of electrojet irregularities in oblique directions.

[18] The meter-scale irregularities are known to be generated by a two-step process or mode coupling [*Sudan et al.*, 1973; *Sudan and Keskinen*, 1979] and their characteristics are controlled by the large-scale waves [*Kudeki et al.*, 1982, 1985, 1987]. One of the observations that is closely related to the large-scale waves is the vertically propagating type-1 waves and their asymmetry. It is generally agreed that the asymmetry of the type-1 echoes are related to the asymmetry in the primary waves themselves [e.g., *Farley et al.*, 1978; *Kudeki et al.*, 1982]. For the observed up-down asymmetry (also applied to east-west asymmetry) of the type-1 echoes, *Farley et al.* [1978] argued that the density perturbation, caused by horizontally propagating large-scale waves, if becomes steep on the backside, they could result into up-down asymmetry. In fact such a development has been noticed in the nonlinear development of gradient drift waves in simulation studies [*Rognlien and Weinstock*, 1975]. Later, *Kudeki et al.* [1985] showed that the up-down asymmetry of the type-1 echoes is a consequence of the nonlinear development of the horizontally propagating large-scale primary waves. They showed that this effect could account for the asymmetry of more than 20% and explains quite satisfactorily the radar observations. On the other hand, steepened structures observed in rocket data [*Pfaff et al.*, 1982, 1987] seem to support the viewpoint of *Farley et al.* [1978] and may be responsible for several asymmetries observed by the east and west beam as well as the up-down asymmetry.

[19] We propose that in addition to the asymmetric horizontal gradient in electron density due to steepening of the primary waves, if any [*Farley et al.*, 1978], the wave fronts may be tilted with respect to the vertical. During daytime, the primary wave fronts may be tilted toward west with the topside toward west of vertical as compared to the bottom. We believe that this would possibly occur naturally in the electrojet due to the height gradient of zonal drift and other background parameters. Nonlinear simulation studies on the large-scale waves show such signature [*Ronchi et al.*, 1991]. *Ronchi et al.* [1991] showed that the large-scale irregularities are stretched in the horizontal direction due to the velocity shear. In addition, if the density perturbations are steep on one side, it is expected that one of the gradients will be more prone for irregularity development than the other and hence the irregularity strength will have preferential direction due to the orientation of the primary structures. In other words, the irregularities will be anisotropic in the zonal plane perpendicular to magnetic field. In fact, recent simulation studies show that significant anisotropy can develop [*Gruzinov et al.*, 1996].

[20] Assuming the zonal phase velocities of the large-scale waves to be 100 m s^{-1} at 105 km and 25 m s^{-1} at 95 km with gradually decreasing velocity as a function of decreasing height [*Kudeki et al.*, 1987], it may be possible to estimate the approximate slopes of the structures. A differential drift of 75 m s^{-1} in 10 km height span would lead to a tilt of 4–16 degrees of the primary wave fronts for wave periods 10–40 s. Accordingly, the wave fronts of the secondary waves are also tilted with respect to the horizontal. In this condition, a radar beam looking in the west direction will satisfy better perpendicularity to these secondary wave fronts as compared to that looking in the east.

[21] The asymmetry in spectral width can similarly be understood. It is believed that the small-scale irregularities in the electrojet are generated either by two-step process or mode coupling [*Sudan et al.*, 1973; *Sudan and Keskinen*, 1979]. Accordingly, spectral width provides information on the turbulent flow field in the medium. Relationship between spectral width and SNR of the type-2 echoes as a function of height has been reported earlier [*Tiwari et al.*, 2003]. It was shown that at lower altitudes, there exists a linear relationship between the two parameters and hence the asymmetry in spectral width is inherent to the asymmetry in the signal strength. Since the west beam satisfies better geometry for observing the irregularities during daytime and encounters more scatterers in the radar pulse volume, it possibly observes wider velocity fields to which the irregularities are associated. In contrast, the east beam observes lesser number of scatterers (due to reduced scattering cross section along the radar wave vector) and hence observes less turbulent velocity fields resulting in narrower spectral width as compared to that of the west beam.

[22] Coming to the height profile of the asymmetry, it is important to examine the nonlinear simulation studies of the electrojet plasma waves [*Ronchi et al.*, 1991; *Hu and Bhattacharjee*, 1999]. It has been noticed that in the lower

part of the electrojet, where there exists shear flow (positive height gradient of velocity), the primary waves are organized in the form of tilted structures in the zonal direction as compared to that at higher altitudes. It has been shown through simulations that these structures are stretched by velocity shear and the energy is transferred to the intermediate scales, which eventually is transferred to the small-scale irregularities observed by the radar. At lower heights, the organized tilted structures (possibly the intermediate scales) would provide conditions for the secondary waves to have preferential direction favoring the west beam to see stronger signal and spectral width during daytime. If similar scenario prevails during night, we would expect the signal strength and spectral width to be larger in the east beam as compared to the west.

5. Concluding Remarks

[23] We have shown that the type-2 echoes show east-west asymmetry in all the three spectral parameters. The vertical drifts of the irregularities are shown to be responsible for the east-west velocity asymmetry, and these large upward velocities are associated with the large-scale primary waves. To explain the SNR and spectral width asymmetries, we proposed that the large-scale primary waves in the lower part of the *E* region are tilted and provide favorable conditions for the west beam to observe stronger echoes and larger spectral width as compared to the east beam. Altitude variability of these tilted primary structures appears to be responsible for the height variation of the asymmetries observed in our data. Further experiments and simulation studies are essential to understand these asymmetries in detail.

