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Oblique VHF Radar Spectral Studies of the Equatorial Electrojet

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A new narrow-beam antenna at the Jicamarca Observatory permits oblique (zenith angle, 25°) radar spectral studies of the electrojet with an altitude resolution down to 1.1 km. Only daytime observations are possible presently, however. The general altitude variations in spectral shape observed are consistent with linear instability theory, if the effect of recombination is included. The height at which the mean Doppler shift of the echo maximizes, however, is about 4 km higher than one would expect on the basis of electrojet models. An increase in the assumed collision frequency would remove the discrepancy. Other data presented strongly suggest that at least some of the variations observed in the type 1 echo phase velocity are due to changes in the temperature of the E region.

The characteristics of the plasma irregularities in the equatorial electrojet have been discussed in several earlier papers [e.g., *Cohen and Bowles,* 1967; *Balsley,* 1969; *Farley,* 1971; *Prakash et al.,* 1969, 1971, 1972; *Farley and Balsley,* 1973; *Balsley and Farley,* 1973] and have been at least partly explained by linear plasma instability theories [*Farley,* 1963; *Maeda et al.,* 1963; *Rogister and D'Angelo,* 1970; *Whitehead,* 1971]. Recently, several nonlinear mechanisms have also been proposed, with varying degrees of success [*Rogister,* 1972; *Sato,* 1973; *Sudan et al.,* 1973; *Lee et al.,* 1974].

Much of our understanding of the physics of the electrojet irregularities is based upon the VHF radar observations in Peru, particularly the spectral measurements. Until recently, the altitude resolution of these measurements was poor, and the observed spectra represented a weighted average over the entire electrojet altitude range. *Balsley and Farley* [1973] reported the first measurements from the Jicamarca Observatory (magnetic dip, 2°N) that partly resolved the electrojet. These measurements were made by looking vertically with the large 50-MHz incoherent scatter array.

Here we present the first results (also at 50 MHz) obtained by looking obliquely with comparable altitude resolution (3 km or better). The antenna was essentially a small physically tilted version of the large array with a very wide beam in the north-south plane (which does not affect the resolution, since echoes are received only from directions nearly normal to the magnetic field) but a narrow beam in the east-west plane. Because of the relatively small collecting area of this antenna the sensitivity was sufficient only for daytime measurements.

Our results show that the oblique spectra vary strongly with altitude. In particular, type 1 (two stream) irregularities are excited only above about 105 km. Such variations are expected on theoretical grounds and had been suggested by earlier data [e.g., *Cohen,* 1973], but the present data give the first direct evidence. Other data, obtained by using the older system without altitude resolution, are presented to illustrate the variation of the type 1 echo Doppler shift with time and the slight spectral asymmetry in the east-west plane that is sometimes observed.

EXPERIMENTAL PROCEDURES

The new narrow-beam oblique antenna used in these experiments consists of four arrays, each of which contains 12 collinear half-wavelength (3 m) elements identical to those used in the large incoherent scatter antenna [*Ochs,* 1965]. They are essentially pieces of coaxial transmission line, the inside conductor of one element being connected to the outside conductor of the next; hence the 12 elements can be fed at only one point at the center of the array, and yet all will radiate in phase. The supporting towers are 19 m high and 41 m apart, yielding a beam that points 25° east of vertical. The beam width in the E-W plane is about 2° for one-way propagation, or about 1° for combined transmission and reception. The N-S beam width is very wide, being essentially the width of a dipole above ground, but is unimportant (except as it affects the gain of the antenna), since echoes are obtained only from waves propagating nearly perpendicular to the magnetic field.

Some of the spectral measurements discussed here were made by using the older steerable array described in earlier papers [e.g., *Balsley and Farley,* 1971]. This antenna is a 2 × 4 element dipole mattress array mounted between two towers and is steerable in the E-W direction. The beam width in the E-W plane is 26.5° between half-power points.

The received scattered signal was sampled at a particular altitude, digitized, and converted into a power spectrum via a 64-point fast Fourier transform. Only one altitude at a time could be calculated on line. The details are similar to those discussed by *Balsley and Ecklund* [1972]. It is possible to tape-record the signal and then to reanalyze the data in order to observe several altitudes simultaneously [e.g., *Balsley and Farley,* 1973]. This procedure was not used for the present data, however. The analog tape recorder available was temperamental and often introduced problems of its own. When exact simultaneity at different altitudes is not required, it is much more practical to do the analysis on line, by stepping through the altitudes sequentially.

