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MS waves induced by RF heating of the ionospheric F-layer.

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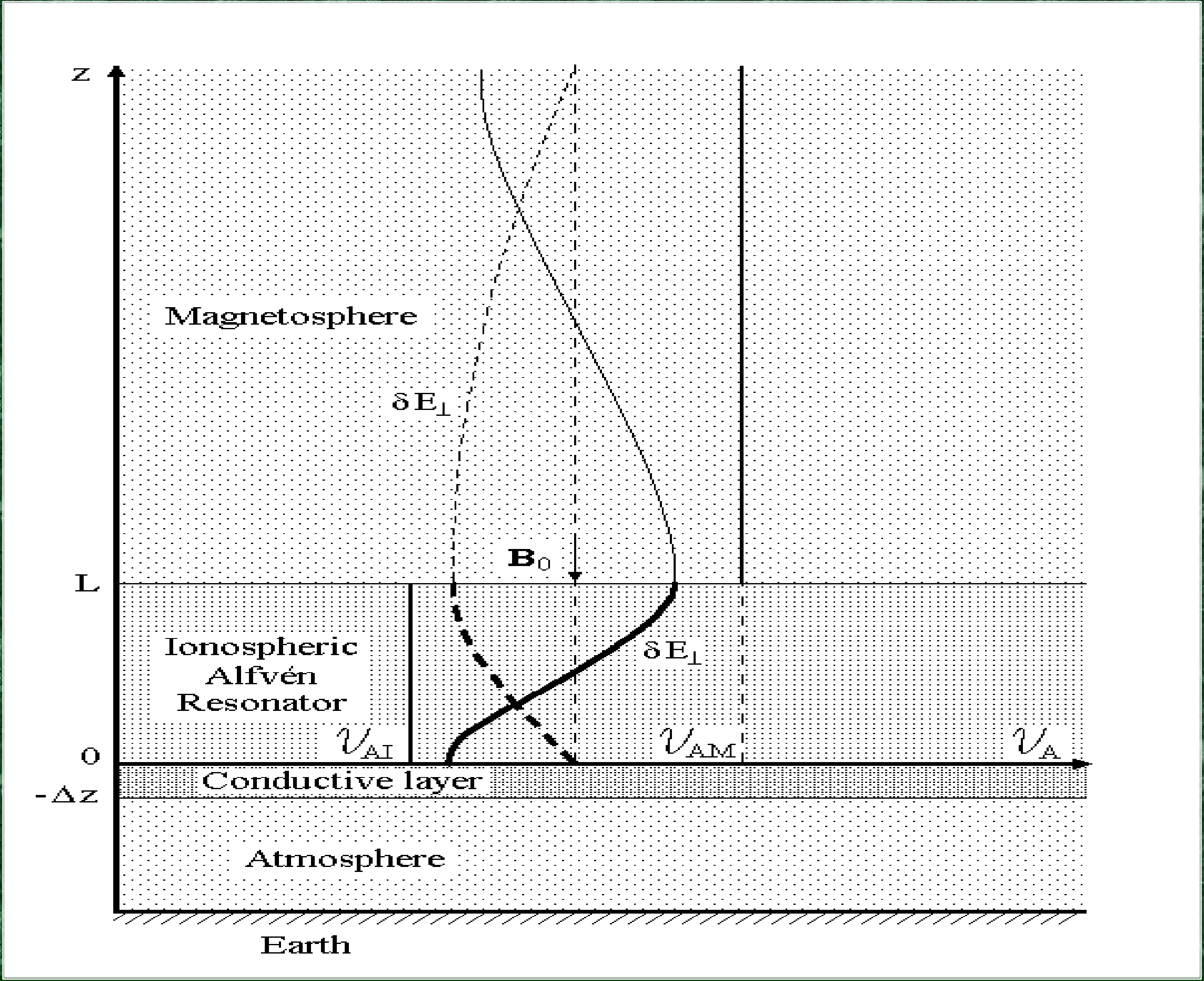
Schematic view



Ground and satellite observations

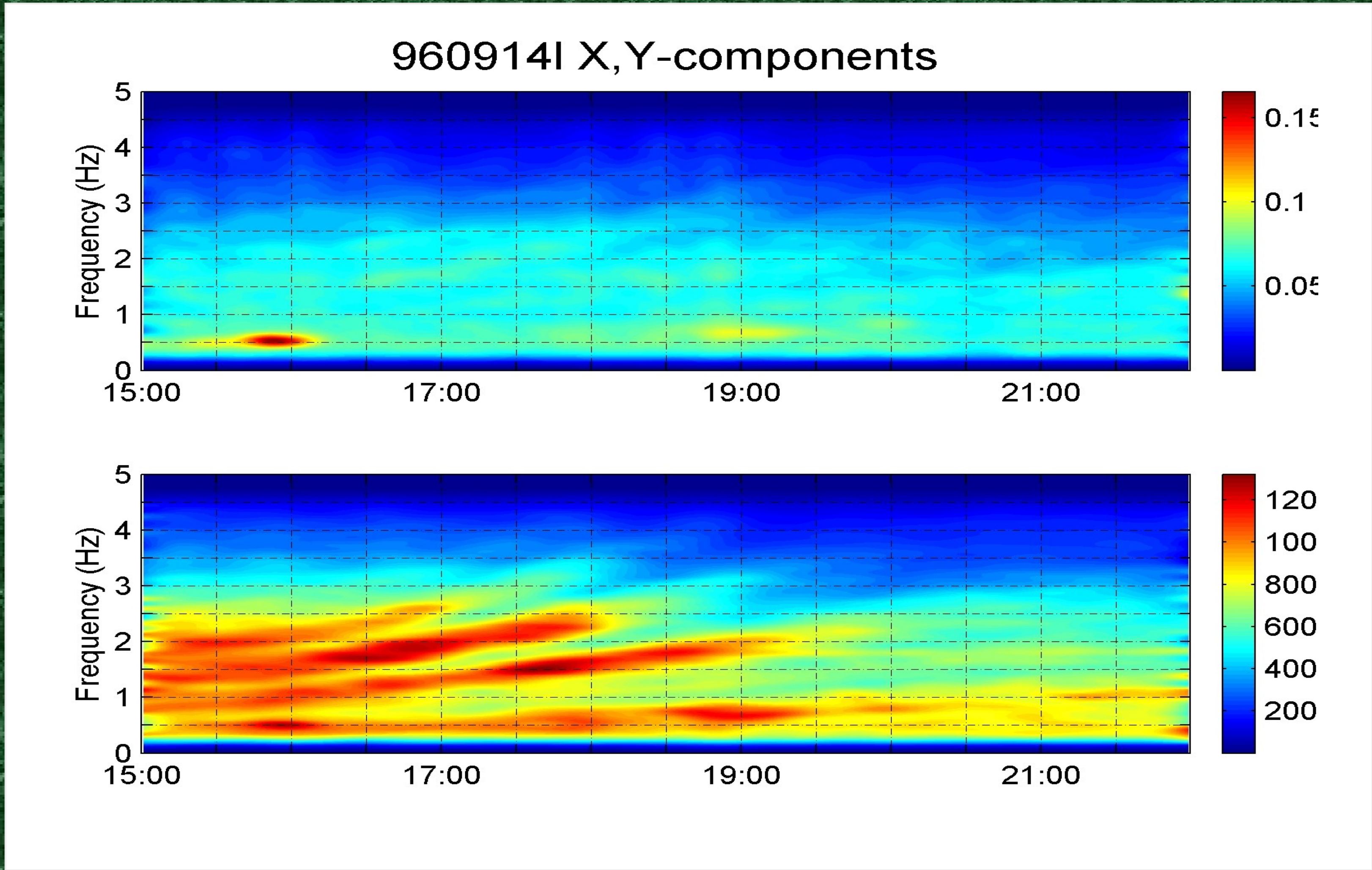
- Nizniy-Novgorod (Middle Russia)
- Borok (Middle Russia)
- Mondy (Siberia, Russia)
- Karimshino (Kamchatka, Russia)

