The Farley-Buneman Spectrum in 2-D and 3-D Kinetic Simulations

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Since the 1960s, the Farley-Buneman instability, also known as the modified two-stream instability, has played in an important role in probing the E-region ionosphere. The intervening years have seen significant progress in the linear theory of this instability, its relation to other instabilities, and some of its observational signatures. However, the saturation mechanism and nonlinear behavior remain important open topics because of their role in controlling energy flow in the E-region plasma.

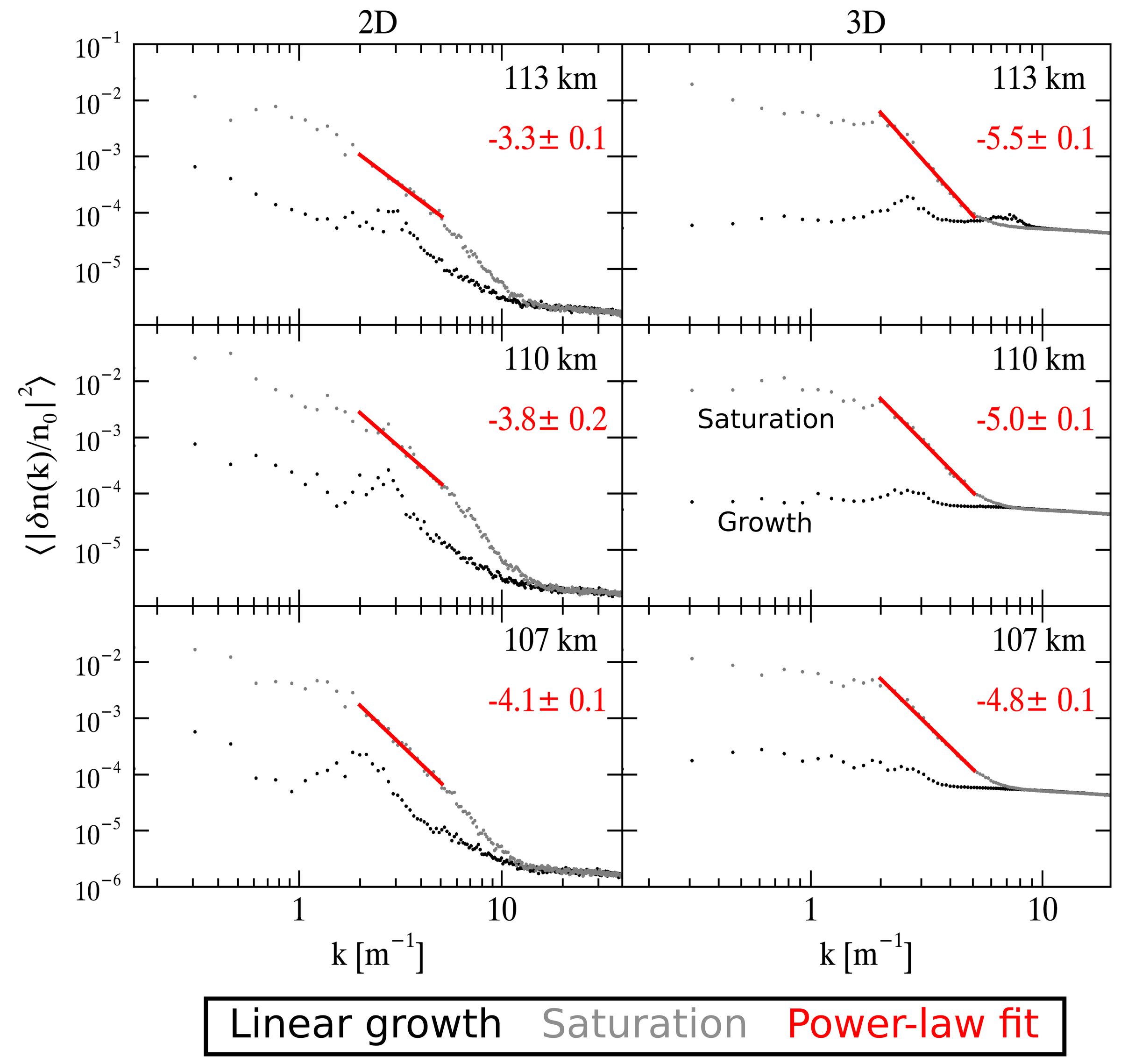
This work explores the nonlinearly saturated state of the Farley-Buneman instability in 2-D and 3-D fully kinetic simulations of the high latitude ionosphere, at three different simulated altitudes: 107, 110, and 113 km. Simulated irregularity amplitude exhibits growth and saturation stages in all runs, but 2-D and 3-D runs exhibit qualitative and quantitative differences. Irregularity growth takes much longer in 2-D than in 3-D. Wave power in the meter-scale regime falls off as a power law at and below the wavelength of peak growth, but the power-law index is larger in 3-D than in 2-D. At longer wavelengths, the 3-D spectrum is much flatter than the 2-D spectrum. This implies that purely 2-D simulations of the Farley-Buneman instability may over-estimate irregularity amplitudes at decameter scales, and may also under-estimate the efficiency of ion Landau damping at the ion mean-free-path scale. From a physical perspective, the relatively flat spectra above the wavelength of peak growth in 3-D simulations imply a wavelength-independent saturation mechanism across a range of altitudes. Finally, both 2-D and 3-D simulations predict that the flow angle of density irregularities should be at least as large at the deviation of relative drift from $\mathbf{E}_0 \times \mathbf{B}_0$ at all altitudes.

