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Radar scatter from equatorial electrojet waves: An explanation for the constancy of the Type I Doppler shift with zenith angle

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[1] The first results from the 430 MHz Advanced Modular Incoherent Scatter Radar Prototype (AMISR-P) at the Jicamarca Radio Observatory were reported by Hysell et al. (2007). We present additional data showing that the phase velocity of Type I echoes is independent of zenith angle, an unexplained property of these waves. We interpret the results using rocket data by predicting the total line-of-sight velocity at the four zenith angles used. We find that the radars preferentially detect waves within 10% of C_s in at least four range gates for all beams and up to eight range gates for the 51 JULIA beam. This result is consistent with recent auroral observations that Type I waves are only generated with **k** vectors near the electron flow velocity, where the latter is the vector sum of the zero-order drift and the perturbation drift due to large-scale waves in the equatorial case. **Citation:** Kelley, M. C., R. A. Cuevas, and D. L. Hysell (2008), Radar scatter from equatorial electrojet waves: An explanation for the constancy of the Type I Doppler shift with zenith angle, *Geophys. Res. Lett.*, *35*, L04106, doi:10.1029/2007GL032848.

1. Introduction

[2] The first results from the seven-panel Advanced Modular Incoherent Scatter Radar Prototype (AMISR-P) from its deployment at the Jicamarca Radio Observatory were reported by *Hysell et al.* [2007], along with simultaneous data from the Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere radar (JULIA). Here, we interpret these results in light of simultaneous radar and rocket electric field measurements [*Kudeki et al.*, 1987; *Pfaff et al.*, 1987; *Kelley*, 1989; *Pfaff et al.*, 1997] and recent results in the auroral zone reported by *Bahcivan et al.* [2005].

[3] Our goal is to explain the long-standing experimental result that Doppler spectra associated with modified two-stream waves at the equator indicate a wave phase velocity close to the acoustic speed (C_s), independent of angle to the zero-order electron flow velocity [*Bowles et al.*, 1960]. This result is in stark disagreement with linear theory, which predicts a wave phase velocity equal to $V_D \cos \theta/(1 + \Psi_0)$ where θ is the angle between the current and the radar beam, V_D is the flow velocity, and $\Psi_0 = \nu_e\nu_i/\Omega_e\Omega_i$ where the numerator of Ψ_0 is the product of the collision frequencies and the denominator is the product of the gyrofrequencies. This equatorial experimental result is also in apparent disagreement with the new auroral zone observations, which indicate that Type I waves are only generated in a narrow cone near the flow velocity [*Bahcivan et al.*, 2005].

[4] The debate over this point is complicated by several factors. First, in the auroral zone, the waves are intense enough to cause electron heating, which changes C_s. Second, there is no universal agreement as to whether the electron and/or ion fluids are isotropic or adiabatic at the wave frequency associated with the Bragg wavelength of the radar used [*Providakes et al.*, 1988]. Finally, the actual rate of electron inelastic energy exchange seems to be 2–3 times higher than that used before in the estimates [*Kagan and St.-Maurice*, 2004; *Kagan and Kissack*, 2007]. At the equator, however, the primary two-stream waves have an amplitude of only a few mV/m [*Pfaff et al.*, 1987] and any heating is not likely. The other issues are less important in this context since the angular effect is much larger than the phase velocity changes due to these other effects.

[5] Here we consider the long-standing problem of the constant value (near C_s) of the phase velocity of equatorial, modified two-stream wave echoes at any angle of the radar beam to the horizontal electron drift velocity, as first reported by *Bowles et al.* [1960].

2. On the Constant Wave Phase Velocity Versus Radar Elevation Angle

[6] Data from the two systems are presented in Figure 1 in a range/Doppler shift intensity format. The range resolution or range gate for AMISR-P (430 MHz) is 0.6 km and for JULIA (50 MHz) it is 1.5 km. The bright red regions, which are particularly clear in the JULIA data at 51 from zenith and the AMISR data at 20, are due to the Type I echoes. Type I waves can also be seen in the vertical AMISR beam and weakly in the other two panels. The centroid of these features all fall around the acoustic speed.

[7] The key to understanding the equatorial results is based on two important factors. First, the drift velocity of importance is the total electron drift velocity, which is equal to the vector sum of the zero-order horizontal drift and the drift induced by intense, large-scale waves. Second, a radar will respond to the most intense wave in the field of view and hence will record the Doppler shift of the most strongly driven waves in the range sampled. If, as we suggest here, there is some portion of the sampled region with a line-of-sight electron drift near C_s, that Doppler will be recorded. Furthermore, *Bahcivan et al.* [2005] have shown that Type I waves are only generated in a narrow cone about the (total) electron drift velocity, which, in the auroral zone, is the same as the zero-order velocity, since large-scale waves rarely seem to occur there.