- Sodankyla (Finland)
- Crete (Greece)
- Table Mountain obs., USA
- FREJA satellite
- FAST satellite
- CLUSTER satellites
- DEMETER

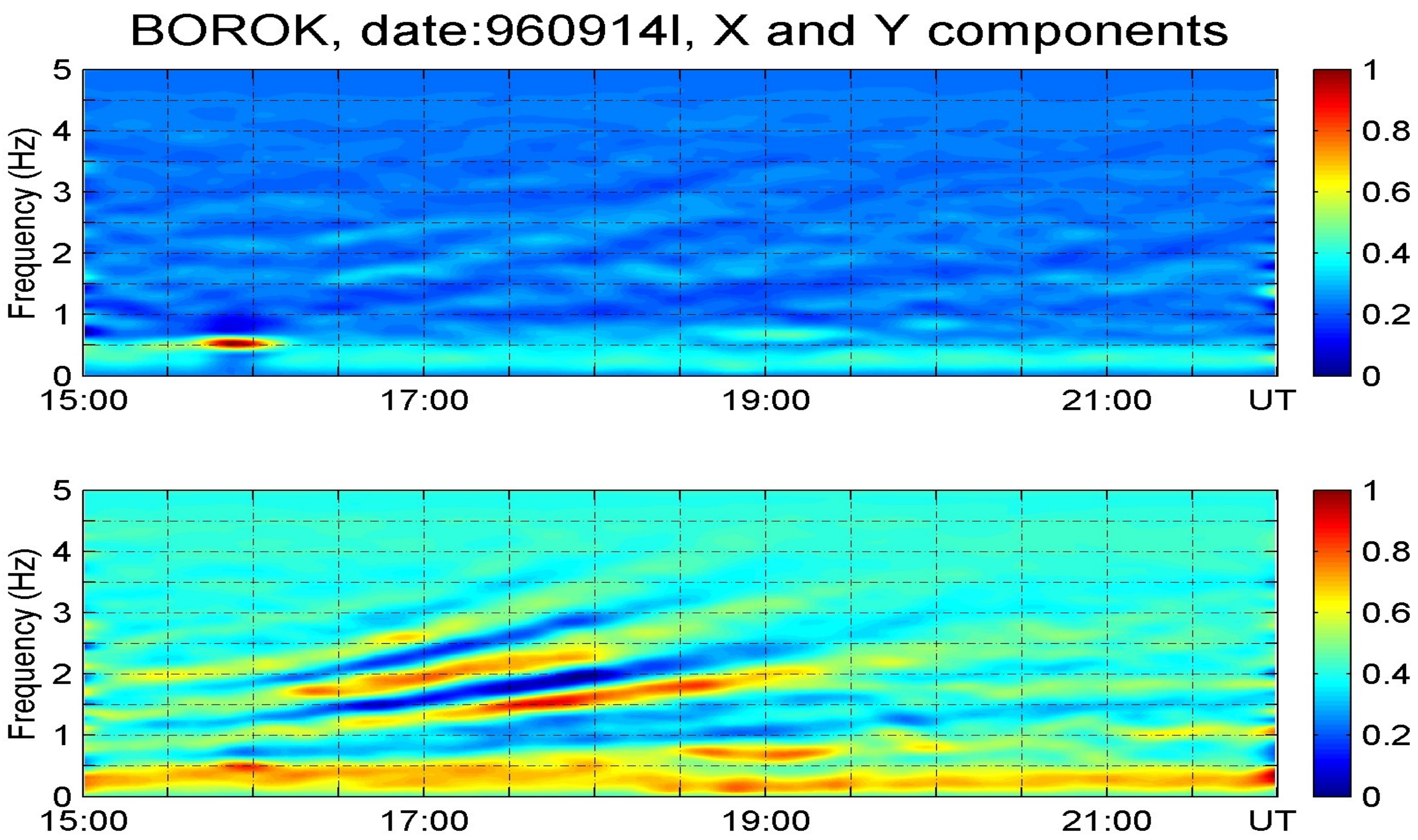
Sources of free energy for the IAR excitation