ALTITUDE VARIATIONS

Experimental results. Examples of spectral data obtained with the narrow-beam oblique system are shown in Figure 1. The transmitted pulse was 8 μs, and the receiver system bandwidth was 45 kHz on January 21 and 200 kHz on January 25; the integration time was about 80 s. The overall altitude resolutions were about 3 and 1.1 km, respectively. On both days the various spectra refer to slightly different observation times, since they were analyzed in real time. However, very little change was observed in the echo characteristics during these observations over periods of 30 min or more. The Doppler shift of the received signals has been converted into radial phase velocity (positive toward the radar), and the time delays into the corresponding altitudes. In the present case the area under each spectral curve is proportional to the corresponding received power. (The same is true for Figures 2 and 4 but not for Figures 5 and 7, which are normalized to a constant maximum amplitude.) The flat part of the spectra is due to the system noise.

The signal-to-noise ratio in Figure 1 is much smaller than that of typical daytime observations obtained by using the steerable array, for several reasons. The short transmitted pulse and the low antenna gain decrease the received signal, and the large bandwidths increase the noise. Furthermore, the oblique antenna cannot handle the full available power of the transmitter. Last, at the small zenith angle used in order to get good height resolution the scattering cross section is fairly small [*Bowles et al.,* 1963].

The received echo was very weak during January 21–25. Figure 1 shows that the spectra from the bottom of the echoing region exhibit a sharp peak centered practically at zero. This feature is observed in all of our high-resolution spectral data. On both days the spectra changed very little up to about 103 km, at which point the phase velocity started to increase with height to a maximum at about 107 km. The maximum echo power was at about 105 km. Above 107 km the power decreased rapidly with height in spite of the relatively larger phase velocities. Other data not shown here exhibit similar behavior.

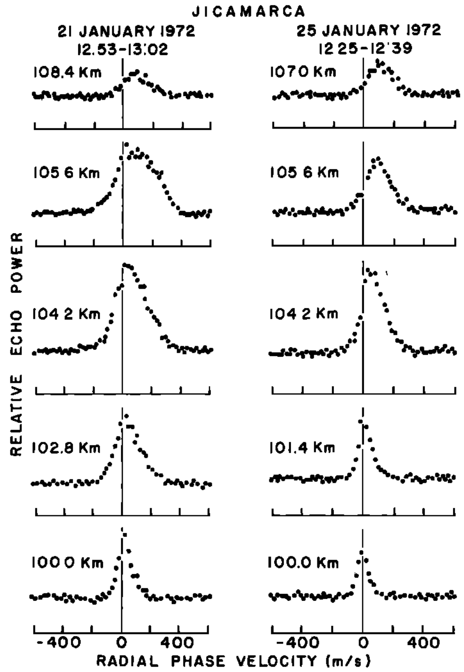

Fig. 1. Typical high-resolution oblique electrojet spectra during periods of very weak backscattered echoes. The antenna elevation angle was 65°E.

On January 26 the power was stronger than it was on the previous days, and type 1 echoes were observed between about 1000 and 1130 hours. Two particular sets of data taken during this period are shown in Figure 2. The set of spectra on the left was obtained just after the appearance of type 1 echoes, and that on the right, when the type 1 echoes were strong. The overall altitude resolution was about 1.1 km, and the integration time was 20 s. Each spectrum was observed at a slightly different time in both sets; however, we verified that the important changes shown in each set are spatial rather than temporal by repeating the observations near 107 km several times during the 5- to 6-min period.

In Figure 2 we can see again the very small phase velocities in the lower echoing region. Between 0940 and 0946 the spectra changed appreciably with height above about 105 km. The spectra were quite wide at about 107 km, some weak type 1 already being present. This finding indicates that the electron drift velocity was near the two-stream threshold. The spectral width decreased smoothly with altitude above 107 km. The maximum echo power was at approximately 107 km.

The curves on the right side of Figure 2 show strong type 1 echoes only between about 105 km and 109 km. In this case the transition between the low and the high phase velocity regions occurred at approximately 104 km. The data in Figure 2 illustrate the large variability of the spectra with height for strong signals. The shape of the spectra from the lower regions, however, does not change appreciably, regardless of the signal strength.

Figure 2 shows a region of minimum echo power at approximately 104 km between 1045 and 1050, although such a minimum is not common at this time of day. This feature can be seen better in Figure 3, which shows an example of the signal voltage received as a function of height (‘A scope’ display). Figure 3 also illustrates the small signal-to-noise ratio typical of these narrow-beam oblique radar measurements.

