Introduction to heating experiments

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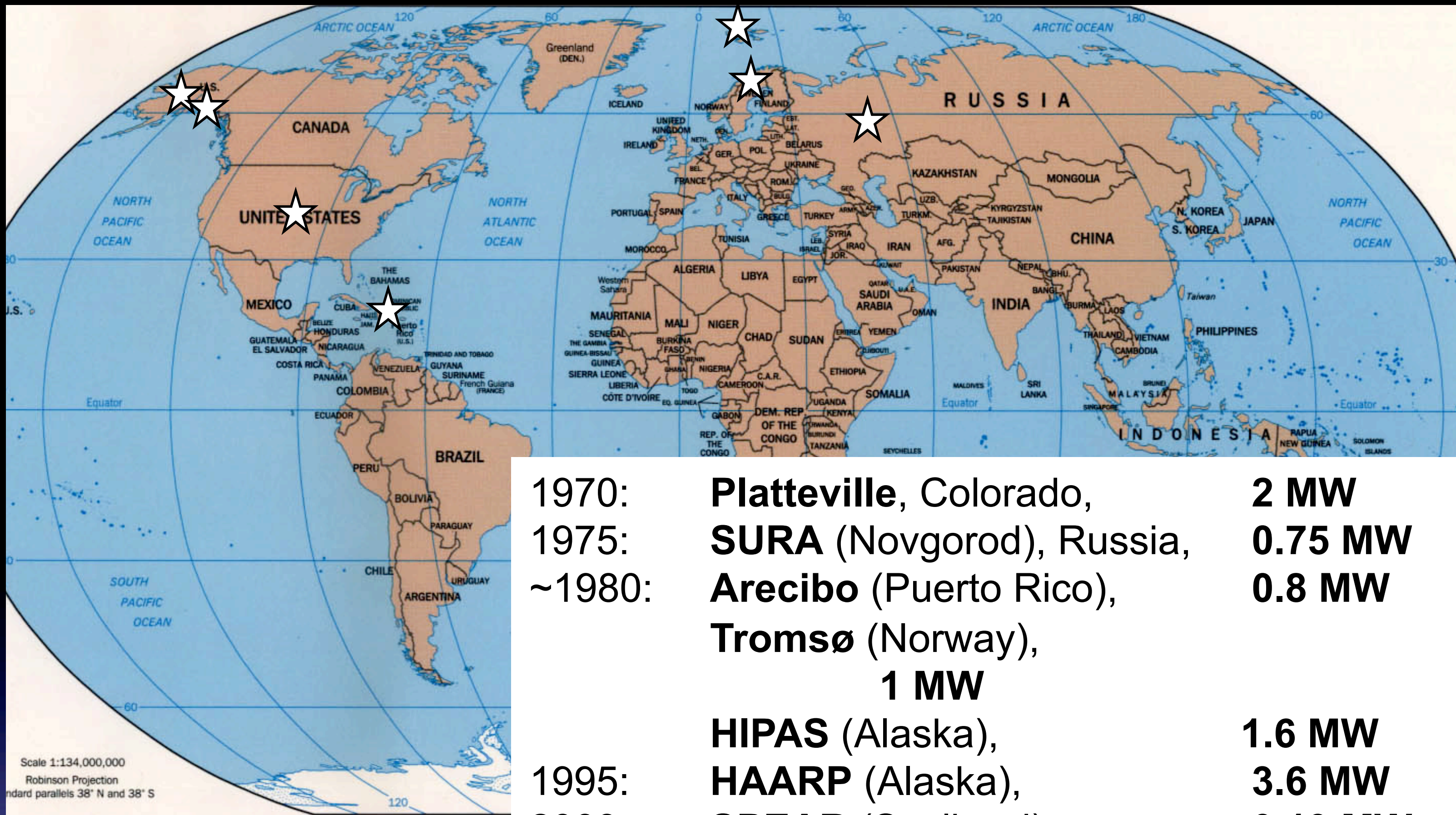
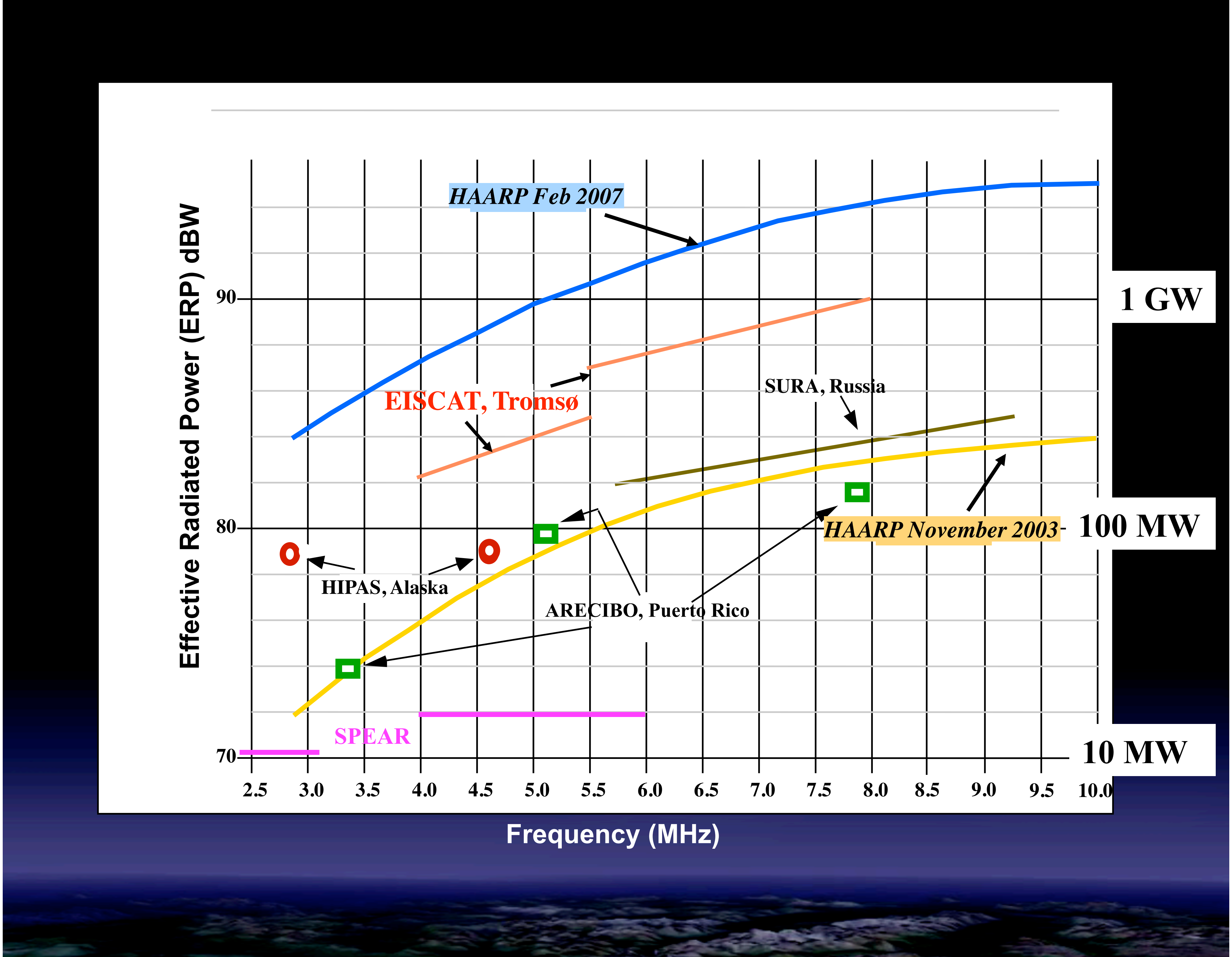
Luxembourg effect (1934)

