Ионосферный отклик на природные и антропогенные воздействия

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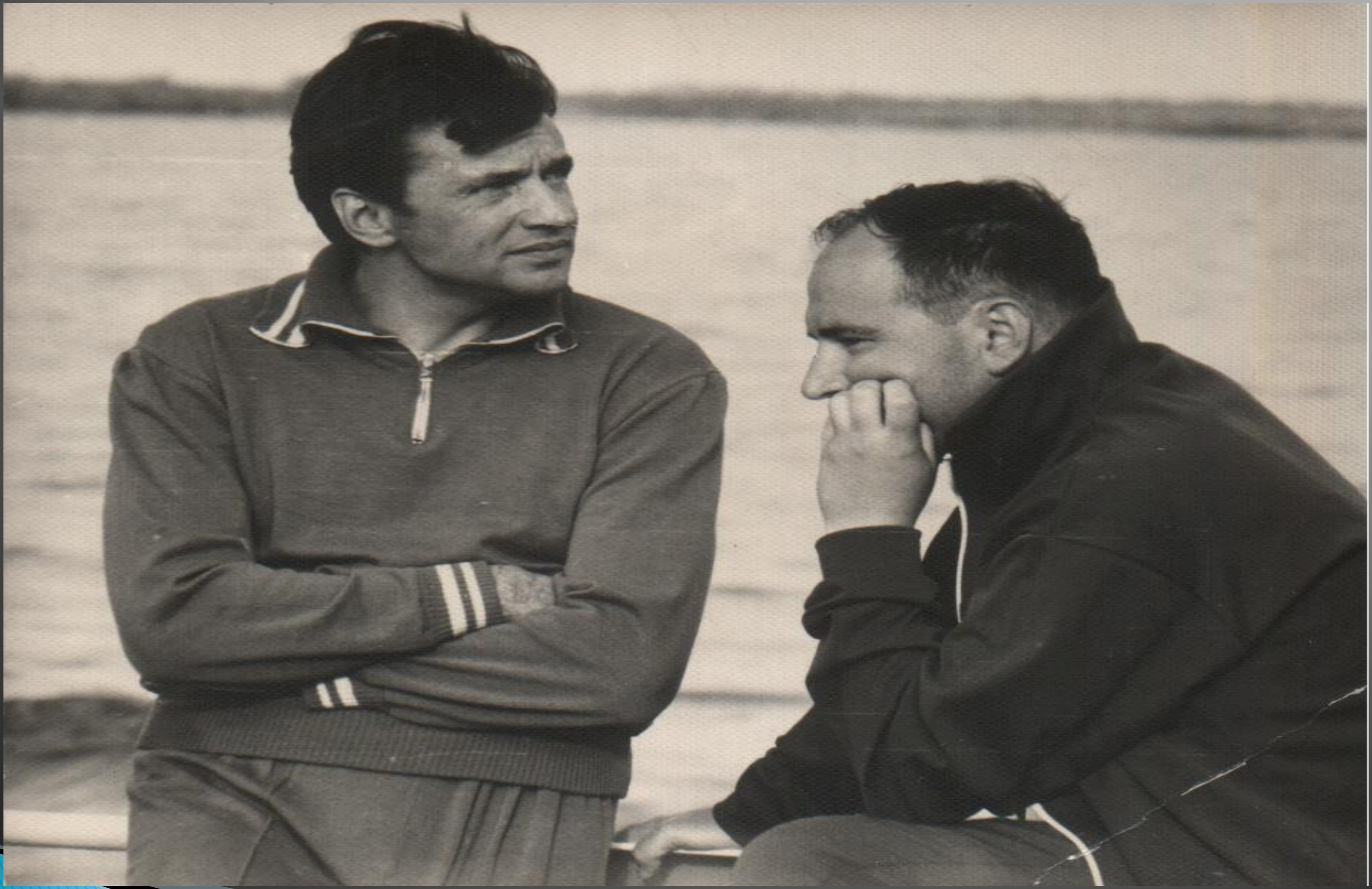
Short history

- The idea of IAR was suggested by Polyakov [1976]
- First experimental evidence: Polyakov and Rapoport [1981], Belyaev et al. [1987]
- Recent experimental studies: Belyaev et al. [1999], Demekhov et al. [2000], Bosinger et al. [2002]
- Theoretical model of the IAR was first developed by Trakhtengertz and Feldstein [1987,1991] and Lysak [1991]
- Recent progress in the theory: Pokhotelov et al. [2000, 2001, 2003, 2004], Lysak and Song [2002, 2003], Pilipenko et al. [2002], Streltsov et al. [2002], Surkov et al. [2004]

Trakhtengertz V and & Feldstein Y



Basic contributions

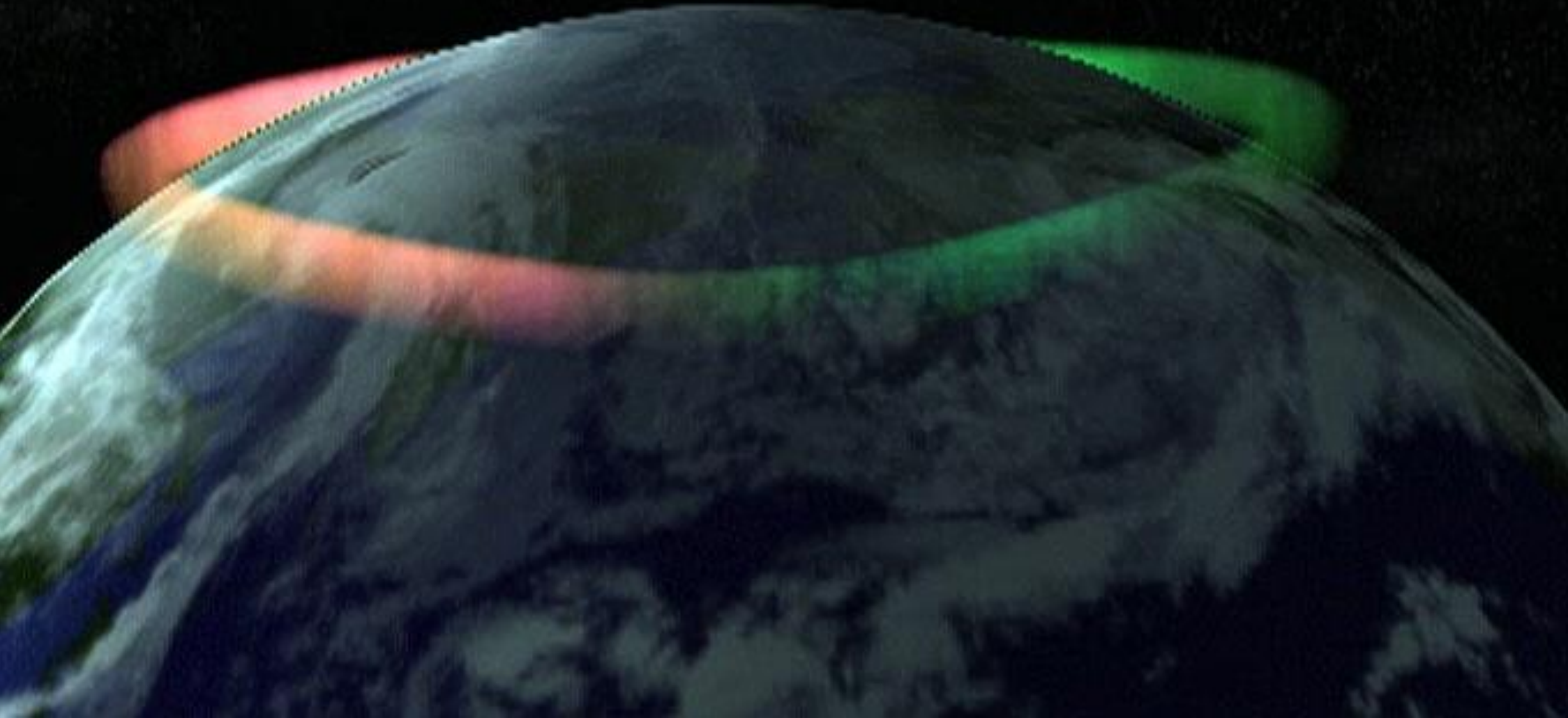
Feldstein Y. I. – SCI – 1970

Feldstein & Starkov, Dynamics of auroral belt and polar geomagnetic disturbances, (PSS, 1967). SCI – 321.

