Radar observations of two dimensional turbulence in the equatorial electrojet, 2

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Radar Observations of Two-Dimensional Turbulence in the Equatorial Electrojet, 2

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Observations with an altitude resolution of about 1 km were made with the large, vertically directed 50-MHz radar system at the Jicamarca Radar Observatory during the day, when the electrojet was strong. Type 1 ('two stream') echoes were seen in a limited range of altitudes, with Doppler shifts corresponding to upward and downward motion at the acoustic velocity. Most of the radar returns were due to type 2 echoes, however. The direction of motion of the type 1 waves sometimes reversed in as little as 1 s, supporting a turbulent model of the electrojet region. During the day the upgoing type 1 waves were observed to be somewhat more easily excited than the downgoing waves, an effect similar to an east-west asymmetry noted in earlier studies. The correspondence between the Jicamarca radar observations and rocket measurements in India is discussed.

INTRODUCTION

The properties of the plasma irregularities generated in the equatorial electrojet have been and are being studied intensively at the Jicamarca Radar Observatory in Peru by using improved radar techniques. Recent work has been described in several publications [e.g., Balsley and Farley, 1973; Fejer et al., 1975a, b]. The results presented here are a continuation of this series.

Most of the recent Jicamarca observations have been made with altitude resolutions of 1-3 km, in contrast to earlier studies in the 1960's which, with a few exceptions, used long pulses and/or wide beam widths and hence could only determine average properties of the entire electrojet echoing region. The present paper deals with daytime spectral observations made with the large, vertically directed 50-MHz antenna at Jicamarca and with short transmitter pulses yielding an altitude resolution of about 1 km. The results extend and confirm similar studies of Balsley and Farley [1973], which were made with an altitude resolution of 3 km at a time when the electrojet was relatively weak and no type 1 ('two stream') echoes were present. The type 2 echoes seen then showed a very 'turbulent' structure; the shape of the spectrum of the scattered signal and the mean Doppler shift changed rapidly with both altitude and time. The present measurements were made when the electrojet was strong and are particularly concerned with the type 1 echoes which were seen in a narrow range of altitudes. The same turbulent character of the medium is apparent. The type 1 irregularities appear, disappear, and reverse direction rapidly.

EXPERIMENTAL PROCEDURE

The measurement techniques were very similar to those described by Balsley and Farley [1973]. The 50-MHz antenna was directed normal to the magnetic field and had a beam width for backscatter of about 0.80, giving a horizontal resolution of about 1.5 km at the altitude of the electrojet. The received signal was tape-recorded by using a direct record (rather than an FM) channel with a bandwidth of about 300 kHz. The vertical resolution (<1 km) was determined by the pulse length (~5 μs) and the bandwidth of the tape recorder. By replaying the tape and sampling the signal at different time delays after the transmitter pulse, simultaneous spectral measurements could be made at any desired altitudes. Some measurements at a single altitude were also made in real time without using the tape recorder. The power spectra in both cases were computed by using a 64-point fast Fourier transform program. Several spectra were averaged to smooth out statistical fluctuations. The pulse repetition frequency was 400 s⁻¹, and thus the data were of poor quality for integration times shorter than a few seconds. Further details of the spectral analysis procedure are given by Balsley and Ecklund [1972].

RESULTS

The data to be presented here were all obtained between 1056 and 1104 local time (75°W, or EST) on January 15, 1973. This period was typical of times when the electrojet is strong and vertically propagating type 1 irregularities can be detected at a discrete Doppler shift corresponding approximately to the acoustic velocity. The signal-to-noise ratio was high, as it usually is in electrojet measurements using the large incoherent scatter system at Jicamarca. Figure 1 shows a small segment in time (26 s) of the data, sampled in steps of 750 m in altitude, except for the lowest altitudes. Figures 2 and 3 show a portion of the data of Figure 1 (labeled A, B, and C) at 106 km expanded in time (shorter integrations) by factors of 2 and 4, respectively, to reveal the temporal behavior in more detail. The spectra in Figure 3 have large statistical fluctuations because of the short integration time (only eight samples of the spectrum were averaged). Figure 4 shows the results of much longer (42 s) integrations at about the same time. The spectra
were measured out to Doppler shifts of ±200 Hz, but only the significant portions are shown in the figures. At the operating frequency of 50 MHz a Doppler shift of +1 Hz corresponds to a downward phase velocity of 3 m/s. The areas under the curves in Figures 1-4 are only approximately proportional to the echo power, due to variations in the gain of the tape recorder amplifiers from one run to the next. Figure 5 shows an accurate plot of total echo power as a function of altitude for this period.

