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Type I radar echoes from theequatorial electrojet with double peaked Doppler spectra

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Type 1 Radar Echoes From the Equatorial Electrojet With Double-Peaked Doppler Spectra

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Normal type 1 radar echoes obtained from relatively large zenith angles have a power spectrum with a single narrow peak whose Doppler shift corresponds approximately to the acoustic velocity in the medium. On some occasions, however, this single maximum splits into two distinct peaks, separated in phase velocity on one occasion by 270 m/s. This bifurcation is most easily observed at large zenith angles during daytime when a narrow antenna beam is used. It has also been seen in a daytime experiment in which radars at Jicamarca and Huancayo simultaneously probed the same region from two different radar zenith angles. The bifurcation has been observed so far only to the west of Jicamarca, over the Pacific Ocean. This spectral splitting could be caused by vertical electron density gradients, such as those associated with 'blanketing' sporadic *E* layers. A sufficiently sharp (scale lengths of a few hundred meters or less) positive gradient on the underside of the layer and negative gradient on the topside would cause the type 1 velocity to be decreased and increased, respectively, during the day, by amounts as large as those observed.

INTRODUCTION

Type 1 radar echoes from the equatorial electrojet are characterized by spectra which have a narrow peak at a Doppler shift corresponding closely to the ion acoustic velocity in the *E* region. Type 2 echoes, which are somewhat better understood, have broader spectra with smaller Doppler shifts. These latter echoes will not be considered in this paper. A considerable amount of experimental and theoretical effort has been expended in the last decade and a half in an attempt to understand the type 1 irregularities and the plasma instability which produces them [e.g., *Bowles et al.*, 1963; *Farley*, 1963; *Cohen and Bowles*, 1967; *Balsley and Farley*, 1971; *Sato*, 1973, 1976; *Lee et al.*, 1974; *Farley and Fejer*, 1975; *Rogister and Jamin*, 1975; *Weinstock and Rognlien*, 1975; *Fejer et al.*, 1975*a*, *b*, 1976; *Hanuise and Crochet*, 1977, 1978].

As was mentioned above, the type 1 spectra normally have a single narrow peak. In this paper, however, we discuss some unusual radar data in which this single peak splits into two, one with a larger and one with a smaller than normal Doppler shift. The measurements were made at Jicamarca and Huancayo in Peru at approximately 50 MHz. The most plausible explanation for the splitting is believed by us to be that the instability threshold was substantially altered by very sharp positive and negative vertical density gradients associated with a narrow layer of enhanced ionization, such as those responsible for 'blanketing sporadic *E*' echoes in the HF band. The possible importance of density gradients for type 1 echoes was first suggested by *Farley and Fejer* [1975]. The predicted effect is negligible at 50 MHz for normal gradient lengths of a few kilometers or more but can become significant for sharp gradients and/or lower radar frequencies. Recent observations made in Africa at several frequencies between 7 and 29 MHz by *Hanuise and Crochet* [1977] support this prediction.

EXPERIMENTAL RESULTS

Our data were obtained with three different radar systems in Peru. The first operated throughout most of 1975 at the Jicamarca Radar Observatory. Its antenna was a grating array of eight lines of dipoles, each of which was about 8 wavelengths long aligned along the magnetic meridian. The lines were separated by about 6 wavelengths, and the resulting pattern in the east-west plane contained 13 narrow lobes pointed at zenith angles ranging from 60°E to 67°W. The system, operated with its own 10-kW peak power transmitter at a frequency of 48.850 MHz and its own dedicated minicomputer and display system, ran continuously and unmanned, recording power and spectral data from each lobe on film.

The data of interest here were obtained from only one of the lobes (pointed 64°W) at delays of 1610 and 1660 μs, which correspond to altitudes centered at about 104.5 and 108 km. The half-power beam width (two way) at this angle was estimated to be approximately 1.7°, and the pulse length was 50 μs, giving an overall altitude resolution of roughly 7 km. This is far from ideal for our purposes, but it was sufficient to give us some discrimination between echoes from the upper and lower portions of the electrojet. The integration time for each spectrum was about 50 s.

