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THE DEPENDENCE ON ZENITH ANGLE OF THE STRENGTH OF 3-METER EQUATORIAL ELECTROJET IRREGULARITIES

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Abstract. Radar measurements in Peru were used to deduce the zenith angle dependence of the scattering cross section of plasma irregularities generated by instabilities in the equatorial electrojet. The irregularities probed by the 50 MHz Jicamarca radar had a wavelength of 3m. The cross section for the type 2 irregularities was isotropic in the plane perpendicular to the magnetic field, while the cross section for the stronger type 1 irregularities varied with zenith angle at a rate of approximately 0.3 dB/degree; the horizontally traveling waves were more than 100 times stronger than those traveling vertically.

Introduction

This paper continues a series dealing with radar studies of plasma instabilities in the equatorial electrojet. The most recent previous papers in the series are by Fejer et al. (1976) and Farley et al. (1978); more extensive reviews of the subject are given by Farley (1979) and Fejer and Kelley (1980). Surprisingly, in all the previous radar investigations there has been only one brief study of the dependence of scattering cross section on direction (Bowles et al., 1963), and this work was fairly crude and was carried out before it was realized that there were two distinct types of irregularities In this paper we discuss a series of 50 MHz measurements designed to determine the zenith angle dependence of the scattering cross section for both type 1 and type 2 irregularities.

The type 2 waves with wavelengths of a few meters or less are generally understood to be generated via a two-dimensional cascade process from irregularities of larger (tens of meters or more) wavelength, and so one might expect the short wavelength waves detected by the radar to have little 'memory' of the direction of the electrojet, i.e., to be relatively isotropic in the plane perpendicular to the magnetic field. The type 1 irregularities, on the other hand, are thought to be in some sense 'directly' excited. They are only observed when the electron drift velocity in the electrojet reaches (at least approximately) the threshold value that linear instability theory predicts will cause the generation of 3m (say) waves, via a basically two-stream mechanism modified by a gradient drift term. The picture is not quite so simple, though, because linear theory would not predict vertically propagating waves (which are observed), and strong perturbations of long wavelength will inevitably (except perhaps in the unusual case of a strong daytime 'counter electrojet'; see Crochet et al., 1979) be present in the electrojet by the time the type 1 threshold is reached. Nevertheless, one might expect the type 1 irregularities to have some directional dependence, i.e., to be strongest when traveling in the direction of the mean electron flow. Our goal in this study was to test these qualitative ideas.

Observations

The geometry of the experiment is shown in Figure 1. Some of the observations were made using steerable (in the E-W direction) dipole 'mattress' arrays for both transmitting and receiving. These antennas had a N-S beamwidth of about 40° and an E-W beamwidth of about 25°. At other times a single dipole was used for transmission and the arrays were used for reception. In all cases the transmitted power was roughly 1 MW, the frequency was 50 MHz, the pulse repetition frequency was 400 Hz, and the pulse duration was approximately 20μs. As the sketch in Figure 1 suggests, the details of the antenna beam are not very important for these relative measurements because the scattering volume is determined by other considerations: in the N-S direction it is limited by the aspect sensitivity (echoes are obtained only from beam directions within 1-2° of perpendicularity to the magnetic field), and in the E-W plane by the pulse length, range gating, and the limited altitude extent (especially during daytime) of the echoing region.

Since we are only interested here in the relative scattering cross section, the usual radar equation can be simplified to (e.g., Bowles et al., 1963)

$$P_r \propto P_t \int_V \sigma(\theta,\underline{r})\, G_t\, G_r\, R^{-4}\, d^3\underline{r}$$

$$\cong P_t\, \sigma(\theta) \int_V W(\underline{r})\, G_t\, G_r\, R^{-4}\, d^3\underline{r} \qquad (1)$$

Here $P_{t,r}$ are the transmitted and received power, $G_{t,r}$ are the antenna gain functions (which may be the same) in the E-W plane, θ is the zenith angle, σ is the scattering cross section per unit volume, R is the range, and V is the scattering volume. For the second line of (1) we assume that V corresponds to a small range of zenith angles and split σ into two components, one of which (the one we are interested in) depends only on zenith angle, and one of which (the function W) describes the altitude dependence, which is controlled by the conductivities, the ambient density gradient, etc. We ignore the aspect sensitivity here. For the normalized weighting function W we use two approximations, based on earlier high resolution vertical incidence observations (Fejer et al., 1976): for the type 2 irregularities we assume a quadratic dependence on altitude with a maximum value of 1.0 at 105.5 km, 0.1 at the 'edges' at 98 and 113 km, and zero

