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LONG WAVELENGTH IRREGULARITIES IN THE EQUATORIAL ELECTROJET

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Abstract. We have used the radar interferometer technique at Jicamarca to study in detail irregularities with wavelengths of a few kilometers generated in the unstable equatorial electrojet plasma during strong type 1 conditions. In-situ rocket observations of the same instability process are discussed in a companion paper. These large scale primary waves travel essentially horizontally and have large amplitudes. The vertical electron drift velocities driven by the horizontal wave electric fields reach or exceed the ion-acoustic velocity even though the horizontal phase velocity of the wave is considerably smaller. A straightforward extension to the long wavelength regime of the usual linear theory of the electrojet instability explains this and several other observed features of these dominant primary waves.

Introduction

In this paper we present preliminary results of a detailed study of kilometer scale, large amplitude, horizontally traveling plasma waves observed in the equatorial electrojet during strong type 1 conditions. A companion paper [Pfaff et al., 1982] discusses similar long wavelength features that are evident in in-situ rocket observations of electron density and electric field fluctuations. The equatorial electrojet plasma irregularities are discussed in recent reviews by Farley [1979] and Fejer and Kelley [1980].

The existence of large scale primary waves was implied by earlier data [e.g., Balsley and Farley, 1973; Farley et al., 1978], but a detailed study of their characteristics became possible only after the introduction of the radar interferometer technique [Farley et al., 1981] at the Jicamarca Radio Observatory. In fact, the success of the interferometer technique is largely due to the modulation of the electron flow by these waves, since they cause the scattering centers to be highly localized within the electrojet. Data presented in this paper include the first successful interferometer measurements of the daytime electrojet turbulence. Earlier publications [Farley et al., 1981; Kudeki et al., 1981], which discussed only nighttime electrojet and spread-F interferometer measurements, raised a number of questions, some of which we hope to answer here. For example, we show that it is not unreasonable to simultaneously observe east-west drift velocities substantially smaller than the ion-acoustic velocity and vertically propagating type 1 waves.

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Observations

The data to be presented here were taken using the 50 MHz Jicamarca array in various interferometer configurations. The Jicamarca radar is sensitive only to vertically propagating 3-meter waves. These act as tracers of the large scale perturbations on which they ride. High resolution data are extracted from the normalized cross spectrum (NCS) of the signals from the two antennas forming the interferometer. The magnitude, or coherence, of the NCS at a particular frequency is a function of the angular size of the wave packet scattering the Doppler shifted signal, and the argument of the NCS, the phase angle, is determined by the angular position of the same wave packet. The indicated position is particularly reliable for Doppler frequencies with large coherence. A detailed discussion of the Jicamarca interferometer technique is given by Farley et al. [1981]. In these vertical incidence experiments, the interpulse period was 2.25 ms and the height resolution 1.75 km. Power and normalized cross spectra were estimated at 1.44 s intervals by averaging over 10 succesive realizations, each computed using a 64-point time series.

Variations in backscattered power. The total power scattered from altitudes giving strong type 1 echoes, as well as the separate components associated with upgoing and downgoing waves, often show periodic variations. An example is shown in Fig. 1. Note the strong periodicity of about 40 s in both components of total power. Since the vertically traveling 3-meter waves are generated by horizontally traveling primary waves [e.g., Sudan et al., 1973], the observed periodicity must be caused by such a wave, propagating in the east-west direction, with a wavelength comparable to or larger than the east-west extent of the scattering volume, for otherwise the dominant fluctuation would have been smoothed out by the spatial integration effect of the finite antenna beamwidth.

Spectral variations. A sequence of power and phase angle spectra covering one complete cycle of the spectral variation lasting about 40 s is presented in Fig. 2. Periods when either upgoing or downgoing type 1 waves are dominant are separated by periods when the spectrum is broad and roughly symmetrical, with strong contributions at the lower frequencies. The phase angle spectra shown in Fig. 2 also exhibit a clear periodic behavior. When type 1 power spectra are observed, the corresponding phase angle spectra are almost flat for the frequency range corresponding to the power spectral peak. When the power spectra are symmetrical, on the other hand, the phase angles usually increase or decrease monotonically with Doppler shift.