The data shown in Figures 1-4 are quite similar to the earlier results given by Balsley and Farley [1973], except that in the present case the altitude resolution is considerably better and the presence of type 1 echoes (the peaks at Doppler shifts of about ±120 Hz) can be detected in many of the spectra, due to a stronger electrojet current.

**Altitude dependence.** Figures 1 and 4 show that the type 1 echoes are observed only in the central portion of the echoing regions, between about 103 and 107 km. The downgoing type 1 waves (positive Doppler shift) are limited to an even narrower region. At the bottom and the top of the echoing region, only type 2 echoes are seen, and the spectrum becomes narrow, symmetrical, and peaked at zero Doppler shift. The series of spectra corresponding to 10h 56m 31s in the second column of Figure 1 illustrates well the variability of the spectral features with altitude. At 108.25 km there is no sign of type 1 echoes, but at 107.5 km both upgoing and downgoing type 1 waves can be clearly seen. The upgoing type 1 waves are slightly stronger than the downgoing waves at 107.5, 106.75, and 105.25 km and

![Fig. 1. Power spectra from vertically propagating 3-m electrojet irregularities. The integration time (Δt) for each spectrum is 5.2 s, corresponding to an average of 32 spectral samples.](image)

![Fig. 2. Expanded version of part of Figure 1 at 106 km with improved time resolution. Time progresses from left to right and downward.](image)

![Fig. 3. Further expansion of part of Figure 1. The four spectra labeled A, for example, correspond to the single spectrum labeled A in Figure 1, with time progressing from left to right. The large scatter in the spectra is due to the small integration time.](image)

![Fig. 4. Electrojet spectra similar to those of Figure 1 but corresponding to a much longer integration time of 42 s. The type 2 spectra can be seen to be practically symmetrical around the zero Doppler shift.](image)
Relative echo strengths. Although we have been emphasizing here the properties of the type 1 echoes, it is clear from Figures 1–4 that most of the echo power at all altitudes and almost all times corresponds to type 2 echoes, with their relatively unstructured spectrum centered (on the average) at zero Doppler shift. This is true even near 106 km, where the type 1 echoes are strongest, except perhaps for occasional very brief periods (Figures 2 and 3). For longer integrations, such as those shown in Figure 4, the type 2 echoes always predominate. When all altitudes are averaged together, as was done in most of the older vertical incidence studies [e.g., Cohen and Bowles, 1967], the presence of the type 1 echoes is even more obscured by the type 2 echoes. This behavior for a vertically directed radar is in sharp contrast to the situation for large radar zenith angles (e.g., 60° from the vertical), for which the type 1 echoes are much stronger at 106 km, 104.5 km, and below. Comparing Figures 1 and 5, we see that the type 1 echoes are present at the height of maximum echo strength and somewhat above it but are not present below it.

Temporal variations. Obvious rapid variations in the shape of the spectrum at a particular altitude can be seen in Figure 1 and in even more detail in Figures 2 and 3, which correspond to only 16 s of the data at 106 km. (In successive reprocessing of the tape-recorded data the starting time of the integrations may vary by a few tenths of a second, and so, for example, the sum of the two curves in part B of Figure 2 does not exactly reproduce the curve labeled B in Figure 1.) We see from these figures that the upward and downward traveling type 1 waves, both of which appear in the curve labeled B in Figure 1, can be resolved into separate time periods if a short enough integration time is used. Although Figure 3 is of poor quality because of the short integration times, it indicates that a complete reversal of the observed direction of propagation of the type 1 waves can take place in a time as short as 1.3 s (middle two spectra of row B of Figure 3).