Trakhtengertz V. Y. – SCI – 1208

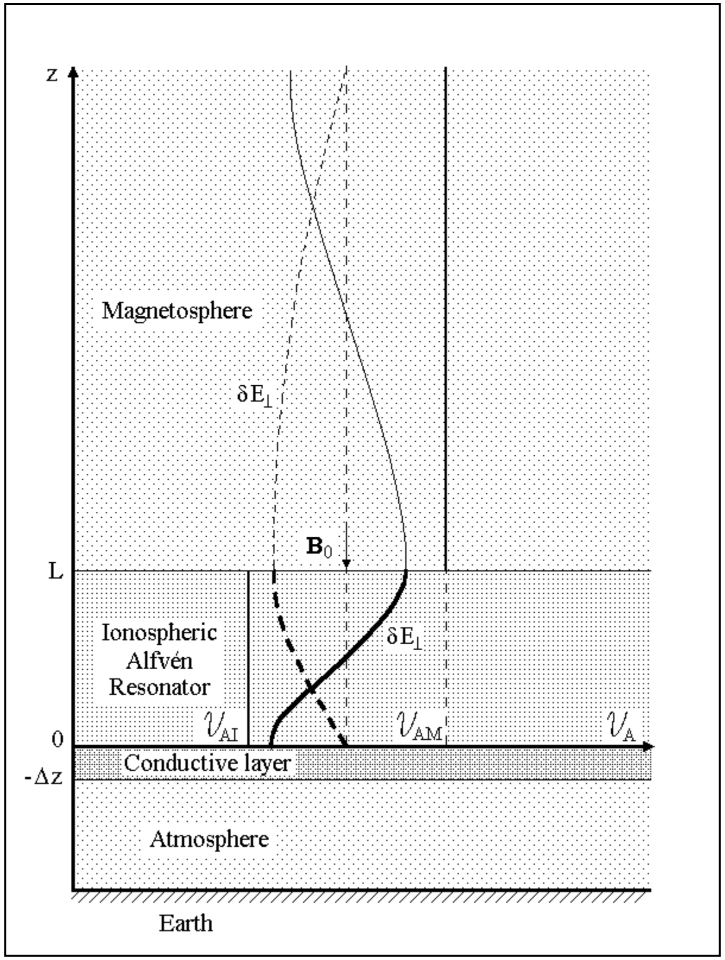
Trakhtengertz V. Y. & Feldstein A. Y., Quiet auroral arcs – ionospheric effect of magnetospheric convection, PSS, 1984.

Turbulent Alfven boundary layer…, 1991.



Авроральное колечко Ольги Хорошевой
(1961, НИИЯФ МГУ)

Schematic view



Ground and satellite observations

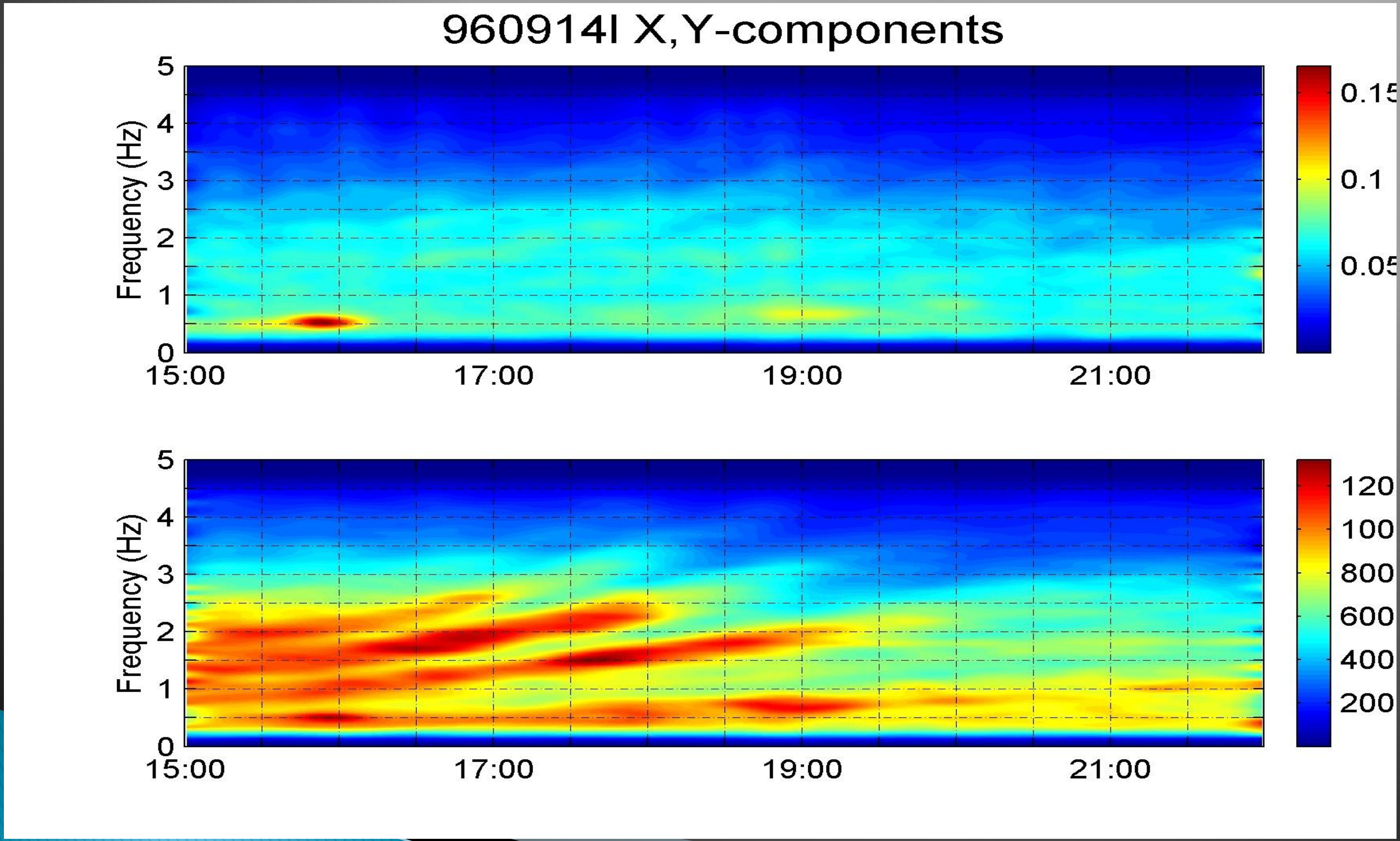
- Nizniy–Novgorod (Middle Russia)
- Borok (Middle Russia)
- Mondy (Siberia, Russia)
- Karimshino (Kamchatka, Russia)

