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From the Selected Works of Bela G. Fejer

January 1, 1975

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Vertical Structure of the VHF Backscattering Region in the Equatorial Electrojet and the Gradient Drift Instability

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Radar measurements made with high spatial resolution and large dynamic range at the Jicamarca Radar Observatory near the time of reversal of the electrojet current provide further proof that the gradient drift instability is in fact responsible for the type 2 irregularities. Echoes are received over a much wider range of altitudes at night than during the day partly because of the change in character of the background electron density profile and partly because of recombination effects, which can be important during the day. It is also shown that one must be cautious, particularly at night, in associating the mean Doppler shift of oblique radar echoes with the maximum east-west electron drift velocity.

This paper continues the series of radar studies made at the Jicamarca Radar Observatory in Peru of irregularities in the equatorial electrojet [Bowles *et al.*, 1963; Cohen and Bowles, 1967; Balsley, 1969; Balsley and Farley, 1971, 1973; Farley and Balsley, 1973]. There are two types of echoes: type 1 echoes, which have a relatively constant Doppler shift corresponding approximately to the acoustic velocity in the medium, and type 2 echoes, which are generally weaker and have a variable and smaller mean Doppler shift. The type 1 irregularities are thought to be directly excited at the observed wavelength (3 m for the 50-MHz radar at Jicamarca) by a modified two-stream plasma instability [Farley, 1963; Buneman, 1963]. The type 2 irregularities are generally considered to be due to a gradient drift plasma instability [Maeda *et al.*, 1963; Knox, 1964; Reid, 1968; Rogister and D'Angelo, 1970]. These irregularities cannot be directly generated at short wavelengths, however; some nonlinear coupling mechanism is necessary. Farley and Balsley [1973] and Balsley and Farley [1973] presented radar evidence that strongly supports a two-dimensional mechanism proposed by Sudan *et al.* [1973]. Computer simulations [McDonald *et al.*, 1974] also support this model. Sato [1973] has suggested a somewhat similar process.

The present paper deals with the detailed altitude structure of the echoing region. A new signal-processing and data display technique, called here the modified range-time-intensity (MRTI) display, allows us to study the structure with an altitude resolution of about 1 km for the most recent data and a dynamic range that is sometimes as large as 60 dB. These new capabilities are particularly important for nighttime observations, for which they reveal a complicated multilayered structure that was unresolved in most earlier studies.

During the day, echoes are observed between 93 and 113 km, with a single maximum in the echo strength at approximately 103 km. At night the echoes are concentrated in many thin layers, which can be at altitudes as high as 130 km. We be-

lieve that the difference is due to two effects: (1) the electron density profile is very irregular at night, with many regions of positive and negative vertical gradient, but is smooth during the day; and (2) recombination effects strongly damp instabilities above 110–115 km during the day but are ineffective at night, when the electron densities are much lower. Because the nighttime echoes are returned from a region extending over several scale heights, electron drift velocities inferred from the mean Doppler shift of the signal scattered from the entire electrojet region [e.g., Balsley, 1969] must be used with caution. One must know the altitude from which at least most of the signal is coming in order to interpret sensibly the spectral data. During the day this is not a problem, but at night it may be.

One of the important results of our observations is that the altitude of the echoing region(s) changes when the electrojet reverses an hour or two after sunset, and the change is exactly the sort that the gradient drift instability theory would predict. This new piece of evidence, when it is added to earlier results, makes the case for the gradient drift theory very convincing indeed.

In the following section we describe briefly the experimental techniques, particularly the MRTI technique. Next we present the data. The linear instability theory is then reviewed and discussed, with particular emphasis on the recombination effects and their significance. Finally, we discuss the data in light of this theory and show that all the observations are consistent with theoretical predictions.

EXPERIMENTAL PROCEDURES

The measurements were made at the Jicamarca Radar Observatory (11°57'S, 76°52'W; magnetic dip, 2°N) at a frequency of 49.92 MHz, corresponding to an irregularity wavelength of about 3 m. The equipment and most of the procedures have been described in the literature [e.g., Cohen and Bowles, 1967; Balsley and Farley, 1971]. Many of the data discussed in this paper, however, were obtained by using the new

MRTI technique developed by one of us (R.W.) in order to improve the studies of the height variation of the backscattered power.

In the conventional range-time-intensity (RTI) display the returned signals are amplitude-detected and then used to intensity-modulate an oscilloscope trace that is swept in time (range). The result is then photographed on a film that moves continuously at right angles to the trace, giving a height-time display of the entire electrojet scattering region [e.g., *Farley and Balsley*, 1973; *Balsley and Farley*, 1973]. The time resolution obtained in this way is very good (individual pulses can even be resolved if that is desired), but the power information is limited by the poor dynamic range (about 6 dB) of most film.

In the modified RTI technique the incoming signal is attenuated by an amount that is increased approximately linearly (in decibels) from 0 to 70 dB in 30 s by mixing the 50-MHz incoming signal with the voltage from a slowly discharging capacitor in a balanced mixer. In other respects the method is identical to the normal RTI procedure. The regions corresponding to the strongest echoes persist the longest in the film strip. Repeating the cycle gives a precise description of the variation of echo power with altitude every 30 s.

When the vertically directed large incoherent scatter array antenna (beam width, $\sim 1^\circ$) is used, the altitude resolution depends only on pulse length and receiver bandwidth. For the 1971 data presented here the resolution was roughly 3 km (15- μ s pulse, 40-kHz bandwidth—the maximum available at that time), whereas for the 1973 data it was reduced to about 1 km (5- μ s pulse, 200-kHz bandwidth).