Samples of the spectral variation at the height of maximum type 1 echo strength on January 26 are shown in Figure 4. The integration time for each spectrum was about 20 s. The type 1 echo power, associated with the acoustic velocity peak, can be seen to be quite variable, whereas the type 2 echo power (the remainder of the signal) changed very little during the period illustrated in Figure 4.

Discussion. The small value of the phase velocity observed at the lower altitudes, even when type 1 waves were present above about 105 km, is consistent with the linear instability theory, which predicts that for waves perpendicular to the earth's magnetic field the oscillation frequency (Doppler shift) is

$$\omega \approx \mathbf{k} \cdot \mathbf{V}_e/(1 + \psi_0)$$

where $\psi_0 = \nu_e \nu_i / \Omega_e \Omega_i$, $\nu_{e,i}$ and $\Omega_{e,i}$ are the usual collision and Larmor (defined as being positive) frequencies, $\mathbf{k}$ is the wave vector, and $\mathbf{V}_e$ is the electron drift velocity (the ions are nearly at rest in relation to the neutral atmosphere). The large collision frequencies below 103 km account for the small phase velocities observed, as is discussed in more detail in a companion paper [*Fejer et al.,* 1975]. At the lowest altitudes in Figures 1 and 2 the phase velocity in some cases appears to be perhaps very slightly negative. If this is a real effect, it could be caused by eastward winds. The electron velocity relative to the ions must be westward during the day to produce the gradient-drift instability (*Rastogi* [1974] has seen sporadic *E* echoes

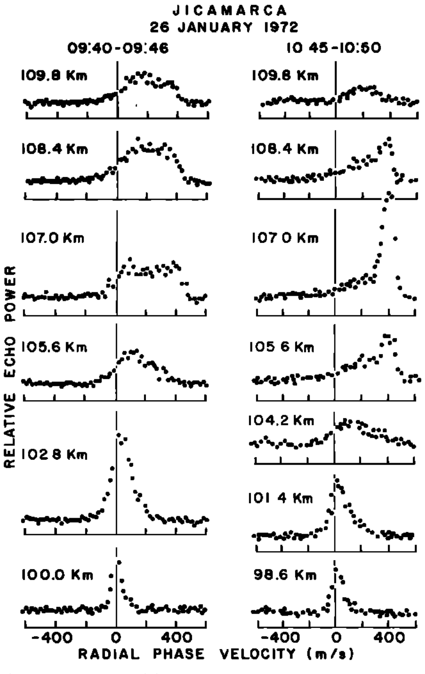

Fig. 2. High-resolution oblique spectra observed at an elevation angle of 65°E during a moderately strong electrojet period.

disappear from ionograms during current reversals, and unpublished radar data from Jicamarca show similar disappearances); therefore the mean Doppler shift during the day should be positive when the antenna is pointed toward the east if the ions are at rest. However, a strong wind driving the ions eastward could conceivably reverse the Doppler shift.

As was discussed by *Fejer et al.* [1975], the daytime absence of echoes above the height of maximum velocity at about 107 km can be explained by the gradient-drift instability, if recombination effects are included. *Fejer et al.* [1975] also consider in detail the height variation of the electrojet drift velocity and the phase velocity of the unstable waves. It is shown that based on the instability theories and on the electrojet model used by *Sugiura and Cain* [1966], the maximum phase velocity should occur at about 103 km. Since the condition for the excitation of two-stream echoes is that the phase velocity exceed the ion acoustic speed, type 1 echoes should occur first at 103 km. Figures 1 and 2 show the maximum phase velocity at about 107 km, which is also where type 1 echoes were first observed. These results suggest that the maximum drift velocity occurs at about 104 km instead of at 100 km, as was indicated by *Sugiura and Cain* [1966] and *Sugiura and Poros* [1969]. There are some further experimental results supporting this conclusion. Rocket measurements in the Indian electrojet zone indicate that the maximum drift velocity occurs at about 105 km [*Prakash et al.*, 1971]. Similar results were obtained from rocket measurements off the coast of Peru [*Richmond*, 1973].