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

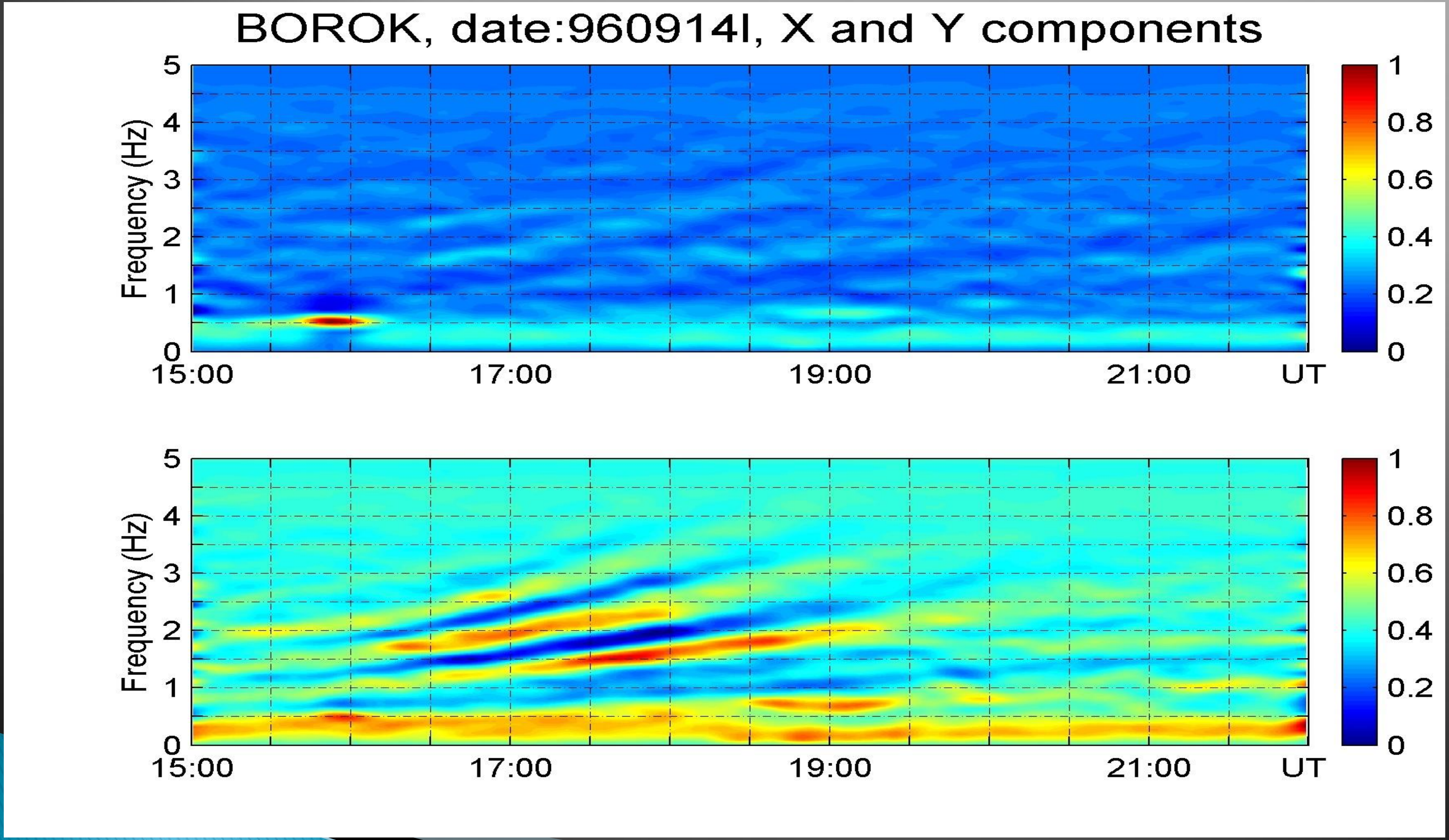
Sources of free energy for the IAR excitation