EISCAT site at Tromso, Norway

Heating facilities since 1970

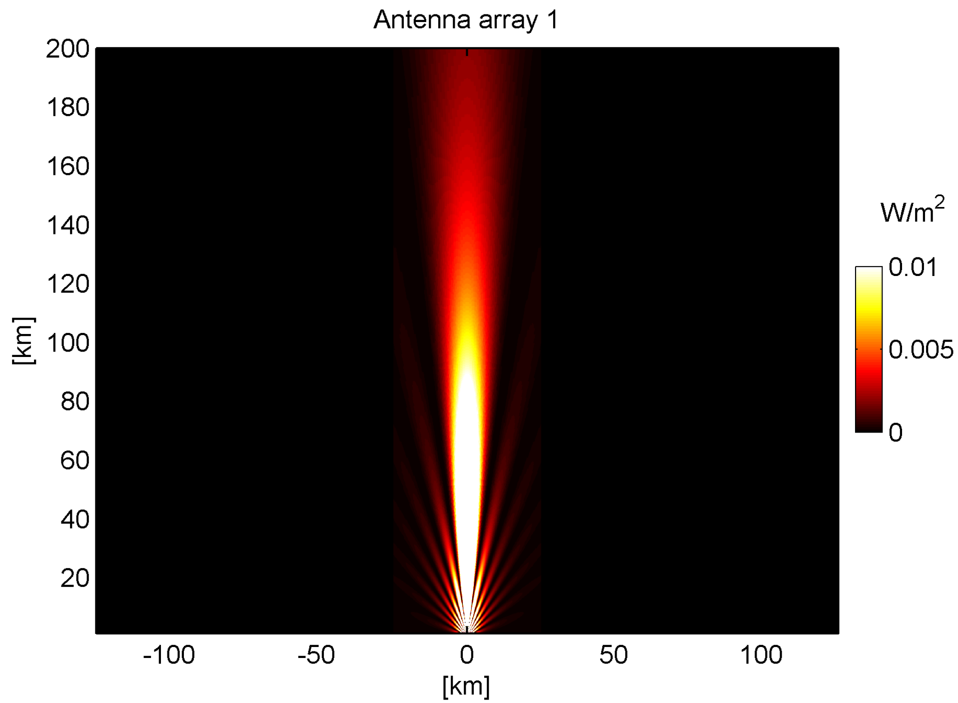


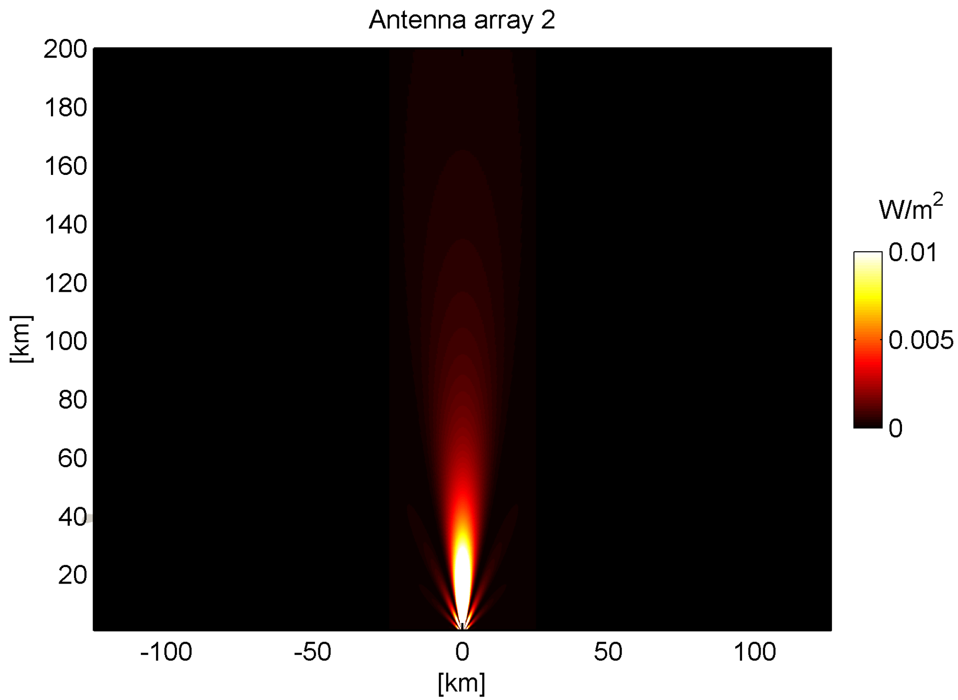
1970:	**Platteville**, Colorado,	**2 MW**
1975:	**SURA** (Novgorod), Russia,	**0.75 MW**
~1980:	**Arecibo** (Puerto Rico),	**0.8 MW**
	Tromsø (Norway), **1 MW**	
	HIPAS (Alaska),	**1.6 MW**
1995:	**HAARP** (Alaska),	**3.6 MW**
2003:	**SPEAR** (Svalbard),	**0.19 MW**


HAARP Feb 2007
EISCAT, Tromsø
SURA, Russia
HAARP November 2003
HIPAS, Alaska
ARECIBO, Puerto Rico
SPEAR
1 GW
100 MW
10 MW
90
80
70
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Effective Radiated Power (ERP) dBW
Frequency (MHz)

Intensity of the EISCAT heater beams

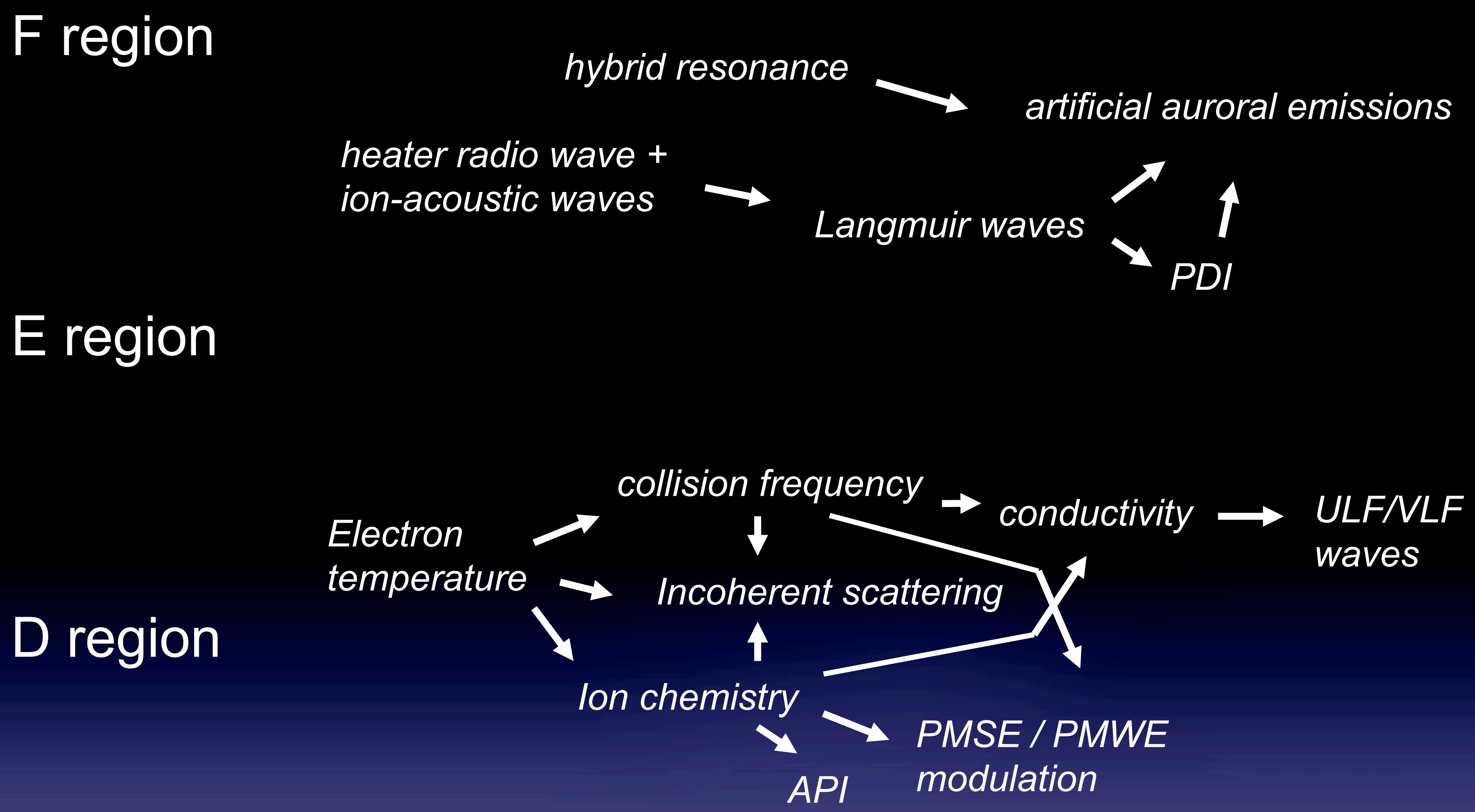
$$I_0 = \frac{PG}{4\pi r^2} = \frac{ERP}{4\pi r^2}$$





	Plateville Colorado USA	Arecibo Puerto Rico	HIPAS Alaska USA	HAARP Alaska USA	Tromsø Norway	SURA Russia	SPEAR Spitsbergen Norway
Geographic Coordinates	40.18 N 104.73 E	18.3 N 66.8 W	65.0 N 147.0 W	62.39 N 145.15W	69.6 N 19.2 E	59.13N 46.1 E	16.05 N 78.15 W
Magnetic Latitude	49.1 N	32 N	76 N	63.09 N	67 N	50 N	
Frequency [MHz]	2.8-10	3-12	2.8-5	2.8-10	4-5.5 5.5-8	4.5-9	4-6
Radiated Power [MW]	2	0.8	1.6	3.6	1.0	0.75	0.19
Antenna Gain [dB]	19	23-26	18-19	up to 40	22-25 28-31	23-26	22
Effective Radiated Power[MW]	100	160	130	up to 4000	180-340 630-1260	150-280	(8) 32

Some active HF heating effects



Outline

Intro
- History: Luxembourg effect
- Facilities around the world
- Two types of heating

Collisional heating
- Radio wave propagation theory
- Modeling the electron temperature
- Effects on incoherent scattering
- Coherent scattering: PMSE/PMWE, API