Subbaraya et al. [1972] attempted to account for this discrepancy between the model conductivities and the observed currents by suggesting that the horizontal electric field in the electrojet increases fairly rapidly with altitude. It is difficult for us to understand how such a large-scale field, driven by the worldwide *E* region wind system and associated polarization charges, can vary significantly on a scale of a few kilometers. It seems to us far more likely that the collision frequencies used in the electrojet models are somewhat too small. The electron drift velocity reaches a maximum (for a constant horizontal electric field) at the altitude for which $\nu_e \nu_i = \Omega_e \Omega_i$. An increase of 30% or so in both collision frequencies would raise the height of the maximum by about half a scale height. Diurnal variations in collision frequency of this order, presumably due to tidal effects, have been detected at Arecibo by incoherent scatter radar measurements [*Wand*, 1969]. It should be possible to detect any similar effects at the equator by studying possible variations in the height of maximum Doppler shift of the electrojet echoes. Unfortunately, incoherent scatter measurements cannot be made in the *E* region at Jicamarca because of the strong interference from the electrojet echoes.

The minimum in echo power, which is sometimes seen at about 104 km (Figures 2 and 3), probably results from the fact that the two driving terms of the electrojet instability are most effective at different altitudes. If the density gradient were strong below 104 km and the two-stream term were strong above, the minimum could be explained.

PHASE VELOCITY OF TYPE 1 IRREGULARITIES

Experimental results. On February 15, 1971, a magnetically disturbed day, two wide-beam steerable antennas were used for spectral measurements. The antenna zenith angles were 60°E and 60°W, and each spectrum represented a 2.5-min integration over the corresponding scattering region (the entire electrojet). Type 1 echoes were observed between about 1000 and 1500 hours, except for a period of about half an hour shortly before noon, when there was a large decrease in the echo power. The normalized spectra shown in Figure 5 illustrate the variation of the type 1 phase velocity during this period. The velocities and backscattered power were large in the morning. The afternoon spectra were obtained shortly before the disappearance of the type 1 echoes from the spectra. In the morning the phase velocities in the east and west were about the same, but in the afternoon the velocity to the east of Jicamarca was about 30 m/s larger than the velocity to the west, indicating a difference between the eastern and the western temperature and/or the neutral wind velocity. When the type 1 echo is strong, as it is in Figure 5, the position of the spectral peak can be estimated to ±10 m/s or better.

The variation of the type 1 phase velocities and total echo power from both east and west, together with the magnetogram from Huancayo during the afternoon on February 15, 1971, is shown in Figure 6. No absolute power calibrations were made, but relative variations in each curve are accurate to within ±1 dB. At about 1300 hours there were large power variations with simultaneous changes in the type 1 phase velocity. The power and phase velocity variations were in the opposite sense, especially in the data from the west. After about 1400 hours the phase velocities behaved rather smoothly; shortly after 1500 hours no type 1 echoes were observed. The power variations are well correlated with

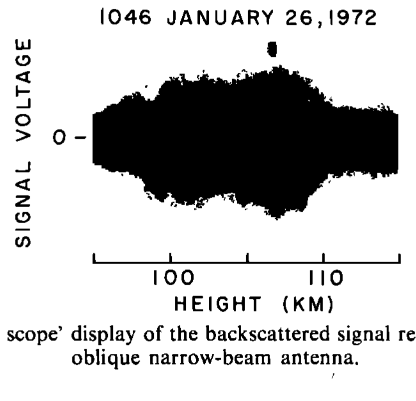

Fig. 3. 'A scope' display of the backscattered signal received by the oblique narrow-beam antenna.

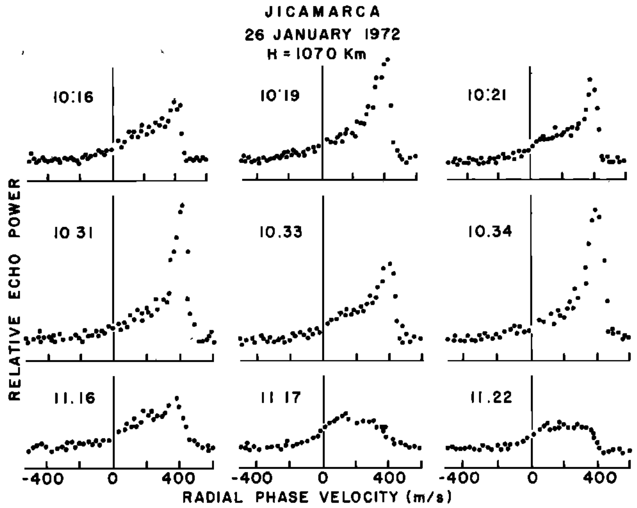

Fig. 4. Spectra observed at 107 km by using the oblique narrow-beam antenna during a period when type 1 echoes were observed.

magnetic field variations, which in turn are related to changes in the electrojet strength. The observations from the east and west are well correlated, with time delays of a few minutes at most, even though the scattering volumes were about 350 km apart.

