Daytime vertical and zonal velocities from 150-km echoes: Their relevance to *F*-region dynamics

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[1] As it was suggested by *Kudeki and Fawcett* [1993], and later shown by *Woodman and Villanueva* [1995], vertical Doppler velocities of daytime 150-km echoes represent the vertical **E** × **B** drift velocities at *F* region altitudes. Recently a special experiment was conducted to compare not only the vertical but also the zonal velocities from 150-km echoes with those from an incoherent scatter radar (ISR) mode perpendicular to the magnetic field. The vertical velocity comparisons show that (1) there is a very good agreement between 150-km velocity and the mean *F*-region **E** × **B** drift, and (2) much better agreement is found with the extrapolated values from the ISR altitudinal profiles. On the other hand poor-to-good agreement is found between their zonal components. Our preliminary zonal velocity results, indicate that there is a poor agreement before noontime, while better agreement is found in the afternoon. *INDEX TERMS:* 2411 Ionosphere: Electric fields (2712); 2415 Ionosphere: Equatorial ionosphere; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 2437 Ionosphere: Ionospheric dynamics; 2439 Ionosphere: Ionospheric irregularities. **Citation:** Chau, J. L., and R. F. Woodman (2004), Daytime vertical and zonal velocities from 150-km echoes: Their relevance to *F*-region dynamics, *Geophys. Res. Lett.*, *31*, L17801, doi:10.1029/2004GL020800.

1. Introduction

[2] Electrodynamics drift estimates represent an important contribution to *F*-region modelling efforts which have shown that the vertical **E** × **B** drift is the primary factor controlling the peak plasma density at low latitudes [e.g., *Anderson*, 1973]. As was suggested by *Kudeki and Fawcett* [1993] and later shown by *Woodman and Villanueva* [1995], vertical Doppler velocities of daytime 150-km echoes represent the vertical **E** × **B** drift velocities at *F* region altitudes. The vertical velocities from 150-km echoes are very precise, because of the strength of the echoes and the narrowness of their spectra, and could be used to extending the database of these field measurements using less powerful and more economical radars.

[3] Echoes from 150-km irregularities were first observed in the early 1960's over the Jicamarca Radio Observatory [*Balsley*, 1964]. Since then, they have been observed at Jicamarca on campaign basis [e.g., *Fawcett*, 1999, and references therein]. They have now been observed at other equatorial longitudes [e.g., *Kudeki et al.*, 1998; *Blanc et al.*, 1996]. These latter observations, confirm that 150-km echoes can be used to study the longitudinal variation of daytime equatorial electric fields using relatively small and inexpensive radar systems as suggested by *Kudeki and Fawcett* [1993].

[4] Briefly, we can summarize the following properties from the radar observations of 150-km echoes: (1) are confined to the daytime at equatorial magnetic latitudes; (2) occur at upper *E* region altitudes, between 140 and 170 km; (3) present narrow spectral widths (<15 m s^{-1}), (4) come from field-aligned irregularities with aspect widths smaller than those from the equatorial electrojet (EEJ) and larger than those of equatorial spread *F* (ESF). More details on the main characteristics of 150-km echoes can be found in *Fawcett* [1999]. Although a large number of observations now exist, the physical mechanisms that cause them are still puzzling. It is out of the scope of this paper to discuss these mechanisms, instead we will concentrate on the empirically tested measurements that are useful for low-latitude studies.

[5] *Woodman and Villanueva* [1995] verified via incoherent scatter radar (ISR) experiments that the 150-km echo vertical velocities are indeed good estimates of *F* region vertical plasma drifts. In this paper, we provide further evidence on the findings by *Woodman and Villanueva* [1995] by performing a concurrent experiment where observations of both, incoherent scatter and 150-km echoes, are optimized. Emphasis is also devoted to the estimates of zonal velocities. First we will describe the experimental technique of the concurrent observations. Then we present the comparisons of vertical (V_z) and zonal (V_x) velocities from 150-km echoes with those obtained from the ISR technique. Finally the results are interpreted and discussed.

