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In-Situ Measurements of Wave Electric Fields in the Equatorial Electrojet

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Abstract. Electric field wave measurements have been performed on two sounding rockets in the equatorial ionosphere. During a daytime flight from Chilca, Peru, intense electrostatic waves were detected on the upward directed electron density gradient. During a nighttime flight from Kwajalein Atoll, similar waves were detected on a downward directed gradient. These results are in agreement with a gradient drift instability explanation of the generation of the waves. The wave amplitudes were as high as 5 mV/m implying perturbation drifts comparable to the driving drift velocities. Power spectra from the turbulent region show a peak at long wavelengths, followed by a nearly flat spectral region before breaking into a power law form with negative index of 3.6-3.7 for λ ≤30 m. Similarities between the spectra of the two flights suggest that the fundamental processes of the instabilities are the same in the daytime and nighttime conditions. The rocket data are consistent with radar results presented in a companion paper which show coherent, kilometer scale waves present in the electrojet.

A companion paper by Kudeki et al. [1982], hereafter referred to as paper 1, describes measurements made at the Jicamarca Radar Observatory using an interferometric technique. These show coherent, large amplitude, kilometer-scale waves in the electrojet, observations that are strongly supported by the data presented here. In addition, the data sets in this paper show perturbed wave electric fields that are comparable to the predicted ambient electric field, and yield wave number spectra over more than three decades in spatial scale and six decades in power.

Introduction

Electrostatic turbulence in the equatorial electrojet has been studied extensively for more than two decades using radar techniques and for more than one decade with rocket density probes (see review by Fejer and Kelley, [1980]). Both of these methods detect the density fluctuation component of the electrostatic waves in the electrojet. In this paper we describe the first rocket observations of the E component of the unstable waves in the equatorial zone.

We present data from two rocket flights, one from the rocket range at Chilca, Peru (magnetic dip = 0.5ø) and one flown from the Island of Kwajalein (magnetic dip = 9ø) in the South Pacific. In the first case, the rocket was launched when the electrojet was strong, at 11:07 local time (16:07 U.T.), on June 7, 1975. At Kwajalein, the data were obtained during nighttime conditions with a lift-off time of 10:40 U.T. on August 8, 1978, which corresponds to a local solar time of 21:40. The electric field detector flown from Peru utilized long cylindrical sensors (6.05 m tip-to-tip with 61 cm exposed) similar to the instrument described by Aggson [1969]. The Kwajalein data were obtained using spherical sensors on the ends of a 3 m tip-to-tip boom system as described by Fableson [1967]. In both cases the telemetry included separate channels for do/low- and ac/high-frequency data.

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Fig. 1. Raw electric field data from (a) daytime (Peru) and (b) nighttime (Kwajalein) flights.
In the data and its effect is apparent in the spectrum at 0.25 Hz. In Fig. 5a, the spectrum was based on the residual after the model was subtracted. In both cases, the waves due to the electrojet turbulence were greater than the "background" power ascertained from spectra taken prior to entry into the unstable region.

The two spectra are remarkably similar. In both cases the wave induced portion of the spectra are characterized by an interval at low frequencies in which the spectral density maximizes. This is followed by a regime in which the spectral density decreases slowly with increasing frequency, and finally by an interval in which the spectrum decreases rapidly in a nearly power law fashion. The spectral indices deduced from a straight line fit to a power law from 150-350 Hz are -3.6 and -3.7 for the Peruvian and Kwajalein data, respectively.

For the Kwajalein flight, we have also made a power spectrum of the data from the fixed bias Langmuir probe, as shown in Fig. 5(b). A similar form is seen in this spectrum as in its electric counterpart, before the density spectrum runs into the noise around 200 Hz. In particular, the density fluctuation spectrum shows a distinct peak at 3.7 Hz. This spectral peak was well resolved since many cycles were encountered in the layer. When the electric field data from the two spin plane antennae are added to create their vector sum, the power spectrum of the resulting signal shows a single peak (indicated by the dashed line) at the same frequency at which the density power spectrum peaks. The double peaks may be explained as an artifact of a spinning directional antenna in the presence of a linearly polarized wave.

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frame is not particularly useful for comparison with theory. In order to proceed, some assumption must be made to convert to wave number in the plasma frame. As discussed in detail by Fredricks and Coroniti [1976] and by Temerin [1979] this is not a trivial problem, particularly when there is a significant phase velocity (as compared to the rocket velocity) in the plasma frame. In this paper we are primarily interested in comparison between the daytime and nighttime data and in the characteristic of the entire spectrum of electrojet waves. We thus make the usual assumption that the frequency of the waves in the rocket frame is related to the wave number via the Doppler shift \( \omega = k \cdot v \). The wavenumber scale is plotted on the top of the spectra in Figs. 4 and 5 under the assumption that \( k \) is perpendicular to \( B \) and that the \( k \) values sampled are parallel to the component of velocity in that direction. Since the rocket velocity, \( v \), was primarily upward while the large amplitude waves discussed in paper 1 appear to have a primarily horizontal phase velocity, their wavelengths would be overestimated using this assumption. It is more likely that the largest wavelength waves measured by the rocket are due to secondary waves generated perpendicular to the direction of the linear instability. At some wavenumber, the turbulence will be isotropic, and our assumption is valid, although it is uncertain at what wavelength this condition is met.

