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

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

ICTP, Trieste, Italy, 14–25 July 2008

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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

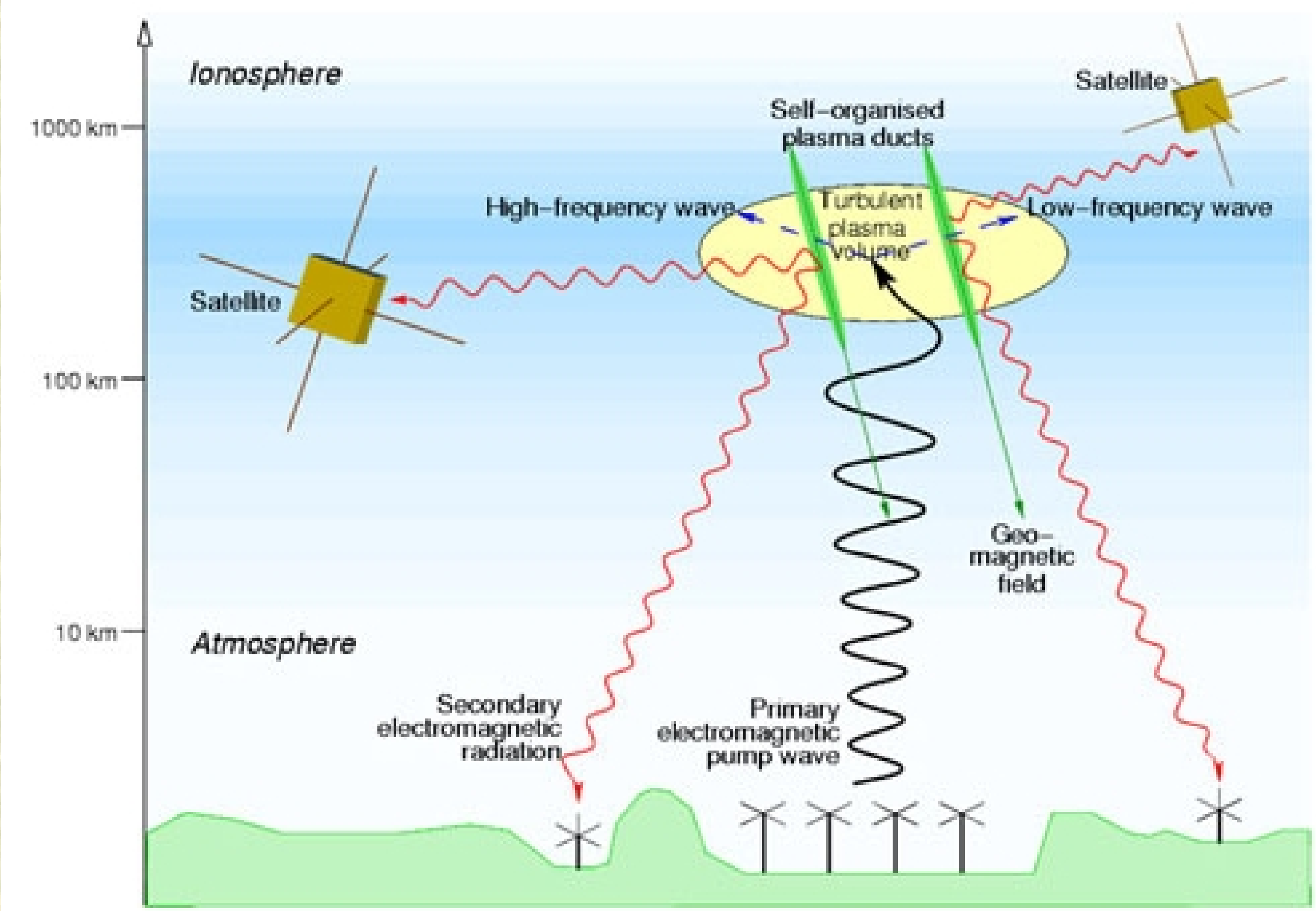
C. Numerical nested grid method to resolve different length scales

