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First results from the Freja HF Snapshot Receiver

Paul M. Kintner, John Bonnell, Steven Powell, and Jan-Erik Wahlund
School of Electrical Engineering, Cornell University, Ithaca, New York

Bengt Holback
Swedish Institute of Space Physics, Uppsala, Sweden

Abstract. The Freja plasma wave instrument has measured electric field waveforms up to 4 MHz in the auroral ionosphere near 1700 km altitude. The HF snapshot receiver responds to natural signals during every passage through the auroral ionosphere and we have currently identified two kinds of signals: broadband whistler mode emissions with a cut-off at the plasma frequency, narrow band Langmuir wave emissions at the plasma frequency, and mixtures of both wave emissions. The Langmuir wave emissions are frequently narrow band ($\Delta f/f \lesssim 10^{-2}$) and exhibit a variety of modulational features. These Langmuir waves exist up to amplitudes of roughly 1 volt/m. At larger amplitudes (a few V/m and $\varepsilon_0 E^2/2nkT \cong 10^{-2}$) the wave spectra broaden and the waveforms appear to be composed of individual wave packets, each with 5-10 wave periods. The narrow band Langmuir waves appear to be very common and are observed on nearly every auroral zone pass in which precipitating electrons are observed.

Introduction

The Freja HF plasma wave receiver has made the first in situ waveform measurements of Langmuir waves in the earth's ionosphere. These Langmuir waves appear to be common, are large amplitude (frequently several hundred mV/m), and are likely short wavelength (a few tens of meters or less) in order to be in resonance with auroral electrons. The waveforms are also frequently narrow band ($\Delta f/f \lesssim 10^{-2}$) and exhibit a variety of modulational features. Occasionally very large amplitude waves are observed ($\gtrsim 1$ V/m) whose spectra are broader ($\Delta f/f \gtrsim 20\%$) and appear to be composed of wave packets lasting only 5-10 periods. During these times, $\varepsilon_0 E^2/2nkT \cong 10^{-2}$.

Langmuir waves are the subject of every first year plasma physics text and have long been suspected to exist in the presence of auroral electron precipitation. Nonetheless these waves have mostly escaped detection in the auroral ionosphere with some important exceptions. Within the ionosphere the auroral electron beam can develop a bump-on-tail instability which should excite Langmuir waves. From the quasilinear viewpoint this process may be short lived since the waves quickly modify the electron beam to form a plateau. This hypothesis has been supported by auroral electron measurements which do not display a peak in velocity space [*Kaufmann et al.*, 1978]. On the other hand strong turbulence theories predict that the initial Langmuir wave energy will transfer to low frequency modes no longer resonant with the electron beam [*Papadopoulos and Coffey*, 1974; *Papadopoulos*, 1977; *Rowland et al.*, 1981] and the electrons will continue to propagate as a beam. Strong turbulence is predicted to occur when $\varepsilon_0 E^2/2nkT \gtrsim 10^{-1}$. Alternatively, in weak Langmuir turbulence waveforms may be modulated by growth in a nonuniform or clumpy plasma [*Robinson et al.*, 1993; *Muschietti et al.*, 1993] or they may be limited in amplitude by three wave interactions and the presence of backscattered electrons [*Newman et al.*, 1994*a*].

Within the ionosphere and auroral electron precipitation, Langmuir waves have only been detected on a few sounding rocket experiments and one satellite. The sounding rocket measurements suggest a range of characteristics from large amplitude (> 500 mV/m) but transient (≤ 1 ms) Langmuir waves to lower amplitude (few mV/m) but longer lived (few seconds) Langmuir waves [*Boehm et al.*, 1984; *Kellogg et al.*, 1984; *McFadden et al.*, 1986]. When auroral electron measurements were available, they typically indicated transient and dispersed auroral electron events over the energy range of a few hundred eV to a few keV. *Ergun et al.* [1991*a*] have suggested that rapid modulation of the Langmuir wave amplitude is consistent with a transverse modulational instability resonant with lower hybrid or ion Bernstein waves. Recently, *Newman et al.* [1994*a*] have suggested that sounding rocket results are consistent with a three wave decay process into ion acoustic waves. Common to all the sounding rocket measurements were short antenna lengths of a few to several meters suggesting that the longer antennas used on many spacecraft were insensitive to these waves. The wavelength of the Langmuir waves was inferred to be $\cong 15$ m by comparing the wave frequency to the velocity of resonant electrons [*Ergun et al.*, 1991*b*].