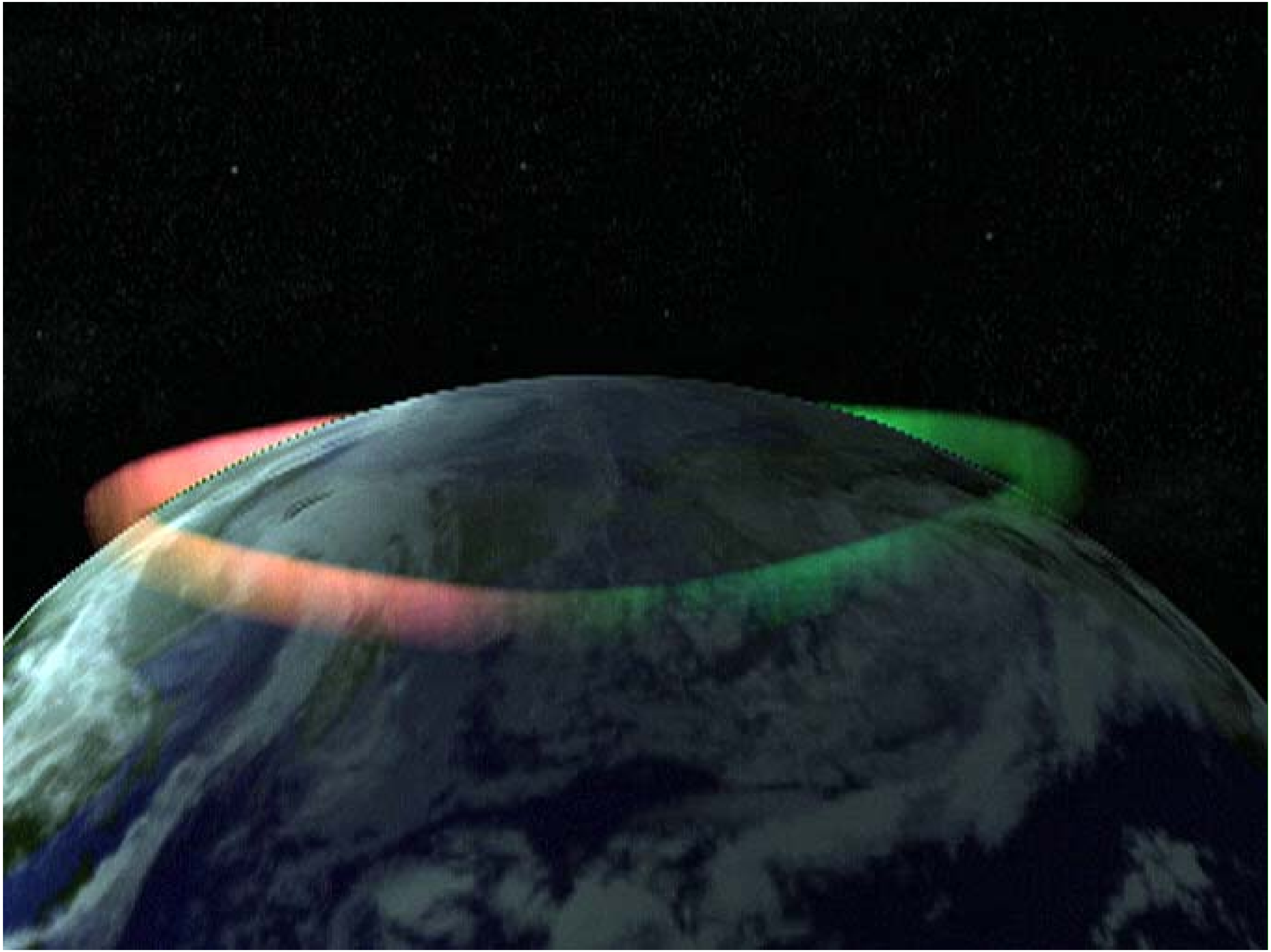
- High-latitudes - Magnetospheric convection (feedback instability)
- Middle-latitudes - Thunderstorm activity
- Neutral winds, Subauroral Polarization Streams (SAPS)