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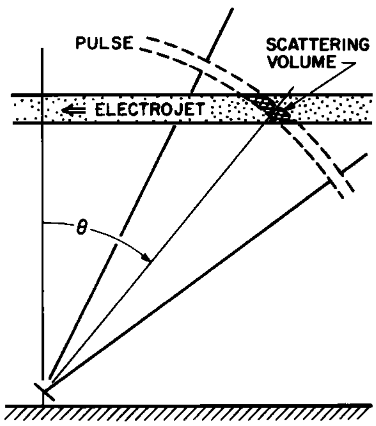

Fig. 1. Sketch of the radar geometry. The echoing region is slightly different for type 1 and type 2 echoes (see text) but is roughly between 100 and 110 km. The size of the scattering volume and the zenith angle Θ are determined as shown by the geometry, pulse length, and timing and are fairly independent of the antenna beam shape except for small zenith angles, which were therefore not studied.

everywhere else; for the type 1 irregularities which occupy a narrower height range, we take W to be unity between 100 and 106.5 km and zero everywhere else. The details of the assumptions concerning W are actually not important as long as we avoids zenith angles smaller than about 20°, as we have done.

For a particular range, pulse length, receiver bandwidth, and antenna pointing direction it is straightforward to work out the integral in (1), taking account of the earth's curvature and the assumed behavior of W, and relate the received power to $\sigma(\Theta)$. Normally the seven ranges sampled for each pointing direction of the antenna were such that the echoes corresponded to angles no more than 7-8° from the antenna axis, in order to minimize systematic errors due to imperfect knowledge of the antenna pattern. The antenna was moved in approximately 10° steps, providing some overlapping of samples. The smallest zenith angles were omitted due to uncertainties associated with the wide antenna beam width, and no data could be obtained for angles greater than 70°. The largest source of uncertainty in the data arises from temporal variations in the electrojet during the period required to step through a complete set of antenna pointing directions. We have tried to minimize these by using only data for which the electrojet remained reasonably steady, as indicated by our own data and by magnetometer records. We also rely implicit assumption that there are no significant longitudinal variations in the electrojet over the region scanned. This assumption seems to be justified most of the time.

We have divided our results according to whether the echoes were (a) almost entirely type 1, (b) entirely type 2, or (c) a mixture of the two. The type 1 echoes have a narrow spectral peak at a Doppler shift corresponding to approximately the ion acoustic velocity, whereas the type 2 echoes have a broader spectral peak at a smaller Doppler shift.

<u>Type 1 Irregularities</u>. On 18 January 1975 measurements were made using the steerable antennas as discussed above during a period when the electrojet was strong and type 1 echoes dominated the returns. The results are shown in Figure 3. The signal-to-noise ratio was very large (as it almost always is for electrojet measurements at Jicamarca), and the integration time was about 80s, and so statistical errors were negligible. The scatter in the data in Figure 3 is due mainly to variations in the electrojet during the 40-50 minutes required to step through all the antenna positions. The scattering cross section varies approximately exponentially with zenith angle over the rather large range of angles studied. The slope of the solid lines is 0.30 dB/degree. Extrapolation of these results (which of course may not be completely justified) implies that the horizontally propagating type 1 waves are probably 25-30 dB stronger than those propagating vertically.

It can also be seen in Figure 3 that the echoes from the west are usually (but not always) stronger than those from the east. This asymmetry has been observed at Jicamarca for many years (e.g., Balsley, 1970) but is not yet understood. It seems most plausible that it is related to the presence of the ocean to the west of Jicamarca and/or the Andes to the east.

It seemed worthwhile to compare the results of Figure 3 to the much earlier Jicamarca observations at 150 MHz of Bowles et al. (1963), the only other study of zenith angle dependence. No spectra were measured so we cannot be sure that their echoes were type 1, but the observations of Balsley and Farley (1971) at three frequencies suggest that type 2 echoes are negligible or weak at 150 MHz. We have replotted the 1963 results in Figure 4, which is very similar to Figure 3, except that in this case the slope is about 0.2 dB/degree. Without knowing more about the 1963 data it is difficult to say whether or not the difference in slopes is significant.

<u>Type 2 Irregularities</u>. In Figure 5 we summarize the results of measurements of type 2

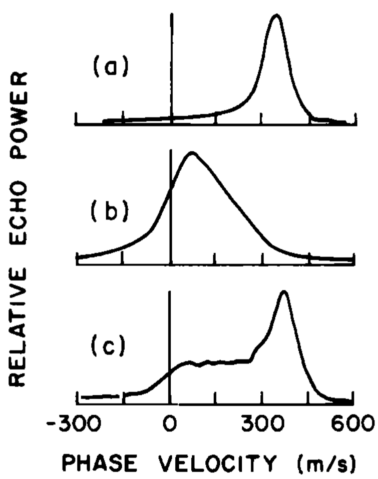

Fig. 2. Examples of power spectra of (a) type 1 echoes, (b) type 2 echoes, and (c) a mixture of both types obtained with an eastward directed 50 MHz radar during the day.