2. Dual-Beam Observations

[6] In Figure 1 we show the pointing directions used in our experiment, which are the same as those used for the ISR east-west drift mode [*Kudeki et al.*, 1999]. Briefly, the Jicamarca antenna is configured to point simultaneously in two directions: ~2.65° and ~1.90° to the east and west of the geomagnetic meridional plane, respectively. The loci of perpendicularity to the magnetic field are shown for heights 150 (+) and 400 (*) km above Jicamarca, according to the extrapolated values obtained from the IGRF2000 magnetic field model. More specific details on the experimental setup are presented by *Kudeki et al.* [1999].

[7] We have conducted two concurrent experiments with the same antenna configuration. Briefly, an ISR experiment was run with the following parameters: interpulse period of 8 ms (1200 km), 3-baud Barker coded transmitted pulses with a total width of 300 μs, and a baud width of 100 μs to provide a nominal range resolution of 15 km with decoded returns. The 150-km echo experiment, consisted of intro-

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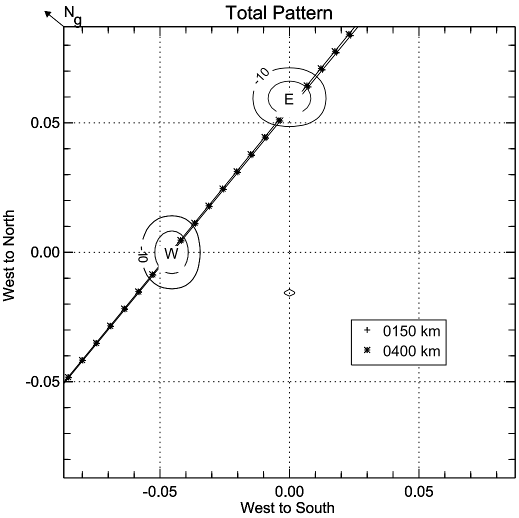

Figure 1. Dual-beam configuration: East (E) and West (W), both perpendicular to **B**. The loci of perpendicularity to the magnetic field are shown for 150 (+) and 400 (*) km above Jicamarca.

ducing a shorter uncoded pulse of 33.33 μs (5 km) to the ISR sequence of transmitted pulses delayed by 6.66 ms (1000 km). The self clutter produced by this additional pulse is negligible given the delayed and the short pulse used. Samples were obtained every 5 km from 45 to 1200 km, and complex raw voltages were recorded for each of the four receiving channels.

[8] Samples between 45 and 1000 km were analyzed with the current ISR drift procedure [*Kudeki et al.*, 1999] obtaining vertical and zonal drifts every 5 minutes and every 15 km with very small error bars. Between 1000 and 1200 km ranges (recall that echoes around ~1150 km come from ~150 km altitude, due to the addition of the delayed narrow pulse), the data were spectrally analyzed with 128-FFT points, 4 coherent integrations and 15 incoherent integrations allowing vertical and zonal velocities every ~1 minute and every 5 km (150 km-5). As in the case of the ISR velocities, the 150-km vertical and zonal velocities were obtained from the linear vector combination of the two radial velocities measured with the oblique beams. Given this way of estimating the velocities, the rms errors of the zonal velocities are ~16 times larger than the rms errors of vertical velocities, in both the ISR and 150-km estimates.

[9] In addition, we have performed a similar processing procedure to the data samples between 100 and 200 km, except no decoding is required for the short pulse. Since the echoes from these ranges come from EEJ and 150-km irregularities, this portion of the data have been decoded and spectrally analyzed using 128-FFT points, 4 coherent integrations, and 15 incoherent integrations allowing vertical and zonal velocities estimates every ~1 minute and every 15 km (150 km-15). This latter procedure is similar to the one performed by *Woodman and Villanueva* [1995].

[10] In summary, we have the following vertical and zonal velocity estimates: (a) altitudinal profiles of *F* region estimates from ISR echoes, and mean *F* region estimates (ISR-15), (b) from 150-km echoes every 5 km (150 km-5), and (c) from 150-km echoes every 15 km (150 km-15). The last two estimates have been obtained by fitting a Gaussian function to the Doppler spectrum to obtain the radial velocities, similar to the procedure used by *Chau* [1998].