Physical Background

The Farley-Buneman instability occurs in a plasma with magnetized electrons and unmagnetized ions. When the electrons stream through the ions quickly enough, the kinetic energy that they impart to the ions via electrostatic fields is great enough to overcome pressure in density perturbations, causing the perturbations to grow.

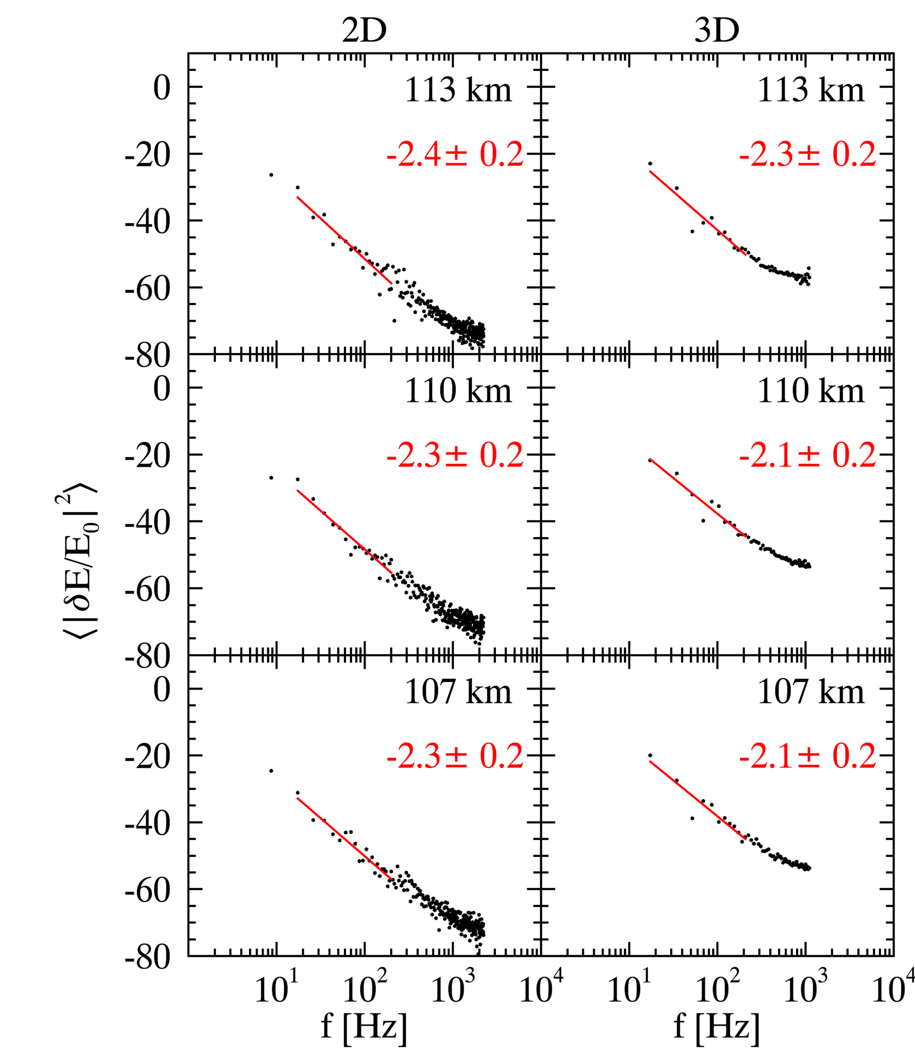
Linear theory predicts that the instability will occur when the driving electric field exceeds a threshold value. That value is roughly 20 mV/m in the auroral zone. Linear theory also predicts that speed and growth rate will change with altitude due to changing neutral density, and that irregularities will flow in the direction of electron-ion relative drift.