Several points are immediately clear, even though the transformation to wave number is not definitive. As mentioned earlier, the two spectra in Figs. 4 and 5a are similar in form. In both cases most of the energy is located in the longest wavelength portion of the spectrum. This dominant wavelength is not the same in the two data sets, being 1000 m in Fig. 4 (day) and 350 m in Fig. 5 (night). Note that the ratio of the zero order density scale lengths driving the two instabilities is approximately the same as the ratio of these two peak wavelengths. The wavelength at which the electric field spectra break from a slowly decaying spectral density to a steep power law is roughly the same in the two cases, about 30 m. The minimum detectable wavelength in each experiment was about 2 m, but there was no indication that the power law would not continue extending the perturbed wavelengths to even shorter scales.

Discussion

The data presented here show perturbation velocities associated with fully developed electrojet instabilities that can be comparable to the driving electron drifts. This result is in agreement with conclusions of radar experimenters and theorists when explaining large Doppler shifts observed independent of the angle between the radar line of sight and the current [Fejer and Kelley, 1980]. The measured electric fields are a lower limit to the actual fields present, and indicate that perturbed vertical electron drifts at least as great as 30-40% of the sound speed (400±50 m/s at Jicamarca) are generated. The condition that the drift velocity exceed the sound speed, which is necessary for production of short wavelength waves by a secondary two-stream instability [Farley, 1963; Sudan et al., 1973], may conceivably be attained.

For the long wavelength approximation, the turbulent electrojet models of Sudan et al. [1973] and Balsley and Farley [1973] easily show from the linear theory the relationship between the electric field and density fluctuations as:

\[
\frac{\Delta E}{(\Delta N/N)} \approx \nu_e \nu_i / (1 + \Omega_e \Omega_i)^{-1} E_{ambient}
\]

where \( \nu = \nu_e \nu_i / (\Omega_e \Omega_i) \), \( \nu_e \) and \( \nu_i \) are the electron and ion collision frequencies and \( \Omega_e \) and \( \Omega_i \) are the electron and ion gyro frequencies. The spectral density of the electric field at the peak in Fig. 5a is 1 mV/mHz^{1/2} while the density spectrum peak value is 0.045 Hz^{-1/2}. Using model values for the collision and gyro frequencies, the calculated ambient electric field is thus 1.6 mV/m. This value is reasonable for the Kwajalein latitude and comparable to \( \delta E \).
Similarity between the electric field spectra imply that the fundamental processes are identical in the two physical situations. During the day the waves were located in a region of positive (upward) density gradient, while at night they were found in a region of negative gradient. Since the vertical electric field is known to reverse sign between daytime and nighttime conditions, the relationship is in good agreement with the linear theory of the gradient-drift instability, which requires that the polarization electric field be parallel to the density gradient for wave generation. Plasma density fluctuation measurements made in a series of rocket flights from India displayed a similar relationship between wave occurrence and the density gradient [Prakash et al., 1972]. The data presented here and in paper 1 suggest that a dominant long wave develops with a wavelength the order of the driving gradient scale length. Generation of this dominant wave is thus best described within the context of the gradient-drift theory. Strong evidence supporting this concept stems from the observation that the gradient scale length seems to control the outer scale at least for the vertical wave number spectrum.

The spectral form suggests that positive growth rates exist throughout a range of wavenumbers just above the regime of maximum intensity, where the spectrum is nearly flat. At high wavenumbers, an "inertial subrange" may exist in which energy cascades to smaller scales where it is absorbed by the largest scale. The observed spectral slope is consistent with the predictions made by Ott and Farley [1974] using dimensional arguments based on an inertial range. Results of numerical simulations by Keskinen et al. [1979] not only agree with the observed spectral slope but also with the observed break in the spectral form at 30 m. However, this does not preclude the possibility that propagating acoustic waves are generated with a power law of this form and contribute to the damping of the larger scale waves. The break in the spectrum occurs at nearly the same wavelength in both data sets. This suggests that the break is controlled by properties of the medium rather than by the free energy source.

In summary, we have studied the electrojet instability process during both daytime and nighttime conditions using the electric field technique to detect the electrostatic waves. The spectra were measured over three decades of wavelength and six decades of power. Strong evidence exists in paper 1 and to some extent in the present data that the gradient drift process dominates the physics and results in an energy "build-up" in the longest wavelength allowed by the system, a length of the order of the driving gradient. These waves grow to large amplitudes and yield perturbation velocities comparable to the driving drift speed. Secondary waves powered by these large drift speeds very likely create the broad flat portion of the observed spectrum. The secondaries may be either of the two-stream or gradient-drift type.

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