3. Results

[11] In Figure 2 obtained on December 17, 2003. Values above 200 km have been obtained with the ISR technique. On the right panels, we show averaged values over time periods indicated with the horizontal color bars at the top of Figure 2a, i.e., red, green, and blue values represent averages for 1045–1300, 1300–1515, and 1515–1730 LT, respectively. The velocities around 150 km have been obtained by linearly extrapolating the ISR values. In the case of the color-shaded plot, extrapolated values have been obtained from the 5-minute profiles, while values on the right panels, from the averaged values. The solid straight lines on the right panels represent the fitted values that were obtained by minimizing the chi-square error statistics using weights inversely proportional to the errors squared. Similar observations were conducted on December 18, 2003.

[12] Note that the averaged values of both components show a linear trend as function of altitude and the slope changes as function of time and from day to day. The vertical results are in reasonable agreement with the results reported by *Pingree and Fejer* [1987], namely, almost constant in the early morning and negative gradients in the afternoon. The zonal drifts are almost constant (in altitude) in the morning and with positive gradients in the afternoon. Given the linear behavior as function of altitude, below we compare the 150-km drift to the extrapolated values obtained every 5 minutes (150 km-fit).

[13] The time series of all four estimates, for both days, are shown in Figure 3, i.e., ISR-15 (averaged ISR values around the *F* peak), 150 km-15, 150 km-5, and 150 km-fit (extrapolated values from ISR drifts). The top panels represent the vertical components, while lower panels the zonal components.

[14] If we compare the 150-km vertical velocities obtained for the specially designed experiment (i.e., 150 km-5) with the other three series (all of them averaged every 5 minutes), we find the following results:

[15] • There is an excellent agreement between 150 km-5 and the extrapolated 150-km drifts (150 km-fit) with mean (μ_d) and rms (σ_d) differences of 0.58 m s^{-1} and 0.90 m s^{-1}, respectively, and a correlation (ρ) of 0.97.

[16] • There is also an excellent agreement between 150 km-5 and the reanalyzed ISR raw data around 150 km (150 km-15) (μ_d = 0.14 m s^{-1}, σ_d = 0.27 m s^{-1}, ρ = 0.99).

[17] • There is very good agreement between 150 km-5 and the mean *F*-region drifts (μ_d = −1.68 m s^{-1}, σ_d = 1.47 m s^{-1}, ρ = 0.93).

[18] • Mean *F*-region drifts are smaller (up to 4 m s^{-1}) than the 150-km velocities, particularly in the afternoon hours. This difference is a consequence of the slope of the vertical drifts as function of altitude.

[19] Now if we do a similar comparison with the zonal velocities, we find that:

[20] • Excellent agreement is found between 150 km-5 and the reanalyzed ISR data around 150 km (150 km-15) (μ_d = −2.29 m s^{-1}, σ_d = 3.69 m s^{-1}, ρ = 0.98).

[21] • The agreement is only poor-to-good between 150 km-5 and both, the mean *F*-region (ISR-15) (μ_d = −16.02 m s^{-1}, σ_d = 10.21 m s^{-1}, ρ = 0.87) and the

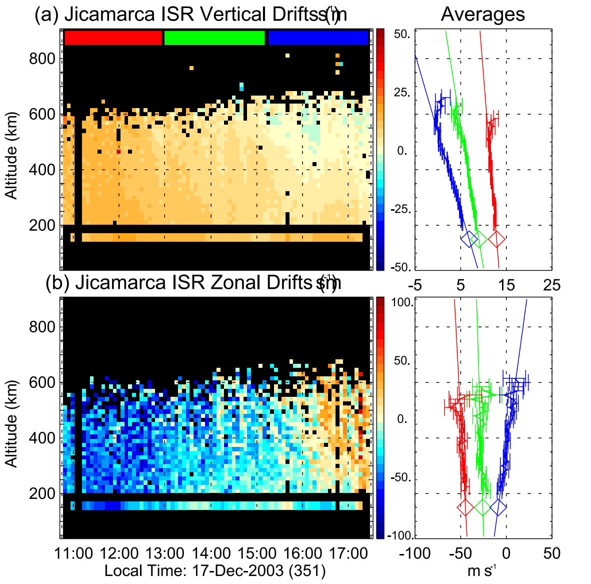

Figure 2. (a) Vertical and (b) zonal drifts over Jicamarca obtained on December 17, 2003. Values above 200 km have been obtained from the ISR technique, while values around 150 km from linearly extrapolating the ISR values. Panels on the right show averaged values with their respective error bars (see text for details).

extrapolated (150 km-fit) (μ_d = -15.86 m s^{-1}, σ_d = 8.15 m s^{-1}, ρ = 0.93) values.