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

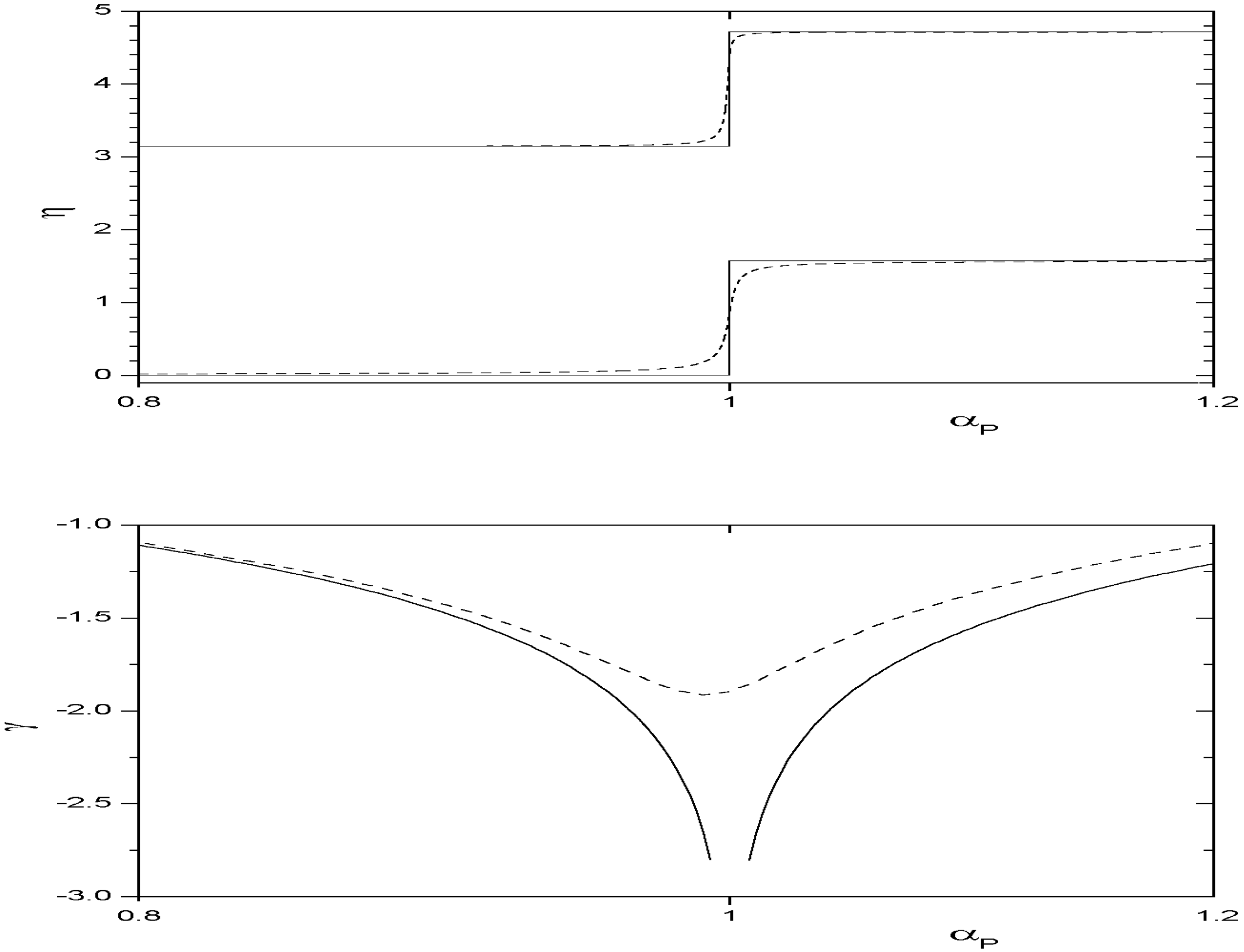
Ground observations of SRS



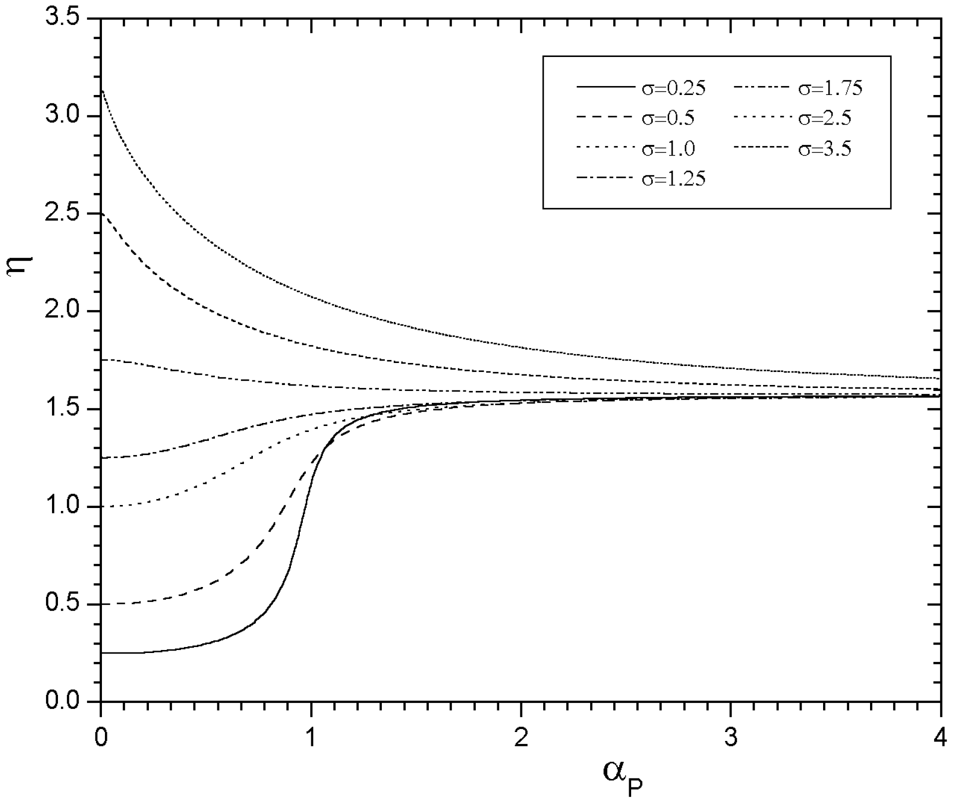
Ground observations of SRS



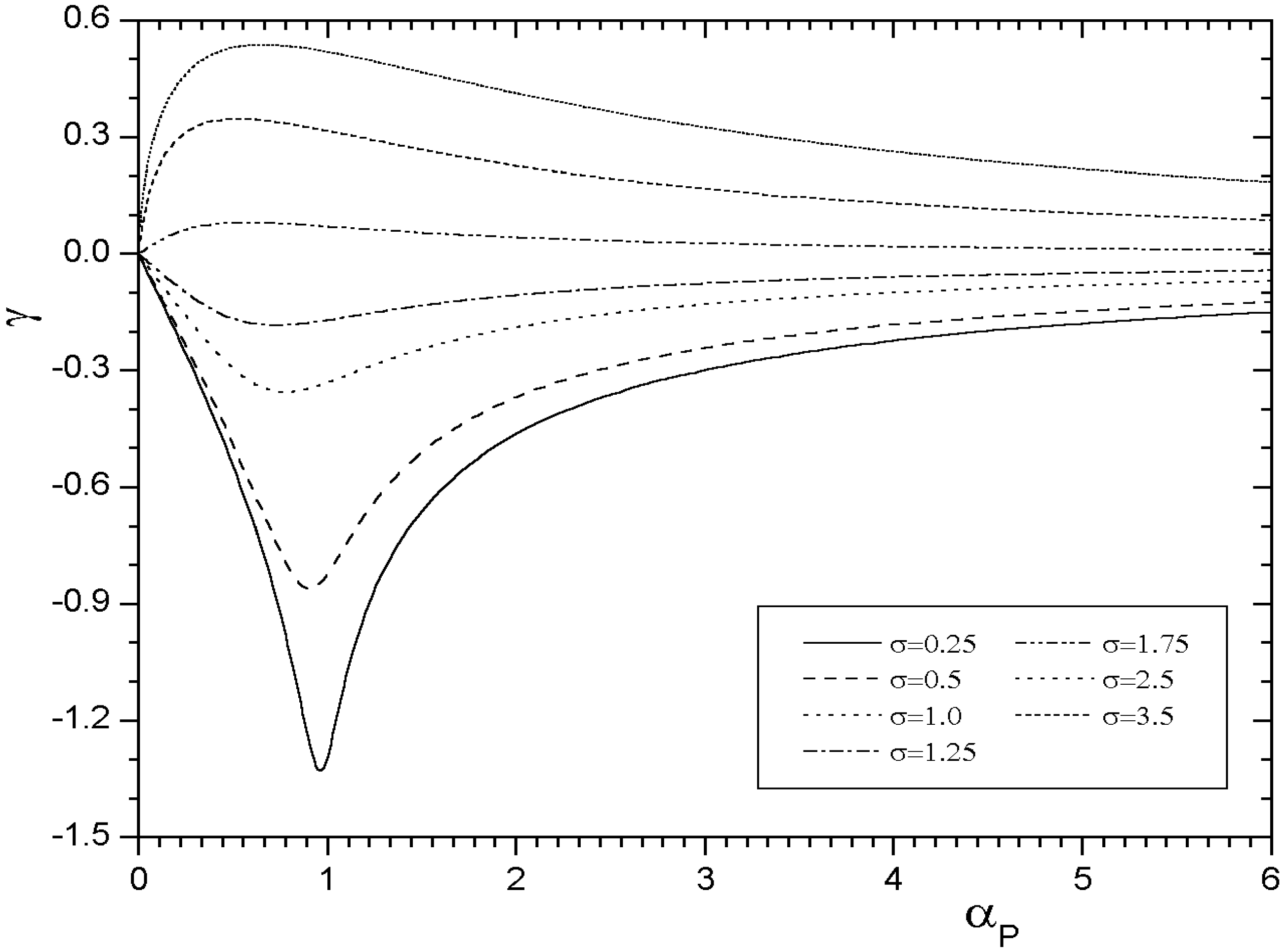
IAR Eigenmodes and damping rates



Eigen-frequencies



Variation of the damping/growth rate in the presence of magnetospheric convection



Basic NL equations

Potentials

$$E_z = \mathbf{E}\cdot\hat{\mathbf{z}} = -\partial_z\varphi - \partial_t A$$

$$\mathbf{E}_\perp = -\nabla_\perp\varphi,$$

$$\mathbf{B}_\perp = \nabla A\times\hat{\mathbf{z}}$$

$$E_\parallel = E_z + \frac{\mathbf{B}_\perp\cdot\mathbf{E}_\perp}{B_0} = D_t A - \partial_t\varphi$$

$$D_t = \partial_t + B_0^{-1}\{\varphi,\ldots\}$$

$$\{A,B\} = (\partial_x A)\partial_y B - (\partial_y A)\partial_x B$$

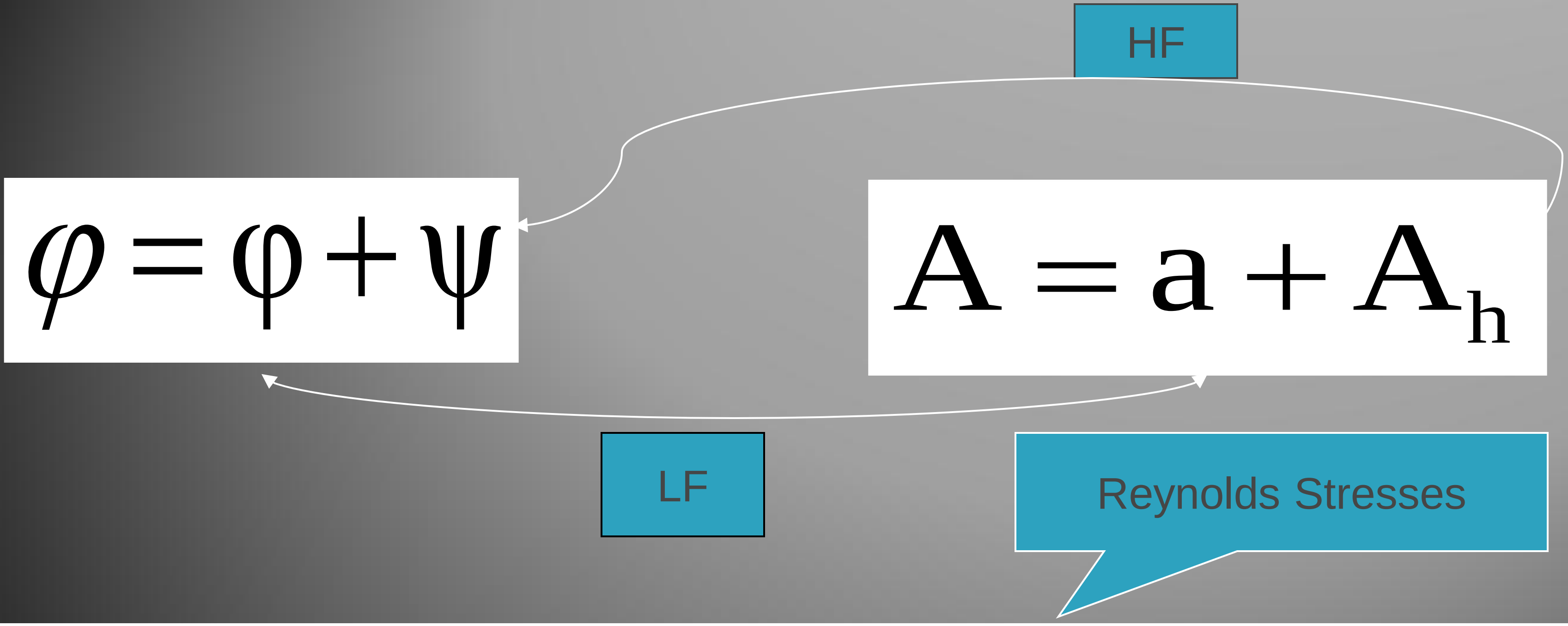
Nonlinear equations

- $D_t\nabla_\perp^2\varphi + v_A^2 D_z\nabla_\perp^2 A = 0,$

$$D_z \equiv \partial_z + B_0^{-1}\mathbf{B}_\perp\cdot\nabla$$

- $D_t(1-\lambda_e^2\nabla_\perp^2)A + \partial_z\varphi = 0.$

Multiscale expansion



HF

$$\varphi = \phi + \psi$$

$$A = a + A_h$$

LF

Reynolds Stresses

$$\partial_t \nabla_\perp^2 \phi = -B_0^{-1}\left(<\{\psi, \nabla_\perp^2 \psi\}> - v_A^2 <\{A, \nabla_\perp^2 A\}>\right)$$

$$\partial_t (1 - \lambda_e^2 \nabla_\perp^2) a = -B_0^{-1} <\{\psi, (1 - \lambda_e^2 \nabla_\perp^2) A\}>$$