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Up-down asymmetry. Figure 1 suggests that up-going type 1 waves are more commonly observed during the day than are down-going waves. The up-going waves are detected over a wider range of altitudes and are generally stronger, on the average, than are type 1 down-going waves at altitudes at which both are seen. This behavior is somewhat more obvious in the longer integrations shown in Figure 4. At 106 km the negative peak is certainly stronger than the positive 'bump' on the spectral curve, and at 103 km a bump can be seen at about −120 Hz, but there is no corresponding feature on the positive side. Further examples of this asymmetry are shown in Figures 6 and 7. The strength of the down-going waves may equal or exceed that of the up-going waves for short periods of a few seconds, but, on the average, the up-going waves always predominate during the day. Preliminary analysis of comparable nighttime measurements made in January 1974 shows that this asymmetry reverses at night. Note that the phase velocity of the up-going and down-going type 1 waves is the same even though the amplitudes are different.

Discussion

Altitude dependence. High-resolution, oblique spectral measurements discussed by Fejer et al. [1975] made with an eastward directed antenna indicated that the strongest type 1 echoes occur at about 107 km, which is slightly higher than the corresponding altitude for the vertical measurements described here. Since the height of maximum drift velocity may change with time, however, simultaneous oblique and vertical spectral measurements would be necessary to determine whether or not the height of the two-stream region really depends on zenith angle, and even then the measurements would not be completely definitive, since the scattering volumes would be different for the two observations.

Turbulent structure. Earlier high-resolution, vertical spectral measurements by Balsley and Farley [1973] showed that the phase velocity of the type 2 waves varied rapidly with time and height and thus provided support for the two-dimensional turbulent model suggested by Farley and Balsley [1973] and Sudan et al. [1973]. The data presented here refer to a period of appreciably stronger echoes, and their general aspects also agree with those in the two-dimensional turbulent model. The idea here is that the type 1 echoes are observed only when the mean (averaged over, say, a few hundred meters) vertical electron velocity exceeds values of the order of the acoustic velocity. If the scattering volume were smaller than the large scale structure, type 1 echoes with both positive and negative Doppler shifts could never be observed simultaneously (i.e., using...
very short integrations), but both types of type 1 echoes could be seen with longer integrations due to horizontal convection of the turbulent structure through the scattering volume. Our scattering volume is probably not quite this small, but nevertheless, the turbulent structure seems to be nearly resolved with the shortest integrations. If we take the characteristic electron velocity here to be of the order of 400 m/s and the characteristic time of the large scale structure to be about 1 s (since significant changes in the spectrum are sometimes observed in times as short as this; see Figure 3), we arrive at a characteristic scale size of about 400 m, which is about half that of the scattering volume. On the other hand, the spectral shape sometimes persists for 10 s or more (see Figure 1), corresponding to a horizontal scale size of several kilometers. These numbers are of course very rough, but they do lead to a self-consistent model which seems to fit the data reasonably well.

Theories based on laminar electrojet models [e.g., Rogister and D'Angelo, 1970; Whitehead, 1971; Lee et al., 1974] are unable to explain the generation of any vertically propagating waves, let alone the type 1 waves traveling vertically, sometimes upward and sometimes downward, that we have described here. In an attempt to deal with this problem, Lee et al. [1974, see note added in proof] and Rogister and Jamin [1975, Appendix B] mention an unpublished suggestion of P. Waldteufel that perhaps the type 1 echoes seen when the antenna is directed vertically are not really traveling vertically but correspond to oblique side lobes of the antenna pattern. This explanation fails for at least two reasons. First, the side lobes of the antenna pattern are very small indeed; the first side lobe is less than 2° off axis and yet is about 27 dB weaker than the main lobe for backscatter measurements. For 10° off axis the response is down by 55–60 dB. Second, even if the side lobes were not small, the corresponding echoes would be eliminated by the range-gating process for all but small off-axis angles. Echoes coming from, say, an altitude of 106 km at a zenith angle of 30° would appear at an apparent altitude of 122 km, not 106 km.

**Comparisons with rocket observations.** Prakash et al. [1972, 1973] studied electrojet irregularities over a large range of scale sizes and showed that during strong electrojet conditions, irregularities with vertical scale sizes in the range 1–15 m, which were observed primarily near 105 km, have a spectral index of zero (no wavelength dependence). The suggestion was made that these irregularities were similar to type 1 irregularities, since their spectral index was different from that of other irregularities attributed to the gradient drift instability. The data presented here have shown, however, that the vertically propagating type 2 waves are always stronger than the type 1 waves during the day, at least for 3-m wavelengths.