On most occasions when type 1 echoes were obtained with this system, the echoes at both delays had essentially identical spectra. On some days (probably less than 10% of the days on which type 1 echoes were seen), however, the type 1 spectra exhibited an unusual broadening followed by the development of a double-peaked structure which often differed at the two ranges. Examples of this sort of behavior are shown in Figures 1 and 2. 'Low' and 'high' refer to the upper and lower altitudes. Figure 1 shows the most spectacular example yet observed of this splitting. On this day, type 1 echoes were observed starting at about 0920 LT (75°W), and the spectra in the two volumes were nearly identical until about 1135, when the spectrum in the lower volume began to broaden. The figure shows the subsequent history of the spectral splitting until

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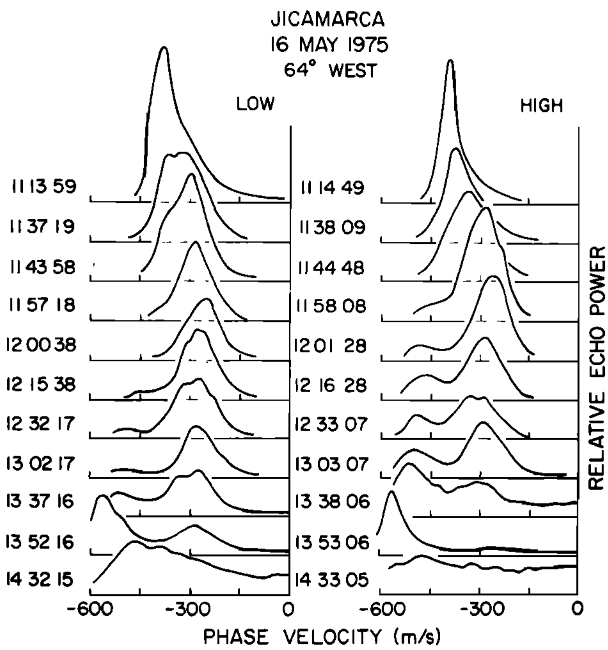

Fig. 1. An example of the evolution of an extreme bifurcation of the type 1 spectrum. The altitude resolution was 6–7 km, and the 'low' and 'high' scattering volumes were centered at approximately 104.5 and 108 km, respectively. The normalization constants of the spectra differ. The radar beam was directed 64° west of vertical.

the type 1 echoes disappeared shortly after 1430. Note that (1) the separation between the peaks is large (almost a 2:1 ratio), (2) the mean of the velocities of the two peaks after the split is roughly equal to the velocity of the single peak before the split, (3) the observations at the higher altitude slightly favor the peak at the higher velocity, and vice versa, and (4) the high velocity peak is the last to disappear (the echoes at ~1430 are very weak; most of the power shown in the bottom panels is due to noise as a result of the normalization procedure used).

Figure 2 shows a second example of the development of double peaks. In this case the high phase velocity peak appeared first in the upper region, while the velocity of the original type 1 peak remained essentially unchanged as its power gradually decreased. The same processes took place in the lower region but started a few minutes later. By 1300 LT all the power at both altitudes was at the high phase velocity, which was almost 100 m/s greater than that of the initial peak, and remained there until the type 1 echoes disappeared at about 1430.

In January 1977, two radar systems, one at Jicamarca and one at Huancayo, were used simultaneously to study the electrojet echoes, the primary aim being to study neutral winds and temperature variations. In addition to these (as yet unpublished) studies, we had the good fortune to obtain further examples of the spectral bifurcation. The geometry of the experiment is shown in Figure 3. The Huancayo antenna was a multibeam array similar to the array used in the 1975 Jicamarca measurements. Eight rows of dipoles, each about 8 wavelengths long, were separated by 3.68 wavelengths. The rest of the radar consisted of a 10-kW peak power transmitter, a dedicated minicomputer display system, and a digital magnetic tape unit. The Jicamarca observations were made by transmitting on a dipole with a peak power of several hundred kilowatts and receiving on two 50-MHz broad beam steerable (in the east-west plane) antennas. The pulse lengths were 50 μs for both systems. The integration times were about 70 s for Jicamarca and 80 s for Huancayo. The exact position of the scattering volume was determined by range gating (using the fact that the electrojet echoes come from a narrow region of altitude). As is shown, there were a total of 17 separate volumes sampled, 9 of which were probed simultaneously by both radars. Actually, only the longitude of the volumes was common; the latitudes were separated by about 13 km, since Huancayo is not exactly magnetically east of Jicamarca. In these measurements the echoes were obtained from the entire altitude range of the electrojet; because of the wider antenna beam widths it was not possible to discriminate between echoes from the upper and lower portions, as was done in 1975. Probably because of this, the spectral bifurcation observed in 1977 was less distinct than that observed in 1975, but it is still readily apparent, as can be seen in Figures 4 and 5. The echoes from Huancayo labeled 67°, 62°, and 38° correspond to volumes 5, 7, and 9 of Figure 3, and the Jicamarca echoes shown in Figure 5 (going from left to right) correspond to volumes 1–6.

