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Full-Scale Numerical Modeling of Turbulent Processes in the Earth’s Ionosphere

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Outline

A. Full-Scale simulations, new tool to study the Earth’s Ionosphere

B. Nonlinear radio wave propagation and induced turbulence

C. Numerical nested grid method to resolve different length scales

D. Summary
Project "Numerical Modeling of the Earth’s Ionosphere"

- 4-year project financed by the Swedish Research Council
- Building a dynamic model of the Earth’s ionosphere – Interaction with electromagnetic radiation/fields
- Application to radio communication, radio telescopes and heating facilities (HAARP, EISCAT, etc.)
- Development of simulation codes and implement them on parallel computers and clusters
Full-scale ionospheric modeling

www.physics.irfu.se
Appleton-Hartree model

\[
\frac{\partial \mathbf{B}_1}{\partial t} = -\nabla \times \mathbf{E}
\]

\[
\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B}_1 + \frac{e n_0(r)}{\epsilon_0} \mathbf{v}_e
\]

\[
\frac{\partial \mathbf{v}_e}{\partial t} = -\frac{e}{m_e} (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}_0)
\]

Eliasson & Thidé, GRL 34, L06106 (2007).
Ionospheric profile, $f_{ce} \approx 1.4$ MHz, $f_0 = 5$ MHz ($\lambda = 60$ m)
Pulse width: $\sim 100 \mu$s ($\sim 500$ wavelengths)
$B_0$: $\theta = 13^\circ$ (Tromsø) Eliasson & Thidé, GRL 34, L06106 (2007).
t=0.886 milliseconds

Eliasson & Thidé, GRL 34, L06106 (2007).
Closeup at t=0.886 milliseconds

Eliasson & Thidé, GRL 34, L06106 (2007).
Closeup at $t=0.948$ milliseconds

Eliasson & Thidé, GRL 34, L06106 (2007).
Parametric processes in the ionosphere

- Three-wave parametric decay instability (Electromagnetic wave $\rightarrow$ Langmuir wave + Ion Acoustic wave)

- Langmuir wave collapse (4-wave decay) and small-scale cavity formation

- Generation of Z mode waves
Nonlinear model

- High-frequency electromagnetic waves (several MHz)
- High-frequency electrostatic (Langmuir) waves
- Low-frequency ion-acoustic waves (few kHz)

Coupled nonlinearly via ponderomotive force and slow density fluctuations.
Generalized Zakharov model

\[
\frac{\partial \tilde{E}_z}{\partial t} = i\omega_0 \tilde{E}_z + \frac{en_s \tilde{v}_{ez}}{\varepsilon_0}
\]

(1)

\[
\frac{\partial \tilde{A}_\perp}{\partial t} = i\omega_0 \tilde{A}_\perp - \tilde{E}_\perp
\]

(2)

\[
\frac{\partial \tilde{E}_\perp}{\partial t} = i\omega_0 \tilde{E}_\perp - c^2 \frac{\partial^2 \tilde{A}_\perp}{\partial z^2} + \frac{en_s \tilde{v}_{e\perp}}{\varepsilon_0}
\]

(3)

\[
\frac{\partial \tilde{n}_e}{\partial t} = i\omega_0 \tilde{n}_e - \frac{\partial (n_s \tilde{v}_{ez})}{\partial z}
\]

(4)

\[
\frac{\partial \tilde{v}_e}{\partial t} = i\omega_0 \tilde{v}_e - \frac{e}{m_e} \left[ \hat{z} \tilde{E}_z + \tilde{E}_\perp + \tilde{v}_e \times \mathbf{B}_0 \right] - \hat{z} \frac{3v^2_{Te}}{n_0} \frac{\partial \tilde{n}_e}{\partial z} - \nu_e \star \tilde{v}_e
\]

(5)

\[
\frac{\partial^2 n_s}{\partial t^2} + 2\nu_s \frac{\partial n_s}{\partial t} - C_s^2 \frac{\partial^2 n_s}{\partial z^2} = \frac{\varepsilon_0}{4m_i} \frac{\partial^2 (|\tilde{E}_\perp| + |\tilde{E}_z|^2)}{\partial z^2}
\]

(6)

Eliasson & Stenflo, JGR 113, A02305 (2008)
Landau damping

Ion Landau damping

\[ \hat{\nu}_s(k_z) \hat{n}_s = C_s \left( \frac{T_e}{T_i} \right)^{3/2} \exp \left( - \frac{T_e}{2T_i} \right) \sqrt{\frac{8}{\pi}} |k_z| \hat{n}_s \]  

(7)

\[ \nu_s \ast n_s = -C_s \left( \frac{T_e}{T_i} \right)^{3/2} \exp \left( - \frac{T_e}{2T_i} \right) \sqrt{\frac{8}{\pi}} \int_0^\infty \frac{n_s(z + \xi) - 2n_s(z) + n_s(z - \xi)}{\xi^2} d\xi \]  

(8)

Electron Landau damping

\[ \hat{\nu}_e(k_z) \hat{v}_{ez} = \left( \frac{\pi}{8} \right)^{1/2} \frac{\omega_{pe}}{|k_z \lambda_{De}|^3} \exp \left[ - \frac{1}{2(k_z \lambda_{De})^2} \right] \hat{v}_{ez} \]  

(9)

Simplified: \[ \hat{\nu}_e(k_z) \hat{v}_{ez} \approx 0.5 \omega_{pe} (\lambda_{De} k_z)^2 \hat{v}_{ez} \]  

(10)

\[ \nu_e \ast v_{ez} \approx -0.5 \omega_{pe} \lambda_{De}^2 \frac{\partial^2 v_{ez}}{\partial z^2} \]  

(11)

(Work in progress ...)

(Work in progress ...).
Simulation result

Eliasson & Stenflo, JGR 113, A02305 (2008)
Simulation result (closeup)

Eliasson & Stenflo, JGR 113, A02305 (2008)
Simulation result (closeup)

Eliasson & Stenflo, JGR 113, A02305 (2008)
Different length scales, nested grid method

Electromagnetic wave

Length scale: ~ 100 m

Electrostatic (plasma) wave

Length scale: ~ 0.1-1 m

Courant condition $\Delta t < \Delta z / c$. $\Delta z = 2$ m, Locally $\delta z = 2$ cm
Case study: Simulation of topside turbulence

Eliasson, GRL 35, L11104 (2008)
Simulation of topside turbulence (continued)

Eliasson, GRL 35, L11104 (2008)
Summary

A. 4-year project on ionospheric simulations.

B. Full-scale ionospheric simulations a new tool to study realistic scenarios.

C. Nested grid method to resolve different length scales.

D. Parametric instabilities, turbulence induced by electromagnetic waves.