The spectral data described here were obtained with the much smaller 50-MHz array at Jicamarca, which is directed perpendicular to the magnetic field but is steerable in the east-west plane.

EXPERIMENTAL RESULTS

Selected profiles of the scattered power from the equatorial electrojet on February 18–19, 1971, are shown in Figure 1. Similar pictures were taken every 30 s for the whole period shown. Every half hour the power scale was expanded by a factor of 4 for easier analysis, and only the expanded pictures are shown here. The expanded plot unfortunately was not obtained at 2000 hours. (All times are 75°W times.) The height resolution of about 3 km was determined primarily by the limited receiver bandwidth. Between approximately 0405 and 0550 the data were contaminated by echoes from the *F* region (spread *F*), which are particularly obvious at 0530. Some spread *F* may also have been present at 1900 hours. In general, the *E* and *F* region echoes can be separated easily by adjusting the pulse repetition frequency (PRF) to avoid aliasing. However, this procedure was not followed during the period under consideration. In this case, ionograms from Huancayo, Peru (12°S, 75°W; magnetic dip, 0.5°N), were used to confirm that the spurious echoes were due to equatorial spread *F* echoes.

Figure 2 shows oblique spectral data corresponding to the power profiles of Figure 1. The steerable array was pointed 60° east of vertical. The pulse width was 15 μ s, the receiver had a bandwidth of 40 kHz, and the PRF was 380 pulses/s, the usual value for electrojet experiments. The Doppler shifts of the backscattered echoes have been converted into radial phase velocities (positive toward the radar) of the unstable waves. Each spectrum represents an integration of about 2.5 min over the entire echoing region. All the spectra were normalized to a

peak value of unity, and so the area under each curve is not proportional to the signal power. Between about 1940 and 2130 and after 0300 the spectral data were too noisy and are omitted. The gain of the steerable array is about 30 dB less than that of the fixed array used for the measurements of Figure 1.

Figure 2 shows that the phase velocities were positive before 1936 and negative after 2130. Since the antenna was pointed to the east, the electrons were moving to the west before 1936 and to the east after 2130. Obviously, the reversal occurred sometime between 1936 and 2130. The behavior of the electrojet echoes near this reversal time has important theoretical implications that will be discussed in detail later. We can also see that the characteristics of the echoing region are quite different before and after the reversal.

Daytime characteristics. From Figure 1 we can see that during the daytime the echo power as a function of height shows a single peak that remains at a nearly constant altitude (about 103 km). Echoes are generated between approximately 93 and 113 km. The steerable antenna used to determine the oblique spectra shown in Figure 2 also gave information on the total echo power (not shown). The variation was less than 5 dB between 1230 and 1700 hours, except at about 1430, when the signal was approximately 10 dB below the maximum value. After 1700 hours the signal decreased progressively until reversal. Figure 1 shows a similar variation for the vertical echo power.

Profiles with a resolution of about 1 km obtained on the morning of January 22, 1973, are shown in Figure 3. These profiles are similar to those discussed above, and again the maximum echo power comes from about 103 km. Recent data (not shown) indicate that sometimes, however, the maximum is at altitudes as low as 100 km. A study of these variations is in progress. Furthermore, data discussed in a companion paper [*Fejer et al.*, 1975], taken with an obliquely directed radar, show maximums at altitudes above 103 km, suggesting a zenith angle dependence.

Reversal. From Figure 2 we can see that the electrojet reversed between 1936 and 2130 because of the change in the sign of the phase velocity of the unstable waves. The minute-by-minute variation of the vertical echo power between 2030 and 2100 hours is shown in Figure 4. The first and last pictures have their horizontal (power) scales expanded 4 times. The short bursts of signal below 100 km at 2049, 2059, and 2100 hours were probably meteor echoes, which are a common occurrence. Since the vertical and oblique signals are related directly to the electrojet current system, echoes cannot be generated at the reversal time. Hence we conclude from Figure 4 that the electron flow reversed at about 2048, a time that is in agreement with the corresponding values observed by *Balsley* [1970] during the December solstitial season. Naturally, there may be some difference between the oblique and the vertical reversal times, since the corresponding scattering volumes were about 170 km apart.

Figure 4 shows that before about 2045 the vertical echo power came from two regions at roughly 100 and 115 km. After 2051, however, the echoes were observed at about 109 km, and there was no power coming from the location of the previous layers. Thus there was an interchange in the altitudes of the echoing regions before and after the electrojet reversal; this is an observation that has important theoretical implications, as we shall see.

Nighttime characteristics. In contrast to the daytime ob-

Fig. 1. Power backscattered from the electrojet at 50 MHz. The large vertically directed incoherent scatter antenna at Jicamarca was used. Spread *F* contaminated the data between 0405 and 0550 and perhaps at 1900. The times are local times (75°W or EST).

servations the nighttime data show a great deal of variability. The most noticeable feature of the nighttime power profiles is their strongly layered structure (Figure 1). Large local power variations are observed, especially below about 110 km, with no apparent changes in the upper part. There seems to be no constant relationship between either the width of the backscattering region or the peak power of the vertical echoes and the average phase velocity of the oblique waves (Figure 2).