Quasi-monochromatic approach

$$(\phi, a) = (\phi_{\mathbf{q}}, A_{\mathbf{q}}) \exp[i(\mathbf{q}\cdot\mathbf{r} - \Omega t)] + c.c.$$

$$\psi = \psi_0 + \psi_+ + \psi_-$$

$$A = A_0 + A_+ + A_-$$

$$(\psi_0, A_0) = (\psi_{\mathbf{k}}, A_{\mathbf{k}}) \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega_{\mathbf{k}} t)] + c.c.$$

$$(\psi_\pm, A_\pm) = (\psi_{\mathbf{k}\pm}, A_{\mathbf{k}\pm}) \exp[i(\mathbf{k}_\pm \cdot\mathbf{r} - \omega_{\mathbf{k}\pm} t)] + c.c$$

$$\omega_{\mathbf{k}\pm} = \omega_{\mathbf{k}} \pm \Omega$$

$$\mathbf{k}_\pm = \mathbf{k} \pm \mathbf{q}$$

Convective cells generation

Dispersion relation

$$\Omega_{\pm} = q\cdot v_g \pm i[b(q\times k)_z^2\,|\psi_0|^2\,B_0^{-2} - \delta\omega^2]^{1/2}$$

$$b = k^2\lambda_e^2(1+k^2\lambda_e^2)^{-1}$$

$$\delta\omega \approx b\omega_k q^2/2k^2$$

Optimal dimensions

$$\left(\frac{q}{k}\right)_{\max}^2 = \frac{2(1+k^2\lambda_e^2)^3}{k_z^2\lambda_e^2}\frac{|B_k|^2}{B_0^2}$$

Maximum growth rate

$$\frac{\gamma_{\max}}{\omega_k} = (1+k^2\lambda_e^2)^3\frac{k^2}{k_z^2}\frac{|B_k|^2}{B_0^2}$$

Competing mechanisms

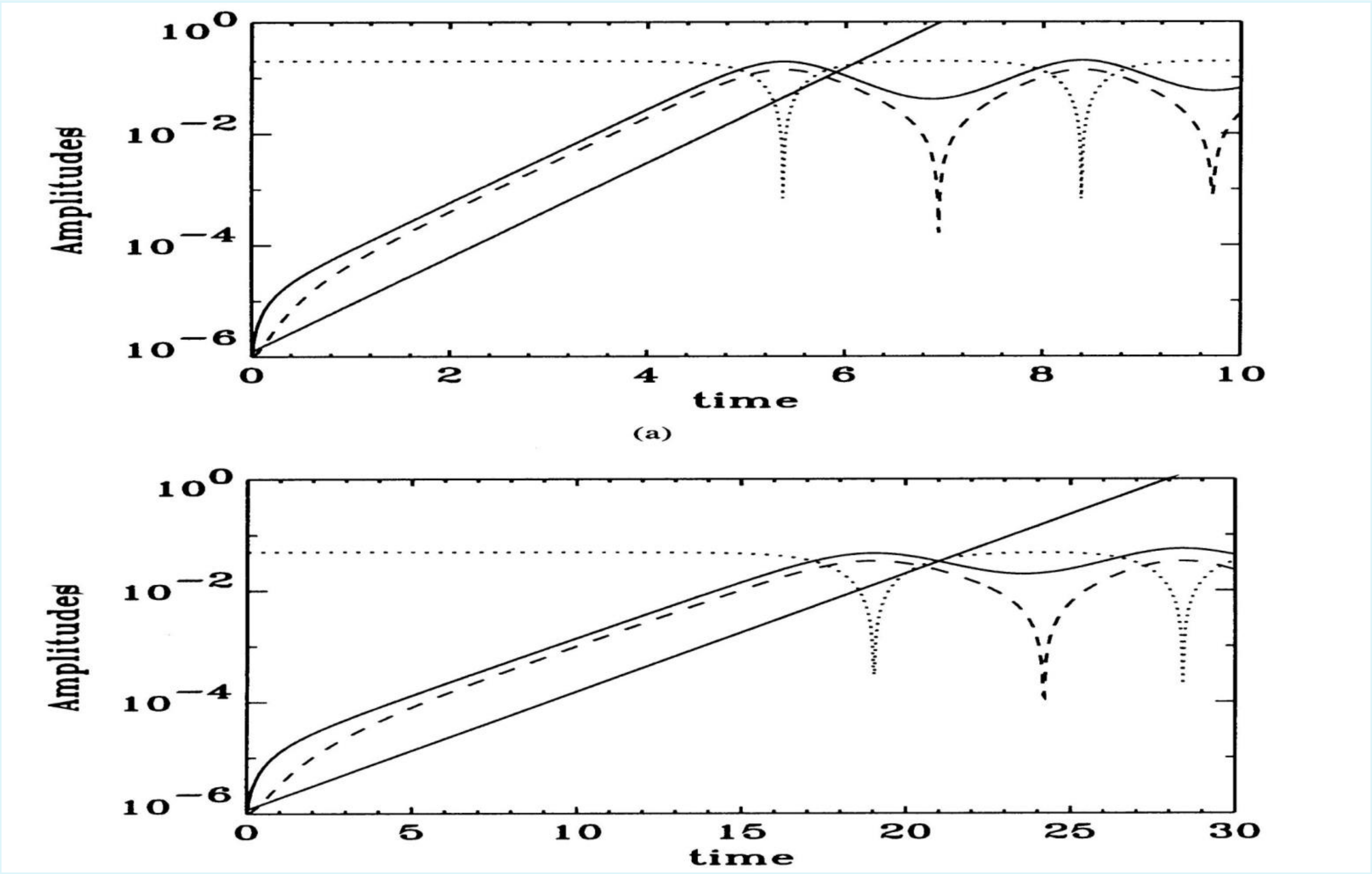
$$\mathrm{IAW} = \mathrm{IAW} + \mathrm{IAW}$$

$$\gamma_{\mathrm{AA}} = 0.15 v_A \lambda_e k_\perp^2 \left|\frac{\mathbf{B}_k}{B_0}\right|^{-1}$$

$$\frac{\gamma_{AA}}{\gamma_{cell}} = 0.15\frac{k_z\lambda_e}{(1+k_\perp^2\lambda_e^2)^{3/2}}\left|\frac{\mathrm{B}_{\mathbf{k}}}{B_0}\right|^{-1}$$

$$\frac{k_z}{k(1+k^2\lambda_e^2)} > \left|\frac{\mathbf{B}_{\mathbf{k}}}{B_0}\right| > 0.15\frac{k_z\lambda_e}{(1+k^2\lambda_e^2)^{3/2}}$$

Numerical Simulation



Suppression of the parametric instability in the auroral cavity

$$d_t(1-\lambda_e^2\nabla_\perp^2)A+\partial_z\varphi=0$$

$$\frac{v_A^2}{c^2}\partial_t\nabla_\perp^2\varphi+d_t\nabla_\perp^2\varphi+v_A^2 d_z\nabla_\perp^2 A=0$$

Relativity of the Alfven velocity

$$\gamma=[2q^2|v_E|^2(b-2\frac{v_A^2}{c^2})-\delta\omega^2]^{1/2}$$

Other predator–prey models

- Hasegawa–Mima model for drift turbulence
- Generation of zonal flows and streamers
- Bohm-like plasma diffusion
- Suppression of drift turbulence
- Charney model for Rossby waves
- Generation of zonal and meridional flows

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 (High Frequency Active Auroral Research Program)

The project started in spring 1997, Gakona Alaska

Similar projects

Russia (Vasilsursk) – SURA
Ukrain –Kharkov region
Tajikistan- Dushanbe
Peru – Jicamarka Radio observatory

Emission power

HAARP (Gakona, Alaska) – 3600 кW
EISCAT (Tromse, Norway) – 1200 кW
SPEAR (Longeer, Norway) – 288 кW

HAARP

Riometer

Basic equations (ionosphere)