The only satellite measurements of Langmuir waves in the auroral ionosphere are from the Aureol/Arcad spacecraft. Over the altitude range of 400-2000 km and at frequencies of up to 2 MHz, the HF plasma wave instrument frequently observed Langmuir waves with amplitudes of roughly 50 mV/m p-p [*Beghin et al.*, 1989]. Occurrence rates varied between 25% and 80% depending on where the spacecraft was located at high latitudes. The HF instrument employed a 40 cm antenna and a sweep frequency receiver which limited the instrumental time resolution to 160 ms.

In this letter we present the first results from the Freja HF plasma wave receiver. This instrument was designed to advance our knowledge of auroral Langmuir waves by measuring short wavelength, transient HF waves. In particular, waveform measurements in the form of snapshots were acquired to study the fine structure of wave emissions.

Instrument Description

The Freja high frequency (HF) receiver is composed of an antenna preamplifier system, gain, an 8-bit analog to digital

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converter operating at 8 Msample/s, 8 kbytes of memory for temporary storage of the digital signal, and a wide band filter and power detector for determining the overall power in the HF frequency range. The receiver can use two separate antennas, each of which contains spherical sensors with preamplifiers in a dipole configuration. The primary antenna is 1.2 m long with preamplifiers that only operate in a high impedance mode up to 4 MHz. This antenna is designed to investigate short wavelength waves. The alternate antenna is 21 m long with dual use (high or low impedance preamplifiers) that operate up to 1 MHz. The preamplifiers from either antenna are combined in a differential amplifier and then a gain of either 2.82 or 133 is applied with a one-pole 50 kHz high pass filter for the short antenna. We only present data from the 1.2 meter antenna.

From this point the signal is split into two paths. The low data rate path goes into a filter-detector which yields a single analog output proportional to the power in the bandpass. This analog output is then used for triggering burst data in the F4 instrument as well as other Freja instruments and for tagging the data quality in the 8 ksample memory.

The high data rate path goes to an 8-bit analog to digital converter operating at 8 Msample/s. The digital output is stored temporarily in an 8 kbyte memory in snapshots of 8, 4, 2, or 1 kbyte which holds approximately 1, 0.5, 0.25 or 0.125 ms of data, respectively. After a snapshot (8, 4, 2, or 1 kbyte) of data is acquired the data is transferred to the main memory in the plasma wave receiver and tagged with a single byte from the filter-detector. By comparing the filter-detector bytes proportional to the power in a data snapshot, the waveform or snapshot with the most power in any 8, 4, 2, or 1 sec interval is selected for the telemetry stream.

The electric field amplitudes to be presented in Figures 2, 4, and 5 are derived from the electric difference potential at the input of two preamplifiers. However, the correct amplitude of the observed HF waves is determined by noting the coupling of each spherical sensor to the surrounding plasma compared to the coupling of the sensor to the preamplifier. At these frequencies the coupling impedance is capacitive and the preamplifier sensor-plasma network can be modeled as two series capacitors.

Assuming the sphere to plasma capacitance to be that of free space yields a correction factor of 8.7, thereby implying that the wave electric fields are larger by this factor than the detected electric fields. In the figures presented hereafter, the correction factor of 8.7 has been included in calculating amplitudes.

Data Presentation

Before examining some HF waveforms we first consider the possible plasma wave modes. Since the ionosphere is dense ($\cong 10^3$ cm^{-3}) when Freja is in the northern auroral zone we expect that most plasma wave modes can be modeled using a Maxwellian plasma and that any nonthermal plasma feature (e.g. electron beams) represents a small perturbation on this model. Given the existence of denser beams, plasma inhomogeneities and non-Maxwellian plasmas, a large variety of other plasma wave modes are possible. Nonetheless, we choose to begin with a model of minimal complexity.