How can we explain this apparent contradiction? First, as Ott and Farley [1974] pointed out, in any comparison between rocket and radar data it must be kept in mind that the 'wavelength' referred to in the rocket measurements are \(2\pi/k_s\), where \(k_s\) is the component of the plasma wave vector \(k\) parallel to the rocket trajectory, the other components of \(k\) being arbitrary; hence the true wavelength will always be less than or equal to the quoted value. Radar measurements do not have this ambiguity; the \(k\) vector and wavelength are uniquely determined. We have just seen that for vertical \(k\) the type 2 waves always dominate at 3-m wavelengths during the day, and the results of Balsley and Farley [1971] suggest that this would be even more true at increasing wavelengths but perhaps less true at decreasing wavelengths. At oblique angles, however, the type 1 echoes can dominate at 3 m. From these considerations we conclude that the suggestion of Prakash et al. [1972, 1973] is probably correct, but it is undoubtedly the obliquely and not the vertically propagating type 1 waves that are responsible for the rocket effects, and furthermore, the true wavelengths are shorter than the values quoted.

**Asymmetries.** The up-down and east-west spectral asymmetries have been mentioned in earlier Jicamarca studies [e.g., Cohen and Bowles, 1967, Figure 1; Balsley, 1970]. Balsley [1970] found from oblique spectral measurements that the electron drift velocities (deduced from the Doppler shift of the type 2 echoes) to the west of Jicamarca were consistently equal to or larger than the corresponding velocities to the east during both day and night. He suggested that this velocity asymmetry might be due to geographical factors such as the land-sea boundary to the west of the observatory or the Andes mountain range to the east. On the other hand, during the day the electrons move from east to west, and so a radar pointed obliquely westward responds to waves which have an upward as well as a westward velocity component. At night, after the electrojet reverses, the waves seen from the west have a partially downward velocity. As a result, one might suspect that the small vertical current in the electrojet plays a role in the asymmetries, but Balsley [1970] argued that on the basis of linear theory at least, this current is far too small to account for the observed east-west velocity differences. Perhaps the nonlinear limiting processes act somewhat differently on the upgoing and downgoing waves, depending upon the direction of current flow. Rogulien and Weinstock [1975] have made suggestions along the latter lines. In any case, it is obvious that geographical factors cannot explain the asymmetry seen at vertical incidence (upward moving type 1 waves being most easily excited during the day and downward moving waves at night), since only a single scattering volume is involved.

In considering the east-west asymmetry, one must be careful to distinguish between the type 1 and the type 2 waves. During both day and night the type 2 mean Doppler shift (and hence the wave phase velocity) and the total echo power are normally slightly larger to the west of Jicamarca than to the east. Type 1 waves are sometimes seen to the west when they are not
seen to the east, but the reverse is seldom true. When the type 1 waves are seen simultaneously in both directions, they usually have the same phase velocity, although small differences can occur, presumably due to differences in the parameters (e.g., temperature, wind velocity) of the medium in the two scattering volumes, which may be separated by several hundred kilometers. For example, Fejer et al. [1975a] discuss a case in which the type 1 phase velocity is larger in the east for some time. We reiterate that this observation should not be confused with the type 2 data in which the velocities are almost always larger in the west.

Conclusions

The data presented here add further support to earlier theoretical and experimental work [Farley and Balsley, 1973; Sudan et al., 1973; Balsley and Farley, 1973] and computer simulations [McDonald et al., 1975], all of which indicate that the structure of the electrojet scattering region is highly turbulent. Sato [1973] has also made somewhat similar suggestions. Most of the echoes received by a vertically directed radar are from slow-moving type 2 irregularities, but when the electrojet is strong, highly variable type 1 echoes with positive and negative Doppler shifts are also observed between about 103 and 107 km; however, even here the type 2 echoes still predominate. Reversals in the observed phase velocity of the type 1 waves can occur in time intervals as short as 1.3 s. These rapid changes are probably due to convection of the turbulent structure through the radar beam. On the average, the upgoing type 1 waves grow to a larger amplitude and are observed over a wider range of altitudes during the day than are the downgoing waves. This up-down asymmetry in the vertically propagating waves may be related to the east-west asymmetry observed in previous oblique spectral measurements.

Finally, we note that considerable care must be exercised in comparing rocket and radar studies of electrojet echoes, since the wavelengths referred to in rocket measurements are not true wavelengths and the direction of the k vector is not determined.

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