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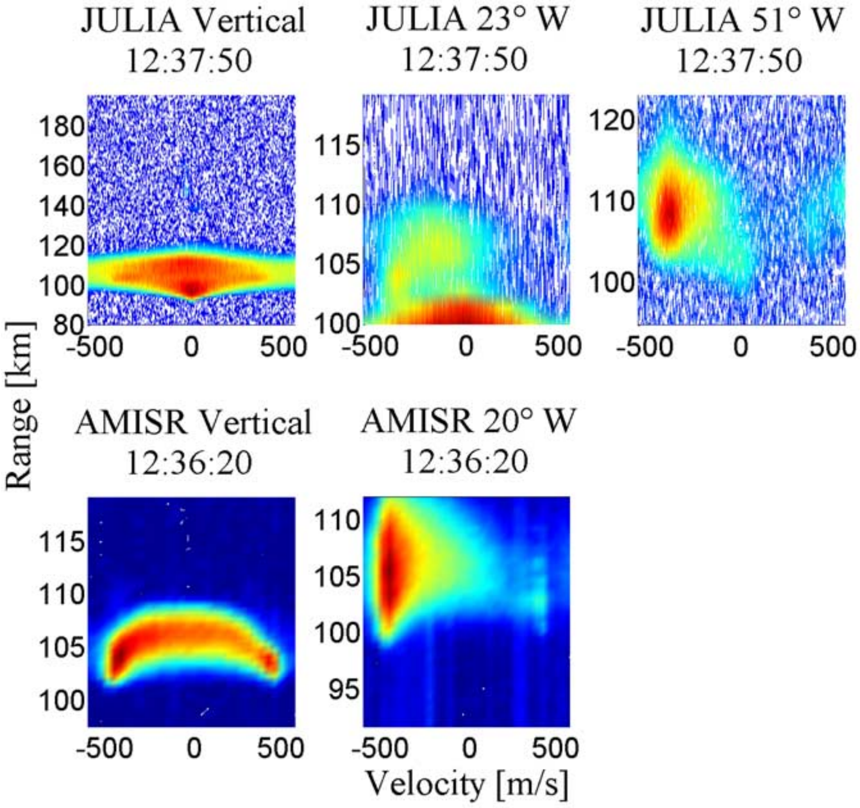

Figure 1. Range-Velocity-Intensity for (top) JULIA and (bottom) AMISR.

[8] To show this result, we use the rocket observations made during the Condor campaign in Peru as reproduced in Figure 2 [*Pfaff et al.*, 1987; *Kelley*, 1989]. The plasma density during the flight had a positive vertical gradient up to the altitude of 107 km. For a few km up to that height, intense horizontal electric fields, and hence large vertical drifts corresponding to large-scale waves, were detected. This is the height range in which both the two-stream and gradient drift instabilities operate. Above this height, the wave amplitude dropped abruptly and the dominant wavelength in the vertical velocities shifted from several km to several meters [*Pfaff et al.*, 1987; *Kelley*, 1989]. It is interesting to note that the field strength, when converted to velocity, seems to saturate at the value $(1 + \Psi_0)C_s$, as plotted with the dashed line. Note that these are the only in situ electric field measurements made in the equatorial electrojet to date under two-stream conditions.

[9] To make our main point, we appeal to prior radar observations (some of which were made during the same event shown in Figure 2), which show that the horizontal wavelengths of daytime large-scale waves are in the range of 2–3 km [*Kudeki et al.*, 1987]. Furthermore, the large horizontal electric fields are present coherently over an altitude range of 4 km. The low apogee of the Condor rocket means that the horizontal velocity of the rocket in the electrojet was comparable to the vertical velocity. We used these experimental results to generate a perturbation vertical velocity, δV_z, every 30 meters along the trajectory. Since the plasma was unstable to the Farley-Buneman (FB) process, the zero-order horizontal drift velocity, V_x, must have exceeded 400 m/s. The electric field data published by *Pfaff et al.* [1997] show that this drift component is nearly independent of height in the region of interest. For each of the vertical drift data points, then, we can compute the