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



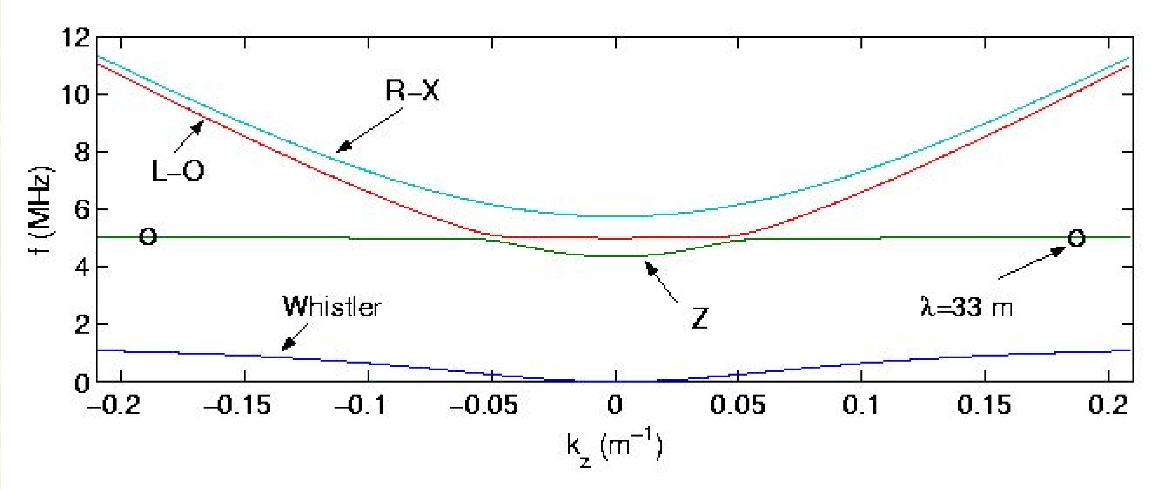
www.physics.irfu.se

Appleton-Hartree model

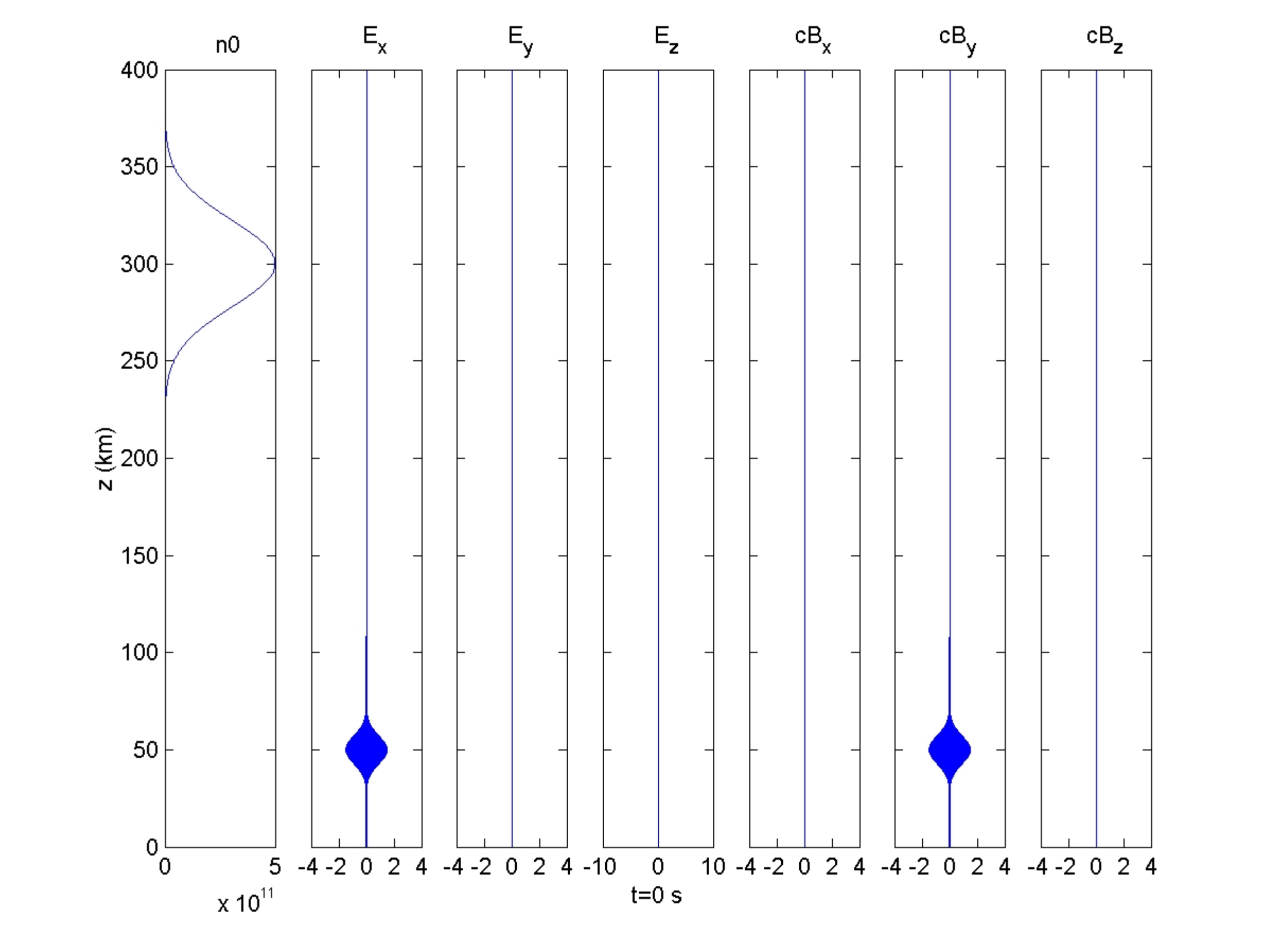
$$\frac{\partial \mathbf{B}_1}{\partial t} = -\nabla \times \mathbf{E}$$