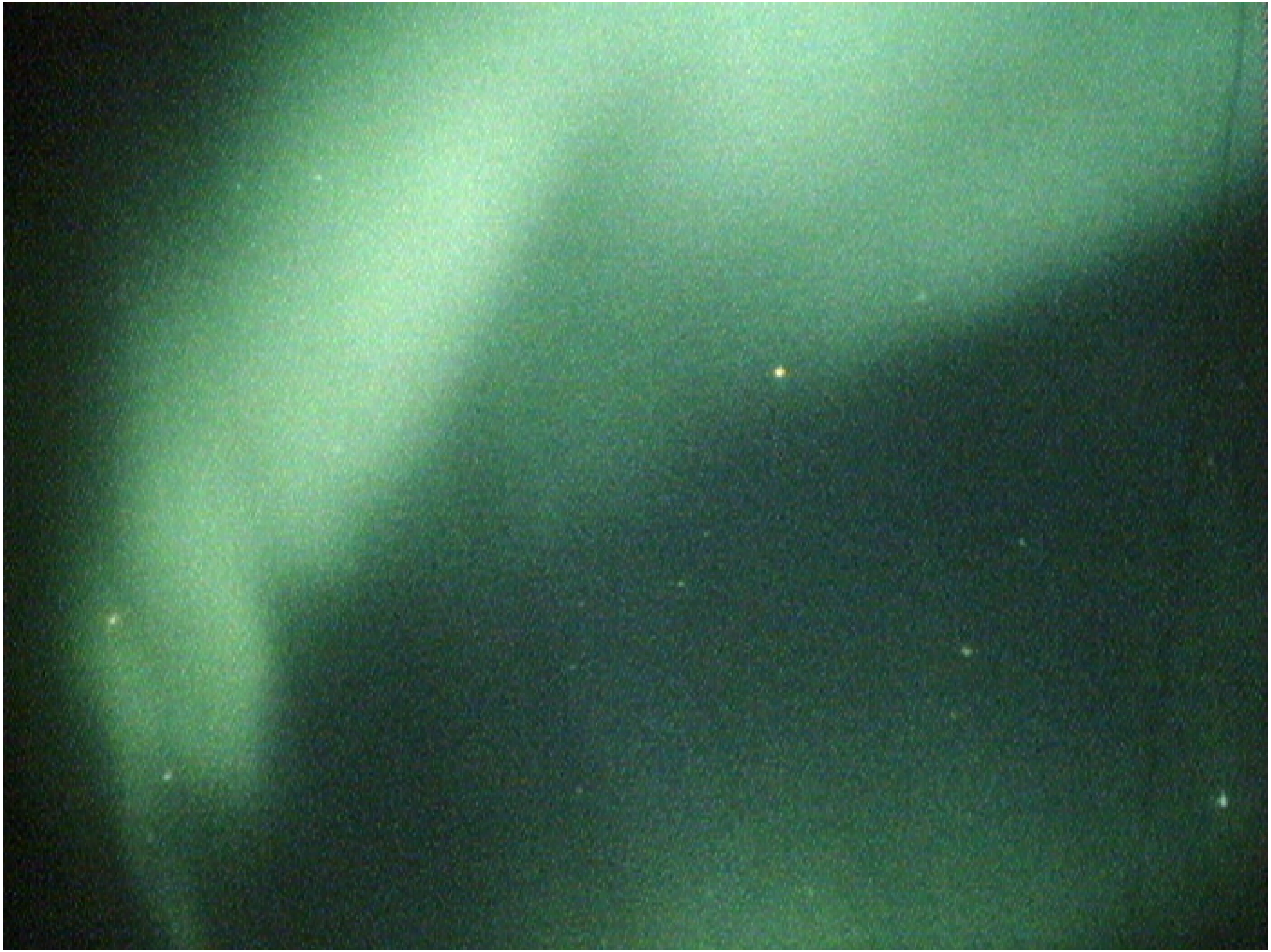
Ground observations of SRS

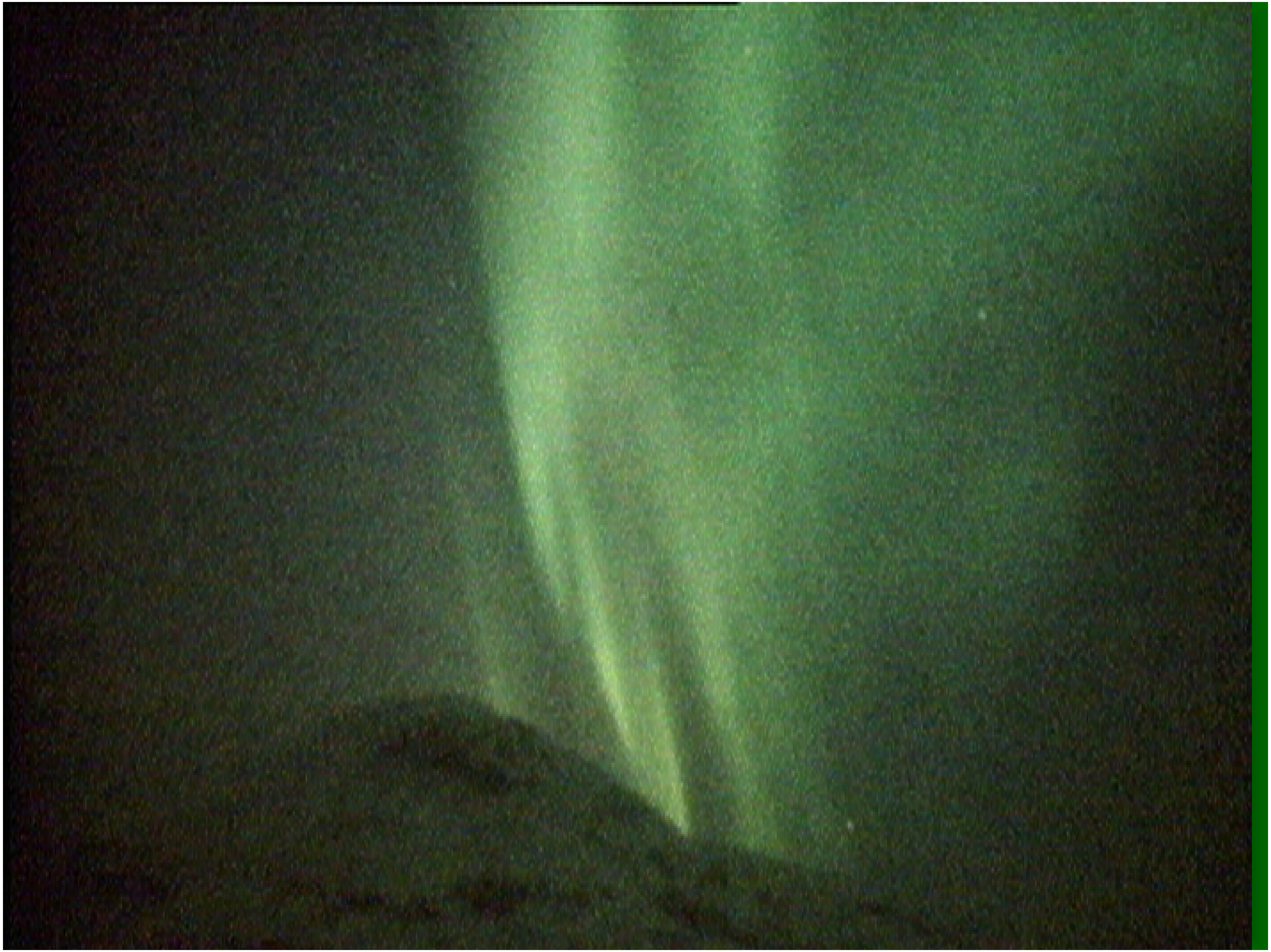


Ground observations of SRS

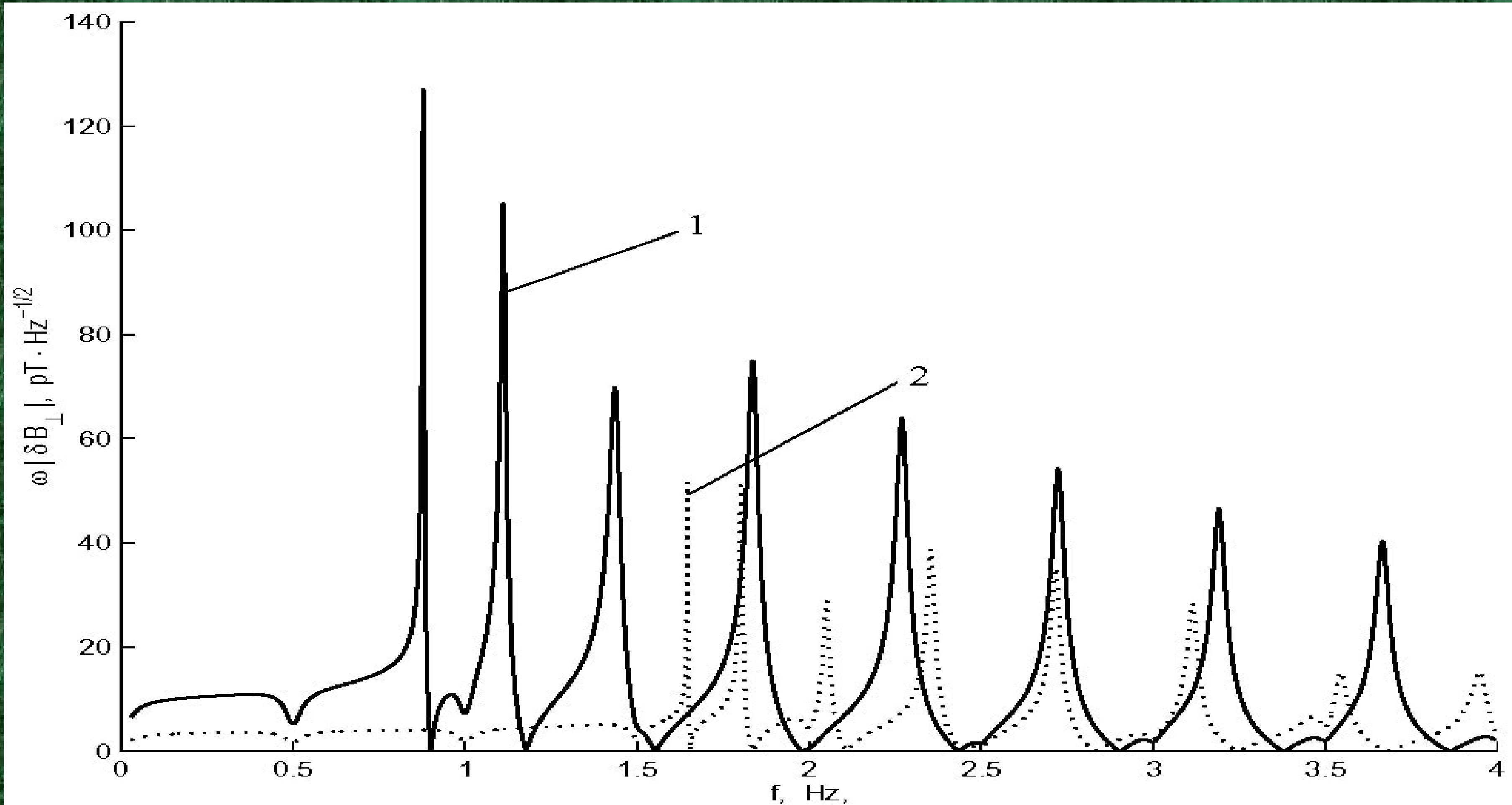