[22] • Mean *F*-region drifts are larger (up to 30 m s^{-1}) than 150 km-5 velocities, particularly before noontime hours. Note that despite the discrepancies before noontime, 150-km zonal velocities follow closely the day-to-day variability of the mean *F*-region zonal drifts.

4. Discussion

[23] The equatorial ionospheric drifts are controlled by the neutral wind generated by the *E*-region and *F*-region dynamos. Reviews on these dynamo theories are given by *Richmond* [1979, and references therein]. During the daytime the *F*-region plasma drifts are strongly coupled to the *E* region at somewhat higher latitudes by the highly conducting magnetic field lines. Therefore the *F*-region drifts are representative of the *E*-region neutral winds that generate the electric fields in the *F* region [e.g., *Woodman*, 1972].

[24] The 150-km vertical velocities are in very good agreement with the mean *F*-region vertical drifts as it was also shown by *Woodman and Villanueva* [1995]. These type of estimates have been used by *Aponte et al.* [1997] to get simultaneously *F*-region density, temperatures and composition, as well as zonal electric fields during the daytime over Jicamarca. Moreover, *Anderson et al.* [2004] have used a long database (more than 200 days) to get a quantitative relationship between ΔH measurements from magnetometers and zonal electric fields inferred from 150-km vertical velocities, similar to the approach presented by *Anderson et al.* [2002].

[25] Much better agreement is found with the linearly extrapolated 150-km vertical drifts (150 km-fit). These results indicate that at daytime, the low-latitude *E*-region zonal electric fields change linearly with latitude. The gradient of this relationship changes for different times of the day and from day-to-day. These gradient changes could shed light on the offset variability found by *Anderson et al.* [2004] when 150-km vertical velocities are correlated with ΔH from magnetometers.

[26] On the other hand, the agreement is poor-to-good between the 150-km zonal velocities and the mean *F*-region zonal drifts. Based on our results, it appears that the daytime low latitude *E*-region zonal wind presents an asymmetry with respect to noontime. Before noontime hours, the gradients for altitudes above ∼200 km over Jicamarca are different than the gradients at lower altitudes (∼150 km). 150-km zonal velocities are smaller than the extrapolated velocities based on the *F*-region ISR zonal drifts. In the afternoon, the gradient for all altitudes observed is almost the same.

[27] A simple model of equatorial electrodynamics (A. Richmond, personal communication, 2004) approximately relates the zonal **E** × **B** velocity (V_x) to the vertical **E** × **B** velocity (V_z), and the zonal neutral velocity (U_n) by,

$$V_x \approx -(\Sigma_H/\Sigma_P)V_z + \int(\sigma_P * U_n \mathrm{d}s)/\Sigma_P \qquad (1)$$

where σ_P is the Pedersen conductivity; Σ_H and Σ_P are the field-line-integrated Hall and Pedersen conductivities, and $\int(.)$ denotes the field-line integral of the quantity in parentheses. The term $\int(\sigma_P U_n \mathrm{d}s)/\Sigma_P$ represents the field-line-averaged zonal neutral wind, weighted by the Pedersen conductivity. This approximation assumes V_x and V_z are constant along field lines, and neglects variations of geometrical scale factors along the field lines. It results from the requirement of current continuity, for which the net