Samples of the nighttime electrojet echoing region on February 20, 1971, and the corresponding oblique spectra, normalized to a constant maximum value, are shown in Figure 5. The spectra were again obtained with the steerable antenna looking 60° east of vertical. In this figure the height markers may be in error by as much as 2 km, although the spacing is correct. Most of the nighttime features observed in Figures 1 and 2 are also seen here. Between 0105 and 0130 a particularly

large power increase was observed at about 100 km with no apparent change in the upper regions. At the same time a comparable increase in the oblique echo power (not shown here) was also observed. The average phase velocity was very small between 0130 and 0230, when most of the echo power came from the lower echoing region. Note that the nighttime echoes can sometimes be nearly as strong as those observed during the day, even though the nighttime electron densities are 1–2 orders of magnitude smaller.

Additional power profiles are shown in Figures 6 and 7 (note the different power scale). In these figures the altitude resolution is about 1 km. No simultaneous spectral measurements are available. The data of Figure 6 cover a period before and after the electrojet postsunset reversal, whereas Figure 7 was obtained before the reversal. These observations were carried out during weak electrojet conditions.

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Fig. 2. Spectral data obtained from the electrojet nearly simultaneously with the data shown in Figure 1. The antenna was pointed 60° east of vertical.

The most important features of these data are the occurrence of several (sometimes five or more) sharply defined layers and the rapid variations of the power profiles with time. The power profiles at about 1900 hours in Figures 6 and 7 are appreciably different from the corresponding data in Figure 1, possibly owing to different electron density profiles and

different driving fields. The height resolution (about 3 km) of the data obtained in 1971 did not resolve closely separated layers. Figure 6 shows another example of the interchange of echoing regions during the current reversal, which in this case occurred between 2047 and 2141.

Figure 7 exhibits the sudden appearance of a fairly strong

Fig. 3. Data similar to those shown in Figure 1 but with an altitude resolution of about 1 km.

Fig. 4. Expanded portion of the data shown in Figure 1 near the time of the electrojet reversal. Note the difference in echo altitude before and after the reversal, which occurred at about 2048–2050 (cf. Figure 11). The random echoes below 103 km at 2048, 2059, and 2100 were probably caused by meteors.

echoing layer at about 104 km after 1846. This is shown in more detail in Figure 8. The much smaller power increase in the layer at 97 km than in that at 104 km is typical of the large and rapid variations that are a common feature of the power profiles in the nighttime echoing region. This particular type of variation is clearly not explicable in terms of electrojet drift velocity variations. It is presumably due to local changes in the electron density gradients and hence the stability of the medium. Such rapid changes are probably associated with horizontal convection of the scattering region into the radar beam, which is only slightly more than 1 km wide in the *E* region. Horizontal velocities of the order of tens of meters per second could account for substantial changes in the echo distribution in 30–60 s.

An example of a rapid variation in both the vertical echo power and the oblique spectra is shown in Figure 9 for a period near sunrise. The echo power profiles were scaled from the MRTI pictures, and the spectra were obtained with the steerable antenna again pointing 60° east of vertical. The rapid decrease in both the echo power and the average Doppler shift implies a corresponding decrease in the driving electric field. Some variation in the electron density distribution probably occurred also, since *E* region sunrise takes place at about 0530 during February and ground sunrise is about 40 min later. Shortly after 0600 the echoes disappeared for some time.

SUMMARY OF THE LINEAR THEORY

A general linear dispersion equation based on the plasma fluid equations and including a number of effects that are usually omitted is derived in the appendix. For the parameters

appropriate to most of the electrojet region the dispersion equation can be solved approximately for the oscillation frequency and growth rate:

$$\omega_r \simeq k(V_{oev} + \psi_0 V_{oiy})/(1 + \psi_0) \quad (1)$$

$$\Gamma \simeq \frac{1}{1 + \psi_0} \left\{ \frac{\psi_0}{v_i} \left[\left(\frac{kV_d}{1 + \psi_0} \right)^2 - k^2 C_s^2 \right] + \frac{v_i}{L_N \Omega_i} \frac{V_d}{(1 + \psi_0)} \right\} - 2\alpha N_0 \quad (2)$$

where $V_d = V_{oev} - V_{oiy}$ is the mean westward (and normal to **B**) electron drift relative to the ions; v_e , v_i , Ω_e , and Ω_i are the usual electron and ion collision frequencies and gyrofrequencies; α is the recombination rate; N_0 is the electron density; $L_N = N(\partial N/\partial z)^{-1}$ is the vertical electron density gradient length; C_s is the acoustic velocity; $\psi_0 = v_e v_i / \Omega_e \Omega_i$; and we assume $\Gamma \ll \omega_r$. For simplicity we have set $k = k_y$ (horizontal and westward propagating waves). These expressions are equivalent to those given in earlier papers [e.g., Rogister and D'Angelo, 1970; Sudan et al., 1973] except for the added damping term due to recombination, which has been neglected in most publications though not all [e.g., Whitehead, 1967, 1971]. The first and third terms on the right-hand side of (2) are the two-stream and gradient drift driving terms, respectively, and have been discussed in detail in earlier papers. The second term describes the diffusive damping.

The main points that we wish to make here are as follows:

1. The recombination term plays an important role in explaining some of the radar observations.

Fig. 5. Samples of nighttime power and spectral data obtained as was discussed for Figures 1 and 2. There is an uncertainty of 2 km in the altitudes for these data (only).

Fig. 6. Power profiles with a resolution of 1 km. The electrojet was weak and reversed between 2047 and 2141.

2. Gradients in collision frequency, magnetic field strength, temperature, and/or drift velocity are not important sources of instability. Most of these latter conclusions were also reached by *Rogister and D'Angelo* [1970], but no details were given. Brief justifications are included here in the appendix.