Usually, the phase velocity varies fairly slowly with time. Sometimes the change is more abrupt, however. An example is shown in Figure 7. The sudden change in spectral shape seems to suggest the replacement of an echoing region by another with slightly different characteristics.

Discussion. The linear instability theories predict that the phase velocity of the irregularities should be proportional to the electron drift velocity. The type 2 echoes seem to be consistent with this prediction, but the type 1 do not. Past data strongly suggest that the Doppler shift of the type 1 echoes always corresponds at least approximately to the ion acoustic speed. How then do we account for variations in the type 1 echoes presented here and in earlier papers [*Balsley and Farley,* 1971]?

We might first suspect that the phase velocity depends at least partly on the electron drift velocity, even if it is not directly proportional, as theory would suggest. In that case, however, the observed phase velocity should be smallest just after the type 1 echoes first appear and just before they disappear, the maximum value occurring in between. This is not what happens. In Figure 6 the maximum velocity is seen when the echoes first appear. Data reported by *Balsley and Farley* [1971] for three different radar frequencies corresponding to 1-, 3-, and 9-m irregularities show that just the opposite behavior is also possible, the maximum velocity occurring just before the type 1 echoes disappear in the afternoon. In other instances very little change in the phase velocity is seen throughout the day.

Furthermore, it would seem reasonable to expect the power of the type 1 echoes to increase with increasing drift velocity (in any case, it certainly should not decrease), as is the case with the type 2 echoes, for which the power is approximately proportional to the square of the drift velocity [*Balsley,* 1969; *Farley and Balsley,* 1973]. Then, however, if the phase velocity also increases with increasing drift, the variations in power and phase velocity should be positively correlated; this is just the reverse of what is shown in Figure 6.

If we assume, then (although we cannot explain it yet on theoretical grounds), that the phase velocity of the type 1 waves in the frame of the neutral gas is always given by the acoustic velocity (with perhaps slight corrections for kinetic effects), there are two possible explanations [*Balsley and Farley,* 1971] for the observed variations: (1) the velocity of the neutral medium relative to the observer is changing, or (2) the temperature of the plasma in the echoing region is changing.

In principle, it is possible to separate these two effects by observing at various zenith angles, but in practice, problems may arise because the different zenith angles correspond to different scattering volumes, where conditions may be different. The data of Figures 5 and 6, for example, show that substantial differences can exist between regions 180 km east and west of Jicamarca. With only one radar it is not possible to examine the same region at different zenith angles. Nevertheless, *Cohen and Hooke* [1975] have used the type 1 spectral data to deduce neutral E-W winds of the order of ±80 m/s, and some recent unpublished work of ours shows that even higher wind velocities are possible.

Neutral winds undoubtedly play an important role in the variations of the type 1 phase velocity. Large E-W winds could explain even the large velocities in the morning shown in Figure 5. However, winds alone cannot explain the opposite variations of the phase velocity and echo power shown in Figure 6 between 1230 and 1330, because the winds should not affect the echo power. A temperature perturbation, however, could account for the observations. A decrease in temperature would decrease the ion-acoustic velocity C_s and also the threshold drift velocity $V_e \simeq C_s(1 + \psi_0)$. A temperature change of ±30°K about a mean of 250°K could explain the data near 1300 hours in Figure 6. Such large variations seem to be quite common in the E region. *Rai and Fejer* [1971] have shown large temperature changes (up to ±50°K) associated with gravity waves in the lower equatorial ionosphere. Similar variations in the E region temperature and ion-neutral collision frequency have been seen at higher latitudes [e.g., *Wand,* 1969; *Salah and Wand,* 1974].

There remains the problem of accounting for the change in ΔH shown in Figure 6. There seems to be no obvious reason

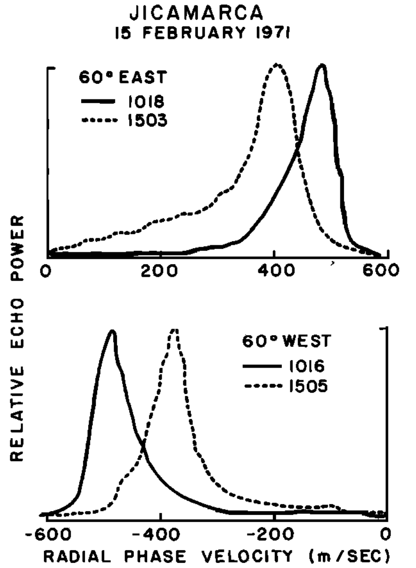

Fig. 5. Type 1 oblique spectra with significantly different phase velocities from eastward and westward moving irregularities. At about 1500 the phase velocity was larger east of vertical. The backscattered power was appreciably stronger in the morning. The spectra were normalized to a constant maximum value.