The bifurcation and shift from a moderate Doppler shift (phase velocity of the order of 300 m/s) to a substantially higher value (velocity of ~450 m/s) appears in the first two columns of Figure 4 (volumes 5 and 7) and in all columns in Figure 5 (volumes 1–6). Note that all of these volumes, which span about 200 km in longitude, are west of Jicamarca. There is apparently a real geographical effect [*Balsley,* 1970, 1977; *Crochet,* 1977]. For example, compare the right-hand columns of Figures 4 and 5. These correspond to virtually the same zenith angle from Huancayo and Jicamarca, respectively, but the first shows echoes from volume 9 over the Andes, while the second involves echoes from volume 6 over the ocean. Further evidence on this point is given in Figure 6, which

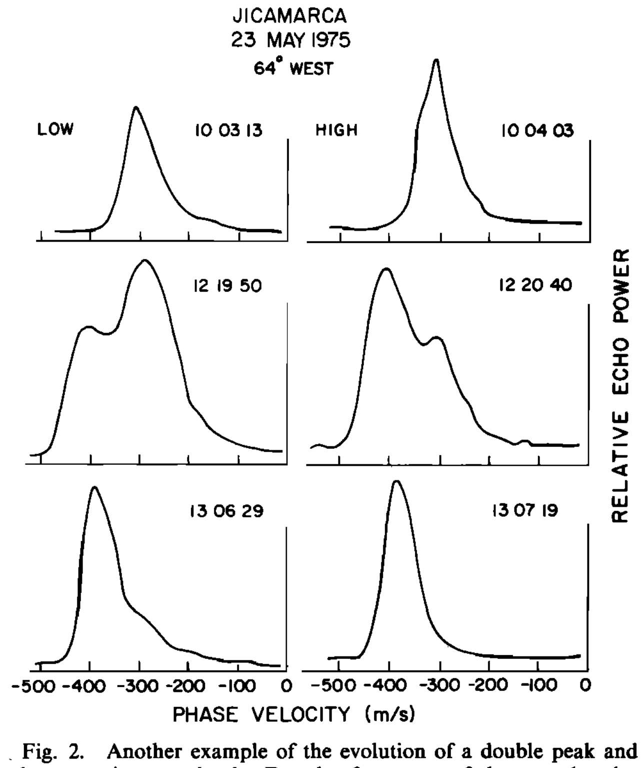

Fig. 2. Another example of the evolution of a double peak and subsequent increase in the Doppler frequency of the type 1 radar echo. For a description of the parameters see the legend for Figure 1.

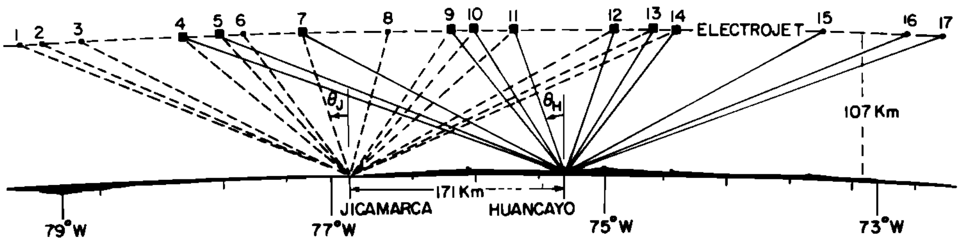

Fig. 3. A schematic representation of the radar geometry during the simultaneous Jicamarca-Huancayo measurements of January 1977. The latitudinal separation of the scattering volumes, as seen from the two observations, was about 13 km.

shows echoes obtained at Jicamarca from the east (volumes 10, 11, and 12). There is no sign of spectral splitting, even at extreme zenith angles. Note also that the spectral peaks in Figure 6 are at approximately 400 m/s, or about the mean of the high and low velocities in Figure 5 (~500 and 300 m/s). The power received at Huancayo from the most easterly volumes (15–17) was small, and the spectra showed no sign of splitting. The echoes from the smallest zenith angles (volumes 7 and 8 from Jicamarca and volumes 11 and 12 from Huancayo) contained at most a weak type 1 component and have been ignored here.