Wave excitation
- Plasma waves in principle
- Artificial aurora
- VLF/ULF waves

Summary

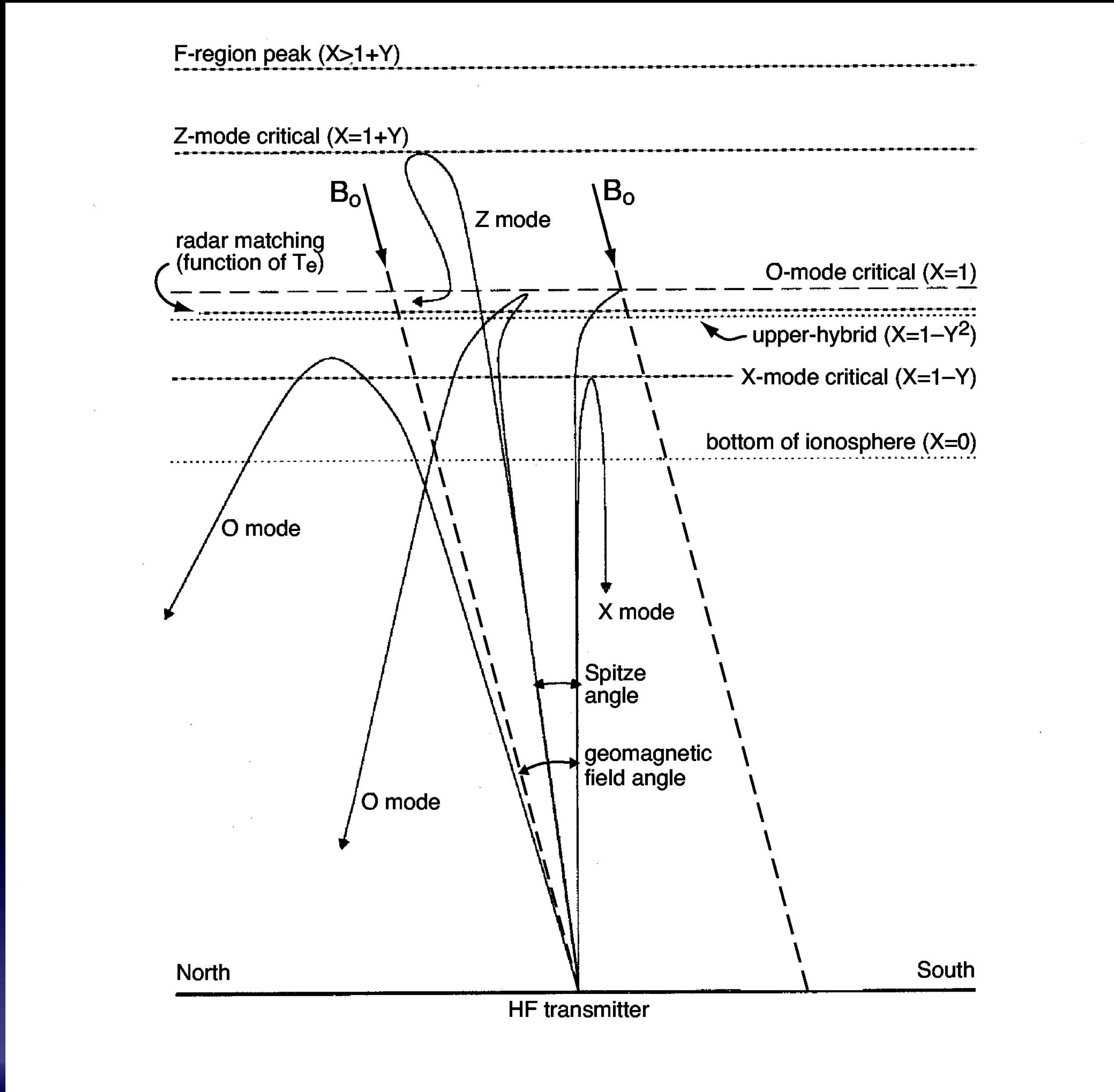
Appleton equation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{(Y\sin\theta)^2}{2(1 - X - iZ)} \pm \sqrt{\frac{(Y\sin\theta)^4}{4(1 - X - iZ)^2} + (Y\cos\theta)^2}}$$

$$X = \frac{\omega_{pe}^2}{\omega^2} = \frac{N_e e^2}{\varepsilon_o m_e \omega^2}, \quad Y = \frac{\omega_{ge}}{\omega} = \frac{eB}{m_e \omega}, \quad Z = \frac{\nu_{en}}{\omega}$$

For detailed discussion, see K.G. Budden:

Radio Waves in the Ionosphere (1961)



F-region peak (X>1+Y)
Z-mode critical (X=1+Y)
B₀
Z mode
B₀
radar matching
(function of Te)
O-mode critical (X=1)
upper-hybrid (X=1–Y2)
X-mode critical (X=1–Y)
bottom of ionosphere (X=0)
O mode
X mode
Spitze
angle
geomagnetic
field angle
O mode
North
South
HF transmitter

Appleton equation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{(Y\sin\theta)^2}{2(1 - X - iZ)} \pm \sqrt{\frac{(Y\sin\theta)^4}{4(1 - X - iZ)^2} + (Y\cos\theta)^2}}$$

$$X = \frac{\omega_{pe}^2}{\omega^2} = \frac{N_e e^2}{\varepsilon_o m_e \omega^2}, \quad Y = \frac{\omega_{ge}^2}{\omega^2} = \frac{eB}{m_e \omega}, \quad Z = \frac{\nu_{en}}{\omega}$$

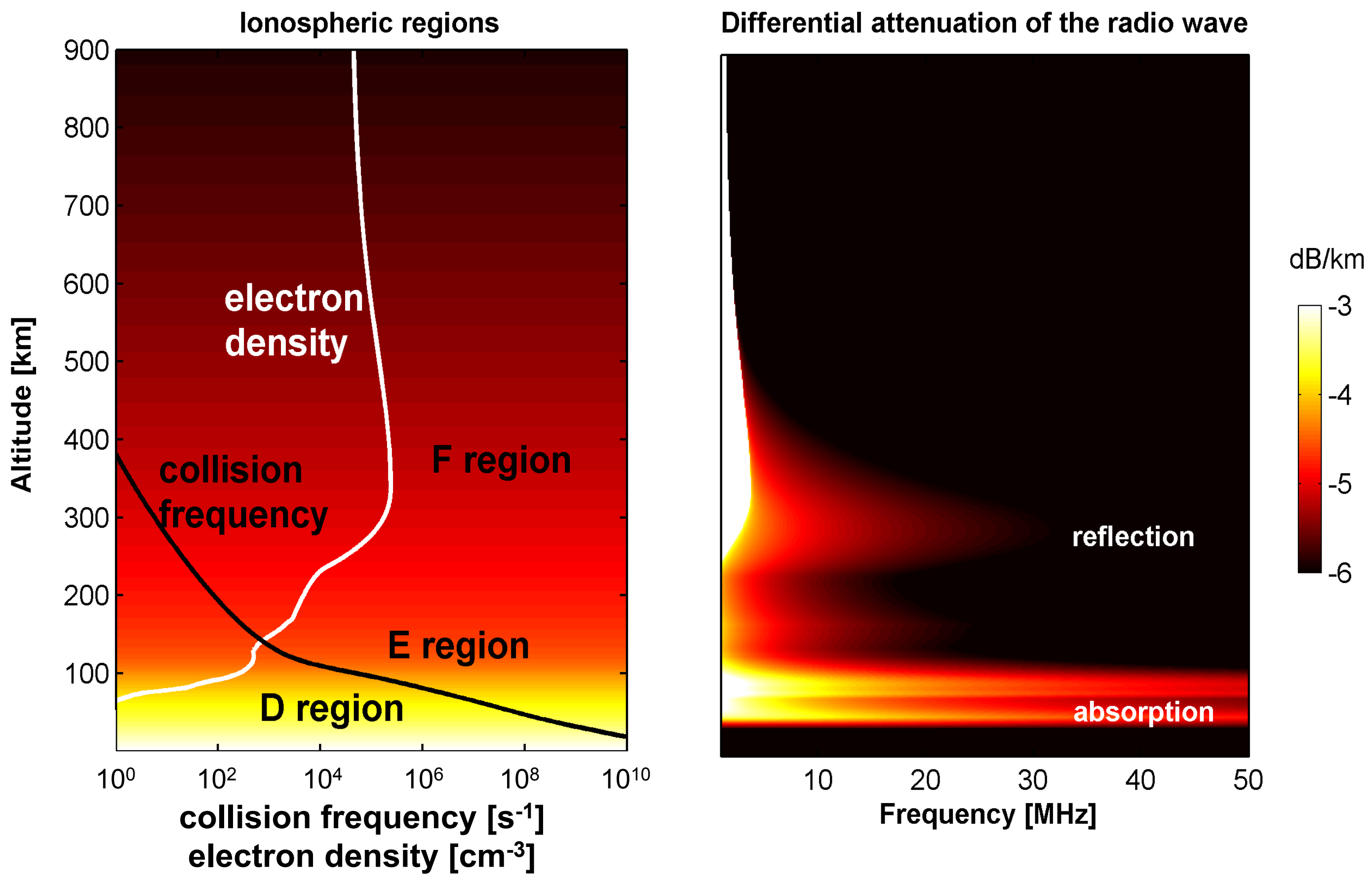
Consider a radio wave propagating in medium described by a complex refractive index $n = \Re(n) + i\Im(n)$. Apply it to the plane wave equation along path r

$$E(r,t) = E_0 \exp\left(i\omega(t - \frac{n}{c} r) \right)$$

$$= E_0 \exp\left(i\omega(t - \frac{\Re(n) + i\Im(n)}{c} r) \right)$$

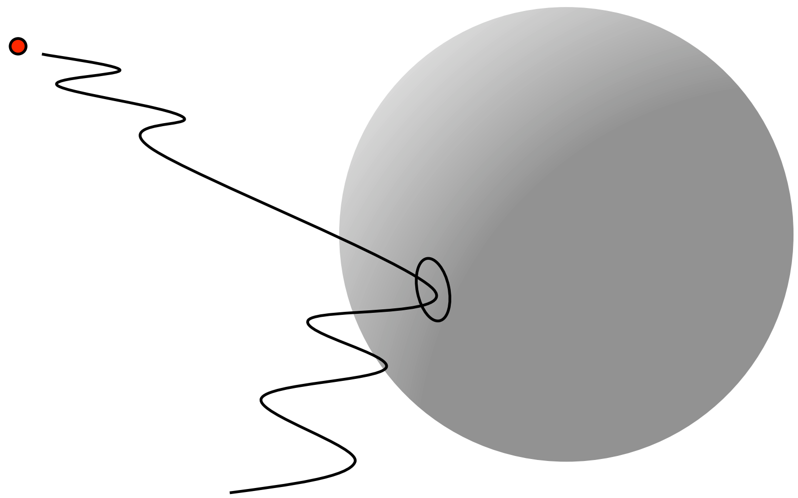
$$= \underbrace{E_0 \exp\left(i\omega\left(t - \frac{\Re(n)}{c} r \right) \right)}_{E'_0} \exp\left(\frac{\omega\Im(n)}{c} r \right)$$

$$E(r) = E'_0 \exp\left(\frac{\omega\Im(n)}{c} r \right) \xrightarrow{I \propto E^2} I(r) = I_0 \exp\left(\frac{2\omega\Im(n)}{c} r \right)$$