Density Spectra

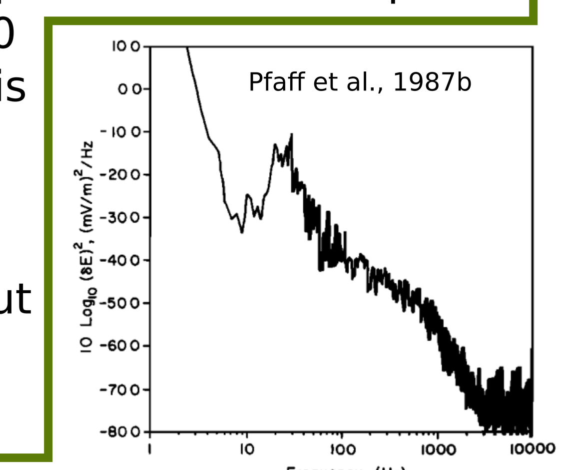


All runs exhibit initial growth at a few meters but the peak is broader and higher in 2-D than in 3-D. Increased long-wavelength growth characterizes all saturated stages. 3-D saturated spectra are nearly flat.

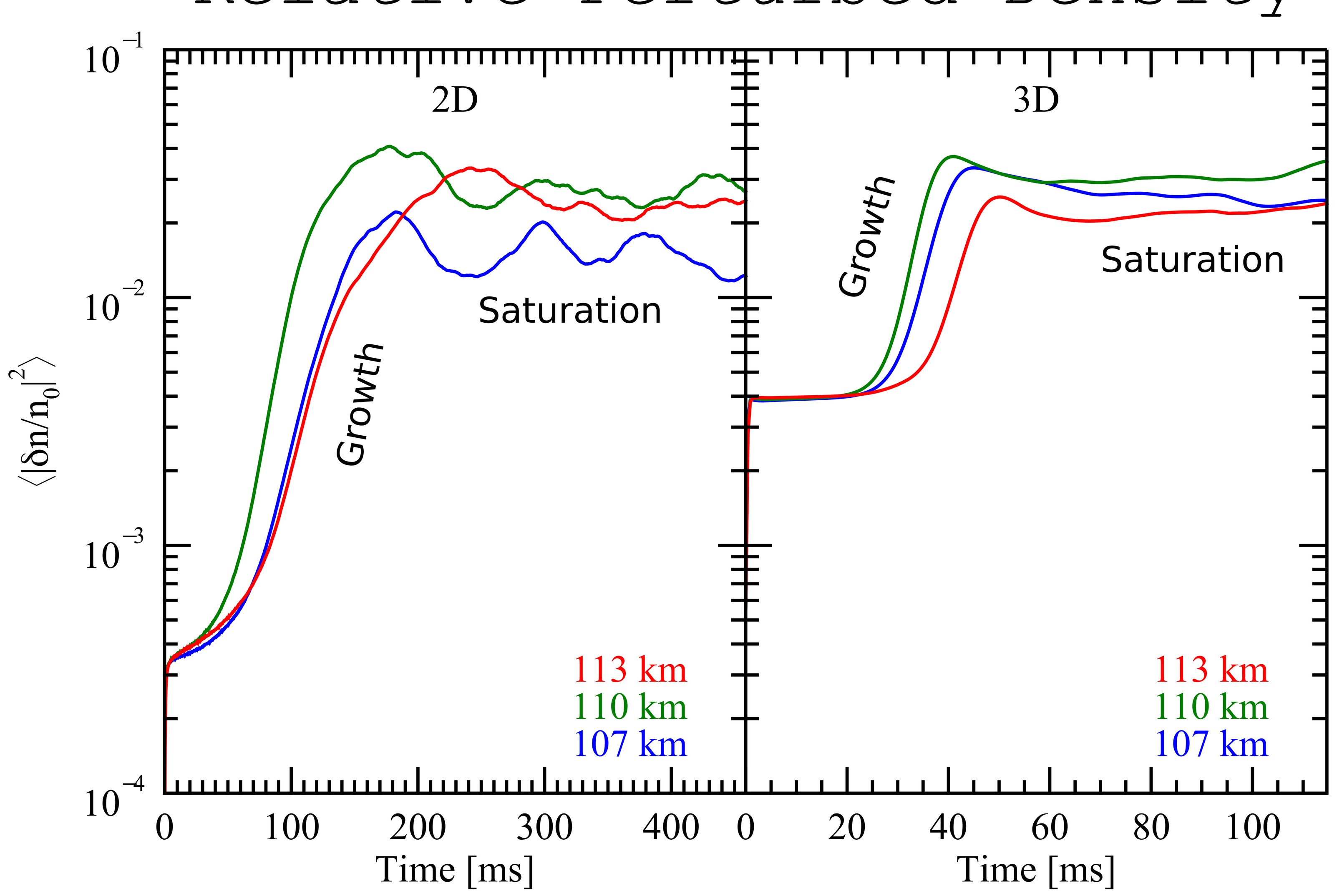
E-Field Spectra



Electric field from a simulated 5.5-m boom shows a power law with slope ≈ -2 in the 20-200 Hz range. This is shallower than the slope in Condor observations but values are similar