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

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

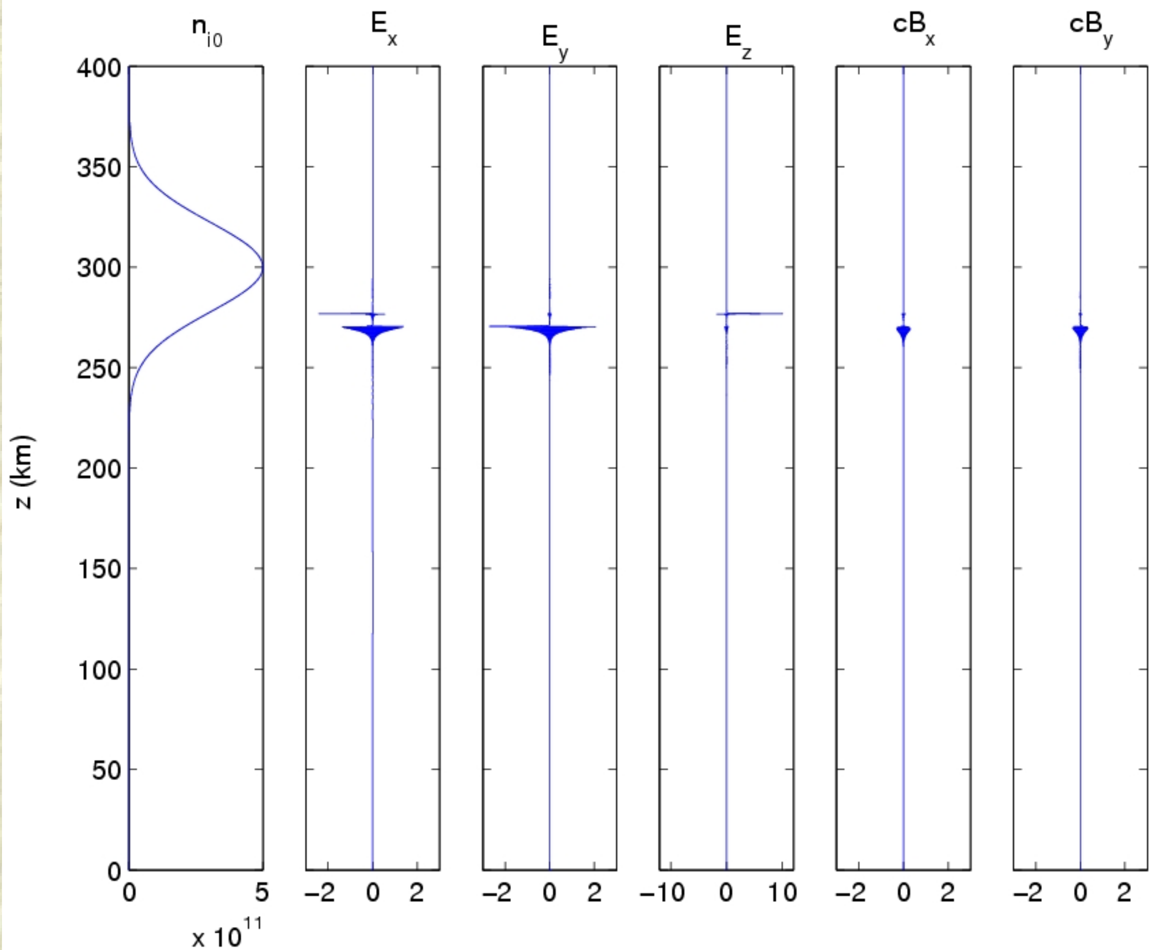


Eliasson & Thidé, GRL **34**, L06106 (2007).



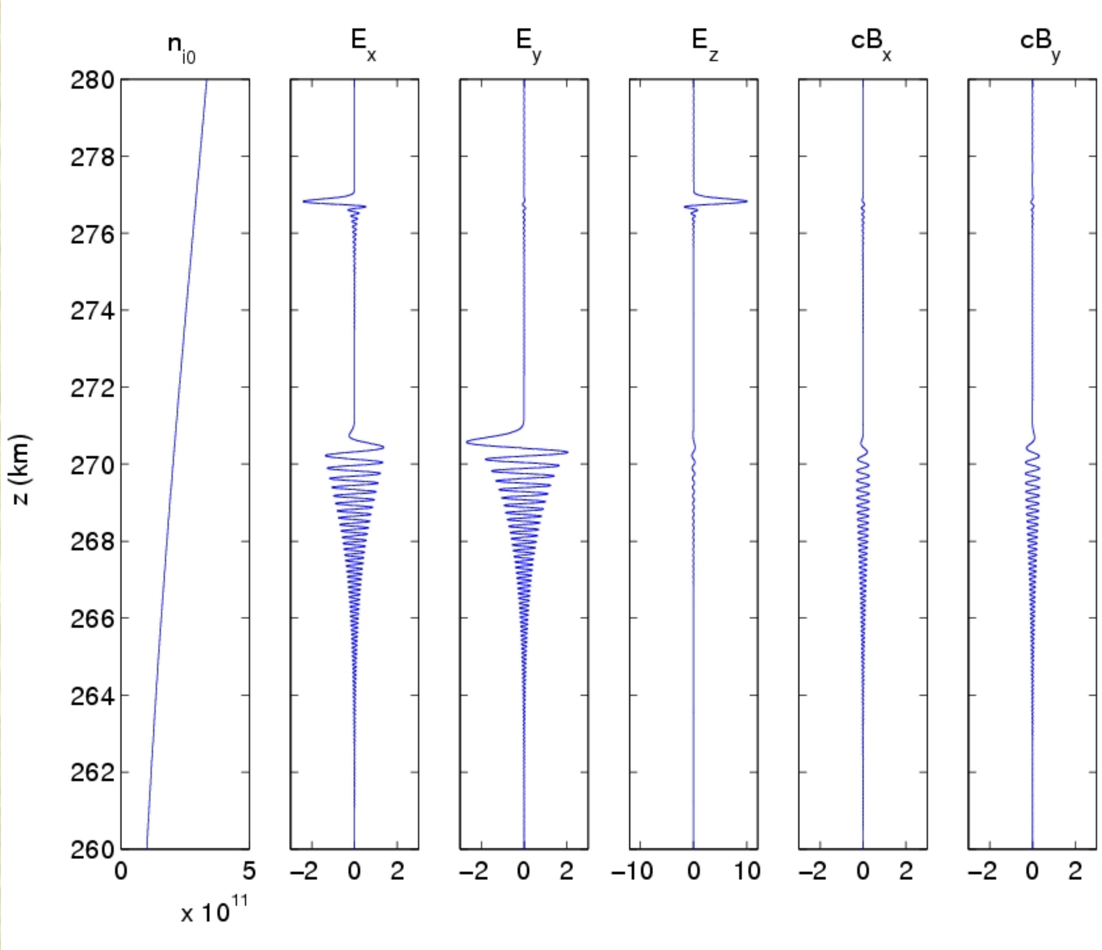
Ionospheric profile, $f_{ce} \approx 1.4$ MHz, $f_0 = 5$ MHz ($\lambda = 60$ m)
Pulse width: $\sim 100\,\mu$s (~ 500 wavelengths)
$\mathbf{B}_0$: $\theta = 13^\circ$ (Tromsø) Eliasson & Thidé, GRL **34**, L06106 (2007).