The type 1 phase velocities measured from Huancayo and Jicamarca for the same scattering volume (but different zenith angles) were observed to be in excellent agreement, as is illustrated in Figure 7 for volumes 4, 5, and 9. When double-peaked spectra were present, the velocity of only the dominant component is plotted. The time at which the amplitude of the large Doppler shift component first exceeds that of the component with the smaller shift in volumes 4 and 5 is somewhat later at Jicamarca than at Huancayo, but otherwise the curves are practically identical, as are the curves for volume 9 (east of Jicamarca), where no splitting occurred. These results imply that the zenith angle of the radar observation is not a crucial factor in determining whether or not the spectrum may develop a double-peaked structure; there is apparently a genuine longitudinal effect.

Discussion

On the basis of our present partial understanding of the type 1 electrojet irregularities, the three physical quantities that determine the phase velocity of the waves are east-west wind velocity (we neglect the vertical component, which unpublished data confirm is a valid approximation), temperature, and vertical density gradient. We must therefore look to these for an explanation of the spectral splitting that we have observed. For reasons that are still not completely understood, the type 1 velocity appears to be the sum of two components, the largest of which, the threshold velocity predicted by linear plasma instability theory, is independent of the radar zenith angle. A smaller component describes the convection of the medium by the east-west neutral wind and is proportional to the sine of the zenith angle. The observed phase velocity V_ϕ, then, is

$$V_\phi = V_0 + V_{\mathrm{EW}} \sin\theta \qquad (1)$$

where V_{EW} is the zonal wind, θ is the zenith angle of the radar beam, and V_0 is the threshold velocity, which is essentially the ion acoustic velocity modified by the effect of density gradients, as discussed by *Farley and Fejer* [1975]. This velocity is given by

$$V_0 = C_S[(1 + F^2)^{1/2} - F] \qquad (2)$$

where

$$F = \nu_i\Omega_e/2\nu_e k^2 L_N C_S \qquad (3)$$

Here $\nu_{e,i}$ and $\Omega_{e,i}$ are the usual collision and Larmor frequencies, C_S is the acoustic velocity (proportional to $T^{1/2}$), k is the radar wave number, and L_N is the electron density gradient length (positive for upward gradients and westward electron flow, or vice versa). For reasonable electrojet parameters and the Jicamarca radar ($k = 2\ \mathrm{m}^{-1}$), F is approximately $110/L_N$, where L_N is measured in meters, and is usually quite small. Figure 8, taken from *Farley and Fejer* [1975], shows the variation of V_0 with gradient length for 50-MHz observations. At longer wavelengths the gradient effect may be quite important, and *Hanuise and Crochet* [1977] have shown that type 1 phase velocities observed with a multifrequency HF radar agree quite well with this theory.

Winds. Could east-west winds somehow produce the spectral splitting? Apparently not. Consider the example in the left column of Figure 1 at 1352:16. The peak velocities are ap-

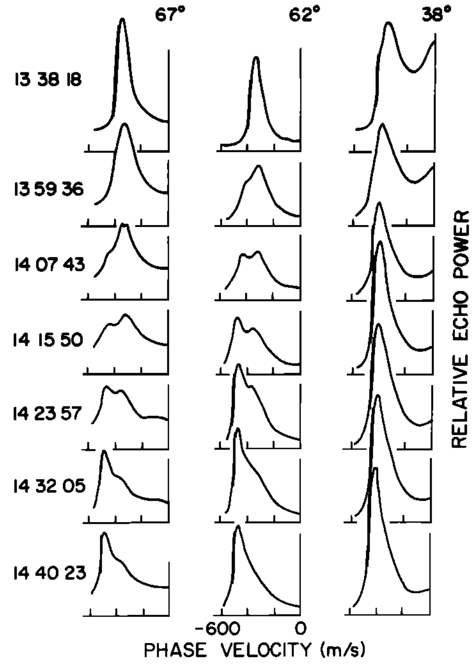

Fig. 4. A set of spectra observed at Huancayo showing the bifurcation effect. From left to right, the scattering volumes are those labeled 5, 7, and 9, in Figure 3. The integration time was ~80 s. The integrations at 38°, 62°, and 67°, began ~160 s, 240 s, and 320 s, respectively, after the times listed at the left.