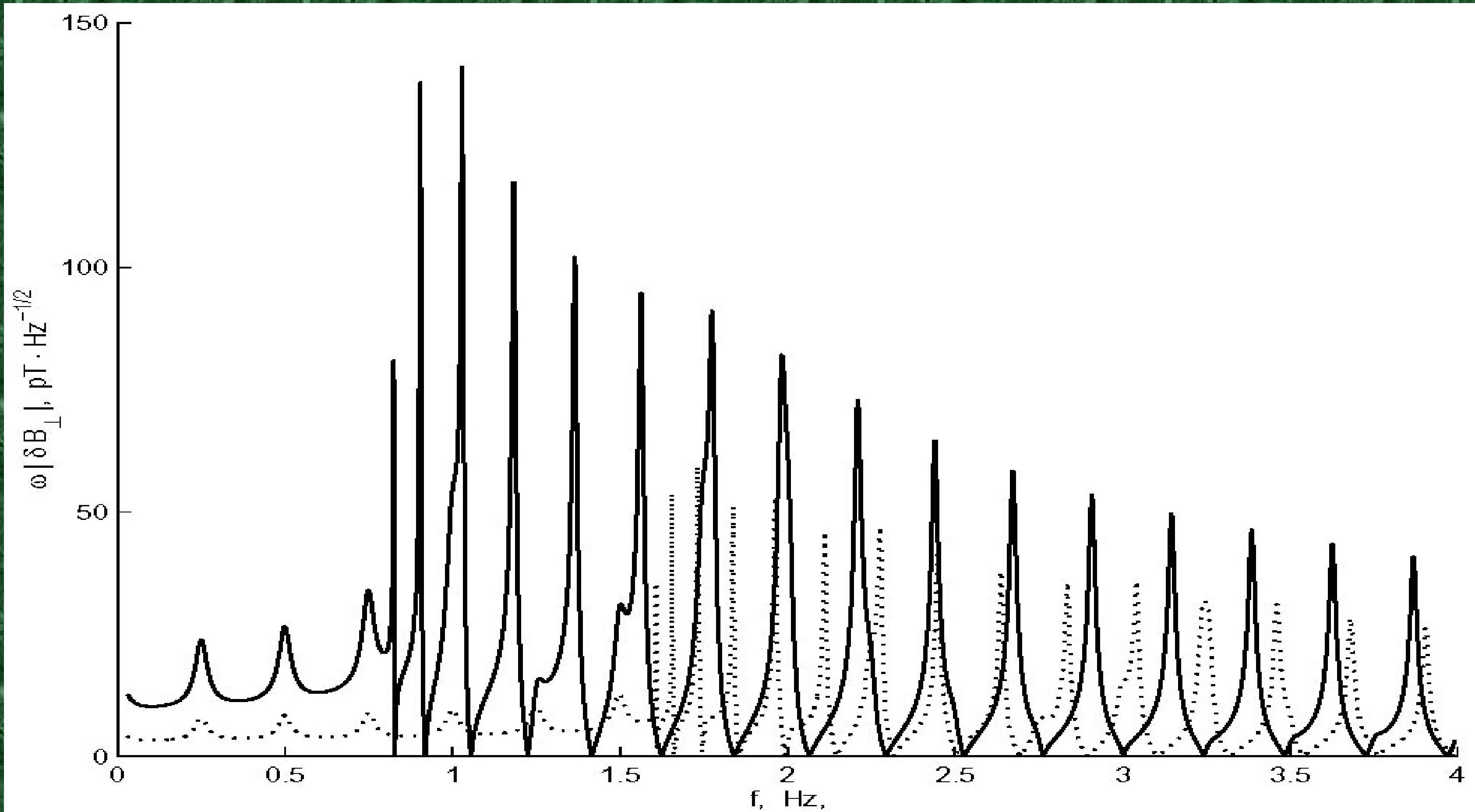




A daytime power spectrum



The nighttime spectrum. The low frequency spikes at 0.25, 0.5 and 0.75 Hz are due the shear Alfven mode