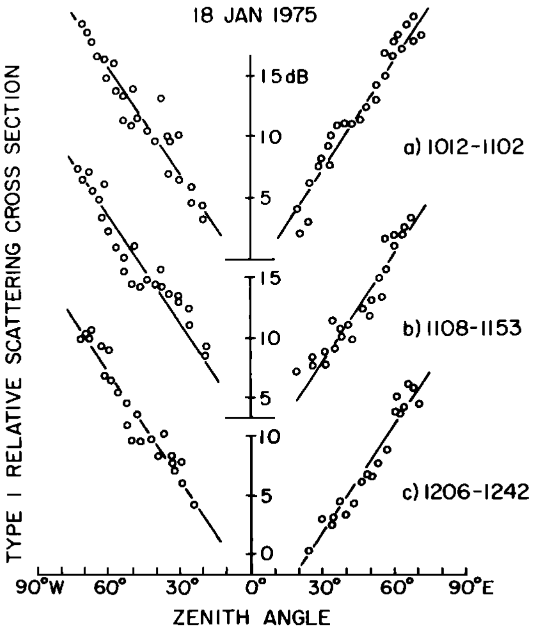

Fig. 3. The dependence on zenith angle of the radar scattering cross section of type 1 irregularities at 50 MHz. Only the relative power levels are important, the absolute value has no significance in this figure and those which follow.

echoes made on 20 October 1975 and 20 January 1977. For these observations we transmitted on the single dipole and used the two steerable antennas to receive simultaneously from the east and west and averaged for about 60s at each antenna position. As a result, the entire sweep was completed in about 7 min. The spread in the data is again believed to be due primarily to variations in the electrojet during the observation period. To within the accuracy of the measurements, the scatter in this case is isotropic, in sharp contrast to the results for the type 1 echoes.

Irregularity Mixtures. When both types of irregularities are present simultaneously, one can attempt to separate their contributions to the total scattered power, but it is difficult to do this very accurately. Following Balsley (1969) we have somewhat arbitrarily assumed that

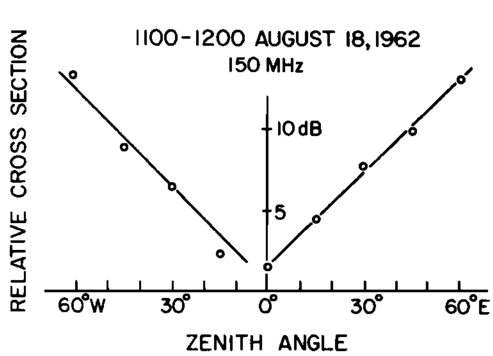

Fig. 4. Zenith angle dependence of scattering at 150 MHz (adapted from Bowles et al., 1963), probably from type 1 irregularities.

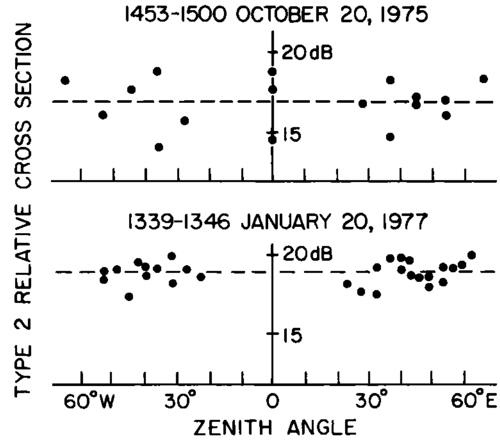

Fig. 5. The dependence on zenith angle of the scattering cross section at 50 MHz of type 2 irregularities.

the type 1 contribution to the spectrum is symmetrical about its peak and that the portion of the signal spectrum with Doppler shifts larger than the value at the peak is entirely type 1. This procedure leads to results such as those shown in Figure 6, which were obtained using the dipole to transmit and the two steerable antennas to receive. The data are similar to those of Figures 3 and 4; the type 2 contributions are isotropic, insofar as one can tell, while the type 1 contribution increases exponentially with zenith angle. The slope in this case is roughly 0.2 dB/degree, but these data are certainly less accurate than those plotted in Figure 3, especially for small zenith angles where the separation of the spectrum into its two components becomes increasingly uncertain.