Ampere's law

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

Here

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

Faraday's law

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

Parallel electron motion

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

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

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

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

Dimensionless form

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

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

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

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

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

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

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

Atmosphere

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

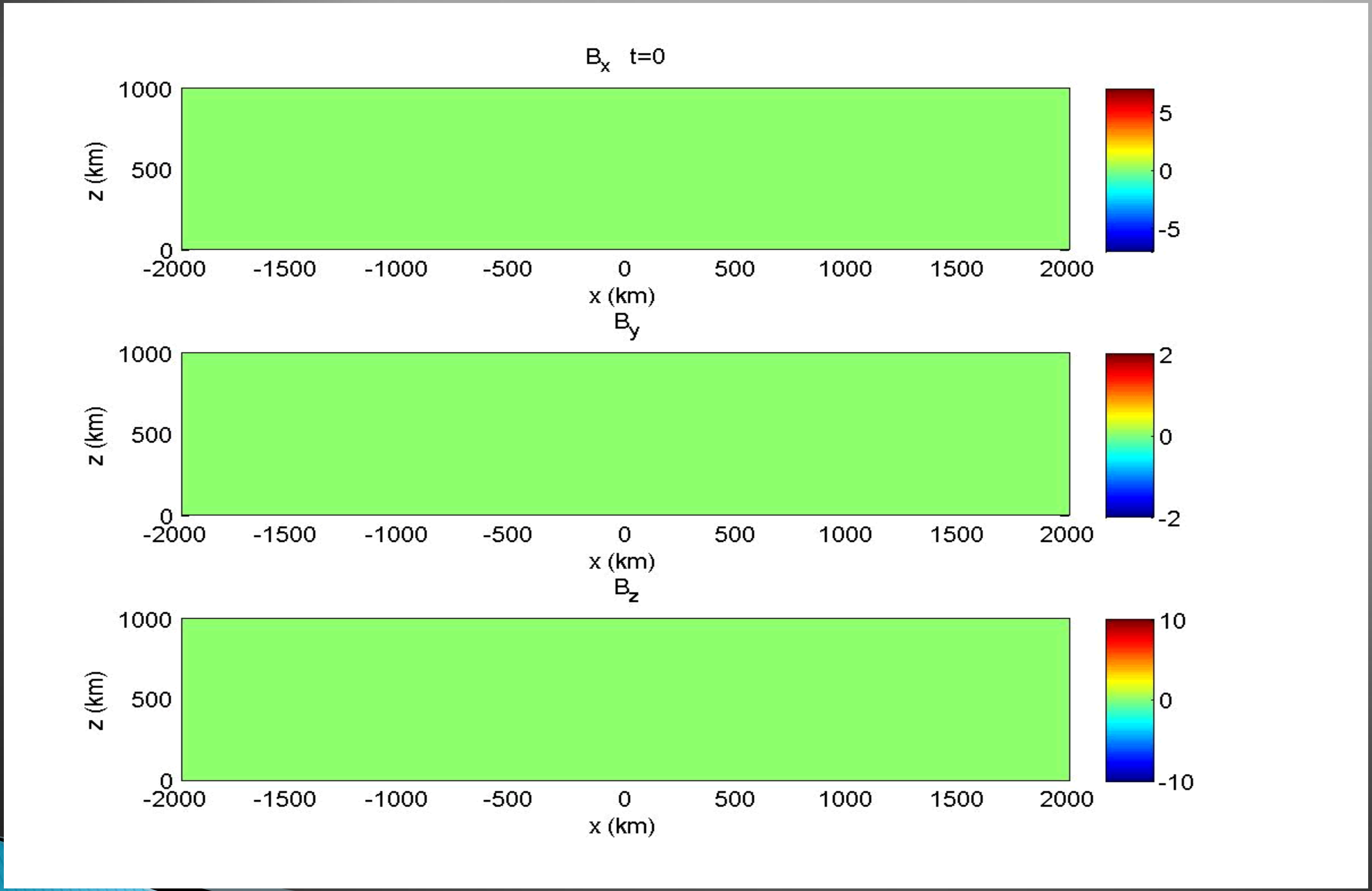
where $\delta = \left(2/\omega\mu_0\sigma_g\right)^{1/2}$ is the skin depth of the solid Earth

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

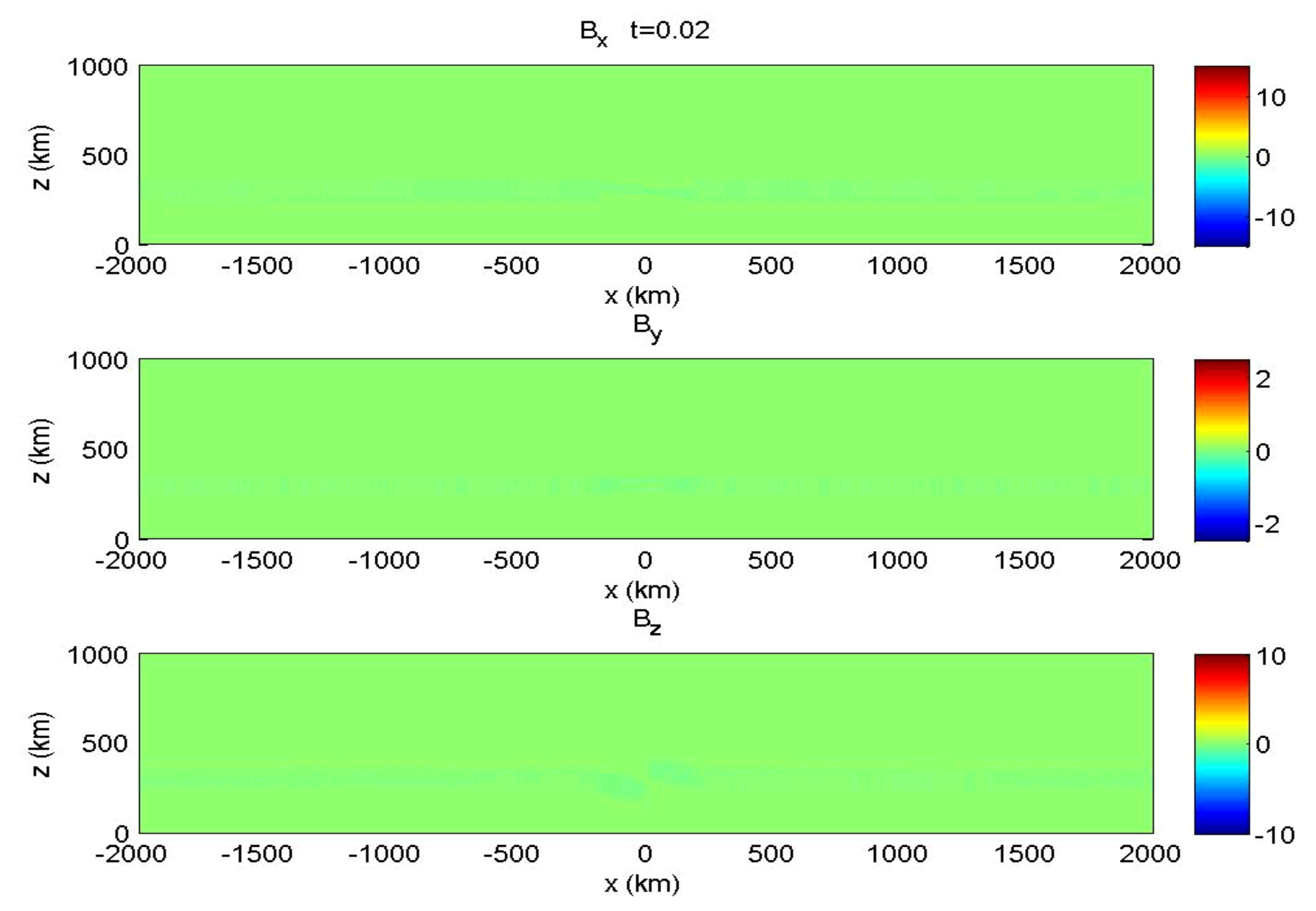
$q = -(\nu_e/\omega_{ce})\partial j/\partial\tau$ and