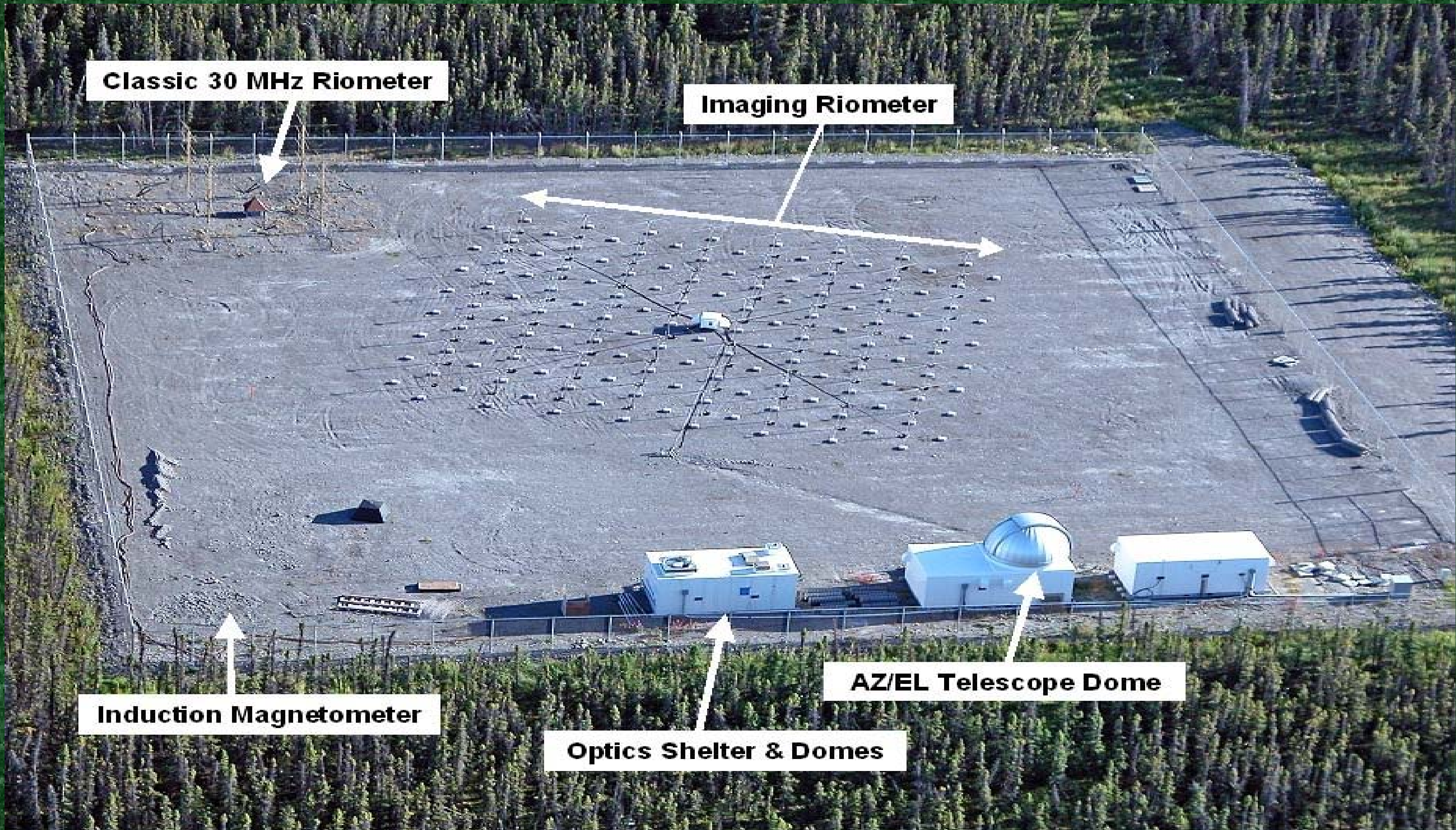
Experimental evidence

Magnetosonic ULF waves generated by modulated ionospheric heating using recently completed HAARP heater were measured on board the DEMETER spacecraft. Modulated F-region ionospheric heating thus provides us with the first artificial Pc 1 source that can propagate laterally in the ionospheric waveguide.

HAARP

Array

General view



Control Center

Flux-gate magnetometer

Riometer

Basic equations (ionosphere)

Ampere's law

$$(\nabla \times \delta \boldsymbol{B})_\perp = \mu_0 (\boldsymbol{J}_\perp + \boldsymbol{J}_H) + \frac{K(z)}{c^2} \frac{\partial \boldsymbol{E}_\perp}{\partial t}$$

Here

$\mathbf{J}_\perp = \sigma_P \boldsymbol{E}_\perp + \sigma_H \boldsymbol{z} \times \boldsymbol{E}_\perp$ and $\boldsymbol{J}_H = (\boldsymbol{B} \times \nabla \delta p) / B^2$

Faraday's law

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

Parallel electron motion

$$\mathrm{E}_\parallel = \mu_0 \lambda^2 \left(\frac{\partial}{\partial t} + \nu_e \right) J_\parallel$$

$$K(z) = 1 + \sum_j \frac{\omega_{pj}^2}{\nu_j^2 + \omega_{cj}^2}$$

$$\sigma_P(z) = \sum_j \frac{n_{0j} q_j^2}{m_j} \frac{\nu_j}{\nu_j^2 + \omega_{cj}^2}$$

$$\sigma_H(z) = -\sum_j \frac{n_{0j} q_j^2}{m_j} \frac{\omega_{cj}}{\nu_j^2 + \omega_{cj}^2}$$

Dimensionless form

$$\left[\frac{\partial}{\partial\tau}+\alpha_P(\varsigma)\right]q=-\frac{1}{K(\varsigma)}\frac{\partial j}{\partial\varsigma}\mp\alpha_H(\varsigma)m$$

$$\left[\frac{\partial}{\partial\tau}+\alpha_P(\varsigma)\right]m=-\frac{1}{K(\varsigma)}\nabla^2 b\pm\alpha_H(\varsigma)q$$

$$-\frac{\beta}{2K(\varsigma)}\nabla_\perp^2\frac{\delta p}{p_0}$$

$$\frac{\partial b}{\partial\tau}=-m$$

$$\frac{\partial}{\partial\tau}\left(1-\frac{m_e}{m_i}\nabla_\perp^2\right)j=-\frac{\partial q}{\partial\varsigma}+\frac{\nu_e}{\omega_{ce}}\nabla_\perp^2 j$$

$$q=\frac{c}{\omega_{pi}^I}\frac{\nabla_\perp\bullet\mathbf{E}_\perp}{Bv_A^I}\qquad m=\frac{c}{\omega_{pi}^I}\frac{\left(\nabla_\perp\times\mathbf{E}_\perp\right)_z}{Bv_A^I}$$

$$j=\frac{J_\parallel}{en_0^I v_A^I}\qquad \mathrm{b}=\frac{\delta B_z}{B}$$

Atmosphere

$$b(\varsigma) = b(H)\frac{k\delta\cosh k\varsigma + (1+i)\sinh k\varsigma}{k\delta\cosh kH + (1+i)\sinh kH}$$

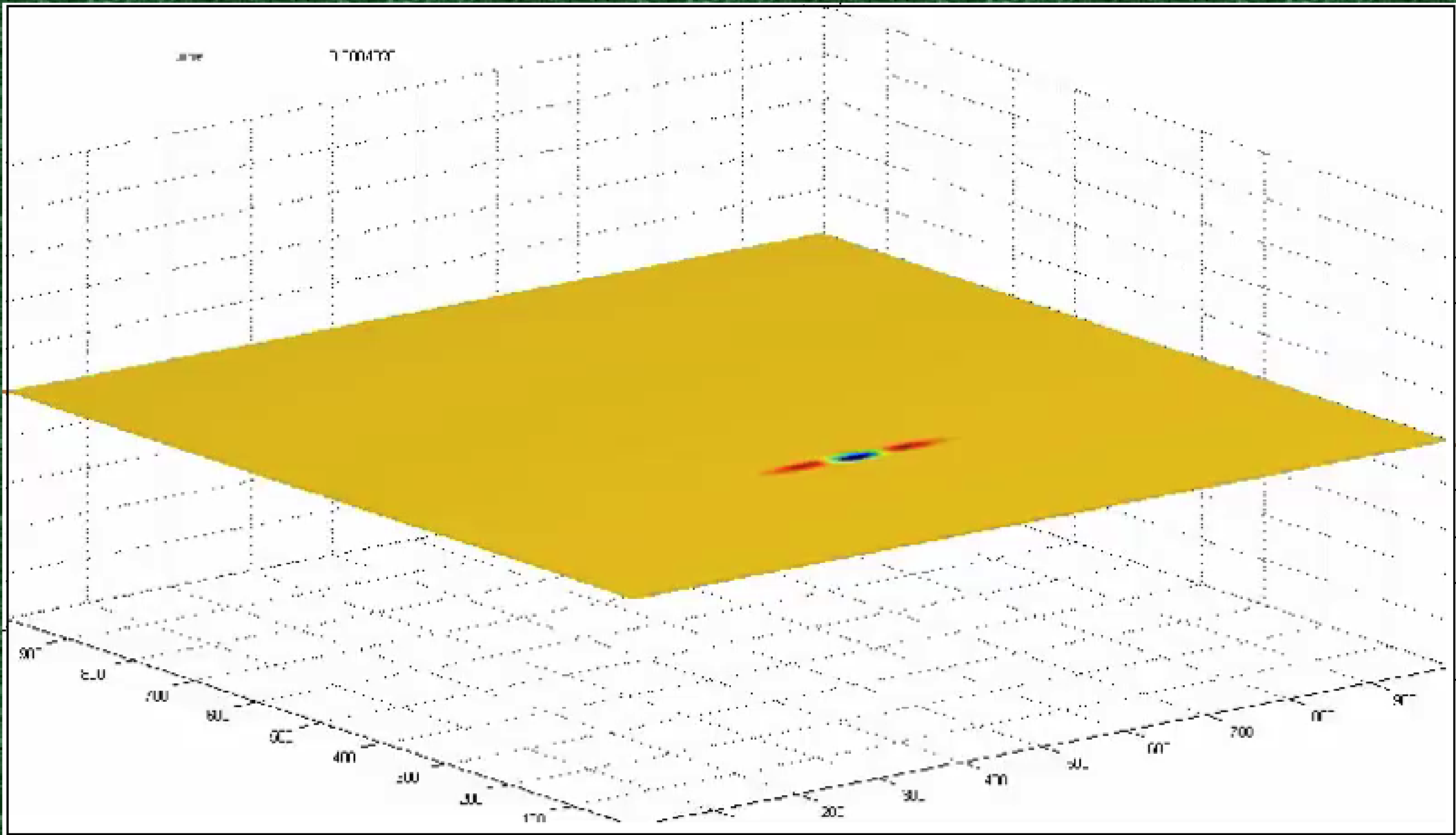
where $\delta = \left(2/\omega\mu_0\sigma_g\right)^{1/2}$ is the skin depth of the solid Earth