Relative Perturbed Density

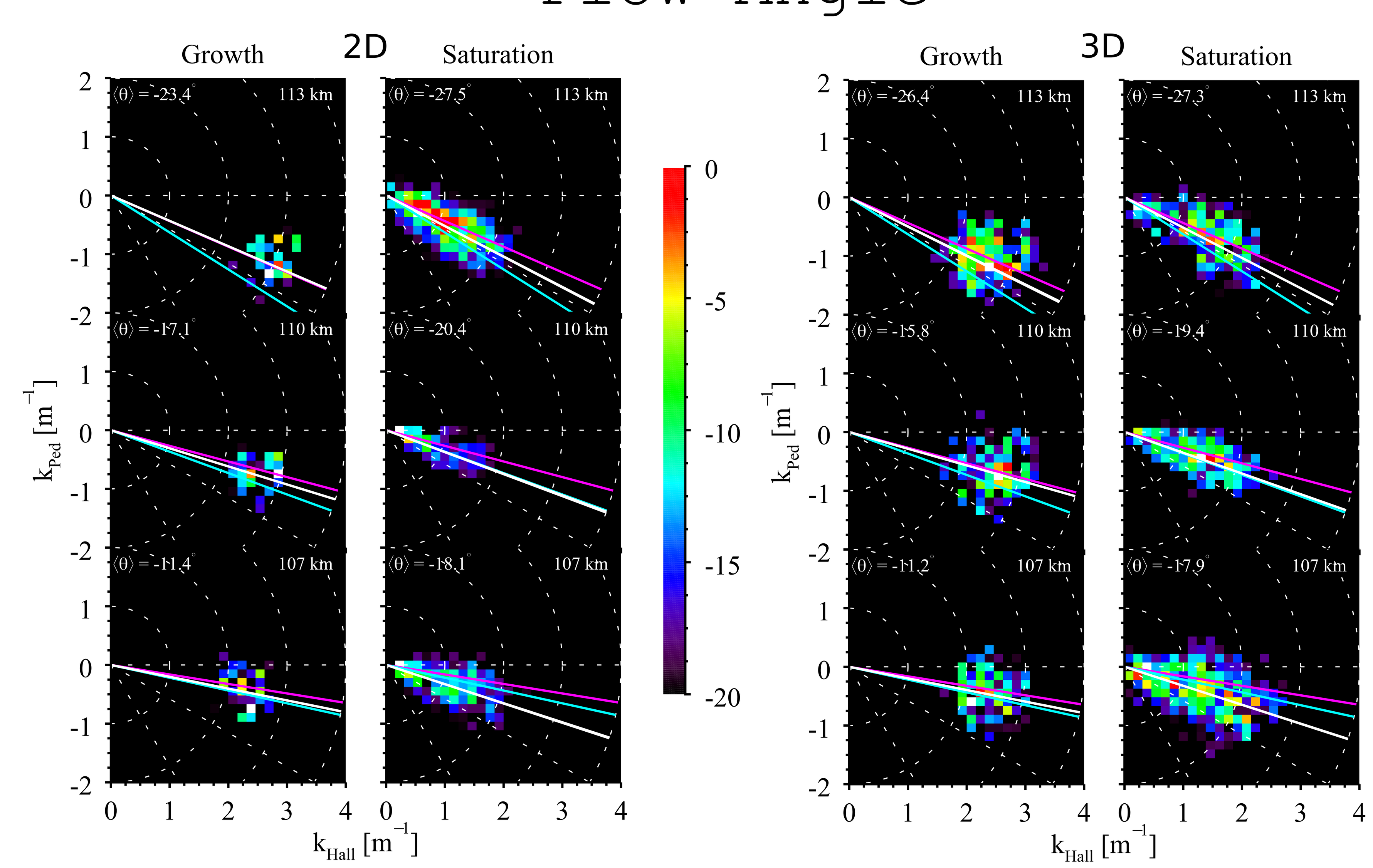


All runs exhibit a growth stage followed by a saturation stage. The saturated amplitude is approximately the same for all runs, at all altitudes. This implies an altitude-independent saturation mechanism. Saturated values of squared RMS amplitude (shown) correspond to perturbed densities 10-15% of background.

Oscillations in 2-D perturbed density correlate with oscillations in temperature. Neither density nor temperature show significant oscillations in 3-D runs.

2-D runs take much longer to saturate than do 3-D runs. The dimension parallel to the magnetic field provides additional modes into which the instability couples energy.

Flow Angle



Magenta: Direction of electron-ion relative drift.
Cyan: Predicted direction of ion thermal instability.
White: Direction of density irregularity flow.

Flow angle approaches the drift velocity angle as altitude increases from 107-113 km.

Flow angle differs by at most a few degrees between 2-D and 3-D runs.

Deviations from the angle of relative drift likely arise from the ion thermal instability, especially at 110 km.

Summary

1) Density perturbations saturate at a similar value across all altitudes in 2-D and 3-D.
2) 3-D simulations saturate more quickly, due to the availability of parallel modes.
3) Density perturbations grow at a few meters in all runs but the shape of the spectrum differs between 2-D and 3-D, especially at decameter wavelengths.
4) Saturated 3-D density spectra are flat above the wavelength of peak growth and fall off sharply below it.
5) Simulated rocket electric field spectra exhibit power-law slopes in the 20-200 Hz range.
6) Density irregularity flow angle is always at least as large as the angle of relative drift.
7) Thermal effects may cause increased deviation at lower altitudes.