3. Even for the type 2 irregularities, for which the phase velocity result (1) seems to be reasonably valid, one must be careful in deducing the electron drift velocity from the mean Doppler shift of the radar echoes.

This third point arises from the fact that the electron drift velocity has a strong altitude dependence. From the simplified

Fig. 7. Series of nighttime profiles illustrating the variability of the echoes.

Fig. 8. Expanded version of part of Figure 7.

electrojet model of *Sugiura and Cain* [1966], in which the vertical current is assumed to be zero, we find the horizontal electron velocity to be

$$V_{eo} = (v_i/\Omega_i)[E_p/(1 + \psi_0)] \quad (3)$$

where E_p is the horizontal driving Petersen field, which is taken to be independent of height in the electrojet region. Using (1) and (3) and neglecting the small contribution due to the ion drift, we find that for horizontally traveling waves,

$$\frac{\omega_r}{k} = V_p \simeq \frac{v_i}{\Omega_i} \frac{E_p}{(1 + \psi_0)^2} \quad (4)$$

Comparing (3) and (4), we see that the electron drift velocity and the phase velocity behave differently with altitude. When $v_e \propto v_i$ is assumed, it can be shown easily that the maximum drift velocity occurs where $\psi_0 = 1$ (i.e., where $v_e v_i = \Omega_e \Omega_i$), whereas the phase velocity and hence the effectiveness of the two-stream driving term maximize where $\psi_0 = 1/2$. The height variation of the horizontal electron velocity and the phase velocity of horizontally propagating waves are plotted in Figure 10 using the results of the *Sugiura and Cain* [1966]

model. It can be seen that for a uniform driving field the maximum phase velocity predicted by the linear theory is about 40% smaller than and occurs about 3 km above the maximum drift velocity. This result suggests that the procedure used by *Balsley* [1969] in estimating the drift velocity (i.e., $V_{eo} = V_p/\sin \theta$, where V_p is the average type 2 phase velocity and θ is the radar zenith angle) underestimates the electrojet drift velocity, both because of the averaging process and because of the neglect of the $1 + \psi_0$ factor. Note, however, that these effects will not substantially alter earlier conclusions about the two-stream instability. The two-stream term in brackets in (2) becomes unstable when the wave phase velocity (since $V_{oiy} \ll V_{oez}$), not the drift velocity, exceeds the acoustic velocity.

DISCUSSION

Most of the experimental results that we have presented can be explained in terms of the linear theory just discussed. The major differences between the daytime and the nighttime characteristics of the echoes are related to differences in the electron density profile in the electrojet region. Figure 11 shows two profiles obtained from rocket measurements over Thumba, India (magnetic dip, $00^\circ 47'S$), near local noon and midnight [*Prakash et al.*, 1972]. Similar profiles have been observed near the coast of Peru [*Aikin and Blumle*, 1968]. During the daytime the electron concentration usually increases upward in the entire E region. In the center of the electrojet (~ 105 km) the electron density is about $1-2 \times 10^6 \text{ cm}^{-3}$, and a typical scale length L_N is roughly 6 km. Nighttime profiles are jagged with much smaller densities and scale lengths, and the scale lengths can be either positive or negative.

Reversal. As we have seen (Figures 1, 2, and especially 4), the most striking characteristic of the nighttime reversal of the electrojet current is the associated change in the position of the echoing region. Before the reversal the electrons drift toward the west, and the gradient drift instability can generate echoes in regions of positive electron density gradient. After the reversal of the electron drift direction, on the other hand, the gradient drift term is positive only in regions of negative vertical electron density gradient. This behavior is illustrated in Figure 12.

Comparing Figures 4 and 12, we see that the data provide a very convincing confirmation of the gradient drift theory. We must remember, of course, that the echo profiles discussed here are from 3-m vertically propagating irregularities that cannot be directly explained by the conventional gradient drift

Fig. 9. Power profiles and oblique spectra (pointing 60° east of vertical) shortly before the morning electrojet reversal.

theories, which assume laminar horizontal electron flow. Neither such short wavelengths nor waves traveling vertically can be directly excited. Recently, however, a turbulent model has been suggested [Farley and Balsley, 1973; Sudan et al., 1973; Balsley and Farley, 1973; McDonald et al., 1974] that seems to be able to account for both of these difficulties.

Daytime echoes. The lower edge of the echoing region is about the same (≈ 93 km; see Figure 1) during the day and night, but the upper edge is much lower during the day. The lower edge is presumably due to the rapid increase in the collision frequencies and hence also in ψ_0 with decreasing altitude. We believe that the daytime upper edge is controlled mainly by recombination effects, which are important during the day but are not at night, when the electron density is greatly reduced. For a mixture of primarily NO^+ and O_2^+ ions the results of Mehr and Biondi [1969] and Kenesha et al. [1970] indicate that $3 \times 10^{-7} \text{ cm}^3/\text{s}$ is a reasonable estimate of the effective recombination coefficient α , and this in turn leads to $2\alpha N_0 \sim 10^{-1} \text{ s}^{-1}$ for the daytime recombination term.