Ionospheric regions
Altitude [km]
900
800
700
600
500
400
300
200
100
electron density
collision frequency
F region
E region
D region
10^0
10^2
10^4
10^6
10^8
10^{10}
collision frequency [s^{-1}]
electron density [cm^{-3}]
Differential attenuation of the radio wave
reflection
absorption
10
20
30
40
50
Frequency [MHz]
dB/km
-3
-4
-5
-6

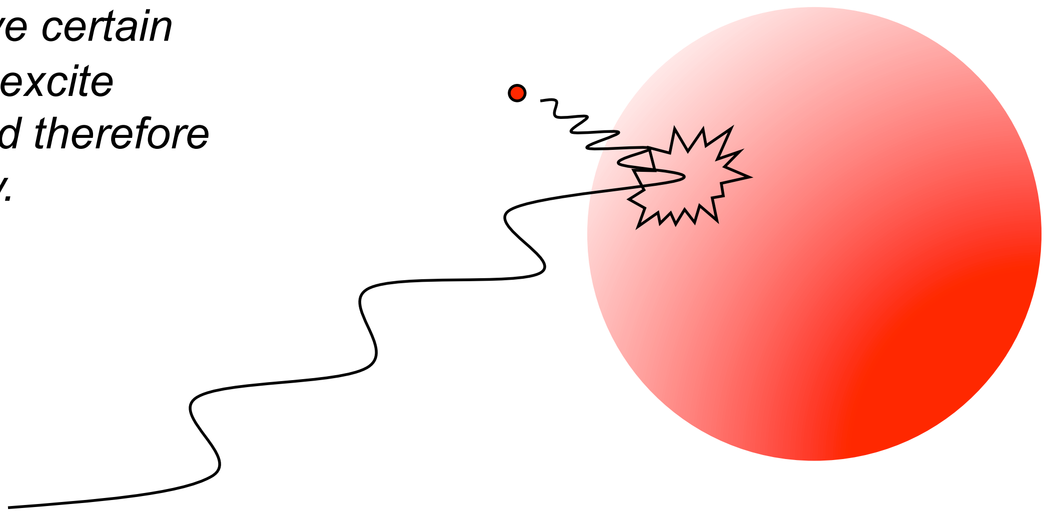
Physical interpretation of the absorption via collisions

Electric field of the radio wave makes electrons as charged particles oscillate. A part of electron energy associated to the oscillation motion is transformed into random kinetic motion in collisions.



Physical interpretation of the absorption via collisions

However, when the electron kinetic energy grows above certain level it can excite neutrals and therefore lose energy.



Energy transfer from the wave to the electron gas

Intensity of the point source radio wave along path r is

$$I(r) = I_0 \exp\left(\frac{2\omega}{c} \int_0^r \Im(n) dr \right) = \frac{PG}{4\pi r^2} \exp\left(\frac{2\omega}{c} \int_0^r \Im(n) dr \right)$$

and absorbed power per volume element is

$$Q(r) = -\frac{dI(r)}{dr} = -\frac{2\omega \Im(n_r)}{c} I(r)$$

Electron energy loss

Electron energy loss processes included in our model

- *Vibrational and rotational excitation of O_2 and N_2 (Pavlov, 1998)*
- *Excitations of atomic oxygen (Stubbe and Varnum, 1972)*

Loss rate L is the energy, lost by electrons, per volume and time unit.

Electrons in a thermal equilibrium

If all the absorbed energy is transferred to electron thermal energy, then the equilibrium between gain and loss is

$$Q(N_e, \nu_{en}, \mathbf{B}, \text{wave parameters}) = L(N_e, T_e, T_n, \text{neutral densities})$$

ω, polarisation(o/x), I

$[O_2]$, $[N_2]$, $[O]$

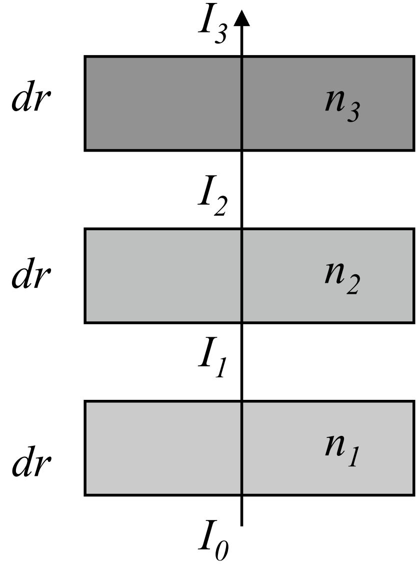
$$\nu_{en} = \nu_{en}(T_e, T_n, \text{neutral densities})$$

The electron temperature is calculated in dr layers:

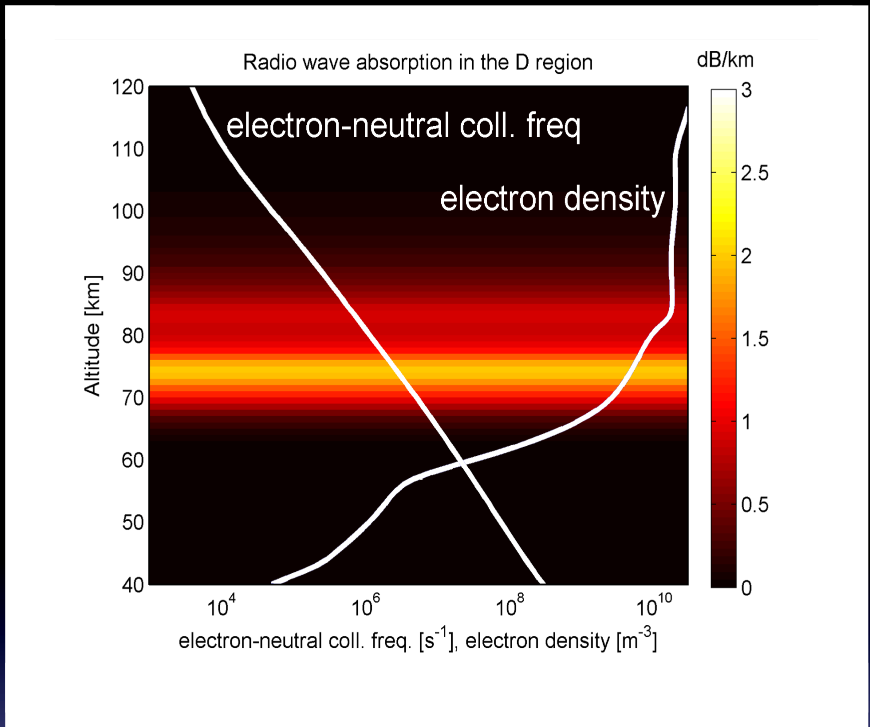
- *Calculate the intensity below*

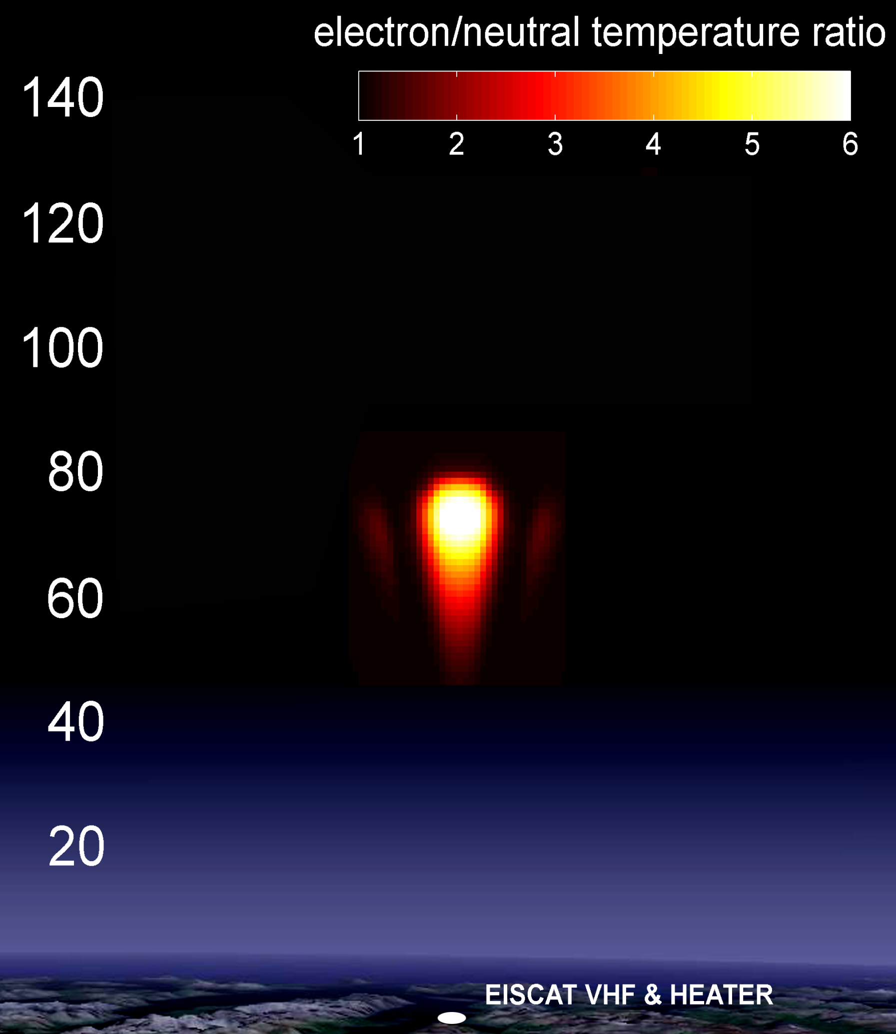
$$I = \frac{PG}{4\pi r^2}\exp\left(\frac{2\omega}{c}\int_0^r \Im(n)\,dr\right)$$