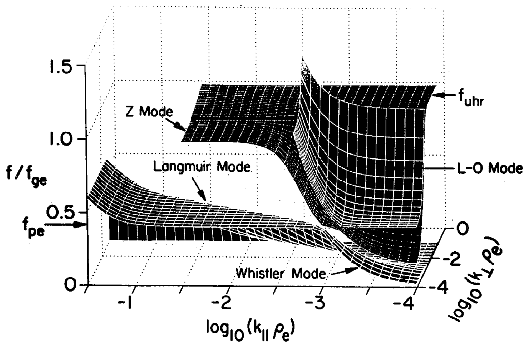

Figure 1. Solutions to the dispersion relationship for a homogeneous, magnetized, Maxwellian plasma with a temperature of 1 eV. Three different solutions (surfaces) are plotted as functions of f/f_{ge}, $k_{\|}\rho_e$, and $k_{\perp}\rho_e$. See text.

The plasma wave modes for frequencies near the electron gyro and plasma frequency and for $T_e = 1$ eV, $n_e = 10^3$ cm^{-3} are shown in Figure 1. This figure assumes homogeneous Maxwellian particle distributions and the surfaces of $D(\omega, k_{\|}, k_{\perp}) = 0$ were developed using the WHAMP code [*Rönmark*, 1981; *André*, 1985]. Typical values for the Freja orbit in the auroral zone are $f_{ge} \cong$ 700-800 kHz and $f_{pe} \cong$ 300 kHz. In Figure 1 three surfaces are displayed in the coordinate system: f/f_{ge}, $k_{\|}\rho_e$, and $k_{\perp}\rho_e$. The uppermost surface, labeled the L-O mode, is the solution of $D(\omega, k_{\|}, k_{\perp}) = 0$ which connects to light waves at large frequencies and has a cut-off at the plasma frequency for small $\mathbf{k}$ ($k_{\|}\rho_e \cong k_{\perp}\rho_e \cong 10^{-4}$). The lowest surface, labeled Langmuir mode and whistler mode, is the solution to $D(\omega, k_{\|}, k_{\perp}) = 0$ which contains Langmuir waves and whistler waves for $k_{\|} \gg k_{\perp}$ and lower hybrid waves (or electrostatic whistler waves) for $k_{\|} \ll k_{\perp}$.

For the case $k_{\|} \gg k_{\perp}$ and $k_{\|}\rho_e \gtrsim 10^{-1}$ the Langmuir mode becomes damped and changes frequency because the phase velocity is approaching the electron thermal velocity from above. In between these two surfaces is a third surface. For $k_{\|} \gg k_{\perp}$ this surface corresponds to the z-mode and it has a resonance at f_{ge}, a short plateau at f_{pe} near $k_{\|}\rho_e = 10^{-3}$ (where the three surfaces nearly make contact), and then a cut-off at $f < f_{pe}$ for $k_{\|}\rho_e = 10^{-4}$. For $k_{\|} \ll k_{\perp}$ this surface corresponds to the upper hybrid mode. Not shown in Figure 1 is the R-X mode which is contained within the concave L-O surface and electron Bernstein modes which exist near $k_{\perp}\rho_e = 1$. One of the electron Bernstein modes connects to the surface labeled f_{uhr}.

In Figure 2 is an example of one common snapshot taken at about 1700 km altitude, 12.3 MLT, and 72° invariant latitude during orbit 5238. The upper panel shows the waveform of a nearly monochromatic sinusoidal signal slowly varying in

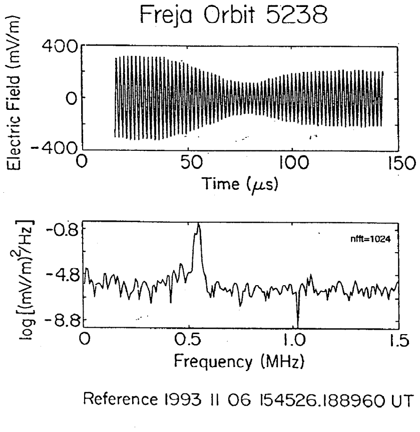

Figure 2. An example of narrow band Langmuir waves. The upper panel contains the waveform and the lower panel contains the power spectrum.