why the observed increase, which is presumably an indication of increased electron drift velocity (although there are other possible causes), should be caused by a temperature decrease. If the drift velocity really did increase, the increase may be unrelated to the temperature decrease, and the apparent negative correlation may be accidental. Future observations of this sort should settle this question. If the negative correlation proves to be real, however, it may be the result of simultaneous temperature and density (and hence collision frequency) changes in the neutral atmosphere associated with tides and/or gravity waves. The observed increase in power at about 1300 hours may be due to either the increased drift velocity or the decreased threshold velocity or both. In any case the one thing that appears to be certain is that a change in the type 1 phase velocity does not imply a corresponding change in the electron drift velocity, in contradiction to the predictions of linear theory.

CONCLUSIONS

The spectra of the radar echoes obtained by looking obliquely at the electrojet irregularities change drastically with altitude, especially when the electron drift velocities are large and the scattering is strong. Type 1 irregularities were observed only in the upper portion of the electrojet, above about 105 km. Before the appearance of the type 1 echoes the width of the local type 2 spectrum becomes quite large. No echoes were observed during daytime a few kilometers above the height of maximum type 1 power, which was at about 107 km. This altitude variation is consistent with the linear gradient-drift instability theory, including the effect of recombination, discussed in a companion paper [*Fejer et al.*, 1975].

The height at which the phase velocity was observed to maximize is about 4 km above that which would be predicted on the basis of the electrojet models of *Sugiura and Cain* [1966] and *Sugiura and Poros* [1969]. Increasing the assumed values of collision frequency by about 30% would account for the discrepancy.

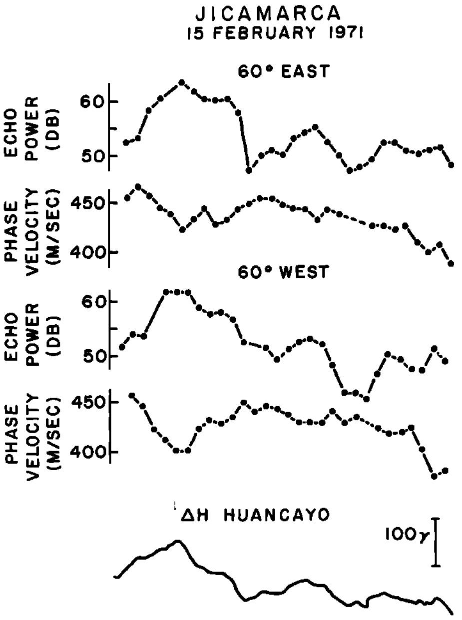

Fig. 6. Daytime variations of the oblique echo power, the type 1 phase velocity, and the horizontal component of the geomagnetic field on February 15, 1971. The type 1 echoes disappeared shortly after 1500 hours. The uncertainties in the velocities are roughly ±10 m/s.

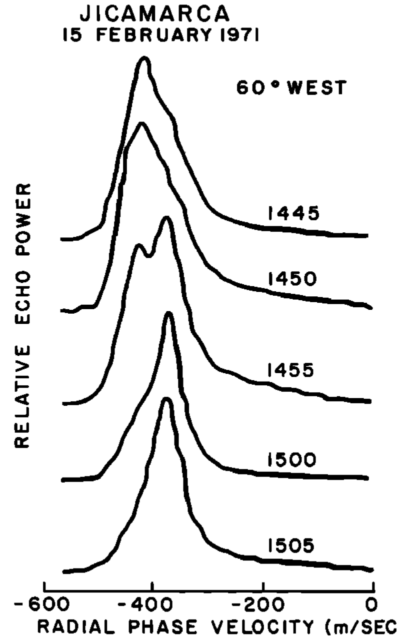

Fig. 7. Example of a fast variation of the type 1 phase velocity. The spectra were normalized to a constant maximum value.

Fairly large variations in the type 1 phase velocity are sometimes observed and cannot be explained by variations in the electron drift velocity. Some of this variation is probably due to variations in the E-W neutral wind velocity, but our results strongly suggest that a significant portion must be due to variations in the temperature of the *E* region.

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