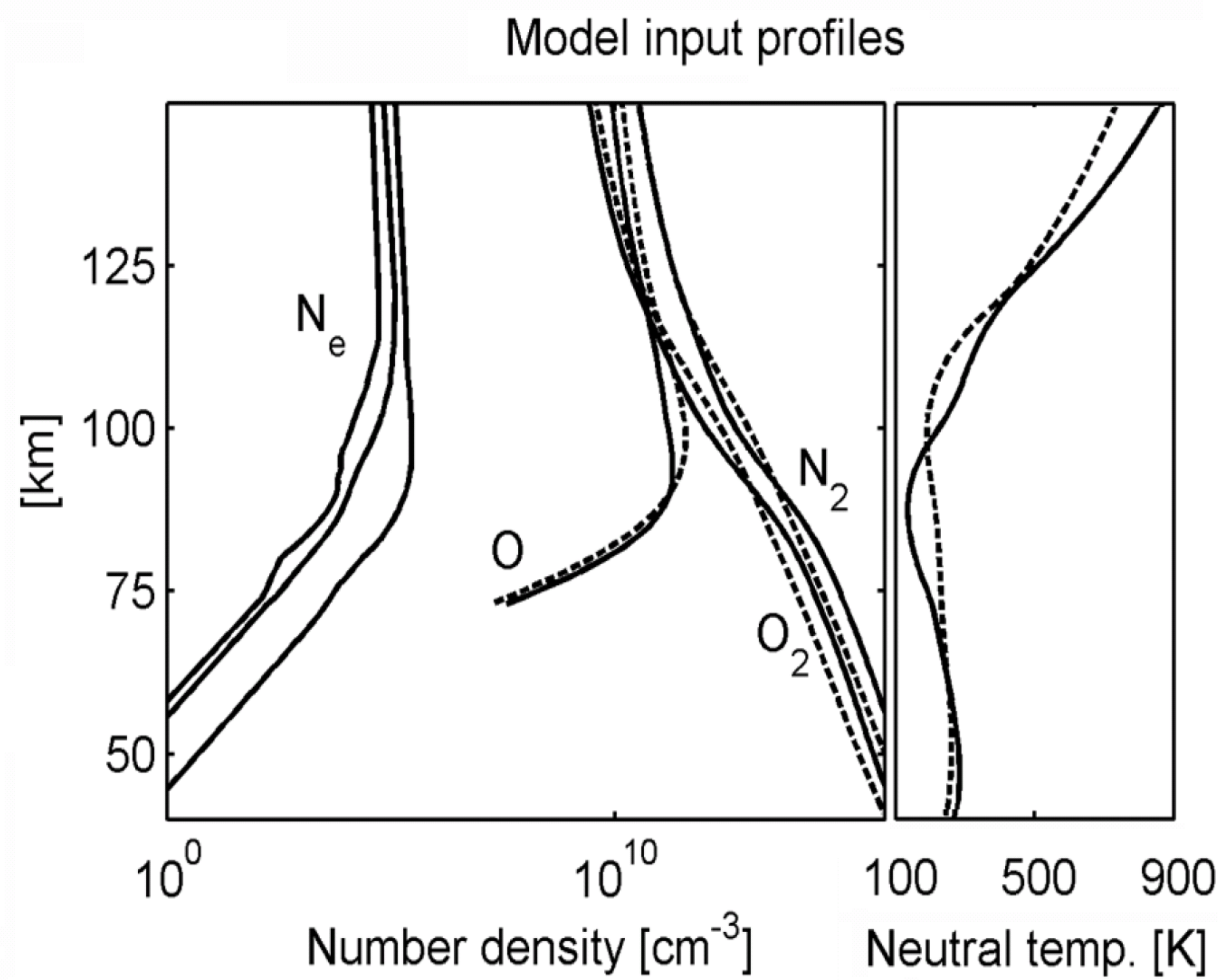
- *Find T_e which obeys the energy balance $Q=L$*
- *recalculate the refractive index in this T_e*