amplitude with a maximum amplitude of about 600 mV/m p-p. The power spectrum of this signal has a single peak near 550 kHz which is very narrow band. The 3 dB points lie in a single frequency bin of 8 kHz width. This spectral signature is very common although the amplitude is close to the upper limit at which this spectral signature can be found. Because the frequency of the spectral peak is below the electron gyrofrequency and because the snapshot was acquired within a region of precipitating auroral electrons, this suggests that the waveform corresponds to a Langmuir wave and 550 kHz corresponds to an electron density of 3.76×10^3 cm^{-3}.

To confirm this suggestion the frequency of these narrow band waveforms was compared to Langmuir probe currents. These theories predict that Langmuir probe currents should be proportional to electron density. So that, if these narrow band waves are in fact Langmuir waves, the Langmuir probe current should be proportional to the square of the wave frequency. Figure 3 shows this comparison. The current from one of the spherical probes (P6) in eclipse is plotted as a function of electron density derived from assuming that the narrow band waves are Langmuir waves. The data has not been corrected for any spin-related effects yet it clearly shows a linear relationship. A least squares fit of probe current as a function of n_e ($n_e = (f_{pe}/8.98\times10^3)^2$) on this log-log plot yields the probe current being proportional to $n_e^{0.96}$. Hence, we conclude that the waves in Figure 2 are in fact Langmuir waves.

We now turn to another kind of emission commonly present in the snapshots. Figure 4 illustrates an example of waveform acquired at about 1760 km altitude, MLT 19.9, and 65.8 invariant latitude during orbit 4862. This waveform also has large amplitudes, about 400 mV/m p-p and exhibits more time variation than the example in Figure 2. The power spectrum in the lower panel gradually increases with frequency to about 500 kHz and then drops by 10^5 in power. This is an example of waves existing at and below the Langmuir frequency. Since waves in both the Langmuir mode and the oblique Langmuir mode (or quasistatic whistler mode) are unstable to auroral electron beams, this appears to be an example of the Langmuir surface in Figure 1 where waves with $k_\perp \cong k_\parallel$ were excited. The cut-off near 500 kHz then corresponds to the Langmuir frequency. *Maggs and Lotko* [1981] has previously pointed out that these waves have oblique group velocities. Since auroral electron beams are confined to magnetic field lines, waves with oblique group velocities are convectively stable. If our interpretation is correct, this implies that the auroral beam-ionosphere environment is absolutely unstable.

Finally, we turn to a snapshot example which contains waveform amplitudes among the largest we have investigated. Figure 5 is a snapshot acquired at about 1650 km altitude 12.0 MLT, and 74° invariant latitude, during orbit 5238. The waveform in this example had an amplitude of 2 V/m p-p. The power spectrum was not narrow band and exhibited a broad peak near 400 kHz with smaller amplitude peaks at larger and smaller frequencies. Close examination of this waveform reveals discontinuities in the wave phase at about 35 μs, 48 μs, 70 μs, 105 μs, and 125 μs. These jumps in phase, roughly every 5-10 wave periods, produce the broadening of the spectral peak at 400 kHz and suggest that the waveform is composed of discrete wave packets, each 5-10 wave periods long.

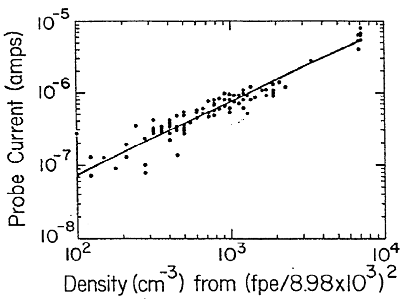

Figure 3. Langmuir probe current as a function of electron density computed from $(f_{pe}/8.98\times10^3)^2$.