When the drift velocity is small and the two-stream term in (2) is negligible, the threshold velocity for instability is given by

$$V_d \geq L_N \left[2\alpha N_0 (1 + \psi_0) \frac{\Omega_i}{\nu_i} + \frac{\nu_e}{\nu_i \Omega_e} k^2 C_s^2 \right] (1 + \psi_0) \quad (5)$$

If for the center of the electrojet region we assume $\Omega_e = 5 \times 10^6 \text{ s}^{-1}$, $\Omega_i = 90 \text{ s}^{-1}$, $\nu_e = 4 \times 10^4 \text{ s}^{-1}$, $\nu_i = 2.5 \times 10^3 \text{ s}^{-1}$, and $C_s^2 = 10^8 \text{ m}^2/\text{s}^2$, then (5) becomes

$$V_d \geq L_N (2\alpha N_0 / 19 + 16/\lambda^2) \quad (6)$$

in mks units. For a daytime value of L_N of 6 km and a recombination time of 10 s the threshold velocity for instability ranges from 70 m/s for 50-m waves to 32 m/s for very long wavelengths. For an altitude of 115 km the gyrofrequencies and recombination rate are unchanged, but the other parameters become approximately $\nu_e = 10^4 \text{ s}^{-1}$, $\nu_i = 620 \text{ s}^{-1}$, $C_s^2 = 1.2 \times 10^8 \text{ m}^2/\text{s}^2$, and $L_N = 15\text{--}20$ km. For these values we find from (5) that the threshold varies from about 360 m/s for a 50-m wavelength down to 260 m/s for very long wavelengths. In other words, at this altitude and above, the recombination effect dominates diffusive damping during the daytime. It can also be deduced from (3) that for a velocity of 500 m/s at 105 km the corresponding velocity at 115 km is only about 150 m/s. Thus the excitation of type 2 irregularities above about 115 km during the day is quite unlikely, in agreement with our data.

Fig. 10. Normalized electron drift velocity and horizontal phase velocity predicted by the linear instability theory and the electrojet model of Sugiura and Cain [1966].

Fig. 11. Typical electron density profiles observed over Thumba, India, near noon and midnight [after Prakash et al., 1972].

From the same sort of arguments one can also conclude that type 1 irregularities can only be excited near the region of maximum phase velocity, which is thought to be at about 103 km (Figure 10). This conclusion is supported by recent spectral data obtained with good altitude resolution and discussed in a companion paper [Fejer et al., 1975].

We might mention in passing that Prakash et al. [1971, 1972] report that their rocket observations indicate the occurrence of small-scale (1–15 m) irregularities up to about 140 km during the daytime, in contrast to our data. It appears to us, however, that their data may be rather marginal and close to the noise level at these higher altitudes. Certainly, the rocket measurement cannot approach the sensitivity of the radar measurement, which as we have seen, has a dynamic range of the order of 60 dB. Unless the ionosphere over India is greatly different from the ionosphere over Peru or there is an exceedingly sharp wavelength cutoff between 3 and 15 m, it is impossible to reconcile our results with the rocket data. Irregularities as strong as those reported for altitudes above 120 km would have given very strong radar signals, which we simply do not see (e.g., Figure 1). We believe that this aspect of the Indian results should be treated with some caution.

Nighttime echoes. At night, because of the very low electron densities and the presumably greater proportion of metallic ions, recombination damping is not important, even at fairly high altitudes. As is shown in Figure 11 and as was mentioned earlier, the gradient lengths are much shorter at night, increasing the strength of the gradient drift driving term, no matter in which direction the electrons are drifting. Since the nighttime electric fields appear to be comparable in strength to those of the day [Balsley, 1973], the echoing region should extend over a wider range of altitudes at night, as is

Fig. 12. Schematic illustration of the unstable echoing regions before and after the postsunset reversal.

observed, for the simple reasons that the instability driving terms are stronger and the damping is weaker.

Phase velocities. As we have pointed out, the phase velocities of the unstable waves should always be less (sometimes by a substantial amount) than the electron drift velocity. When most of the echo power comes from the bottom of the electrojet, as it does between 2330 and 0200 in Figure 1 and between 0130 and 0230 in Figure 5, we should observe small Doppler shifts corresponding to velocities much smaller than the maximum electron drift velocity. Hence the average Doppler shift of an oblique echo may often not be a good measure of the electric field strength at night, unless the height of the echoing region is known. Unfortunately, we cannot as yet make oblique measurements at night with altitude resolution comparable to that of the vertical measurements because of lack of sensitivity in the oblique system. There is no reason to suspect, however, that the altitude distribution would differ greatly. Measurements in the daytime, when good resolution can be obtained with the oblique system, show no substantial difference in altitude between the vertical and the oblique echoes.

These considerations suggest that the technique used by *Balsley* [1969, 1973] to estimate the electron drift velocity (and hence the electric field) from the average phase velocity of oblique radar echoes can lead to considerable errors at night. On the other hand, *Balsley* normally used the average phase velocity for his estimates only when the spectrum was fairly symmetrical about the mean, as is usually the case during the day (when the echoing region is narrow). When both slow and fast waves are observed in clearly asymmetrical spectra, only the fast waves are taken into account to estimate the maximum drift velocity, even when the slower waves have larger amplitudes. *Cohen* [1973] has shown that the oblique spectra can often be separated into two or even three reasonably symmetrical components, each presumably corresponding to echoes from a particular altitude. The fastest of these components should give the most consistent estimate of the electric field if no information about the altitude distribution of the echoes is available. As was mentioned before, the $1 + \psi_0$ factor, which was neglected in previous drift velocity calculations, must also be estimated and included. As Figure 10 shows, the drift velocity may be substantially larger than the measured phase velocity.

In spite of these difficulties we must emphasize that the radar measurements provide a reliable way of systematically measuring the electrojet electric field during the day. During the night it is admittedly somewhat less satisfactory, but it seems to be the best method available at present.