In the atmosphere $\partial/\partial\tau = 0$

$q = -(\nu_e/\omega_{ce})\partial j/\partial\tau$ and

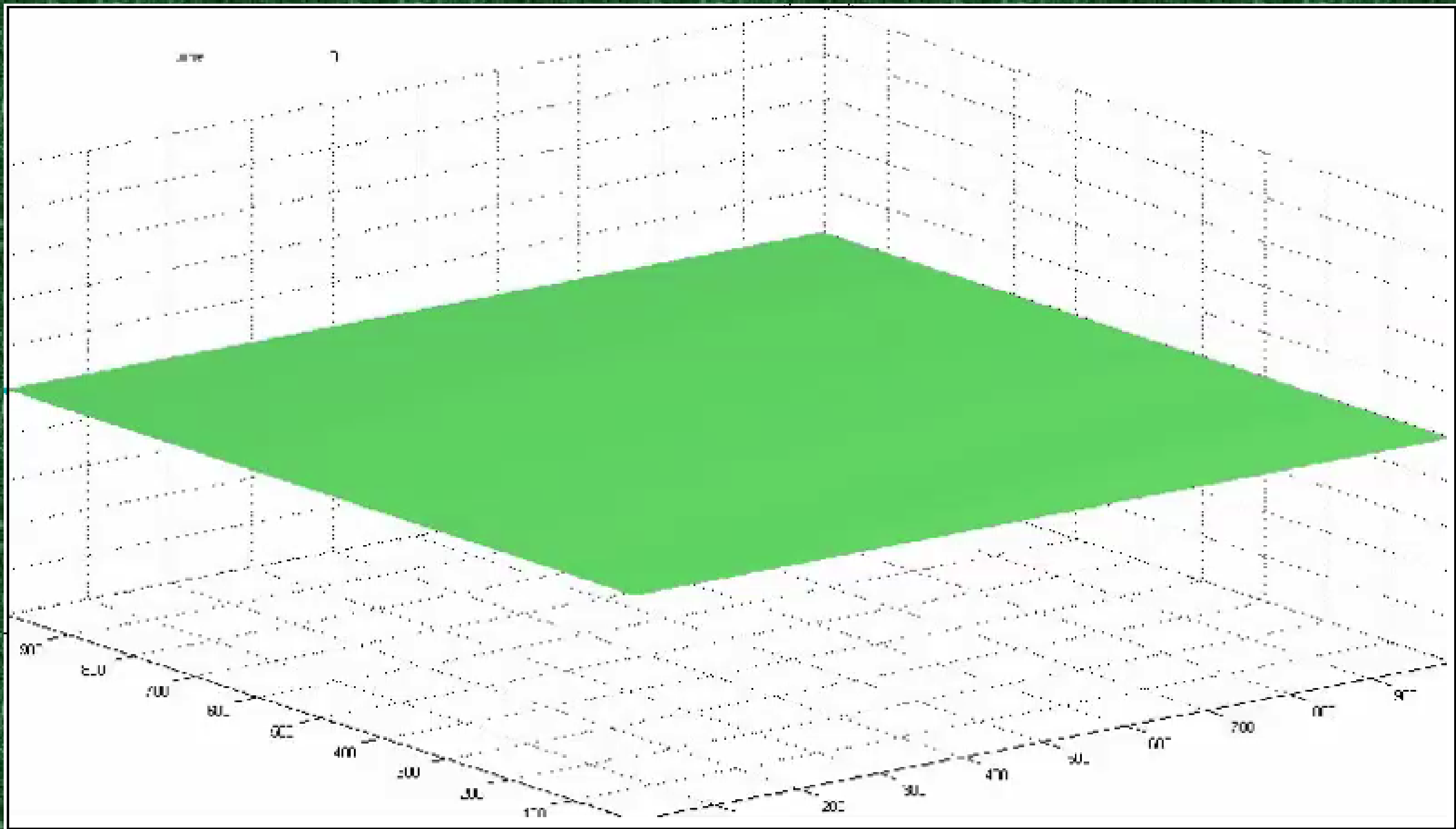
$$\frac{\partial}{\partial\varsigma}\left(\frac{\nu_e}{\omega_{ce}}\frac{\partial j}{\partial\tau}\right) + \frac{\nu_e}{\omega_{ce}}\nabla_\perp^2 j = 0$$