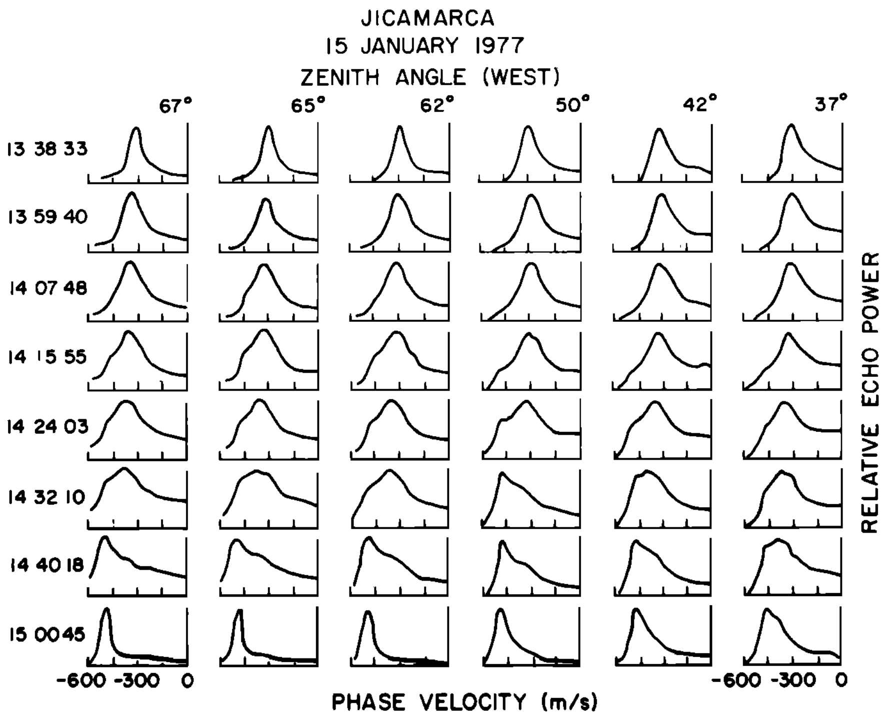

Fig. 5. Normalized spectra from volumes 1–6 observed at Jicamarca. The antenna beam width for these measurements was much broader than it was for those shown in Figures 1 and 2; the echoes are from the entire altitude range of the electrojet. The spectral broadening, splitting, and shifting can be seen here but are not as well defined as in Figures 1 and 2.

proximately 560 and 290 m/s. At the zenith angle of 64° a sudden discontinuity (a smooth change would just broaden the spectrum, not split it), occurring within at most a kilometer or two, of about 300 m/s in the wind velocity would be required. A wind pattern shifting from, say, 150 m/s eastward to 150 m/s westward in a few kilometers or less in the *E* region seems quite unlikely, although discontinuities of the order of 100 m/s have been seen in the *E* region [e.g., *Teitelbaum and Sidi*, 1976].

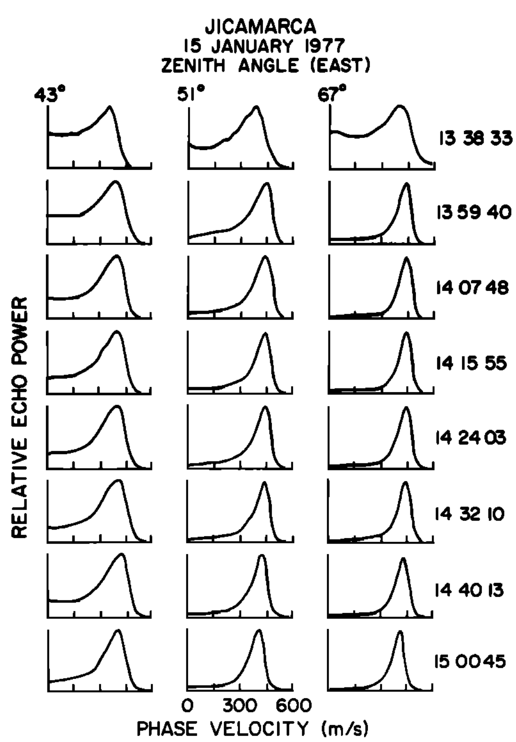

Fig. 6. Spectra from volumes 10, 12, and 14 to the east of Jicamarca during the period covered by Figure 5. Note the complete absence of broadening and/or double peaks in this case. Note also the Doppler shift of the peak in comparison to the values of Figure 5.