CONCLUSIONS

Our data show marked differences between day and night. During the day the echoes are detected only in a relatively narrow altitude region about 20 km wide centered near 103 km, and most of the echo power comes from a region only about 10 km wide. Above about 115 km no echoes were observed during the day, even though a signal 50 dB weaker than the maximum could have been detected. These results are in conflict with some of the Indian rocket measurements in the electrojet that seem to indicate the presence of weak, small-scale irregularities above 120 km during the day. Theoretical calculations reported here show that one would not expect the electrojet plasma to be unstable above about 115 km during the day because of the damping effect of recombination.

At night, recombination becomes negligible because of the much lower electron densities. This fact, together with the very jagged nature of the nighttime electron density profile, leads to increased instability at night and accounts for the observation that signals are scattered from many thin layers extending up to altitudes of at least 130 km.

The observed detailed changes in the height of the echoing regions before and after the electrojet reversal can easily be accounted for by the gradient drift plasma instability and as a result, provide a convincing confirmation of that theory.

Because the nighttime echoes come from a wide range of altitudes and the electron drift and the wave phase velocity are strong and different functions of altitude, one must be quite careful in attempting to infer the strength of the nighttime electric field from oblique spectral measurements. Unless the data are handled properly, the field strength will be underestimated.

APPENDIX

We develop here a general fluid theory for instabilities in the electrojet, including the effects of recombination, ion magnetization, and gradients in electron and ion density, collision frequency, gyrofrequency, and drift velocity. Most of these effects of course are negligible in most situations. We assume the waves to be electrostatic, and refraction and propagation effects are neglected. The relevant equations are the continuity equations for electrons and ions, the equations of motion, and Poisson's equation:

$$\partial N / \partial t + \nabla \cdot (N \mathbf{v}) = Q - \alpha N^2 \quad (\text{A1})$$

$$m \frac{D \mathbf{v}}{D t} = q(-\nabla \Phi + \mathbf{v} \times \mathbf{B}) - \frac{\nabla P}{N} - m \mathbf{v}(\mathbf{v} - \mathbf{U}) \quad (\text{A2})$$

$$\nabla^2 \Phi = e(N_e - N_i) / \epsilon_0 \quad (\text{A3})$$

where Q and α are the production and recombination rates, D/Dt is the convective derivative, $\mathbf{U}$ is the neutral particle velocity, and the other symbols have their usual meanings. Viscous effects are neglected, since collisions with neutral particles dominate.

Linearizing these equations and setting $\mathbf{U} = 0$ for simplicity give

$$Dn / D t + \nabla \cdot (N_0 \mathbf{v}) + n \nabla \cdot \mathbf{V}_0 = -2\alpha n N_0 \quad (\text{A4})$$

$$m N_0 \left[\frac{D \mathbf{v}}{D t} + \nu \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{V}_0 \right] - q N_0 \mathbf{v} \times \mathbf{B} = -q N_0 \nabla \phi - \nabla p + \frac{n}{N_0} \nabla P_0 \quad (\text{A5})$$

$$\nabla^2 \phi = e(n_e - n_i) / \epsilon_0 \quad (\text{A6})$$

where $\mathbf{v}$, n , p , and ϕ are the perturbations. Taking the divergence of the background drift velocities to be zero, we can neglect the third term on the left-hand side of (A4). The third term on the left-hand side of (A5) can also be neglected, since it is several orders of magnitude smaller than the collision term. If we now assume the perturbations to be proportional to $\exp[i(\mathbf{k} \cdot \mathbf{r} - \omega t)]$, we can write the solution of (A5) in the form

$$N_0 \mathbf{v} = \mathbf{M} \cdot [-ik(q N_0 \phi + p) + (n / N_0) \nabla P_0] \quad (\text{A7})$$

where $\mathbf{M}$ is the 'ac' version of the usual mobility tensor. If we choose a coordinate system with the x , y , and z axes directed north, west, and upward, respectively, the mobility tensor is given by

$$\mathbf{M} = \begin{bmatrix} \mu_0 \cos^2 I + \mu_p \sin^2 I & \mp \mu_H \sin I & (\mu_p - \mu_0) \sin I \cos I \\ \pm \mu_H \sin I & \mu_p & \pm \mu_H \cos I \\ (\mu_p - \mu_0) \sin I \cos I & \mp \mu_H \cos I & \mu_p \cos^2 I + \mu_0 \sin^2 I \end{bmatrix} \quad (\text{A8})$$

where I is the dip angle (positive in the northern hemisphere); the upper and lower signs refer to ions and electrons, respectively; and

$$\mu_0 = \frac{1}{m(\nu - i\omega')} \quad \mu_p = \frac{1}{m} \frac{\nu - i\omega'}{\Omega^2 + (\nu - i\omega')^2} \quad (\text{A9})$$

$$\mu_H = \frac{1}{m} \frac{\Omega}{\Omega^2 + (\nu - i\omega')^2} \quad \omega' = \omega - \mathbf{k} \cdot \mathbf{V}_0 \quad \Omega = \left| \frac{e\mathbf{B}}{m} \right|$$