[24] **Acknowledgments.** The 18 MHz radar operated from TERLS belongs to and is operated by Space Physics Laboratory. We are grateful to the engineering staff for the successful operation of the radar for the observations presented here. Much of the work reported in this paper was done while AKP and DT were at Space Physics Laboratory.

[25] Arthur Richmond thanks Donald Farley and another reviewer for their assistance in evaluating this paper.

References

Balsley, B. B. (1970), A longitudinal variation of electron drift velocity in the equatorial electrojet, *J. Geophys. Res.*, *75*, 4291.

Bowles, K. L., B. B. Balsley, and R. Cohen (1963), Field-aligned *E* region irregularities identified with acoustic plasma waves, *J. Geophys. Res.*, *68*, 2485.

Cohen, R., and K. L. Bowles (1967), Secondary irregularities in the equatorial electrojet, *J. Geophys. Res.*, *72*, 885.

Crochet, M., C. Poman, and C. Hanuise (1976), Radar profiles of the equatorial electrojet, *Geophys. Res. Lett.*, *3*, 673.

Farley, D. T., B. G. Fejer, and B. B. Balsley (1978), Radar observations of two-dimensional turbulence in the equatorial electrojet: 3. Night-time observations of type-1 waves, *J. Geophys. Res.*, *83*, 5625.

Farley, D. T., W. E. Swartz, D. L. Hysell, and C. Ronchi (1994), High resolution radar observations of daytime kilometer-scale wave structure in the equatorial electrojet, *J. Geophys. Res.*, *99*, 299.

Fejer, B. G., D. T. Farley, B. B. Balsley, and R. F. Woodman (1976), Radar observations of two-dimensional turbulence in the equatorial electrojet: 2, *J. Geophys. Res.*, *81*, 130.

Gruzinov, A. V., N. Kukharkin, and R. N. Sudan (1996), Two-dimensional convective turbulence, *Phys. Rev. Lett.*, *76*, 1260.

Hu, S., and A. Bhattacharjee (1999), Gradient drift instability and turbulence in the nighttime equatorial electrojet, *J. Geophys. Res.*, *104*, 28,123.

Ierkic, H. M., B. G. Fejer, and D. T. Farley (1980), The dependence of zenith angle of the strength of 3-meter equatorial electrojet irregularities, *Geophys. Res. Lett.*, *7*, 497.

Janardhanan, K. V., et al. (2001), HF backscatter radar at the magnetic equator: System details and preliminary results, *Ind. J. Radio Space. Phys.*, *30*, 77.

Kudeki, E., and D. T. Farley (1989), Aspect sensitivity of equatorial electrojet irregularities and theoretical implications, *J. Geophys. Res.*, *94*, 426.

Kudeki, E., D. T. Farley, and B. J. Fejer (1982), Long wavelength irregularities in the equatorial electrojet, *Geophys. Res. Lett.*, *9*, 684.

Kudeki, E., D. T. Farley, and B. J. Fejer (1985), Theory of spectral asymmetries and nonlinear currents in the equatorial electrojet, *J. Geophys. Res.*, *90*, 429.

Kudeki, E., B. G. Fejer, D. T. Farley, and C. Hanuise (1987), The condor equatorial electrojet campaign: Radar results, *J. Geophys. Res.*, *92*, 13,561.

Pfaff, R. F., M. C. Kelley, B. G. Fejer, N. C. Maynard, and K. D. Baker (1982), In-situ measurements of wave electric fields in the equatorial electrojet, *Geophys. Res. Lett.*, *9*, 688.

Pfaff, R. F., M. C. Kelley, E. Kudeki, B. G. Fejer, and K. D. Baker (1987), Electric field and plasma density measurements in the strongly driven daytime equatorial electrojet: 1. The unstable layer and gradient drift waves, *J. Geophys. Res.*, *92*, 13,578.

Ravindran, S., and B. V. KrishnaMurthy (1997), Up-down asymmetry of type-I plasma waves in the equatorial electrojet region, *Ann. Geophys.*, *15*, 774.

Rognlien, T. D., and J. Weinstock (1975), Theoretical properties of two-dimensional electrojet turbulence, *Radio Sci.*, *10*, 239.

Ronchi, C., R. N. Sudan, and D. T. Farley (1991), Numerical simulations of large-scale plasma turbulence in the daytime equatorial electrojet, *J. Geophys. Res.*, *96*, 21,263.

Sudan, R. N., and M. J. Keskinen (1979), Theory of strongly turbulent two-dimensional convection of low-pressure plasma, *Phys., Fluids*, *22*, 2305.

Sudan, R. N., J. Akinrimishi, and D. T. Farley (1973), Generation of small scale irregularities in the equatorial electrojet, *J. Geophys. Res.*, *78*, 240.

Swartz, W. E., and D. T. Farley (1994), High-resolution radar measurements of turbulent structures in the equatorial electrojet, *J. Geophys. Res.*, *99*, 309.

Tiwari, D., K. A Patra, K. S. Viswanathan, N. Jyoti, C. V. Devasia, K. S. V. Subbarao, and R. Sridharan (2003), Simultaneous radar observations of the electrojet plasma irregularities as 18 and 54.95 MHz over Trivandrum, India, *J. Geophys. Res.*, *108*(A10), 1368, doi:10.1029/2002JA009698.

Tsunoda, R. T., and W. L. Ecklund (2002), East-west asymmetry in type-2 echoes and enhanced electron drift in the equatorial electrojet, *Geophys. Res. Lett.*, *29*(8), 1180, doi:10.1029/2001GL014582.

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