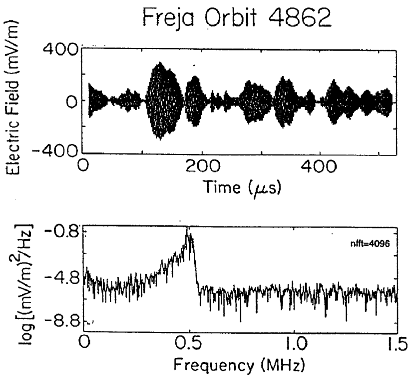

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Figure 4. An example of whistler mode or quasistatic whistler mode emissions. The upper panel contains the waveform and the lower panel contains the power spectrum.

During orbit 5238 about a dozen snapshots were acquired with the features in Figure 5. The largest waveform amplitude was 2.5 V/m p-p. Papadopoulos (personal communication, 1994) has suggested that the broad power spectrum is a feature of strong turbulence and wave packet collapse. The corresponding ratio of electric field energy density to thermal plasma density ($\varepsilon_0 E^2/2nkT$) was the order of 10^{-2}, although there is substantial error in this calculation from our ignorance of electron density and temperature during this period.

Summary and Conclusions

This letter presents examples of Langmuir waveforms in the auroral ionosphere near 1700 km altitude. Typically, waveform snapshots with amplitudes of several mV/m to several hundred mV/m were acquired nearly continuously in the auroral

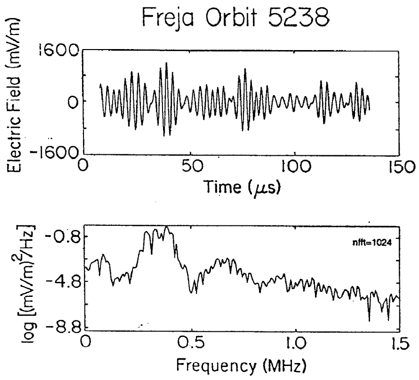

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Figure 5. Large amplitude waves associated with the Langmuir frequency.

zone. The waves are frequently narrow band. That is, the width of the spectral peak at the Langmuir frequency is much less than the frequency of the peak, $\delta f/f \lesssim 10^{-2}$. Assuming that the observed wave frequency corresponds to the Langmuir frequency in the generation region, this implies that observed waves originate in a narrow range of densities, $\Delta n_e/n_e < 0.5 \times 10^{-2}$. For a plasma scale height of 500 km, this yields a generation length of 2.5 km along a magnetic field line.

One disadvantage of a snapshot receiver is that wave activity cannot be evaluated between snapshots. Unfortunately the packing factor of Langmuir waves is critical to understanding the effect of these waves on the ionosphere. We note that Langmuir waves which are generated by auroral electrons and escape the generation region are weakly damped in a 1 eV ionosphere. As the Langmuir waves propagate into regions of larger or smaller electron density, the wave mode will change to maintain a constant frequency and will be primarily confined to a single dispersion surface as shown in Figure 1. For Langmuir waves which propagate onto the whistler mode (or oblique Langmuir mode or the quasistatic whistler mode) they may be able to propagate into the lower ionosphere. However, waves which refract toward smaller $k_{\|}\rho_e$ will damp on the thermal electron tail producing electron heating in the upper ionosphere. Roughly speaking the waves which propagate upward and into smaller electron densities will lose their energy to the thermal electron population. In this case Langmuir waves are a potential pathway for auroral electrons to heat the upper ionosphere. To evaluate the significance of this pathway, the packing factor of Langmuir waves must first be determined.

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J. Bonnell, Department of Electrical Engineering, 353 E & TC, Cornell University, Ithaca, NY 14853.

B. Holback, Swedish Institute of Space Physics, Uppsala Division, S-755 91, Uppsala, Sweden.

P. M. Kintner, Department of Electrical Engineering, 302 E & TC, Cornell University, Ithaca, NY 14853.

S. Powell, Department of Electrical Engineering, 321 E & TC, Cornell University, Ithaca, NY 14853.

J.-E. Wahlund, Department of Electrical Engineering, 306 E & TC, Cornell University, Ithaca, NY 14853.

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