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

Vertical magnetic field

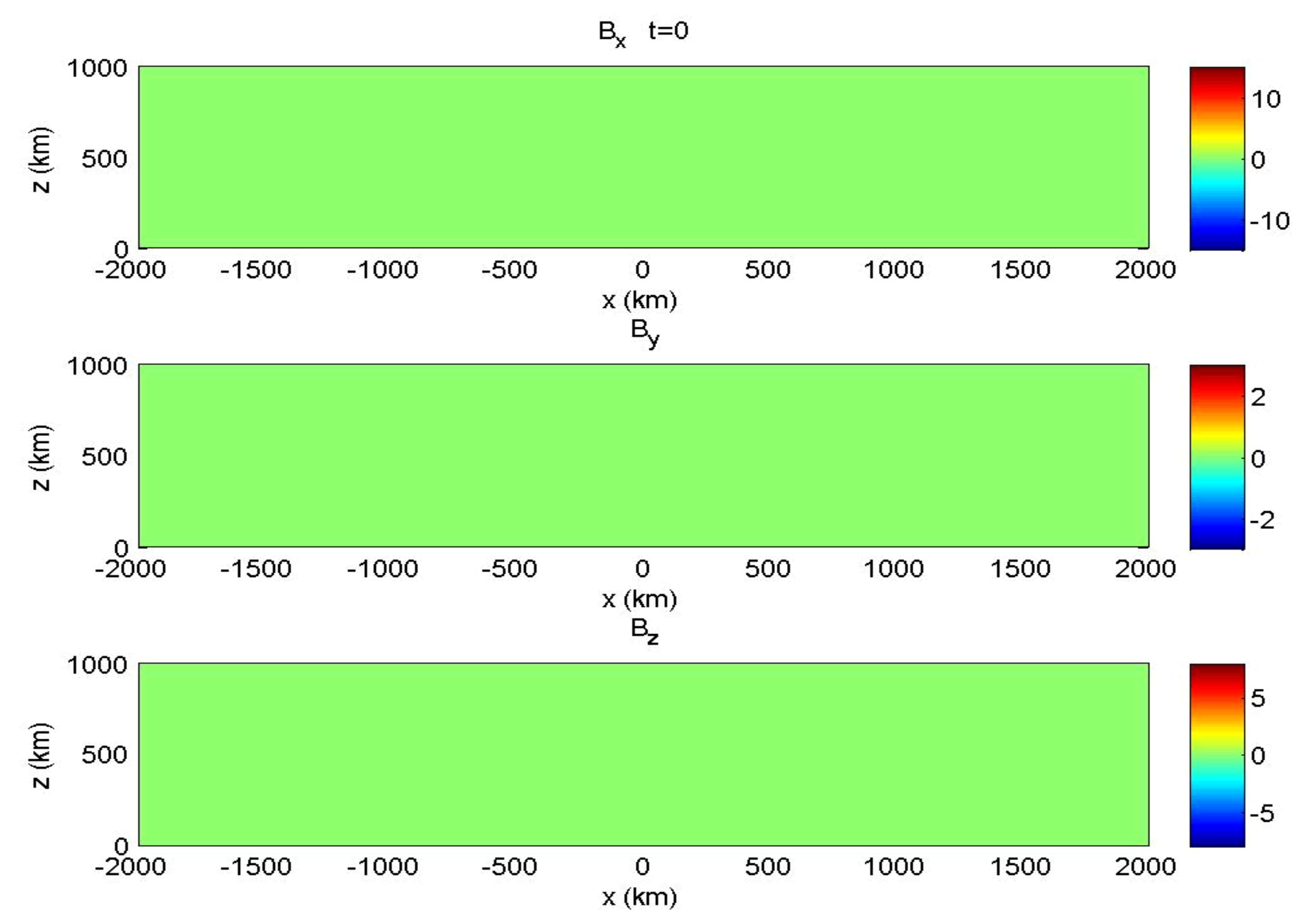


Oblique MF



B_x t=0.02
1000
500
0
z (km)
-2000
-1500
-1000
-500
0
500
1000
1500
2000
x (km)
10
0
-10
B_y
1000
500
0
z (km)
-2000
-1500
-1000
-500
0
500
1000
1500
2000
x (km)
2
0
-2
B_z
1000
500
0
z (km)
-2000
-1500
-1000
-500
0
500
1000
1500
2000
x (km)
10
0
-10

Dipole MF


B_x t=0
1000
500
0
z (km)
-2000
-1500
-1000
-500
0
500
1000
1500
2000
x (km)
10
0
-10
B_y
2
0
-2
B_z
5
0
-5

Conclusions

- Alfven waves excited in the IAR practically never appear as small amplitude linear disturbances
- Parametric instability provides a substantial damping of the IAR eigenmodes and an essential mechanism of energy transfer from small-scale AWs to large and mesoscale convective motions
- The convective cells can interact with the background medium and develop 2D NL motions in the form of Kelvin-Stuart vortex streets
- Such a scenario constitutes a dynamical paradigm for intermittency in the ionospheric turbulence containing nonlinearly coupled AWs and convective motions

Деметер

Запущен 29 июня 2004 г. С космодрома Байконур. Полярная орбита. Высота 710 км.

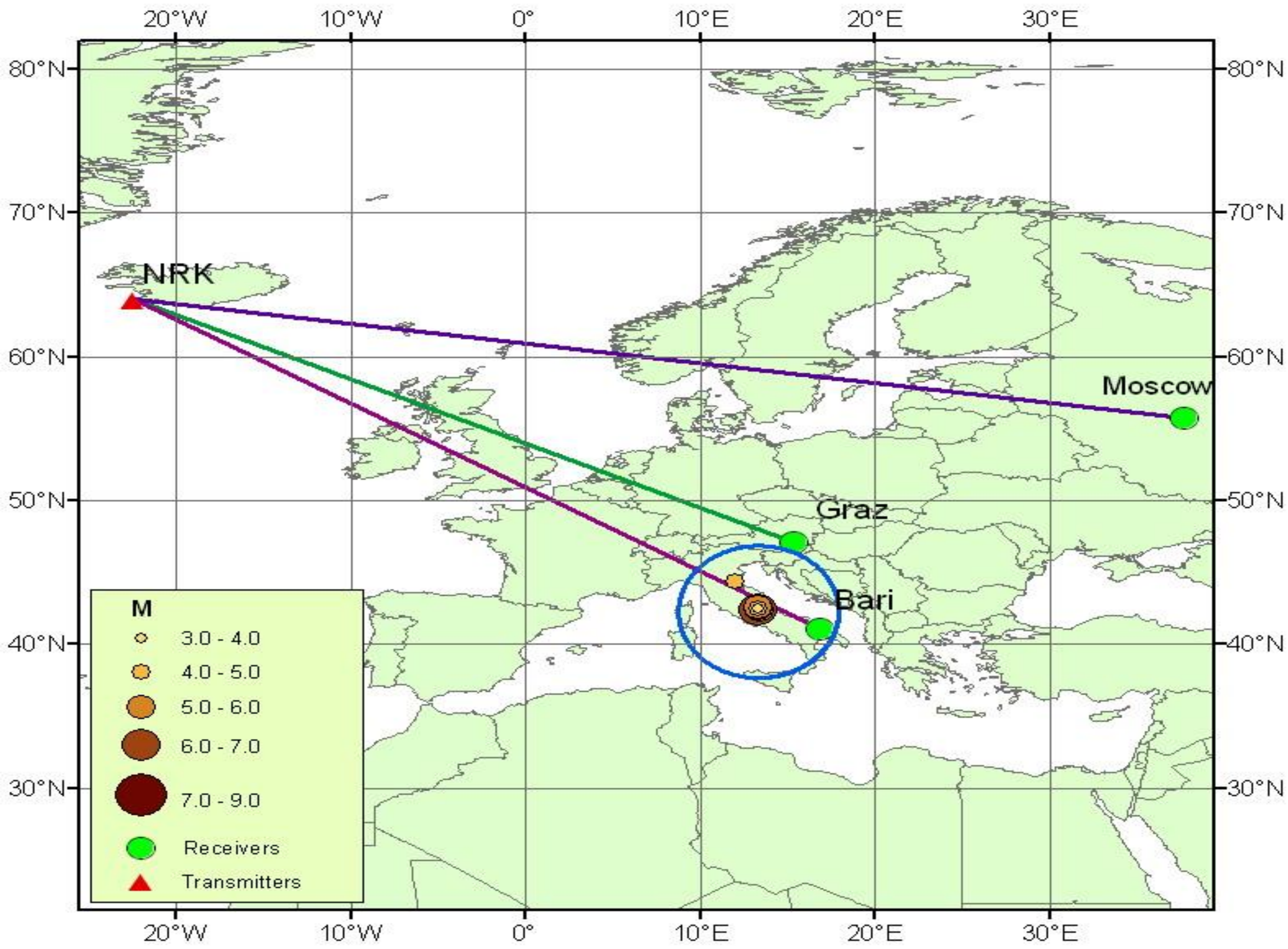
Demeter (Detection of Electro-MagneticEmissions Transmitted from Earthquake Regions)