t=0.886 milliseconds



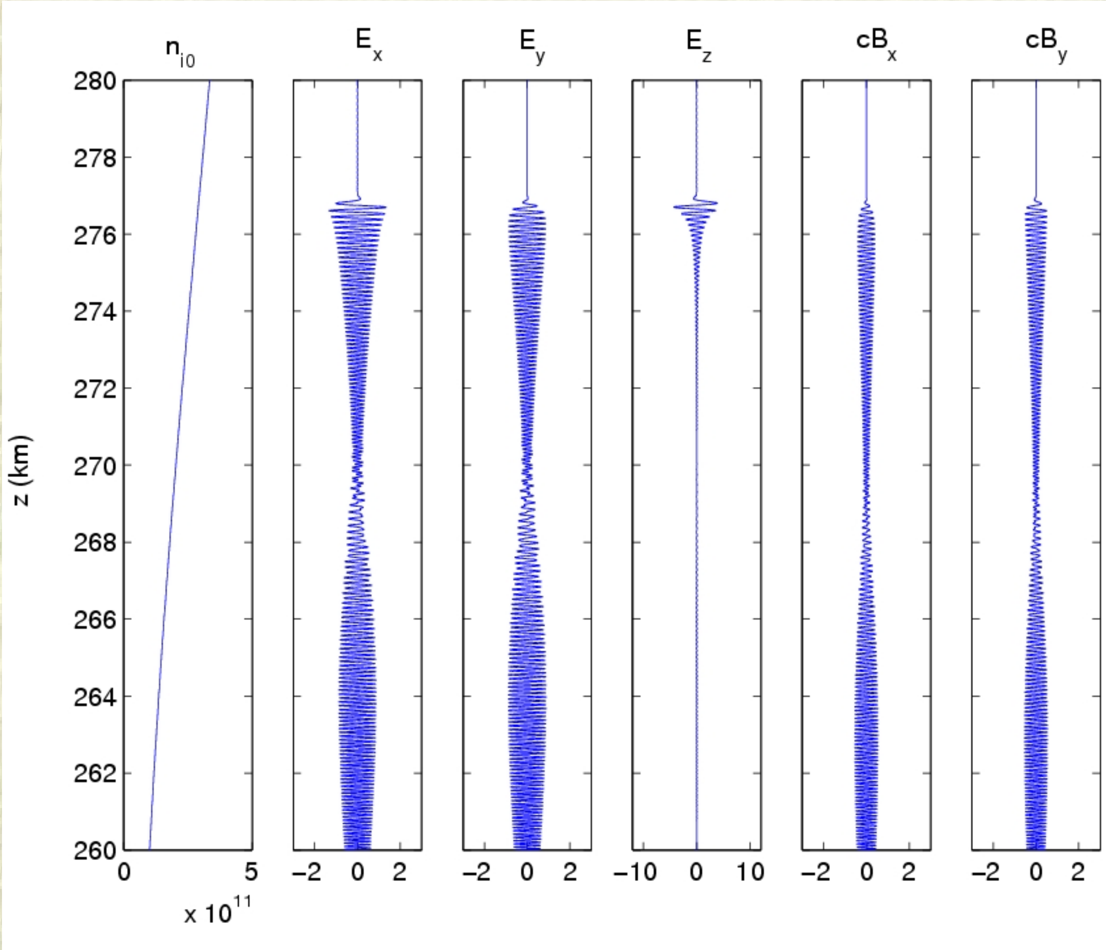
Eliasson & Thidé, GRL **34**, L06106 (2007).

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

$$\frac{\partial \widetilde{E}_z}{\partial t} = i\omega_0 \widetilde{E}_z + \frac{e n_s \widetilde{v}_{ez}}{\varepsilon_0} \quad (1)$$

$$\frac{\partial \widetilde{\mathbf{A}}_\perp}{\partial t} = i\omega_0 \widetilde{\mathbf{A}}_\perp - \widetilde{\mathbf{E}}_\perp \quad (2)$$

$$\frac{\partial \widetilde{\mathbf{E}}_\perp}{\partial t} = i\omega_0 \widetilde{\mathbf{E}}_\perp - c^2 \frac{\partial^2 \widetilde{\mathbf{A}}_\perp}{\partial z^2} + \frac{e n_s \widetilde{\mathbf{v}}_{\mathrm{e}\perp}}{\varepsilon_0} \quad (3)$$

$$\frac{\partial \widetilde{n}_e}{\partial t} = i\omega_0 \widetilde{n}_e - \frac{\partial (n_s \widetilde{v}_{ez})}{\partial z} \quad (4)$$

$$\frac{\partial \widetilde{\mathbf{v}}_\mathrm{e}}{\partial t} = i\omega_0 \widetilde{\mathbf{v}}_e - \frac{e}{m_e}\left[\widehat{\mathbf{z}}\widetilde{E}_z + \widetilde{\mathbf{E}}_\perp + \widetilde{\mathbf{v}}_\mathrm{e} \times \mathbf{B}_0\right] - \widehat{\mathbf{z}}\frac{3v_{\mathrm{Te}}^2}{n_0}\frac{\partial \widetilde{n}_\mathrm{e}}{\partial z} - \nu_\mathrm{e} * \widetilde{\mathbf{v}}_\mathrm{e} \quad (5)$$

$$\frac{\partial^2 n_s}{\partial t^2} + 2\nu_s * \frac{\partial n_s}{\partial t} - C_s^2 \frac{\partial^2 n_s}{\partial z^2} = \frac{\varepsilon_0}{4m_i}\frac{\partial^2 (|\widetilde{\mathbf{E}}_\perp| + |\widetilde{E}_z|^2)}{\partial z^2} \quad (6)$$

Eliasson & Stenflo, JGR **113**, A02305 (2008)

Landau damping

Ion Landau damping

$$\widehat{\nu}_s(k_z)\widehat{n}_s = C_s \left(\frac{T_e}{T_i}\right)^{3/2} \exp\left(-\frac{T_e}{2T_i}\right) \sqrt{\frac{8}{\pi}}\,|k_z|\widehat{n}_s \quad (7)$$

$$\nu_s * n_s = -C_s \left(\frac{T_e}{T_i}\right)^{3/2} \exp\left(-\frac{T_e}{2T_i}\right) \sqrt{\frac{8}{\pi}}\frac{1}{\pi} \int_0^\infty \frac{n_s(z+\xi) - 2n_s(z) + n_s(z-\xi)}{\xi^2}\, d\xi \quad (8)$$