Spectrograms. Power spectral variations are most compactly displayed as spectrograms, which

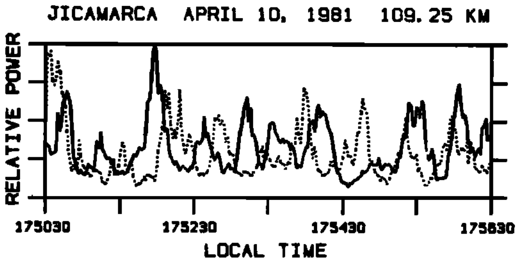

Fig. 1. Components of the total backscattered power corresponding to upgoing (full line) and downgoing (dashed line) waves. Both waveforms have been normalized by the same value, and the power scale is linear.

are frequency-time-intensity plots. Examples from two adjacent altitudes are presented in Fig. 3. The patterns show roughly sinusoidal waveforms with power alternating between upgoing and downgoing waves. The waveforms, which are essentially in phase at the two altitudes shown, can be associated with the dominant velocity perturbation field. Although not shown here, the height correlation for the period displayed is actually strong for at least four adjacent altitudes, corresponding to a range of 7 km. Another example, this time from a nighttime experiment, is shown in Fig. 4.

Wavelength determination. We have already argued that the dominant scale sizes are comparable to or larger than the size of the scattering region (~1 km). A more precise determination of the dominant wavelength can be made by measuring the east-west drift velocity of the scattering centers using the interferometer technique [Farley et al., 1981] and combining this information with the observed period of variation. For the data displayed in Fig. 3, which has an oscillation period of about 40 s, we found the westward velocity to be about 100 m/s, implying a dominant wavelength of approximately 4 km. Similarly, we estimate a value of 5 km for the nighttime data shown in Fig. 4. Other data not presented here show similar periodic behavior with dominant wavelengths of 2-6 km.

Discussion

Large amplitude kilometer scale waves clearly play an important role in the plasma physics of the equatorial electrojet. The phase angle data in Fig. 2 show that upgoing and then downgoing scattering centers enter the east end (during daytime) of the scattering volume and drift across, exiting at the west end. A second point to note is that the primary waves are fairly monochromatic, at least over short periods. We defer a full investigation of this point, possible wave steepening effects, and asymmetries, etc. to a later paper, but it is obvious from Figs. 1, 3, and (to a lesser extent) 4 that the large scale waves are not noise-like. Finally, since upgoing and downgoing type 1 waves are periodically observed, the vertical electron velocity associated with the dominant primary waves must reach the two-stream threshold of about the ion-acoustic velocity. When the crest or trough of the dominant mode is inside the scattering volume, the corresponding velocity perturbation generates the upgoing or downgoing type 1 waves observed by the radar, and the corresponding backscattered power reaches high values (the peaks in Fig. 1). Shorter wavelength primary waves must have smaller perturbed velocity amplitudes, for otherwise vertically propagating type 1 waves would be observed with no interruptions as a result of spatial integration. Note that the ion-acoustic speed C_s (~360 m/s) is considerably larger than a velocity of about 100 m/s measured by tracking the motion of the scattering centers across the scattering volume for the period shown in Fig. 3. Similar differences were noted in earlier interferometer studies [Farley et al., 1981].

The motion of the scattering centers, according to our model, is the phase velocity of the dominant primary wave, rather than a particle velocity such as the horizontal or vertical electron drift. It would be a bit surprising if the vertical perturbation electron velocity, even of the primary waves, significantly exceeded the velocity of the ambient horizontal electron drift, which is the driving force of the entire instability process. Furthermore, numerous earlier papers have shown that the horizontal drift during two-stream conditions does reach or exceed the ion-acoustic velocity, generating horizontally traveling type 1 waves which are considerably stronger than those propagating vertically [Ierkic et al., 1980]. At first glance, these various observations seem inconsistent with the usually quoted results of linear theory that tell us that the wave phase velocity should be only slightly less than the driving electron drift velocity. However this theory only applies to short and moderate wavelengths, a regime characterized by $kL \gg 1$, where k is the irregularity wavenumber and L is the electron density scale length (~3-30 km). The theory is quite different for large scale ($kL \sim 1$) waves.

The oscillation frequency and growth rate for this case can be easily obtained from the general dispersion relation given in Sudan et al. [1973], omitting the usual assumption that the growth rate is small compared to the oscillation frequency. Ion inertial effects and ambipolar diffusion are both negligible, and we also