Magnetic field



movie

Field-aligned current



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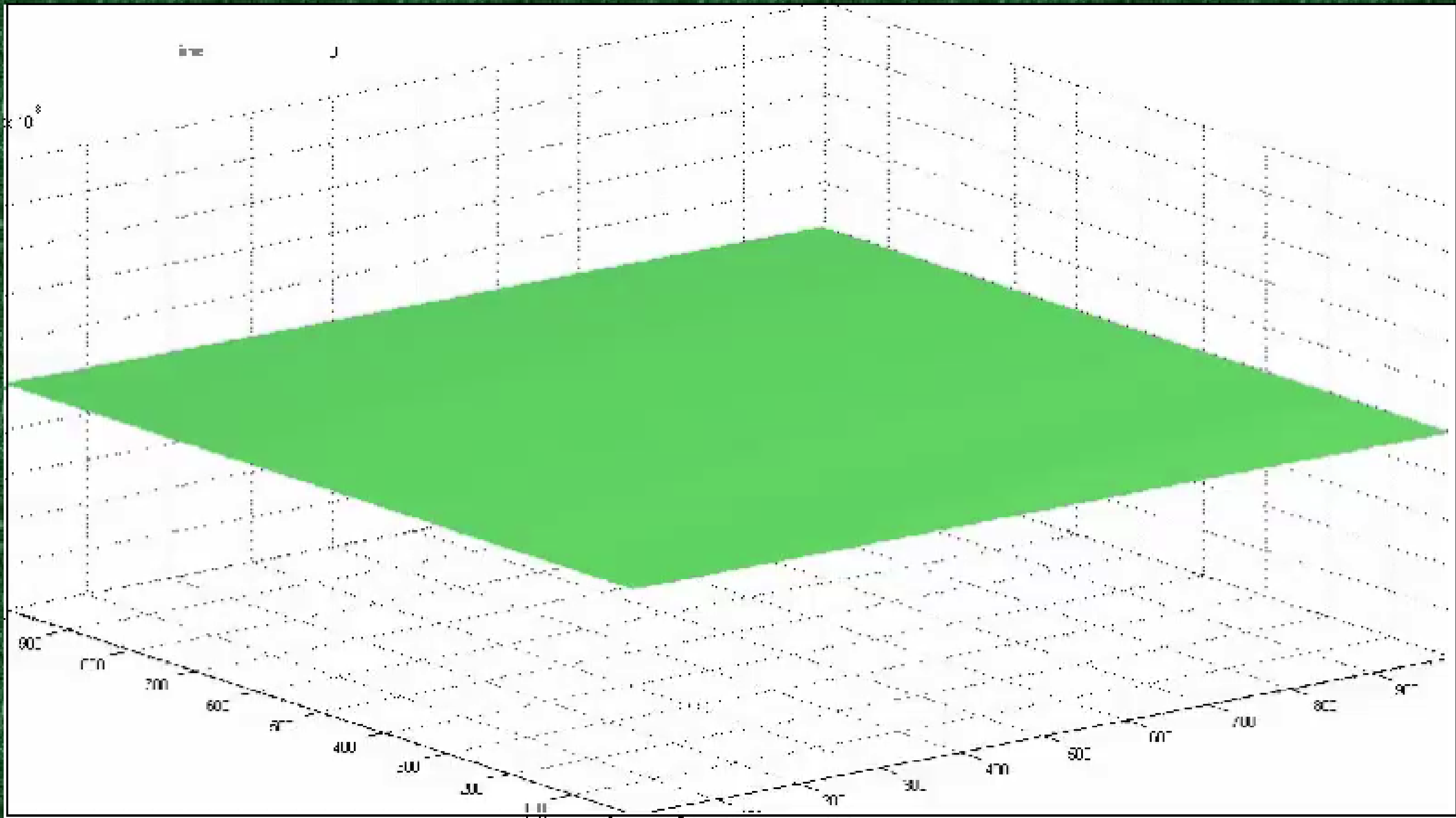

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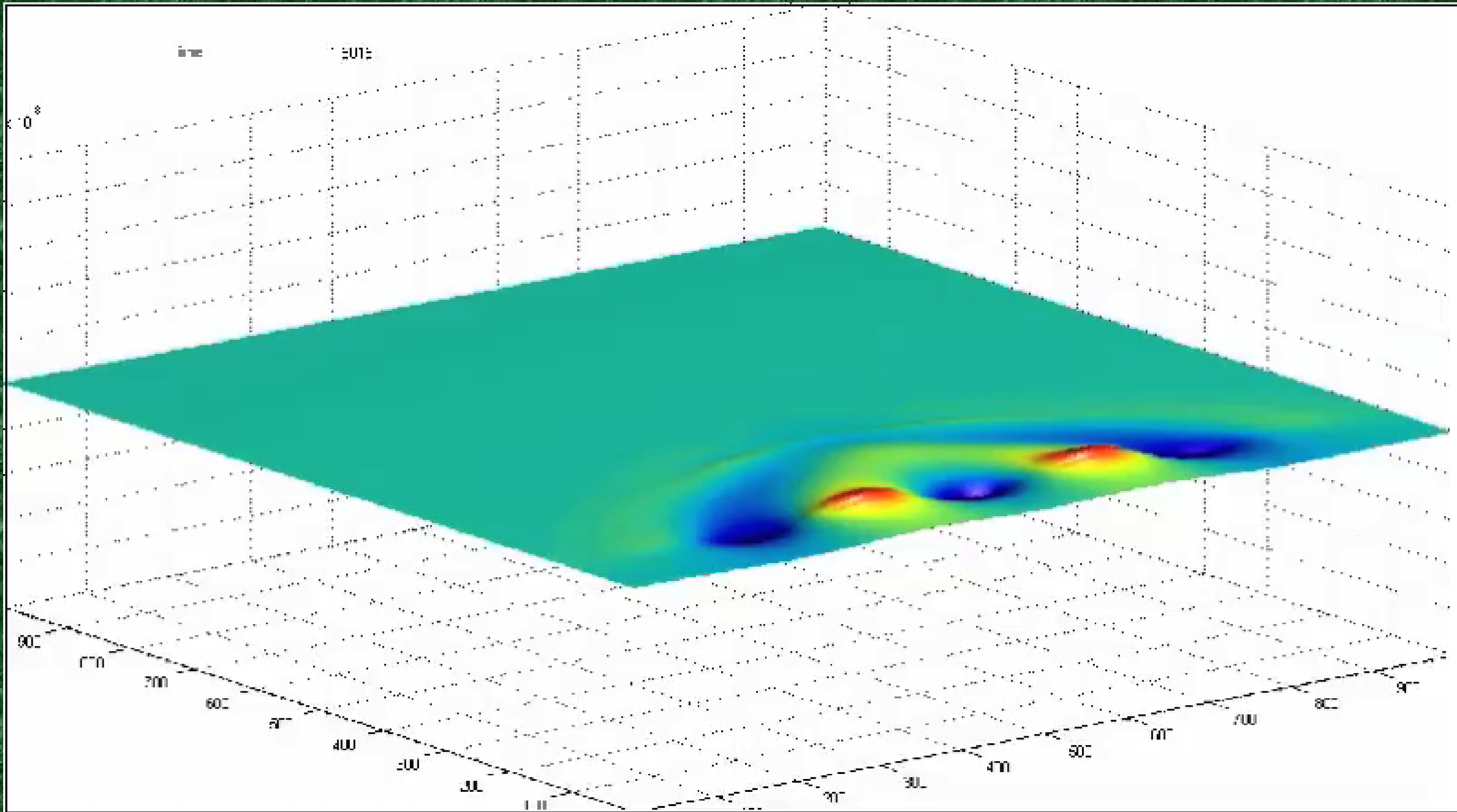
Field aligned current



movie

Thank you!