Electron Landau damping

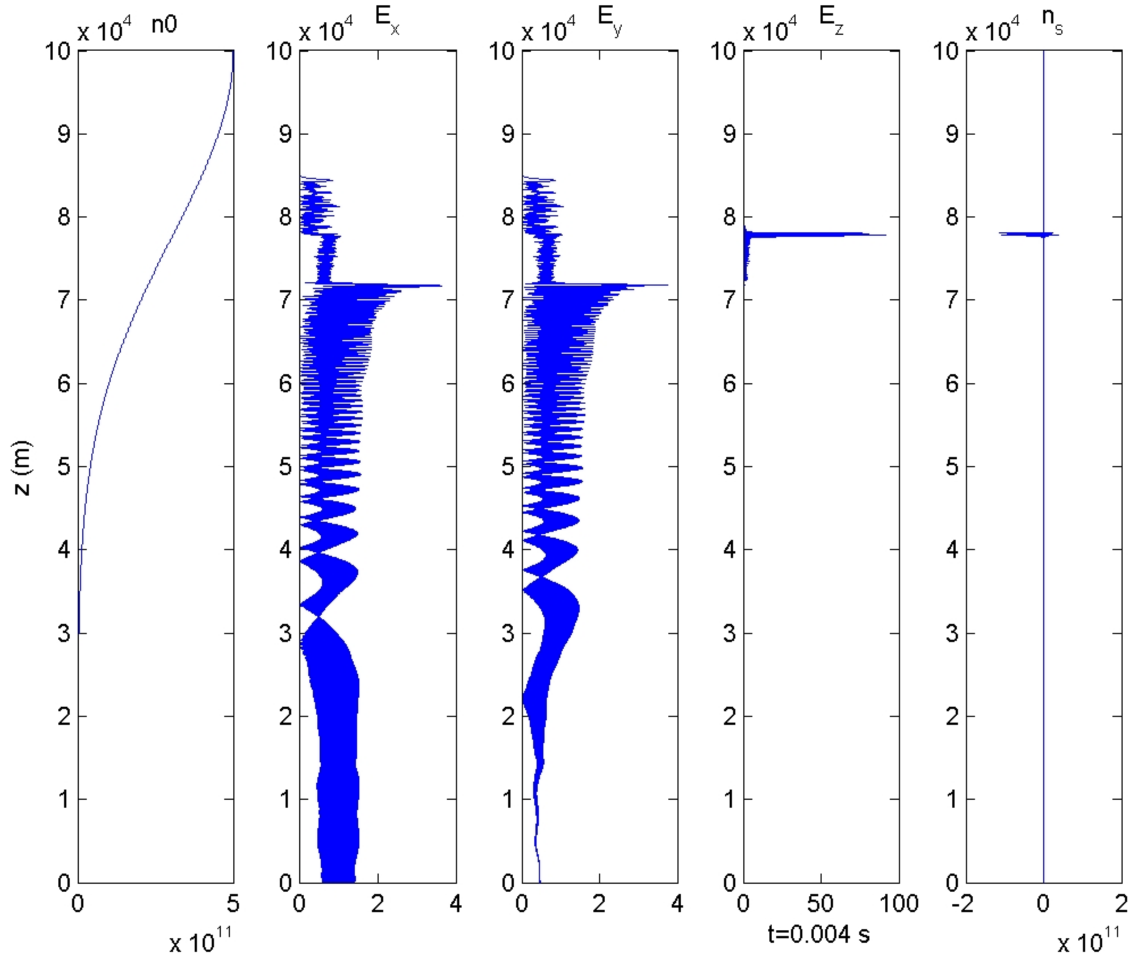
$$\widehat{\nu}_e(k_z)\widehat{v}_{ez} = \left(\frac{\pi}{8}\right)^{1/2} \frac{\omega_{pe}}{|k_z\lambda_{De}|^3} \exp\left[-\frac{1}{2(k_z\lambda_{De})^2}\right] \widehat{v}_{ez}. \quad (9)$$

Simplified: $\widehat{\nu}_e(k_z)\widehat{v}_{ez} \approx 0.5\omega_{pe}(\lambda_{De}k_z)^2\widehat{v}_{ez}.$ (10)

$$\nu_e * v_{ez} \approx -0.5\omega_{pe}\lambda_{De}^2 \frac{\partial^2 v_{ez}}{\partial z^2}. \quad (11)$$