If this example is not sufficiently convincing, consider the data of January 15, 1977. The left-hand column of Figure 4 and the column labeled 42° in Figure 5 correspond to echoes from volume 5 in Figure 3. The Huancayo (Figure 4) velocity peaks are at approximately 485 and 338 m/s, giving a separation of 147 m/s. The corresponding values for the Jicamarca observations are 472 and 319 m/s, a difference of 153 m/s. The Huancayo velocities are slightly larger, perhaps owing to a westward wind of the order of 50–70 m/s. The important point for this discussion, however, is that the velocity differences between the two peaks are essentially identical; if anything, the Jicamarca difference is larger, whereas if winds caused the splitting, the Jicamarca separation whould be smaller, only 73% of the Huancayo separation, owing to the difference in zenith angles.

Temperature. Temperature discontinuities could in principle explain the observations, but as with winds, this explanation is not quantitatively reasonable. To refer again to the example in Figure 1 quoted in the last paragraph, the velocity difference of almost a factor of 2 implies a temperature difference of almost a factor of 4, which seems completely out of the question. As was mentioned above, we note also that a smooth temperature change in a few kilometers of even this magnitude will simply broaden the spectrum, not split it.

Density gradients. Within the framework of existing theory, the density gradients are our last hope. We need large gradients to cause a substantial frequency shift and sharp discontinuities in the gradients to explain the splitting. For example, a thin 'triangular' density profile in the electrojet re-

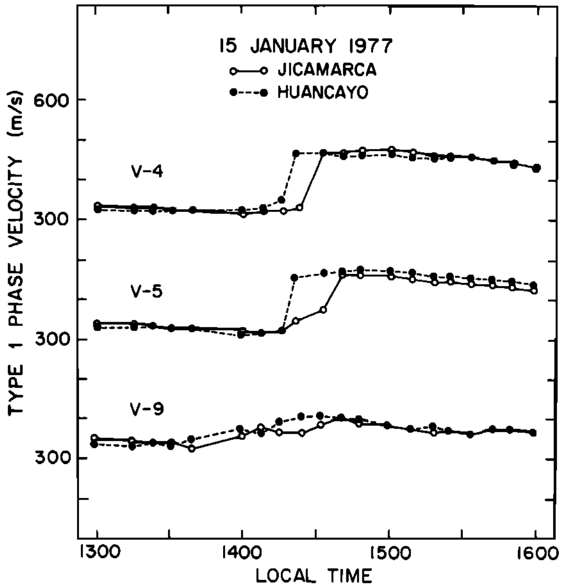

Fig. 7. The variation of the phase velocity corresponding to the spectral maximum for the echoes observed simultaneously at Jicamarca and Huancayo. The effect of the splitting can be seen in the data from volumes 4 and 5; no such effect occurs in volume 9, which is east of Jicamarca and over the Andes.

gion with a steep positive gradient on the bottomside changing suddenly to an equally steep negative gradient on the topside would give the results seen in Figure 1 if the gradient length were 300–400 m (see Figure 8). Echoes from the bottomside of the layer, where the gradient is destabilizing, would have the smallest Doppler shifts, and echoes from the topside would have the largest. When the layer is absent, the shift should be about midway between these two extremes. These predictions are in accord with our observations, which, in spite of the poor altitude resolution, at least crudely suggest that the echoes with the higher Doppler shift are coming from the upper part of the echoing region, and vice versa. The gradients required in this case are admittedly very sharp, but on the other hand, the example shown in Figure 1 is the most extreme ever observed. Note also that the shift of the single peaks shown in the top spectra of Figure 1 is midway between the double peaks seen after 1300, and the single peaks observed to the east of Jicamarca in Figure 6 are midway between the double peaks of Figure 5.

So-called 'blanketing sporadic E' layers thin enough to account for our observations have been observed with rockets [*Smith,* 1966; *Smith and Mechtly,* 1972; *Szuszczewicz and Holmes,* 1977] and more crudely with radar [*Ioannidis and Farley,* 1972; *Behnke and Vickrey,* 1975; *Miller and Smith,* 1978] at mid-latitudes and have been seen on ionograms at equatorial latitudes, where they may persist for hours. Of course, ionograms cannot give a detailed layer profile with the required resolution, but it seems likely that vertical gradients at the equator could be as steep or even steeper (owing to suppression of vertical diffusion) than they are at temperate latitudes. Unfortunately, there are no ionosonde records for the regions from which the spectrally bifurcated echoes were obtained.