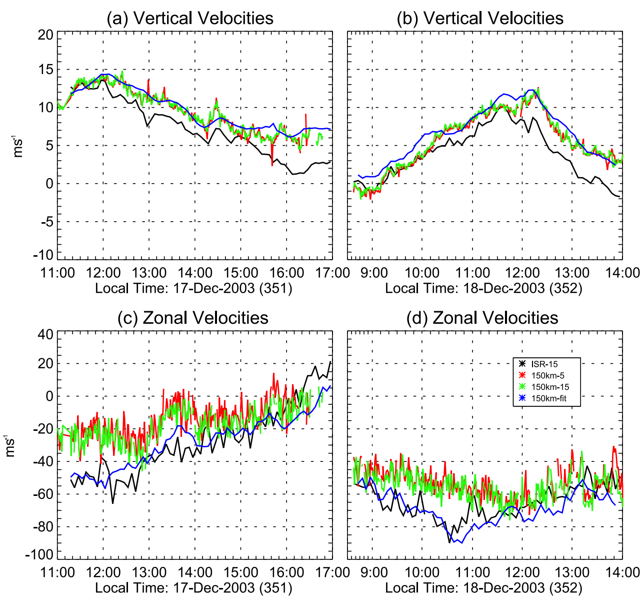

Figure 3. Time series of (top) vertical and (bottom) zonal velocities observed on December 17, 2003 (left) and December 18, 2003 (right). Black, red, green, and blue represent, ISR-15, 150 km-5, 150 km-15, and 150 km-fit, respectively.

outward electric current, integrated along a field line, must vanish if zonal gradients of the zonal electric current density are negligible.

[28] The vertical drift V_z is constrained not to vary much with altitude: because the electric field must be curl-free, the vertical gradient of V_z is balanced by the zonal gradient of V_x, which is usually small because of the broad zonal extent of the ionosphere as compared with its vertical extent. During the day, models predict that Σ_H/Σ_P varies relatively weakly with altitude above 140 km. The weighting of U_n by σ_P means that winds from *E*-region altitudes, where σ_P is largest, contribute significantly to the integral. Therefore, the term $\int(\sigma_P U_n \mathrm{d}s)/\Sigma_P$ can be rather different from the local wind U_n, and V_x represents the *E*-region zonal neutral winds at different latitudes.

[29] However, the poor-to-good agreement between 150-km zonal velocities and the mean *F*-region ISR drifts suggest that either (1) there are significant changes in latitude, particularly closer to the magnetic equator, of the *E*-region zonal winds, or (2) the local U_n contributions are not negligible around 150 km. To support the latter, $\int(\sigma_P U_n \mathrm{d}s)/\Sigma_P$ might vary significantly with altitude, because U_n often varies strongly with altitude, especially below 200 km. Moreover, a large fraction of the path length along the field line lies at altitudes near the apex, and so the value of U_n near the apex can still contribute significantly to the integral, even when σ_P is smaller near the apex than at lower altitudes.

[30] In order to get a better understanding of the zonal velocities from 150 km-echoes, we plan to work with the three-dimensional numerical model of the low-latitude ionospheric electrostatic potential implemented by *Hysell et al.* [2002]. We could drive the model with the NCAR model winds and see what the zonal drifts look like everywhere and also how important local vs. nonlocal forcing is for the 150 km altitude regime.

[31] The excellent agreement between velocities obtained with the special experiment and those obtained after reanalyzing the data from the standard ISR experiment, suggest simultaneous 150-km and ISR experiments are not needed in the future. Moreover, we plan to reanalyze the ISR drift database, particularly those campaigns when rawdata were recorded, to study the 150-km vs. *F*-region velocities as function of season, solar conditions and magnetic activity. We expect to be able to get an empirical model of the altitudinal gradient of the vertical drift. This model in conjunction with the measured 150-km vertical drifts might be useful to infer not only the mean *F*-region vertical drift but also the altitudinal profile.

5. Conclusions

[32] On the basis of our results, we have corroborated [*Woodman and Villanueva*, 1995] results. Namely, the vertical Doppler velocity from 150-km is a very good measurement of the *F*-region $\mathbf{E} \times \mathbf{B}$ vertical drift. Much better agreement is found with the extrapolated (in altitude) values from ISR vertical drift profiles. On the other hand, the agreement between daytime zonal components (150-km vs ISR *F* region) is not good, particularly before noontime. Further work is needed to study how important local vs. nonlocal forcing is for the zonal velocities measured from 150-km echoes.

[33] Finally, we expect the zonal velocities from 150-km echoes to be also very useful to the studies of the equatorial electrodynamics at these altitudes and maybe at latitudes few degrees away from the magnetic equator. Comparisons with other techniques and models should be done to assert the validity of zonal velocities from 150-km echoes.

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