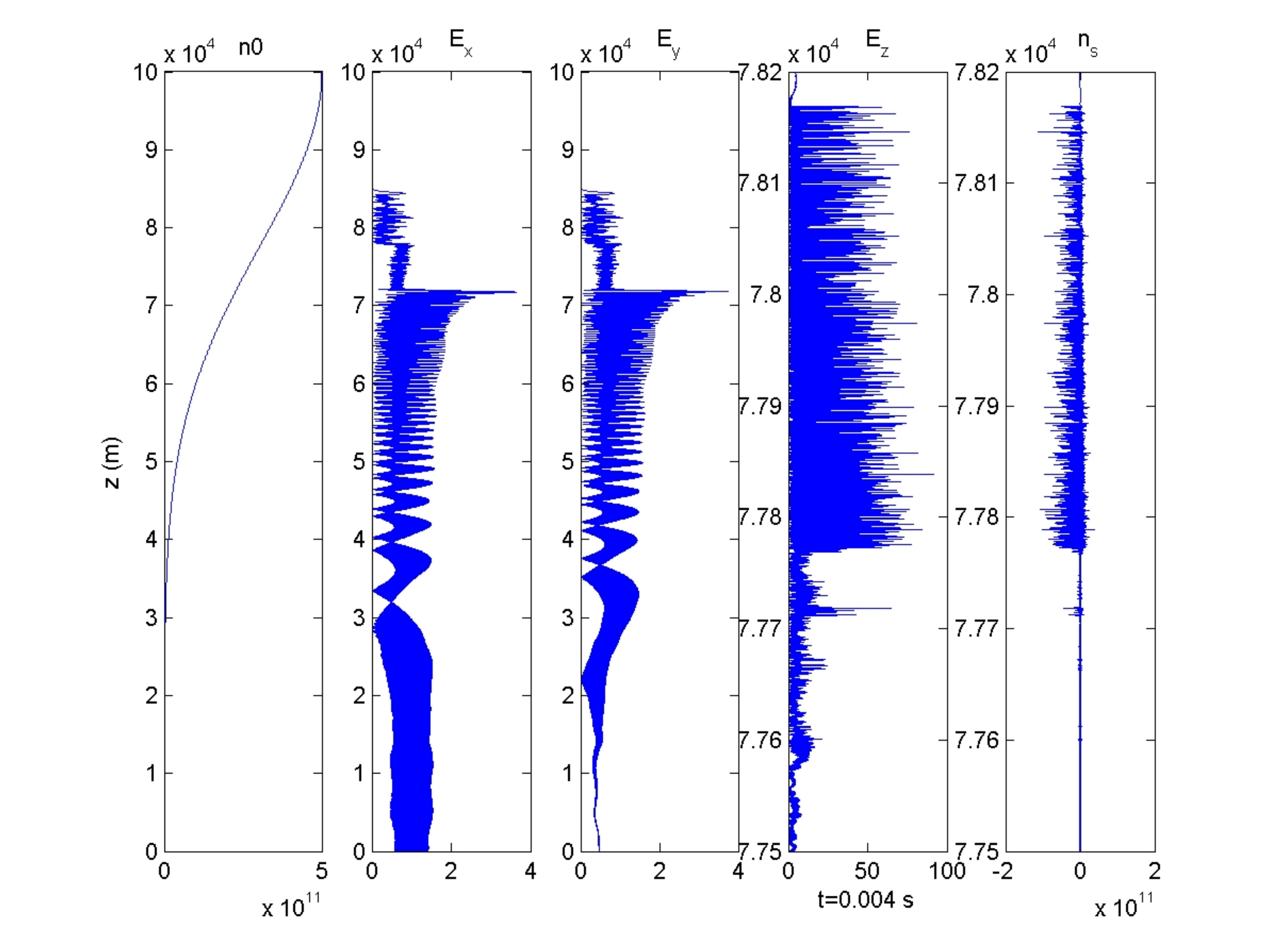
(Work in progress ...)

Simulation result



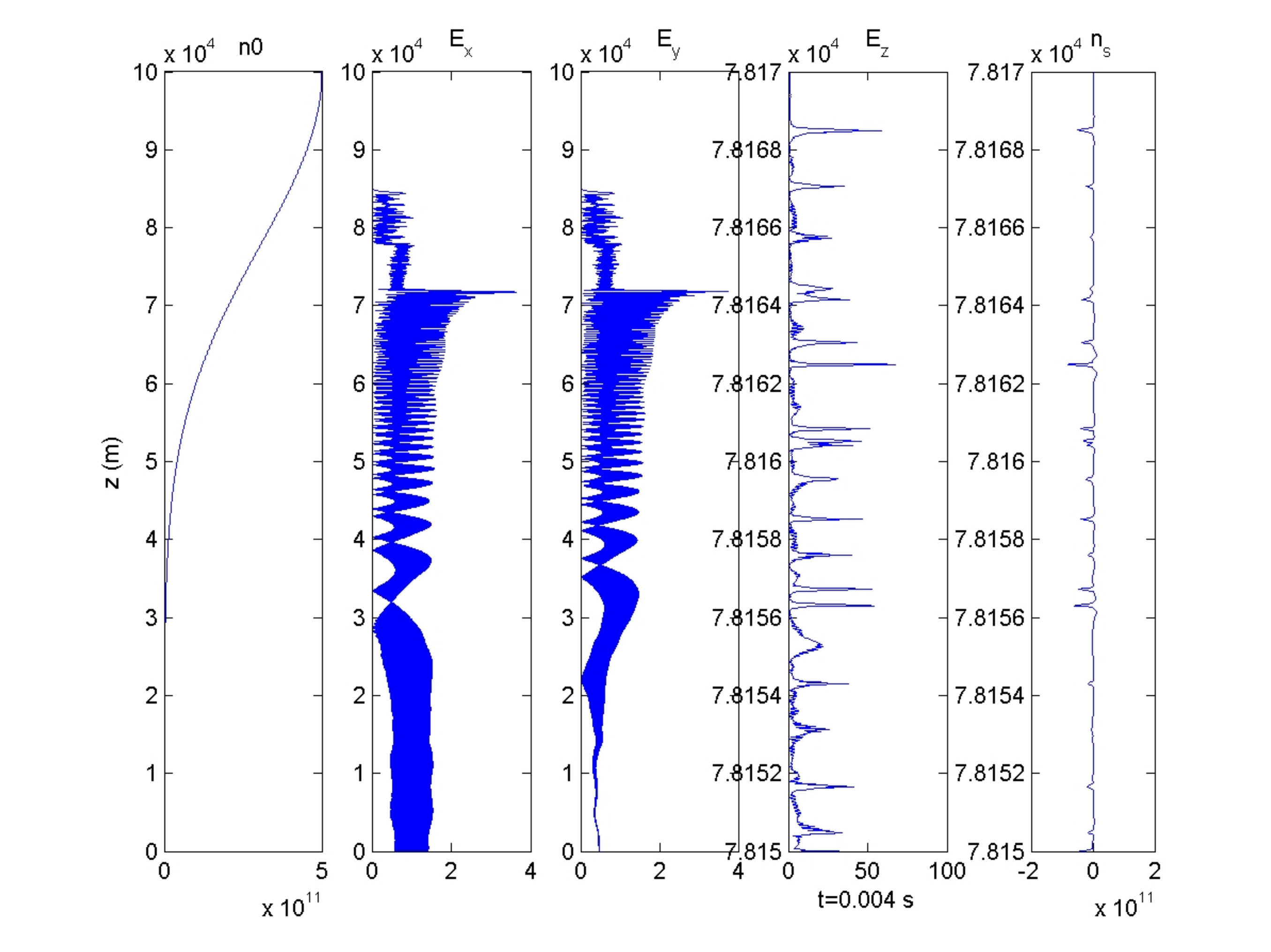
Eliasson & Stenflo, JGR **113**, A02305 (2008)