We now assume that the zero-order parameters of the medium change only in the z direction, and we take $N_{oe} \approx N_{oi}$. Combining (A4), (A6), and (A7) then gives the dispersion relation

$$\frac{\epsilon_0 k^2}{N_0 e^2} + \sum_{i=e,i} \left\{ \left[\left(L_N^{-1} + \frac{\partial}{\partial z} \right) \hat{a}_z \cdot \mathbf{M}_i \cdot \mathbf{k} + i \mathbf{k} \cdot \mathbf{M}_i \cdot \mathbf{k} \right] \right. \\ \cdot \left[\omega_i' + i2\alpha N_0 + \gamma_i K T_i \left(\frac{\partial}{\partial z} (\hat{a}_z \cdot \mathbf{M}_i \cdot \mathbf{k}) \right) \right. \\ \left. - L_N^{-1} \mathbf{k} \cdot \mathbf{M}_i \cdot \hat{a}_z + i \mathbf{k} \cdot \mathbf{M}_i \cdot \mathbf{k} \right. \\ \left. \left. + i \frac{\partial}{\partial z} (L_N^{-1} \hat{a}_z \cdot \mathbf{M}_i \cdot \hat{a}_z) \right]^{-1} \right\} = 0 \quad (\text{A10})$$

where $\hat{a}_z$ is a unit vector directed upward, L_N is the density gradient length defined by $L_N^{-1} = N_0^{-1} \partial N_0 / \partial z$, and γ is the usual specific heat ratio that can vary between 1 and 5/3 depending upon the extent to which the perturbations are isothermal or adiabatic.

In this form the dispersion relation includes various effects (other than kinetic) in a relatively compact format. Inertial effects and gradients in collision frequency and so forth are incorporated into the mobility tensor terms. The dispersion equation can be solved approximately for the oscillation frequency ω_r and the growth rate Γ ($\omega = \omega_r + i\Gamma$) without too much difficulty, but the general result will obviously be very cumbersome. Let us instead consider a few simpler cases. First, we set the dip angle $I = 0$, appropriate to the magnetic equator. The theory is only valid for wavelengths longer than the ion mean free path (mfp) or the mfp $\times 2\pi$ perhaps; this means that the wavelengths will also be large in comparison with the Debye length, and hence the first term in (A10) can be neglected. We can also certainly neglect electron inertia, since $\omega_r \ll \nu_e$ for all cases of interest. This approximation also eliminates all terms involving gradients in electron drift velocity. We retain ion inertial effects but neglect gradients in the ion drift velocity (since the ion drift itself is quite small). We also consider $\mathbf{k}$ to be nearly perpendicular to the magnetic field $\mathbf{B}$, so that $k \approx k_\perp$, where $k_\perp^2 = k_y^2 + k_z^2$. For altitudes below about 120 km we can neglect ion magnetization, and finally, we will neglect for the moment gradients in the collision frequencies and electron gyrofrequency. We then find the approximate solutions for $\omega_r \lesssim \nu_i$ and $\Gamma \ll \omega_r$, given by

$$\omega_r \approx [\mathbf{k} \cdot (\mathbf{V}_{0e} + \psi \mathbf{V}_{0i})] / (1 + \psi) \quad (\text{A11})$$

$$\Gamma \approx -2\alpha N_0 + (1 + \psi)^{-1} \left\{ \frac{\psi}{\nu_i} [(\omega_r - \mathbf{k} \cdot \mathbf{V}_{0i})^2 - k^2 C_s^2] \right. \\ \left. + \frac{1}{L_N k^2} \left[(\omega_r - \mathbf{k} \cdot \mathbf{V}_{0i}) \left(\frac{\nu_i}{\Omega_i} k_y + \psi_0 k_z \right) \right. \right. \\ \left. \left. - (\omega_r - \mathbf{k} \cdot \mathbf{V}_{0e}) \left(\frac{\nu_i \Omega_i}{\nu_i^2 + \omega_i'^2} k_y - k_z \right) \right] \right\} \quad (\text{A12})$$

where

$$\psi = \psi_0 \left(\frac{k_\perp^2}{k^2} + \frac{\Omega_e^2 k_z^2}{\nu_e^2 k^2} \right) \quad \psi_0 = \frac{\nu_e \nu_i}{\Omega_e \Omega_i}$$

$$C_s = [K(\gamma_e T_e + \gamma_i T_i) / m_i]^{1/2}$$

A version of (A12) with further simplifications is quoted in the main text (equation (2)).

To examine the effects of the neglected gradients in collision frequencies and gyrofrequencies, we simplify by neglecting ion inertia and setting $\mathbf{k}$ horizontal and perpendicular to $\mathbf{B}$ (i.e., $k = k_y$). We then find that (A11) is essentially unchanged, except that $\psi \rightarrow \psi_0$, and (A12) becomes approximately

$$\Gamma \approx -2\alpha N_0 + \frac{\psi_0}{1 + \psi_0} \left\{ -\frac{k^2 C_s^2}{\nu_i} + \frac{V_d}{1 + \psi_0} \right. \\ \left. \cdot \left[\frac{\Omega_e}{\nu_e} (L_N^{-1} - L_N^{-1}) + 2 \left(\frac{\Omega_i}{\nu_i} - \frac{\nu_e}{\Omega_e} \right) L_N^{-1} \right] \right\} \quad (\text{A13})$$

where $L_N^{-1} = \Omega^{-1} \partial \Omega / \partial z$ and $L_\nu^{-1} = \nu^{-1} \partial \nu / \partial z$.

In the electrojet region, $-L_\nu \sim 5\text{--}10$ km, $-L_N \sim 10^3$ km, and $\Omega_e / \nu_e \gg |\Omega_i / \nu_i - \nu_e / \Omega_e|$, and so only the driving term involving the electron density gradient L_N is important. The neglect of the other gradient terms was discussed initially by Akinrimisi [1971] and recently in a more general way by Fejer [1974].

Acknowledgments. The wholehearted cooperation of the staff of the Jicamarca Radar Observatory contributed substantially to the results presented here. Support for this work was provided by National Oceanic and Atmospheric Administration grant 04-4-022-16 and National Science Foundation grant GA-38404.