The modelled heating effect

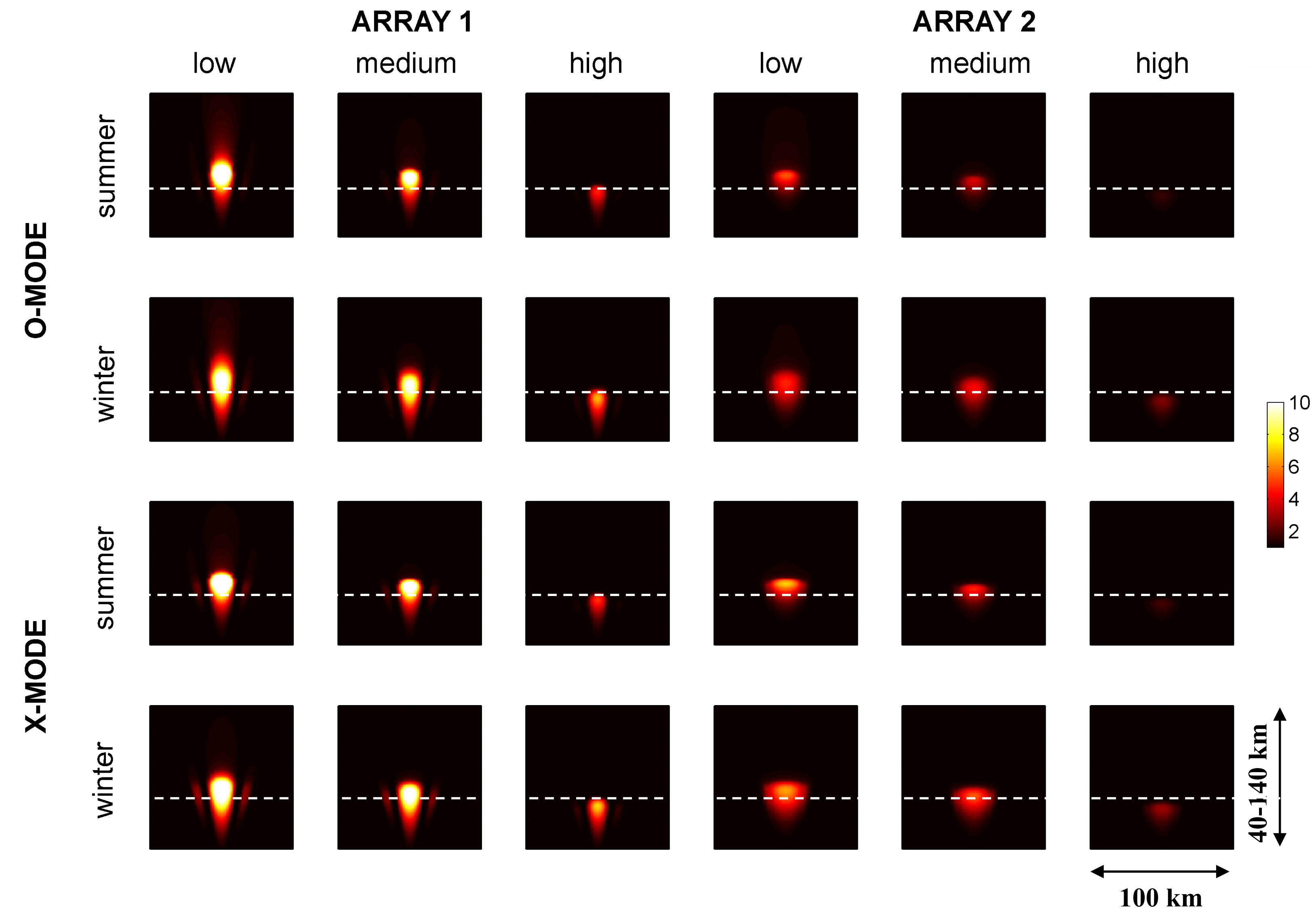




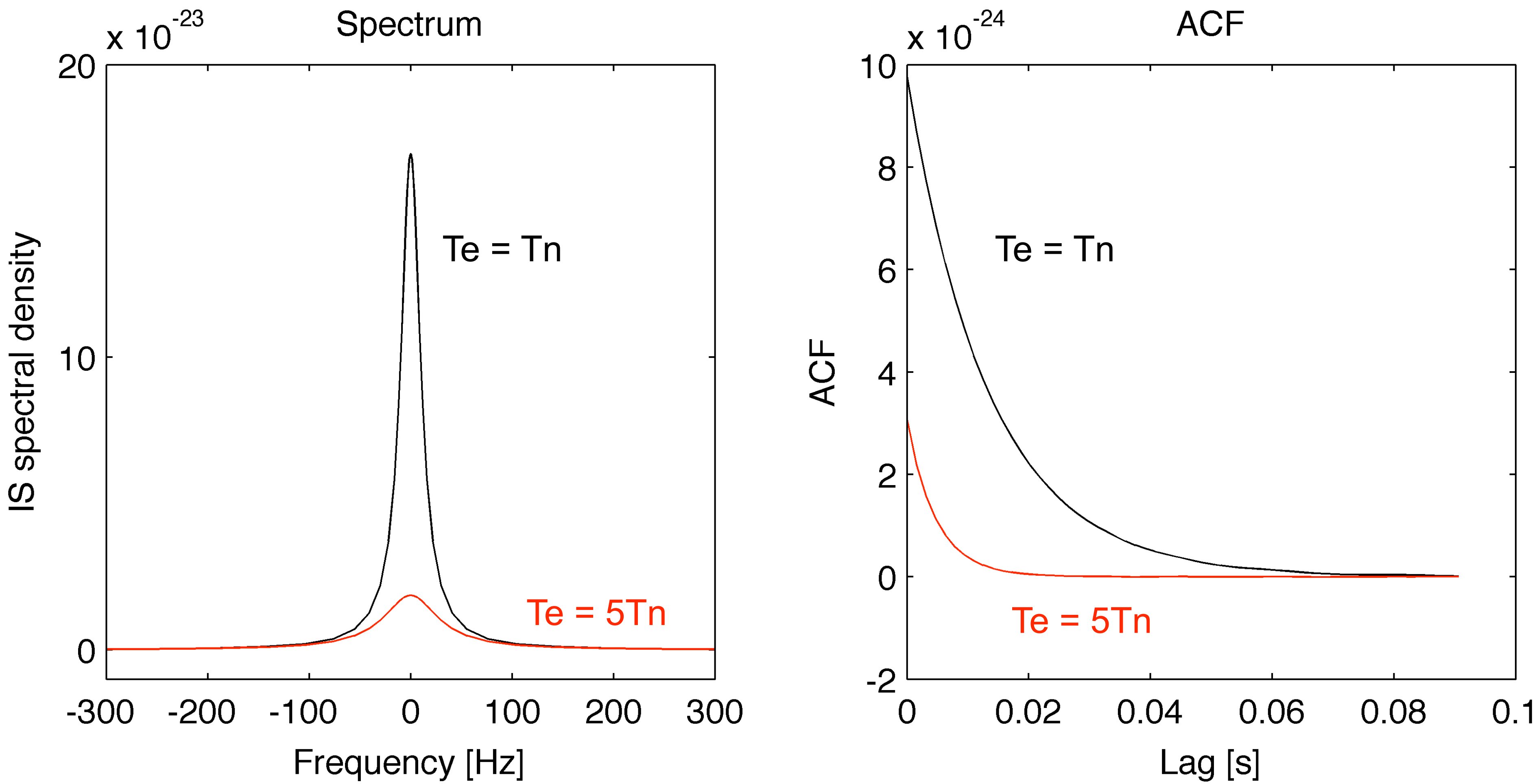


Model input profiles
[km]
125
100
75
50
N_e
O
N_2
O_2
10^0
10^10
100
500
900
Number density [cm^-3]
Neutral temp. [K]

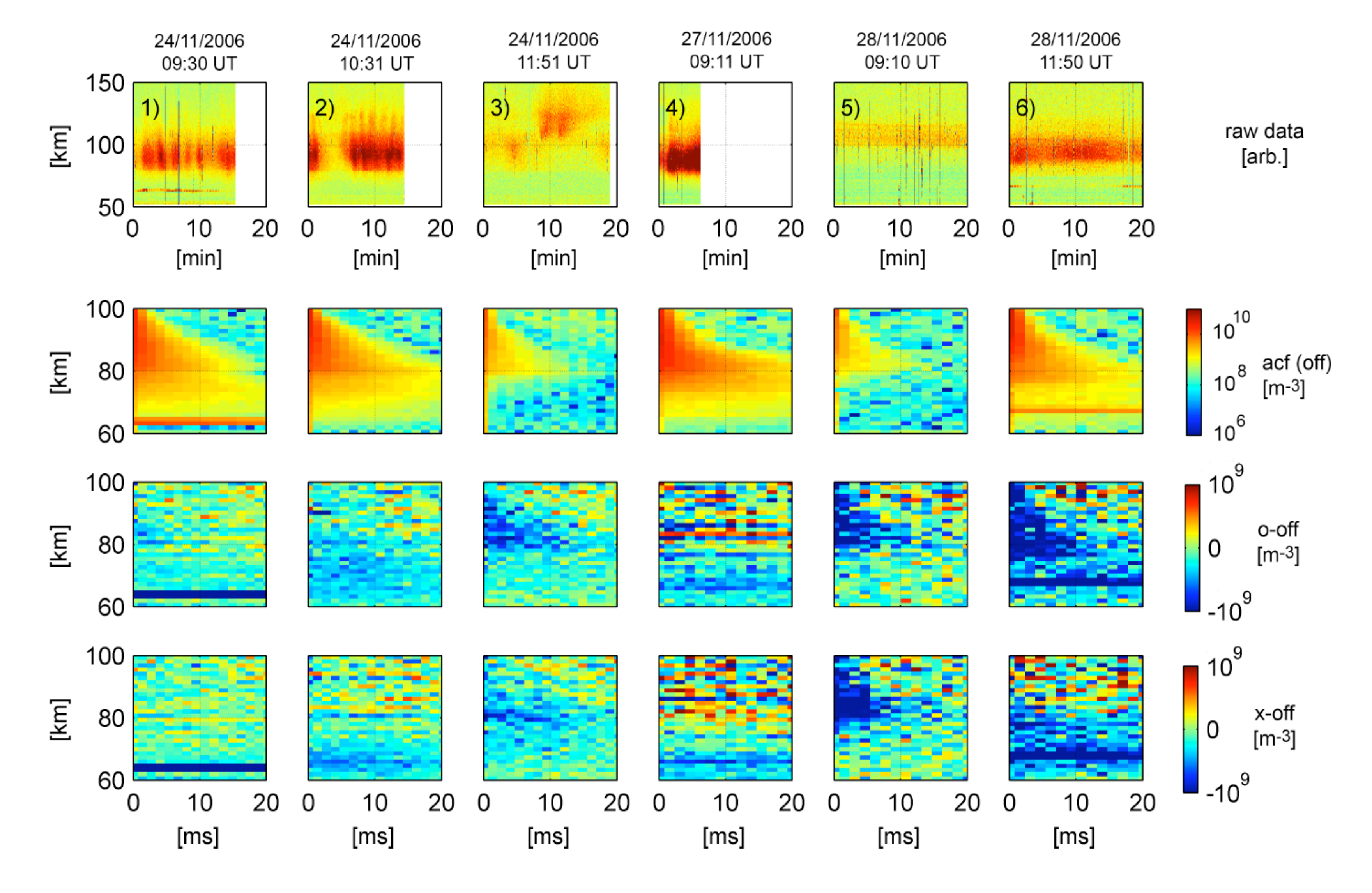
Modelled heating effect in the D region



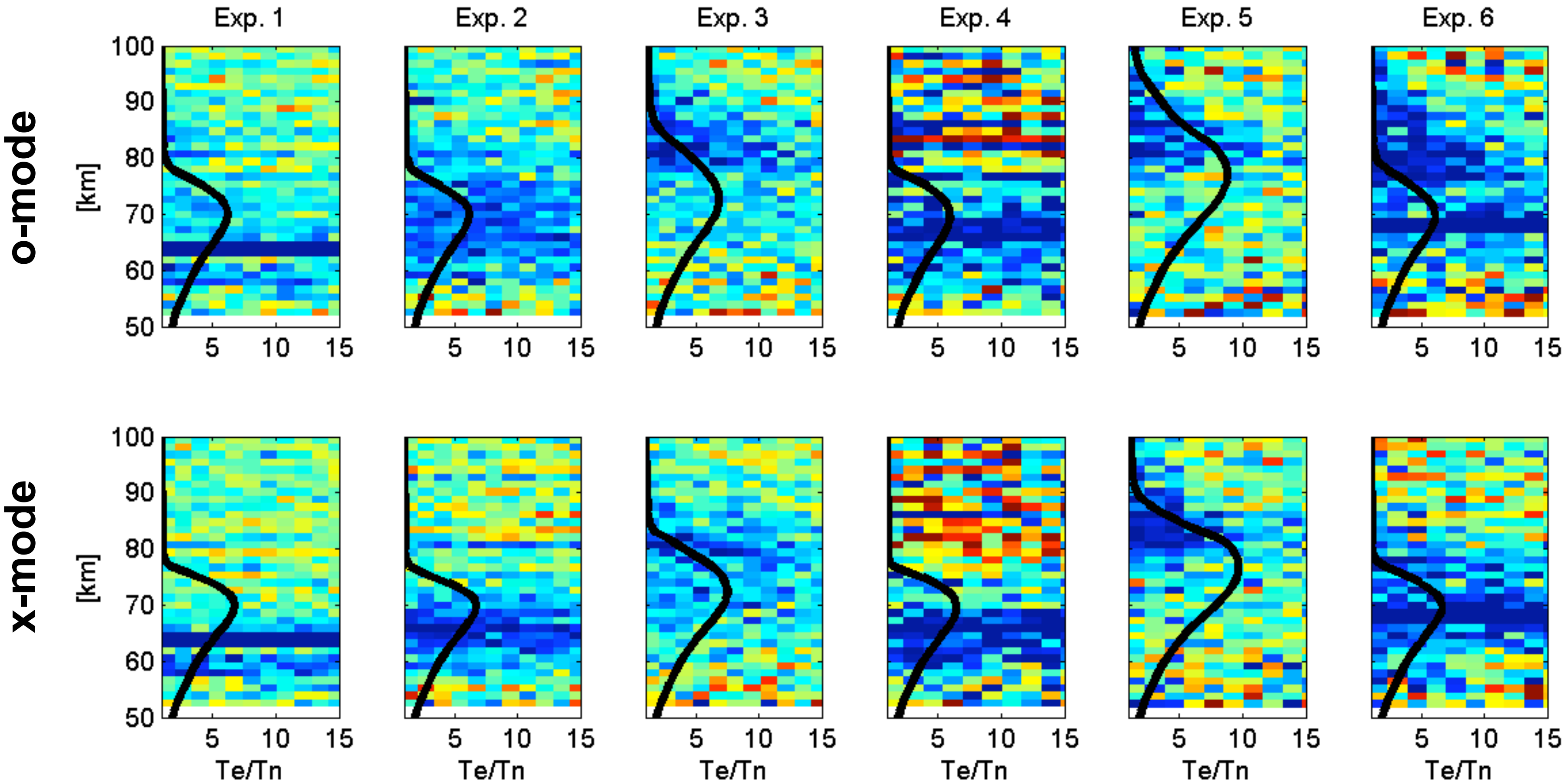
Heating effect on IS spectrum



Heating signature in the IS signal (2006)