Simulation result (closeup)



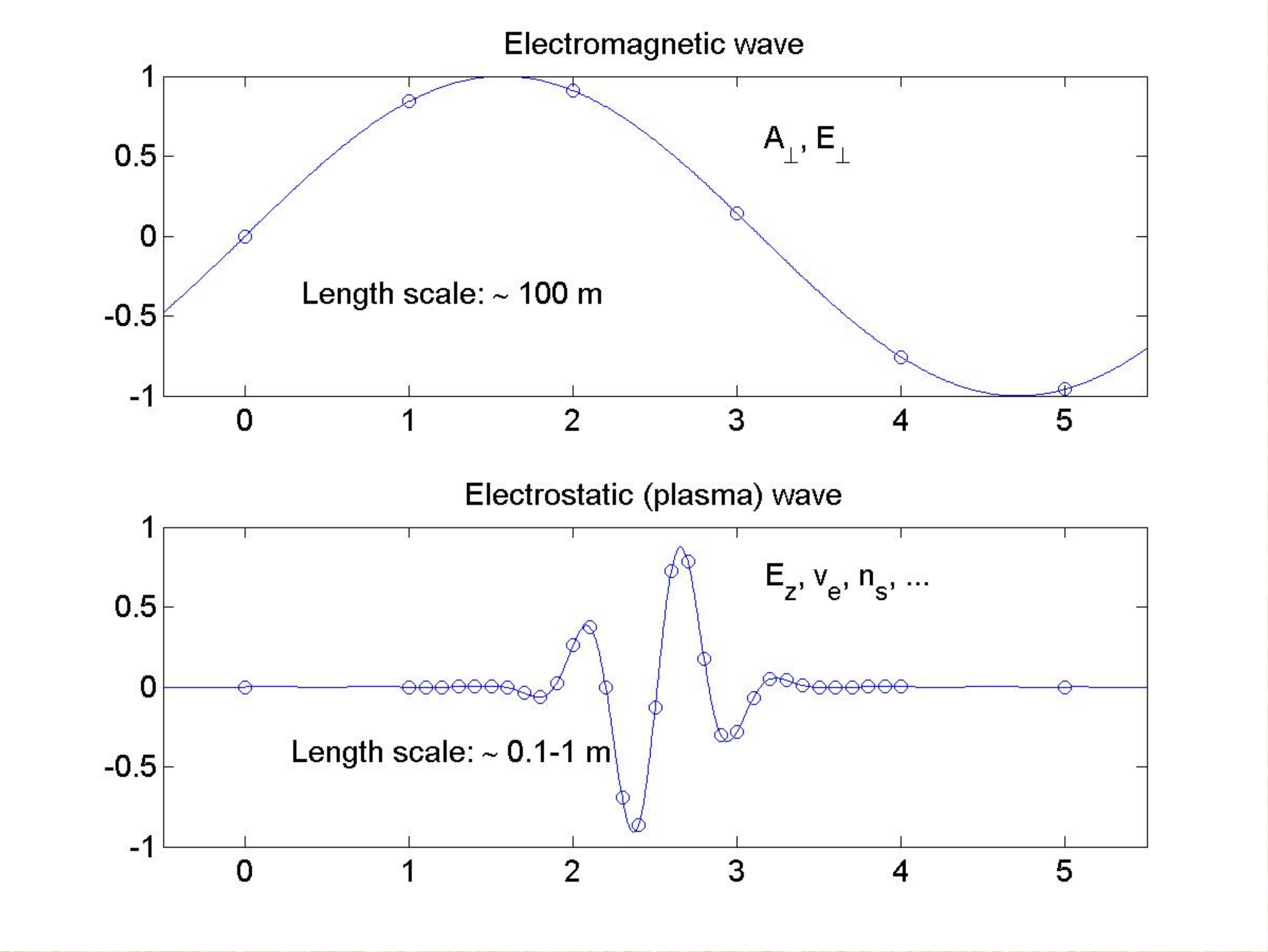
Eliasson & Stenflo, JGR **113**, A02305 (2008)

Simulation result (closeup)