Differences in the exact shape, position, and motion of a thin layer would produce various spectral shapes. A somewhat flat-topped or rounded density profile would give a rather broad spectrum, with perhaps two (or more) relatively weak peaks corresponding to regions of approximately constant gradient. If the layer moves slowly downward through the thin (~3 km for daytime type 1 electrojet echoes; see *Fejer et al.* [1975*a*]) electrojet region, as would be the case for a layer driven by gravity-wave-associated wind shear, we would expect the type 1 Doppler peak to first decrease in frequency, then broaden or split, and then increase to above the original value. A tilted layer drifting through the beam would produce the same sequence if the tilt were upward in the direction of travel. This is a very typical scenario; the converse has never been observed. Part of this sequence might not be observed if the layer is a localized patch (as is often the case at temperate latitudes; see *Miller and Smith* [1978]) which drifts horizontally into or out of the radar beam. The fact that a distinct bifurcation of the type 1 spectral peak is quite rare at Jicamarca but a moderate broadening of the peak is not seems consistent with the gradient explanation; only profiles with unusually sharp gradients and distinct kinks at the right altitudes will produce an obvious splitting. One way to confirm our hypothesis that gradients cause the splitting would be to observe the effect simultaneously at two well-separated radar frequencies. The magnitude of the separation in phase velocity would be largest for the lowest frequency. As yet, no such data exist, unfortunately.

We do not understand why this effect has been observed only to the west of Jicamarca, over the ocean. It is doubtless related to other east-west electrojet asymmetries which have been observed at Jicamarca [*Balsley,* 1970, 1977] and which are also not understood.

African observations. *Crochet et al.* [1979] reported examples of similar spectral splitting observed in Africa during very strong daytime counterelectrojet (eastward electron drift) conditions using a 14.2-MHz radar. They suggest that their observations can be accounted for by strong winds and refraction effects. We will not comment further on this paper here; we merely wish to emphasize that this explanation cannot account for the Jicamarca observations, for which refraction is not important and unrealistic wind patterns would be required.

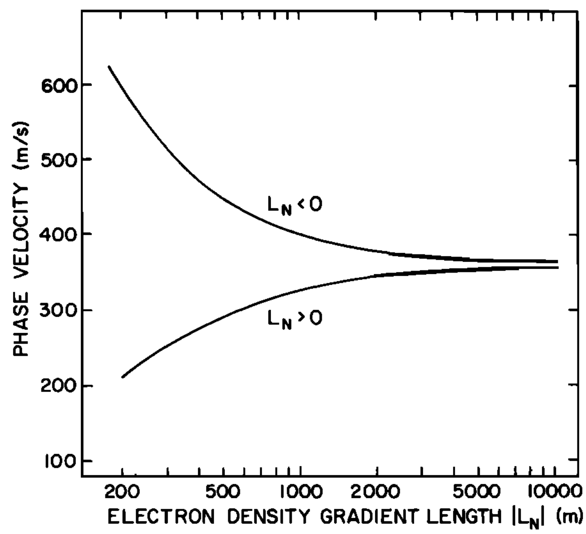

Fig. 8. The effect of an electron density gradient on the type 1 threshold phase velocity for 3-m irregularities near the center of the electrojet scattering region. The length L_N is $N_0(dN/dh)^{-1}$, and the electrons are assumed to be drifting to the west (daytime conditions; upward electric field).

CONCLUSIONS

Density gradients appear to be the most plausible source of the splitting of type 1 echo spectra which is occasionally observed to the west of Jicamarca, over the Pacific Ocean, but not to the east, over the Andes. In any case, it seems most unlikely that sudden discontinuities in temperature or wind velocity could explain the observations; the discontinuities required are just too extreme. This gradient explanation, discussed in the previous section, may not be the whole story, however; in the absence of a quantitative nonlinear theory which explains the simple type 1 spectrum, it is premature to assume that we completely understand this more complicated observation. In particular, we need to understand why the spectral peak (or peaks) appears to correspond always to the threshold velocity, independent of radar zenith angle, even when the threshold is strongly affected by a vertical gradient. The fact that this does appear to be the case, however, further supports the hypothesis of *Farley and Fejer* [1975], outlined in (1)–(3). This gradient effect may make it difficult to determine temperature variations accurately by studying variations in the type 1 phase velocity. There seems to be no easy way to separate the temperature and gradient effects.

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