Model vs. data for the 2006 experiments



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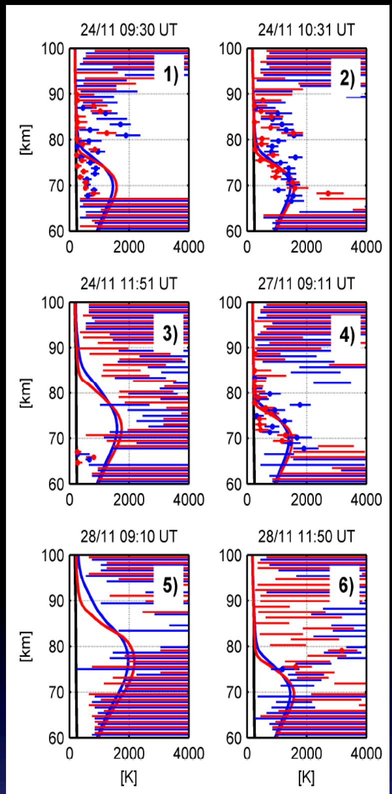
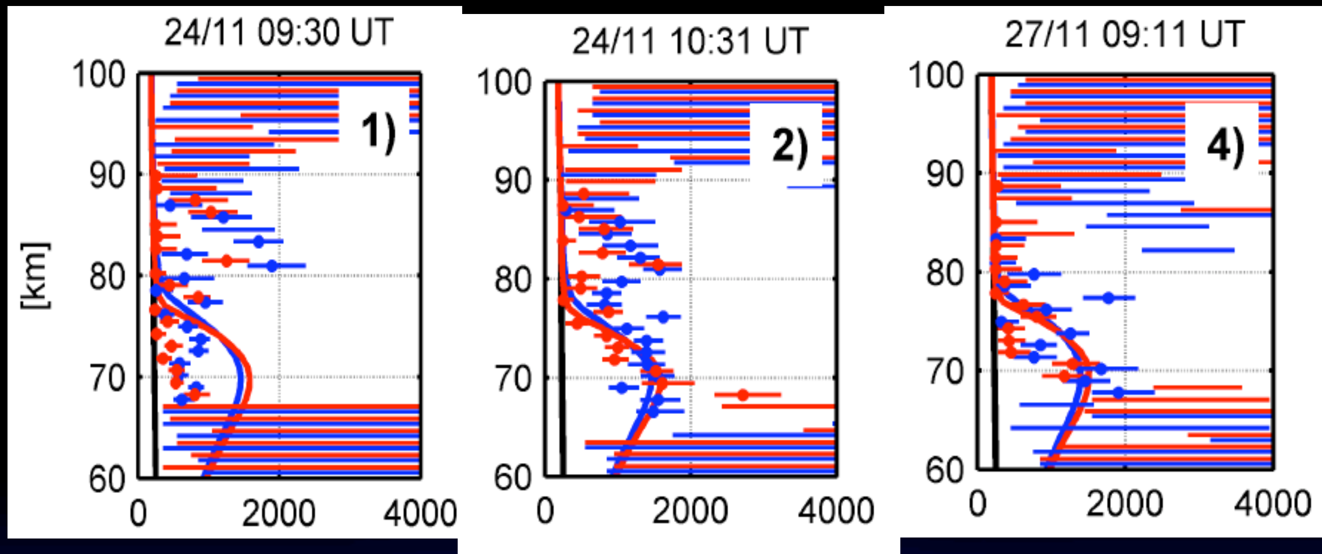
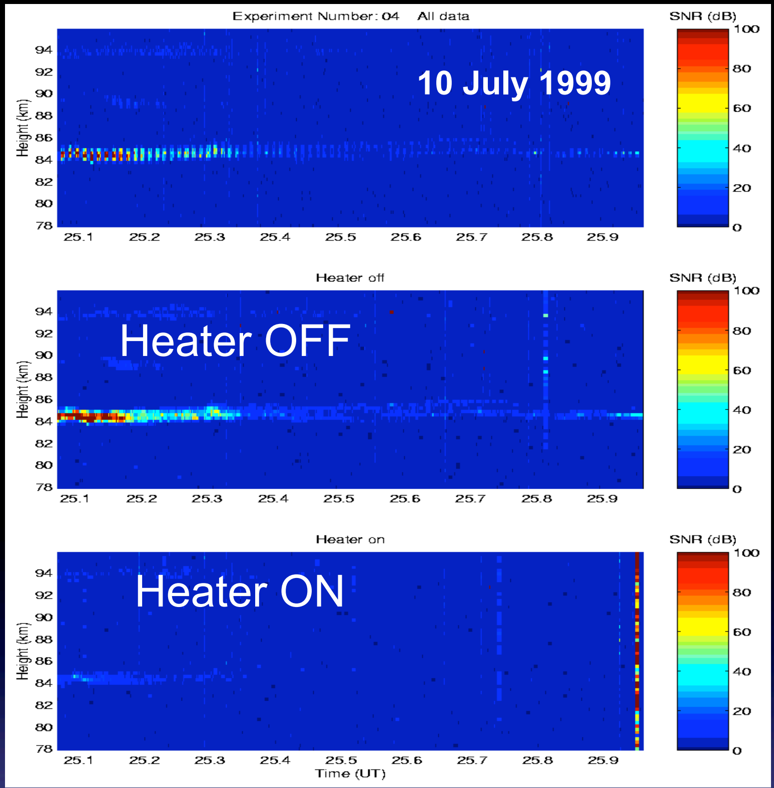