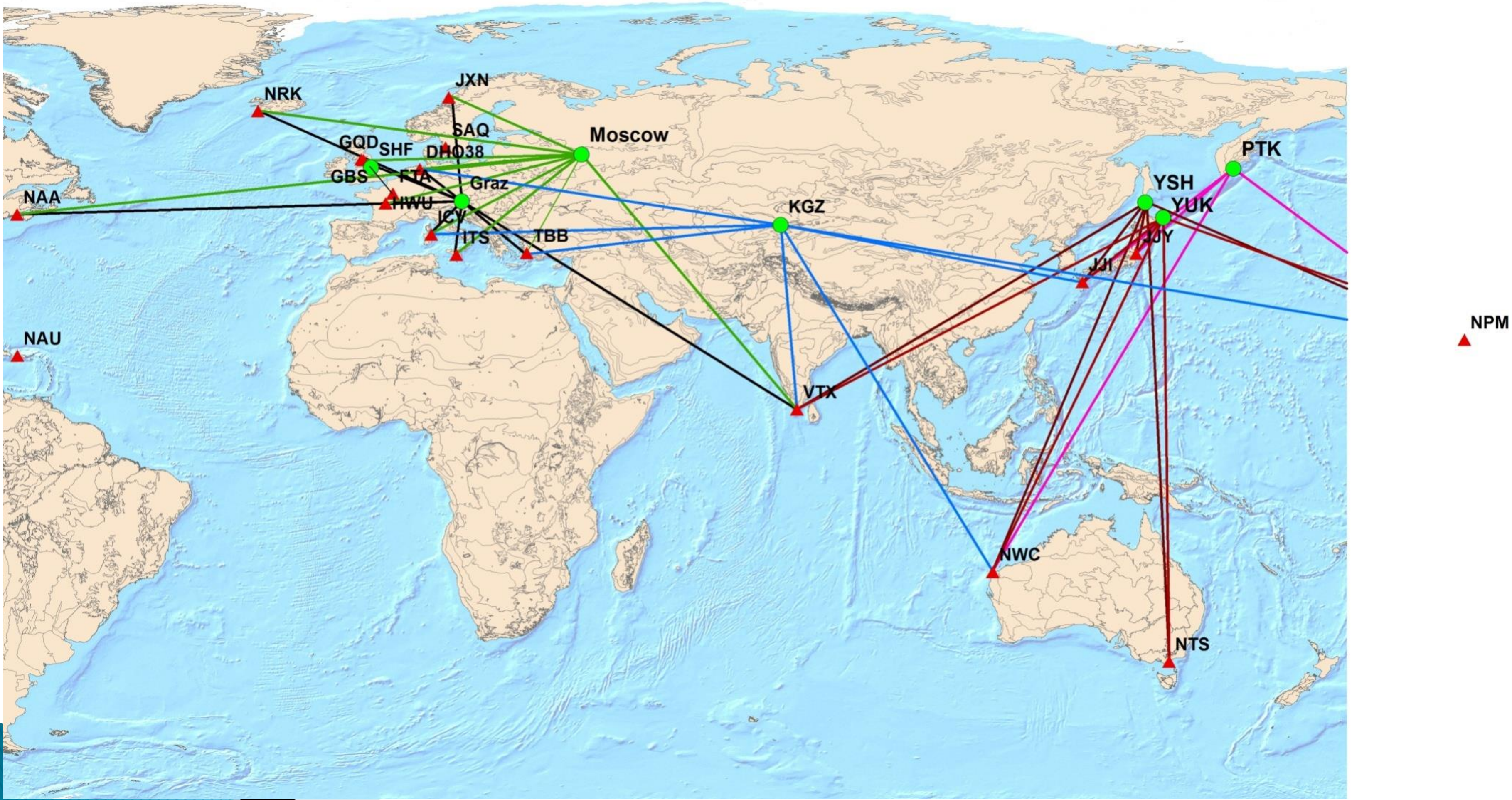
ОНЧ сигнал распространяется между Землей и ионосферой как в сферическом волноводе, нижней стенкой которого является поверхность Земли, а верхней – самая нижняя часть ионосферы – слой D. Эффективная высота отражения сигнала обычно принимается днем 70, а ночью - 90 км. Характер распространения ОНЧ сигнала определяется главным образом величиной и градиентом электронной плотности около границы атмосфера-ионосфера.

Впервые метод мониторинга ОНЧ сигналов системы «ОМЕГА» в связи с сейсмической активностью был применен сотрудниками нашего института:

Gokhberg M.B., Gufeld I.L., Rozhnoy A.A. et al. Study of seismic influence on the ionosphere by super long-wave probing of the Earth –ionosphere wave–guide, *Phys. Earth and Planet. Inter. 1989. V. 57, № 1-2. P. 64-67.*

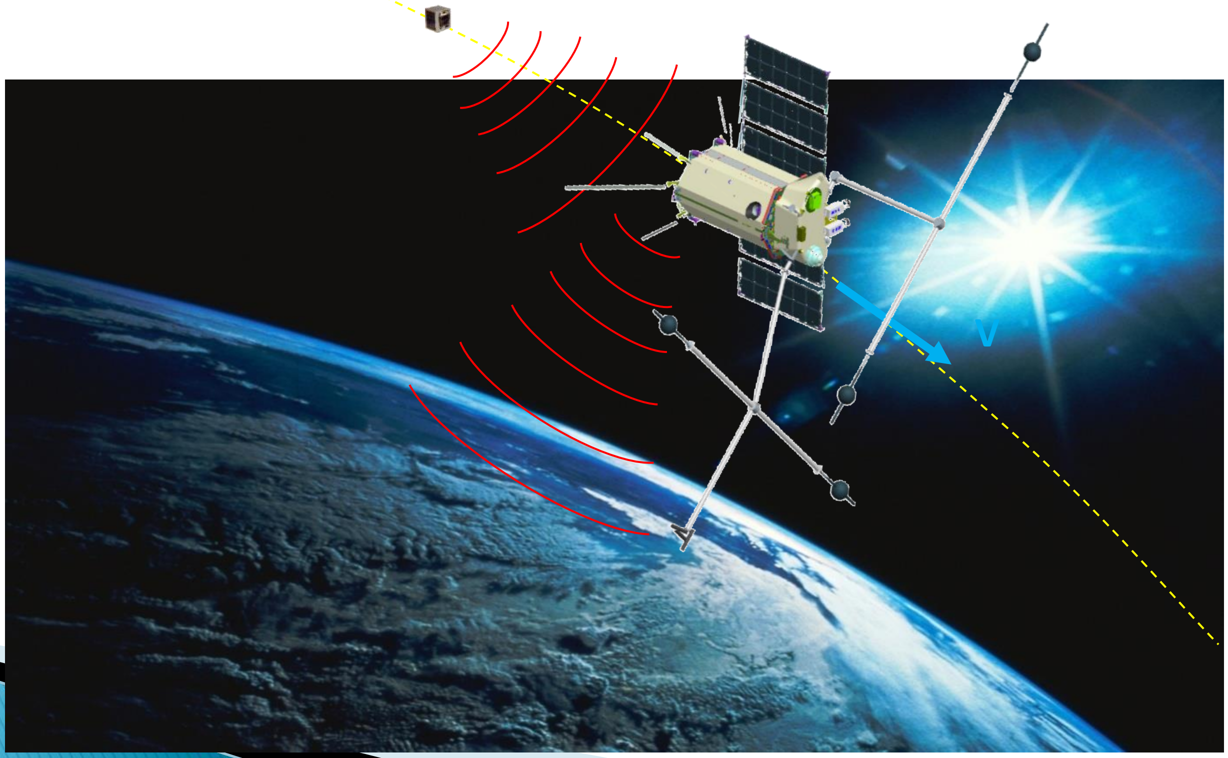
Гуфельд И.Л., Рожной А.А., Тюменцев С.Н. Возмущения радиоволновых полей перед Рудбарским и Рачинским землетрясениями, *Изв. АН Физика Земли. 1992, N 3, с. 102-106*


20°W
10°W
0°
10°E
20°E
30°E
80°N
70°N
60°N
50°N
40°N
30°N
NRK
Moscow
Graz
Bari
M
3.0 - 4.0
4.0 - 5.0
5.0 - 6.0
6.0 - 7.0
7.0 - 9.0
Receivers
Transmitters


JXN
NRK
SAQ
Moscow
GQD
SHF
DHO38
GBS
FTA
Graz
NAA
HWU
ICV
ITS
TBB
KGZ
PTK
YSH
YUK
JJY
JJI
NPM
NAU
VTX
NWC
NTS

The detection of natural disaster precursors through micro- and nano satellite observations in the Earth's ionosphere

Joint Russia – UK satellite project Twinsat



Thank you!