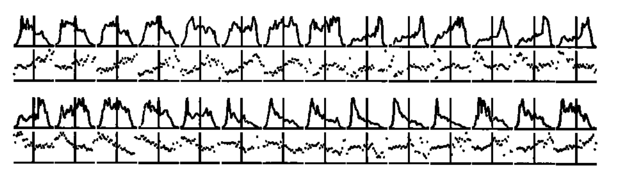

Fig. 2. Sequences of power (P) and phase angle (Φ) spectra, with time progressing from left to right and top to bottom, in 1.44 s intervals and starting at 17:53:42 L.T. The horizontal axis for each spectrum is the Doppler velocity, ranging from -666 m/s (upward) on the left to +666 m/s (downward) on the right. Each power spectrum is normalized to its own peak value. The phase angles range from 0° at the bottom to 180° at the top, which corresponds to an east-west separation of about 3.2 km at 109.25 km for the interferometer baseline of 101.82 m.

neglect recombinations for the moment. Then the oscillation frequency and growth rate for horizontally propagating modes (normal to B) are

$$\omega_k = kV_d(1+\Psi)^{-1}(1+k_o^2/k^2)^{-1} \quad (1)$$

$$\gamma_k = k_oV_d(1+\Psi)^{-1}(1+k_o^2/k^2)^{-1} \quad (2)$$

where V_d is the mean horizontal electron drift velocity, $\Psi = \nu_e\nu_i/\Omega_e\Omega_i$, $k_o = (\nu_i/\Omega_i L)(1+\Psi)^{-1}$, and $\nu_{e(i)}$, $\Omega_{e(i)}$ are the usual electron(ion) collision and gyro frequencies, respectively. Similar expressions were given by Rogister [1972]. Note that for $k_o/k \ll 1$ we recover the usual results for short wavelengths. For typical ionospheric parameters at 105 km, $k_oL \sim 23$, or $\lambda_o \sim 0.27L$. Hence for density scale lengths of several kilometers, the observed kilometer scale waves belong to the $k \sim k_o$ regime. According to (1), the large scale waves are dispersive, with phase velocity decreasing with increasing wavelength; e.g., for $k=k_o$ the phase velocity is one half the short wavelength value of $V_d/(1+\Psi)$ and is far less than the mean electron velocity. Under type 1 conditions, say, with V_d=360 m/s, the phase velocity would be about 150 m/s. This theoretical result accounts nicely for our observations.

Another obvious question is: why do waves with $k \sim k_o$ dominate the wavelength spectrum? Linear theory again provides at least a partial answer. Large scale waves are driven primarily by the gradient-drift mechanism. This term decreases rapidly with increasing wavelength for $k<k_o$ and eventually becomes less than recombinational damping [e.g., Fejer et al., 1975], which we have neglected so far. To include it we add $-2\alpha N_o$ (about $-0.06\ s^{-1}$ during daytime) to the right hand side of (2). Here α is the dissociative recombination coefficient ($\simeq 3\times10^{-7} cm^3/s$) and N_o is the background electron density. Since the driving term in this limit is proportional to $(1+k_o^2/k^2)^{-1}$ and the recombinational damping is independent of wavelength, there will be a long wavelength cutoff that is likely to be in the vicinity of $k=k_o$, at least during the day. Therefore, we expect scale sizes larger than about k_o to be

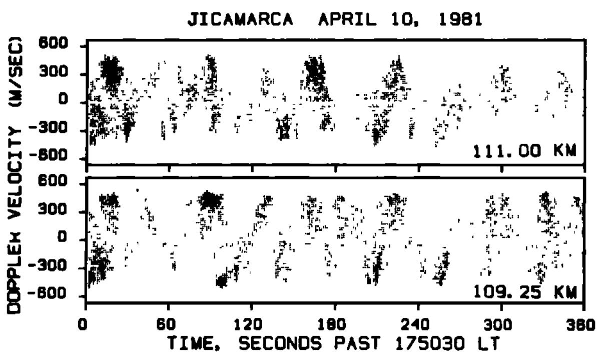

Fig. 3. Spectrograms of returned signal. Each spectrogram (not each individual spectrum) is normalized to its own peak power. The power values are divided into nine linearly spaced levels, with the darkest shades corresponding to the largest power values. Negative Doppler velocities indicate downgoing waves.

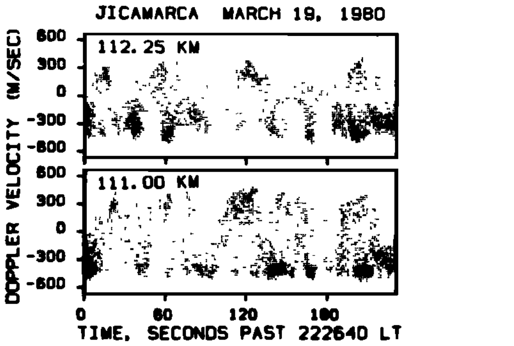

Fig. 4. A set of spectrograms from a nighttime experiment.

linearly damped and the "outer scale" to vary with the electron density scale length. This is in good agreement with daytime interferometer observations that indicate dominant wavenumbers of about k_o. At night recombinational damping is much smaller, and so the dominant waves should have larger values of k_o/k and even smaller phase velocities. This conclusion is also in agreement with our nighttime interferometer observations, which have shown eastward velocities of the scattering centers as small as 30 m/s during strong type 1 conditions. Note that k_o may be larger at night than during the day because of sharper density gradients, and so the values of k for primary waves may not change greatly.