Discussion

The two-dimensional isotropy of the short wavelength type 2 irregularities is consistent with current models of the generation of these irregularities. Linear instability theory indicates that the horizontal electron drift and vertical density gradients associated with a moderate electrojet ($V_d \lesssim$ 100-200 m/s, say) cannot generate any 3m waves, let alone

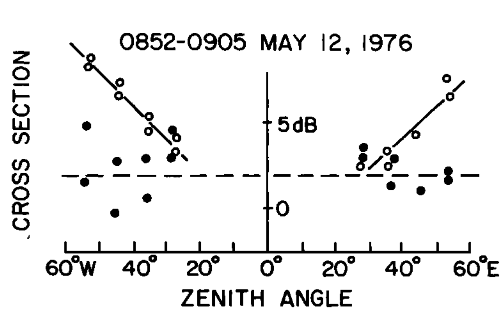

Fig. 6. Relative scattering cross section data obtained at 50 MHz when both type 1 and 2 echoes were observed simultaneously (see Figure 2c). The open circles represent type 1, the solid dots type 2. A somewhat arbitrary procedure was used to divide the received power into the two components.

vertically propagating ones. In an effort to explain the observations of these waves, Farley and Balsley (1973) suggested a two-dimensional cascade process in which horizontally propagating large scale irregularities (small horizontal k vectors), which are linearly unstable, first develop; these produce vertical drifts and horizontal density gradients which generate additional smaller scale irregularities traveling vertically; and so on. This concept was shown to be quantitatively reasonable by Sudan et al. (1973), and shortly thereafter Sato (1973) made a similar suggestion. Subsequently a considerable effort has been devoted to two-dimensional numerical simulations of the type 2 irregularities. Some of the recent simulations (e.g., McDonald et al., 1975; Ferch and Sudan, 1977; Keskinen et al., 1979) reproduce the radar results (the Doppler spectral shape as well as the isotropic k spectrum) quite well and show clearly that the above ideas are correct; a two-dimensional cascade soon generates small scale irregularities propagating in all directions. Sudan and Keskinen (1977, 1979) have also shown that some features of the data can be explained analytically using the nonlinear 'direct interaction approximation'.

Our understanding of the type 1 irregularities is not nearly as advanced. Insofar as these irregularities are more or less 'directly excited' by a horizontal electron drift at more than the ion acoustic velocity, it is probably not surprising that the horizontally propagating waves would be the strongest, but we cannot say much more. There is no theory which even suggests what the dependence on direction (in the plane perpendicular to the magnetic field) should be, and certainly none which explains an exponential dependence with a slope of 0.3 dB/degree.

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References

Balsley, B.B., Some characteristics of non-two-stream irregularities in the equatorial electrojet, J. Geophys. Res., 74, 2333, 1969.

Balsley, B.B., A longitudinal variation of electron drift velocity in the equatorial electrojet, J. Geophys. Res., 75, 4369, 1970.

Balsley, B.B., and D.T. Farley, Radar studies of the equatorial electrojet at three frequencies, J. Geophys. Res., 76, 8341, 1971.

Bowles, K.L., B.B. Balsley, and R. Cohen, Field aligned E region irregularities identified with ion acoustic waves, J. Geophys. Res., 68, 2485, 1963.

Crochet, M., C. Hanuise, and P. Broche, HF radar studies of two-stream instability during an equatorial counter-electrojet, J. Geophys. Res., 84, 5223, 1979.

Farley, D.T., The Ionospheric Plasma, in Solar System Plasma Physics L.J. Lanzerotti, C.F. Kennel and, E.N. Parker (eds.), North Holland, New York, 1979.

Farley, D.T., and B.B. Balsley, Instabilities in the equatorial electrojet, J. Geophys. Res., 78, 227, 1973.

Farley, D.T., B.G. Fejer, and B.B. Balsley, Radar observations of two-dimensional turbulence in the equatorial electrojet, 3. Nighttime observations of type 1 waves, J. Geophys. Res., 83, 5625, 1978.

Fejer, B.G., and M.C. Kelley, Ionospheric irregularities, Rev. Geophys. Space Phys., in press, 1980.

Fejer, B.G., D.T. Farley, B.B. Balsley, and R.F. Woodman, Radar observations of two-dimensional turbulence in the equatorial electrojet, 2, J. Geophys. Res., 81, 130, 1976.

Ferch, R.L., and R.N. Sudan, Numerical simulations of type II gradient drift irregularities in the equatorial electrojet, J. Geophys. Res., 82 2283, 1977.

Keskinen, M.J., R.N. Sudan, and R.L. Ferch, Temporal and spatial power spectrum studies of numerical simulations of type II gradient drift irregularities in the equatorial electrojet, J. Geophys. Res., 84, 1419, 1979.

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