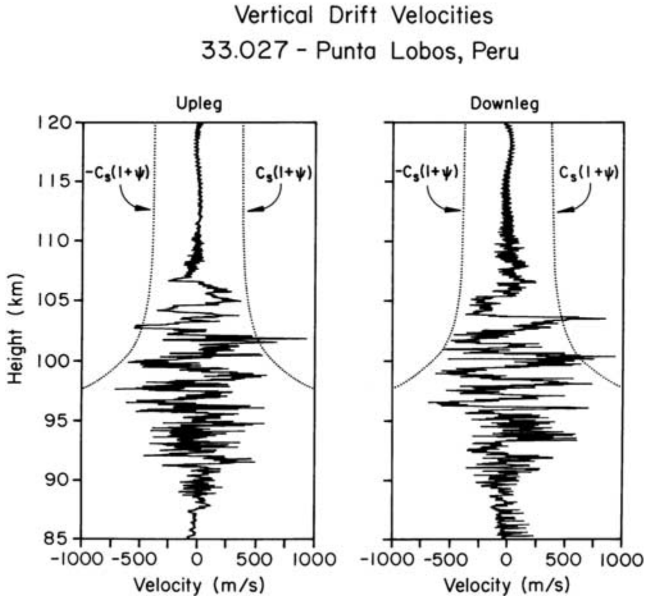

Figure 2. Observations from the Condor rocket campaign in 1987 (adapted from *Pfaff et al.* [1987]).

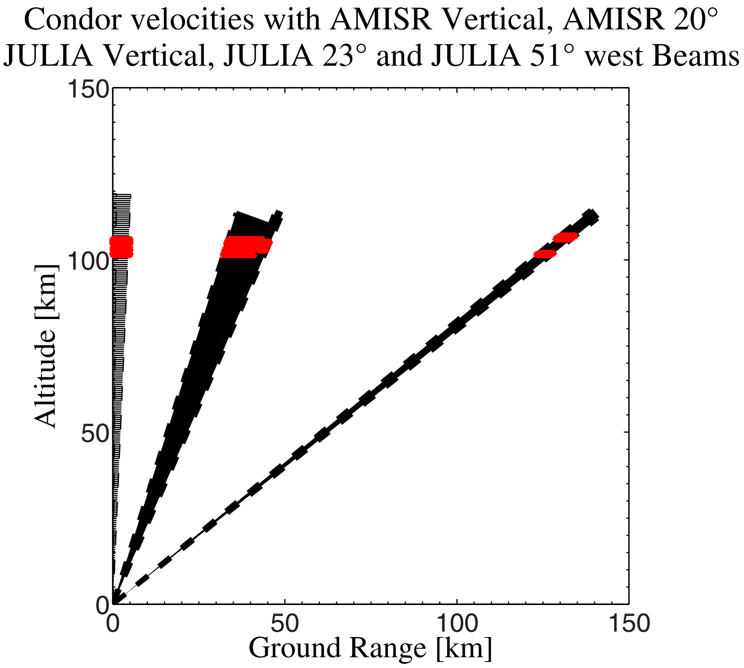

Figure 3. Regions for the AMISR Vertical and 20° west beams and the JULIA Vertical, 23° and 51° degree west beams in which the projection of the total electron velocity on the radar line of sight exceeded $0.9(1 + \Psi_0)C_s$. The narrow beam corresponds to the Julie system and the wide beam to AMISR-P. They overlap slightly in the vertical and intermediate zenith positions.

total electron drift velocity, $V_T = (V_x^2 + \delta V_z^2)^{1/2}$. The V_T we determine lies roughly along a 45 angle in a region approximately 10 km × 10 km. Since the horizontal perturbation and vertical fields are nearly independent of altitude, the drifts along the trajectory are representative of the entire volume.

[10] Figure 3 shows how a region with these total drift vectors would be interrogated by the JULIA radar at three different zenith angles for the system beam width and range resolution, as well as for the AMISR-P radar at its two zenith angles. The red regions in Figure 3 correspond to range/azimuth bins in which the line-of-sight velocity exceeded the factor of $0.9(1 + \Psi_0)C_s$. For this purpose, we used the isothermal value for C_s. Almost certainly, the most intense waves are those with a phase velocity vector nearest the flow angle. Furthermore, the results of *Bahcivan et al.* [2005] indicate that the only two-stream waves generated are near the flow direction. This implies that the radar will preferentially detect such waves if they are in the range gate and will hence register their Doppler velocity. By our criterion, this echo will be registered at a phase velocity in excess of $0.9C_s$. Thus, it is clear that, at the equator, the radars will always see a near-constant Doppler shift as a function of angle when the horizontal drift velocity is large and when intense, large-scale waves are present. The long-standing problem seems resolved.

3. Conclusions

[11] The results reported by *Bahcivan et al.* [2005] that the narrow spectral component of electrojet waves is generated in a small cone of angles about the total electron flow velocity seems to explain both the auroral zone results and those at the magnetic equator. The long-standing question as to why the equatorial Doppler shift is independent of radar elevation seems to be solved.

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