The large amplitude of the longest waves may result from the fact that non-linear mode coupling is a relatively ineffective loss process for these waves because they are highly dispersive; the participating modes have quite different phase velocities and cannot couple strongly, in contrast to the situation at shorter wavelengths. Thus, the large scale perturbations can grow until other saturation mechanisms (e.g., quasilinear effects) become important. Rogister [1972] studied mode coupling effects for large scale waves and concluded that a maximum density perturbation of about 25% would be reached for $k=k_o$. This treatment, however, assumed small drift velocities, $V_d<0.1C_s$, and is not directly applicable to our data.

Since the large scale dominant waves during type 1 conditions ($V_d \sim C_s$) have associated vertical electron velocity amplitudes of about C_s, the resultant local electron velocity (mean plus dominant perturbed velocity) in any direction will equal or exceed C_s in localized regions inside the scattering volume, particularly near the crests and troughs of the dominant wave (for large zenith angles the threshold will be exceeded even considerably away from the crests and troughs). Thus we should expect type 1 waves traveling in a wide range of directions to be generated, in agreement with numerous obsevations [Fejer and Kelley, 1980]. The increase of type 1 scattering cross-section with zenith angle [Ierkic et al., 1980] is qualitatively consistent with the fact that the threshold velocity will be exceeded for a larger fraction of the dominant wave for larger zenith angles. Thus, the existence of large amplitude, large scale dominant waves, as well as mean electron velocities of about C_s, are necessary conditions for the generation of type 1 waves traveling in many directions.

The radar observations of Crochet et al. [1979] during rare strong counter-electrojet conditions, when the daytime electron drift exceeded the ion-acoustic velocity in the "reversed" (eastward) direction, also support this model. The observed departures from the usual type 1 echo characteristics (e.g., the dependence of Doppler shift upon zenith angle) can be explained as being due to the absence of large scale primary waves, because during reversed current conditions the gradient-drift mechanism is stabilizing, not a source of instability.

The phase angle spectra of Fig. 2 show the existence of 3 meter waves even where the local vertical velocity is less than the two stream threshold. Simple calculations show, however, that the density gradient length associated with kilometer scale waves ($-\delta n/kN_o$) is too long to excite secondary 3-meter waves. Thus, sharper density gradients associated with intermediate scale (tens of meters) waves, which are also linearly unstable, must exist. The amplitudes of these intermediate waves must be appreciably smaller than the kilometer scale wave amplitudes (otherwise we would not observe a dominant wave effect), but they must be large enough to produce the required density gradients. It can be easily shown that the second condition is met if the wave amplitudes decrease with wavelength more slowly than k^{-1}; i.e., if the wave power spectrum is proportional to k^{-n}, with $n < 2$. Such spectra observed in rocket measurements are reported in the companion paper [Pfaff et al., 1982].

The convection of vertical 3-meter waves by the dominant kilometer scale waves gives rise to the peculiar phase angle spectral shapes with positive and negative slopes presented in Fig. 2 and also in Farley et al. [1981]. In the dominant velocity field, short scale waves with similar phase velocities will be found close to each other, and the observed spectral shapes will show cyclical variations as the primary wave moves in the east-west direction. The phase angle spectrum will also depend on the relative sizes of the dominant waves and the scattering volume. A more detailed discussion of the phase spectral shapes, as well as possible wave steepening and asymmetry effects will be presented in a future publication.

Conclusions

The Jicamarca radar interferometer studies of the equatorial electrojet clearly show that large amplitude, horizontally propagating plasma waves with wavelengths of a few kilometers exist during strong type 1 conditions. With velocity amplitudes comparable to the ion-acoustic velocity, these large scale waves strongly affect both type 1 and type 2 3-meter waves and undoubtedly affect intermediate length waves as well. These dominant waves are dispersive, which may partially explain their large amplitudes, and have phase velocities considerably smaller than the mean electron velocity, in agreement with observations. Experimental evidence and theoretical considerations taken together indicate that the scale size of the dominant waves is controlled by the electron density gradient length and the recombination rate.

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