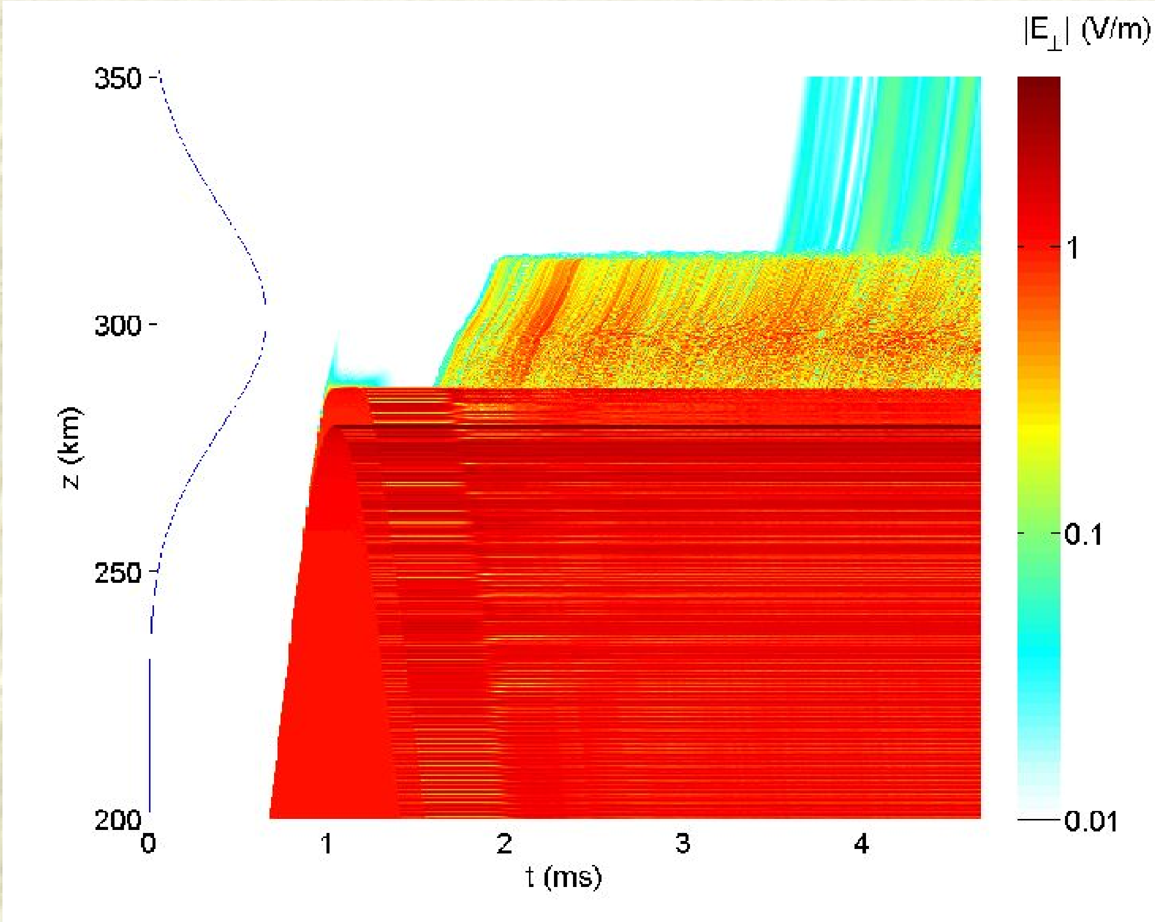
Eliasson & Stenflo, JGR **113**, A02305 (2008)

Different length scales, nested grid method



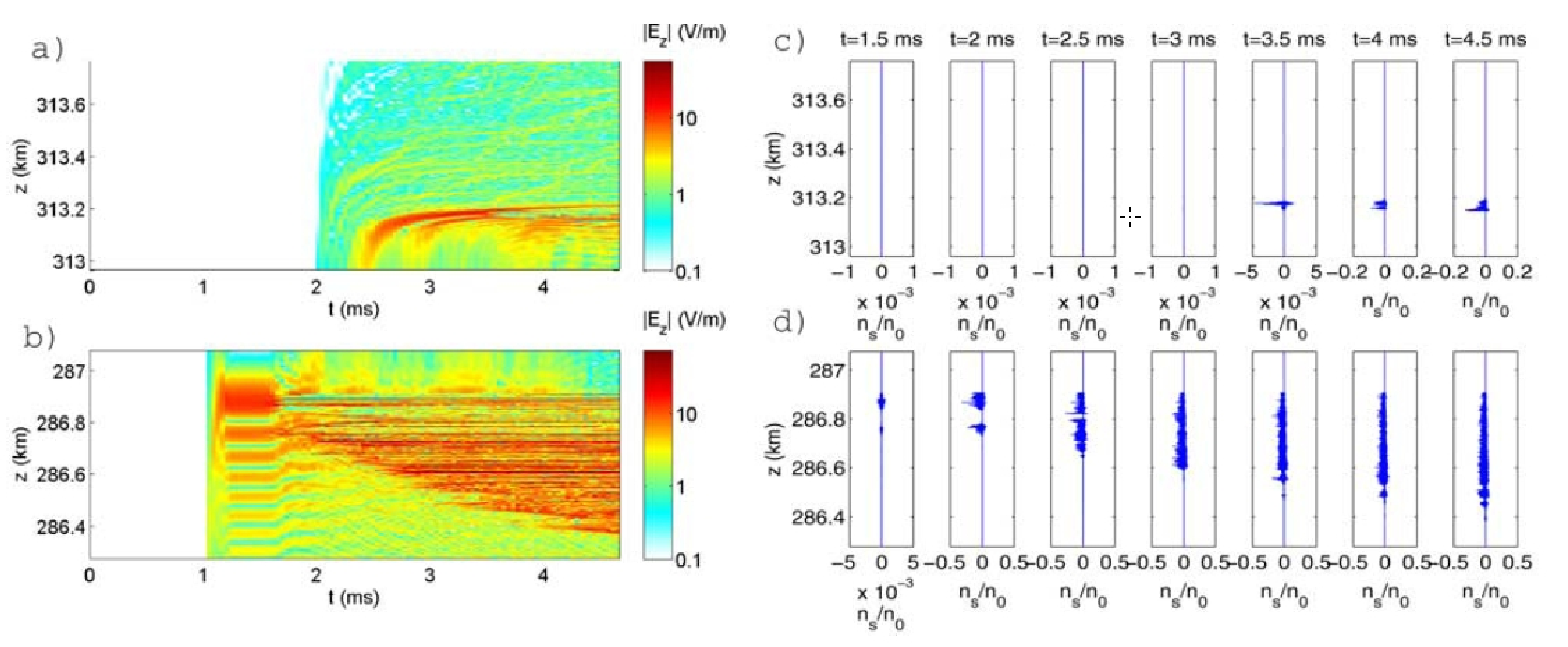
Courant condition $\Delta t < \Delta z/c$. $\Delta z = 2$ m, Locally $\delta z = 2$ cm

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.