The Editor thanks B. E. McDonald and A. Register for their assistance in evaluating this paper.

REFERENCES

- Aikin, A. C., and L. J. Blumle, Rocket measurements of the E region electron concentration distribution in the vicinity of the geomagnetic equator, *J. Geophys. Res.*, **73**, 1617-1626, 1968.
- Akinrimisi, J., Theory of ionospheric irregularities in the equatorial electrojet plasma, Ph.D. thesis, Cornell Univ., Ithaca, N. Y., 1971.
- Balsley, B. B., Some characteristics of non-two-stream irregularities in the equatorial electrojet, *J. Geophys. Res.*, **74**, 2333-2347, 1969.
- Balsley, B. B., Equatorial electrojet: Seasonal variation of the reversal times, *J. Geophys. Res.*, **75**, 4369-4371, 1970.
- Balsley, B. B., Electric fields in the equatorial ionosphere: A review of techniques and measurements, *J. Atmos. Terr. Phys.*, **35**, 1035-1044, 1973.
- Balsley, B. B., and D. T. Farley, Radar studies of the equatorial electrojet at three frequencies, *J. Geophys. Res.*, **76**, 8341-8351, 1971.
- Balsley, B. B., and D. T. Farley, Radar observations of two-

- dimensional turbulence in the equatorial electrojet, *J. Geophys. Res.*, **78**, 7174-7179, 1973.
- Bowles, K. L., B. B. Balsley, and R. Cohen, Field-aligned *E* region irregularities identified with ion acoustic waves, *J. Geophys. Res.*, **68**, 2485-2501, 1963.
- Buneman, O., Excitation of field aligned sound waves by electron streams, *Phys. Rev. Lett.*, **10**, 285-287, 1963.
- Cohen, R., Phase velocities of irregularities in the equatorial electrojet, *J. Geophys. Res.*, **78**, 2222-2231, 1973.
- Cohen, R., and K. Bowles, Secondary irregularities in the equatorial electrojet, *J. Geophys. Res.*, **72**, 885-893, 1967.
- Farley, D. T., Two-stream plasma instability as a source of irregularities in the ionosphere, *Phys. Rev. Lett.*, **10**, 279-282, 1963.
- Farley, D. T., and B. B. Balsley, Instabilities in the equatorial electrojet, *J. Geophys. Res.*, **78**, 227-239, 1973.
- Fejer, B. G., Radar studies of small-scale plasma irregularities in the equatorial electrojet, Ph.D. thesis, Cornell Univ., Ithaca, N. Y., 1974.
- Fejer, B. G., D. T. Farley, B. B. Balsley, and R. F. Woodman, Oblique VHF radar spectral studies of the equatorial electrojet, *J. Geophys. Res.*, **80**, this issue, 1975.
- Kenesha, T. J., R. S. Narcisi, and W. Swider, Jr., Diurnal model of the *E* region, *J. Geophys. Res.*, **75**, 845-854, 1970.
- Knox, F. B., A contribution to the theory of the production of field-aligned ionization irregularities in the equatorial electrojet, *J. Atmos. Terr. Phys.*, **26**, 239-249, 1964.
- Maeda, K., T. Tsuda, and H. Maeda, Theoretical interpretation of the equatorial sporadic-*E* layers, *Phys. Rev. Lett.*, **11**, 406-407, 1963.
- McDonald, B. E., T. P. Coffey, S. Ossakow, and R. N. Sudan, Preliminary report of numerical simulation of type 2 irregularities in the equatorial electrojet, *J. Geophys. Res.*, **79**, 2551-2554, 1974.
- Mehr, F. J., and M. A. Biondi, Electron temperature dependence of recombination of O_2^+ and N_2^+ ions with electrons, *Phys. Rev.*, **181**, 264-271, 1969.
- Prakash, S., S. P. Gupta, and B. H. Subbaraya, Experimental evidence for cross-field instability in the equatorial ionosphere, *Space Res.*, **11**, 1139-1145, 1971.
- Prakash, S., B. H. Subbaraya, and S. P. Gupta, Rocket measurements of ionization irregularities in the equatorial ionosphere at Thumba and identification of plasma irregularities, *Indian J. Radio Space Phys.*, **1**, 72-80, 1972.
- Reid, G. C., The formation of small-scale irregularities in the ionosphere, *J. Geophys. Res.*, **73**, 1627-1640, 1968.
- Rogister, A., and N. D'Angelo, Type 2 irregularities in the equatorial electrojet, *J. Geophys. Res.*, **75**, 3879-3887, 1970.
- Sato, T., Unified theory of type 1 and 2 irregularities in the equatorial electrojet, *J. Geophys. Res.*, **78**, 2232-2243, 1973.
- Sudan, R. N., J. Akinrimisi, and D. T. Farley, Generation of small-scale irregularities in the equatorial electrojet, *J. Geophys. Res.*, **78**, 240-248, 1973.
- Sugiura, M., and J. C. Cain, A model equatorial electrojet, *J. Geophys. Res.*, **71**, 1869-1877, 1966.
- Whitehead, J. D., Instabilities in the gradient of ionization and sporadic-*E*, *J. Atmos. Terr. Phys.*, **29**, 1285-1297, 1967.
- Whitehead, J. D., The equatorial electrojet and the gradient instability, *J. Geophys. Res.*, **76**, 3116-3126, 1971.

(Received June 14, 1974;
accepted December 19, 1974.)