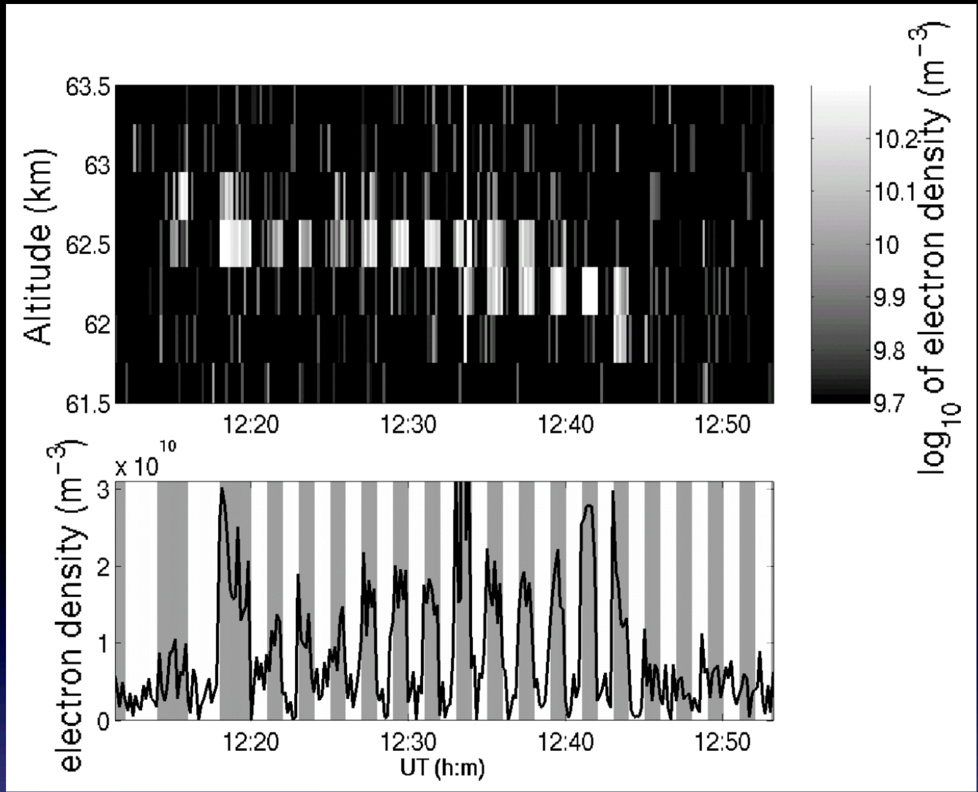
Kero et al., Ann Geophys, 2008

PMSE & PMWE

PMSE at 85 km



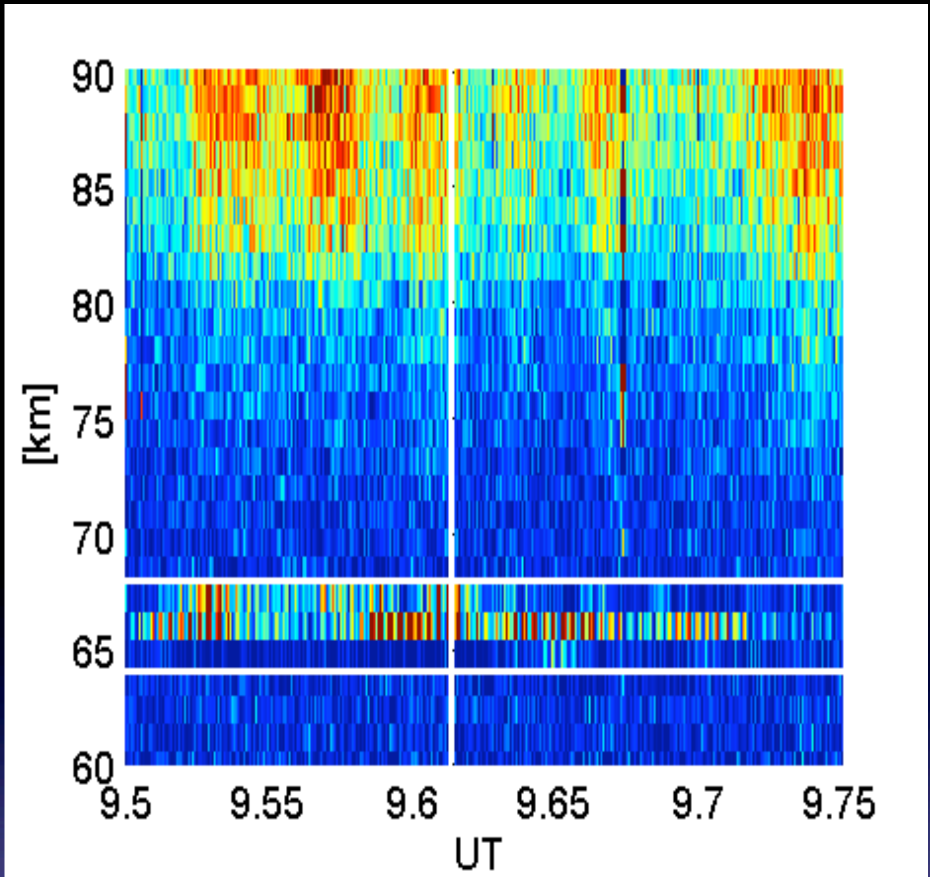
PMWE at 63 km

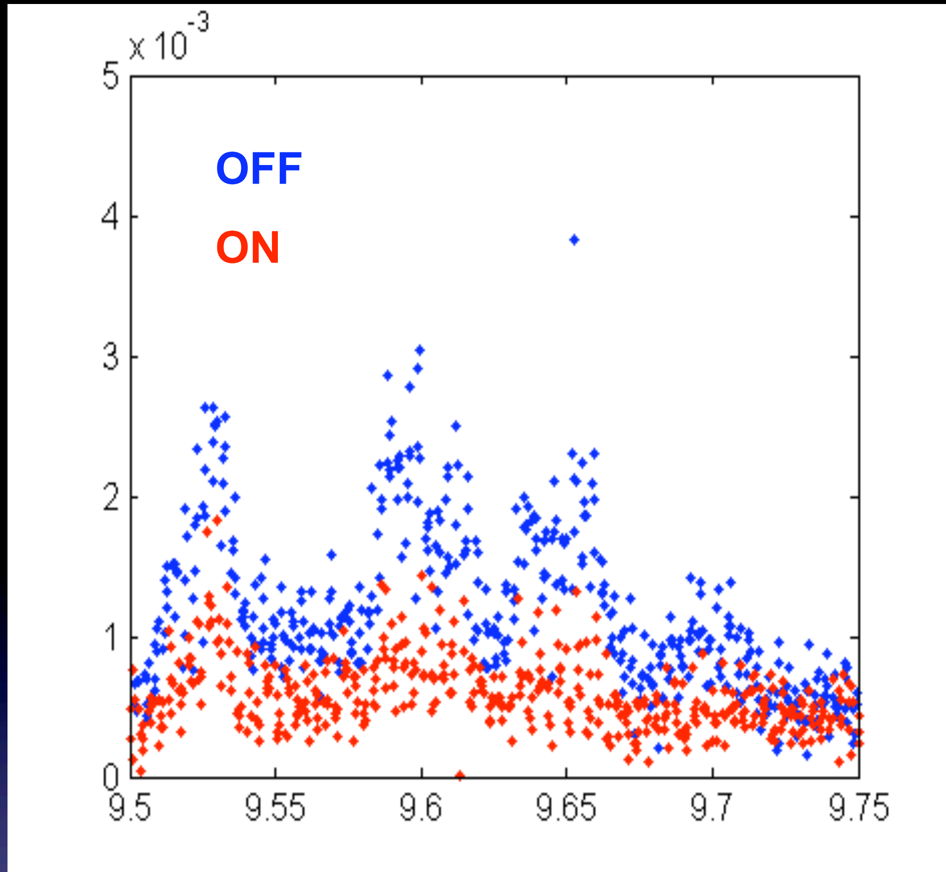


Kavanagh et al., GRL, 2006

PMWE modulation

24th November 2006

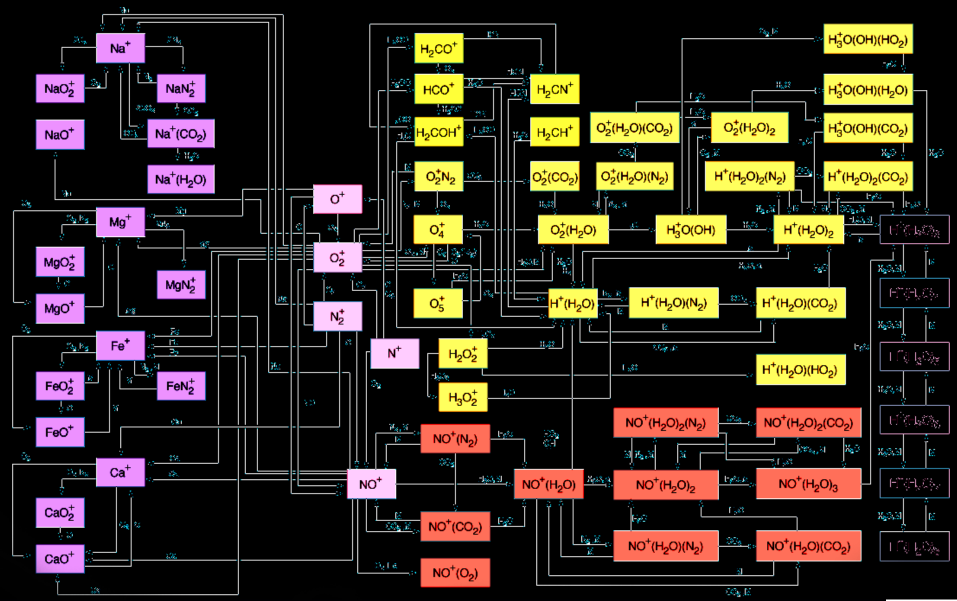




Sodankylä Ion Chemistry model (SIC)

Detailed 1-D time dependend chemistry

- 63 ions (27 negative) & 13 neutrals
- 20-150 km in 1 km resolution
- several hundred reactions
- vertical transport

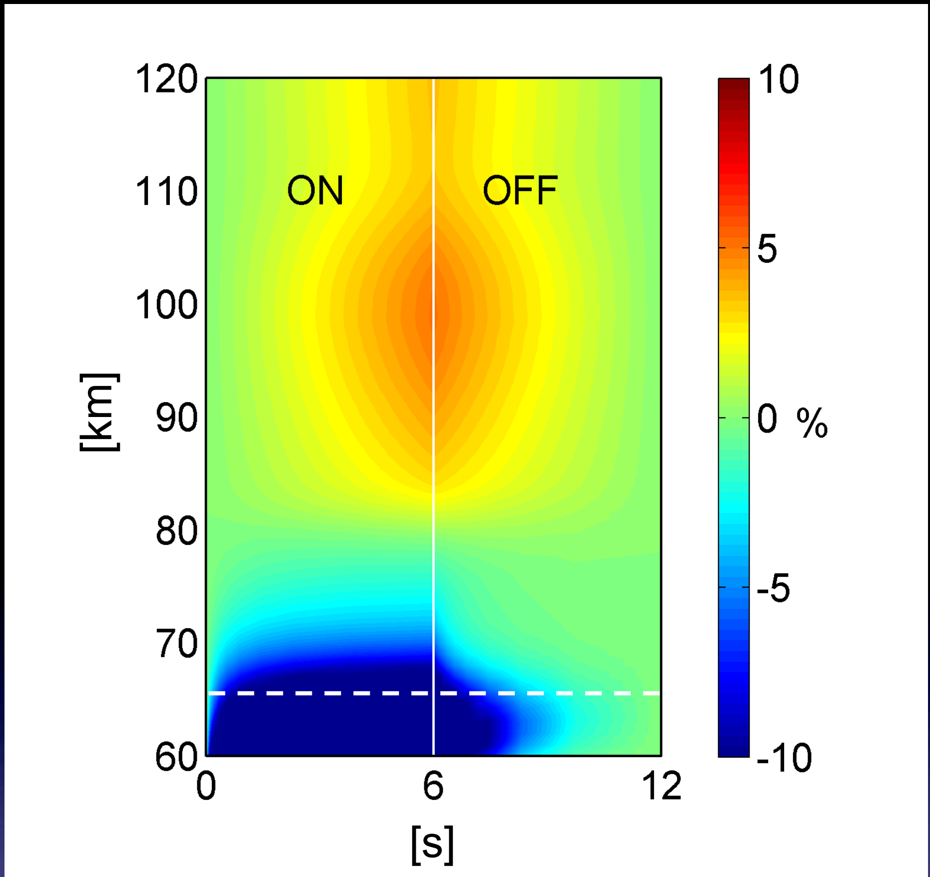


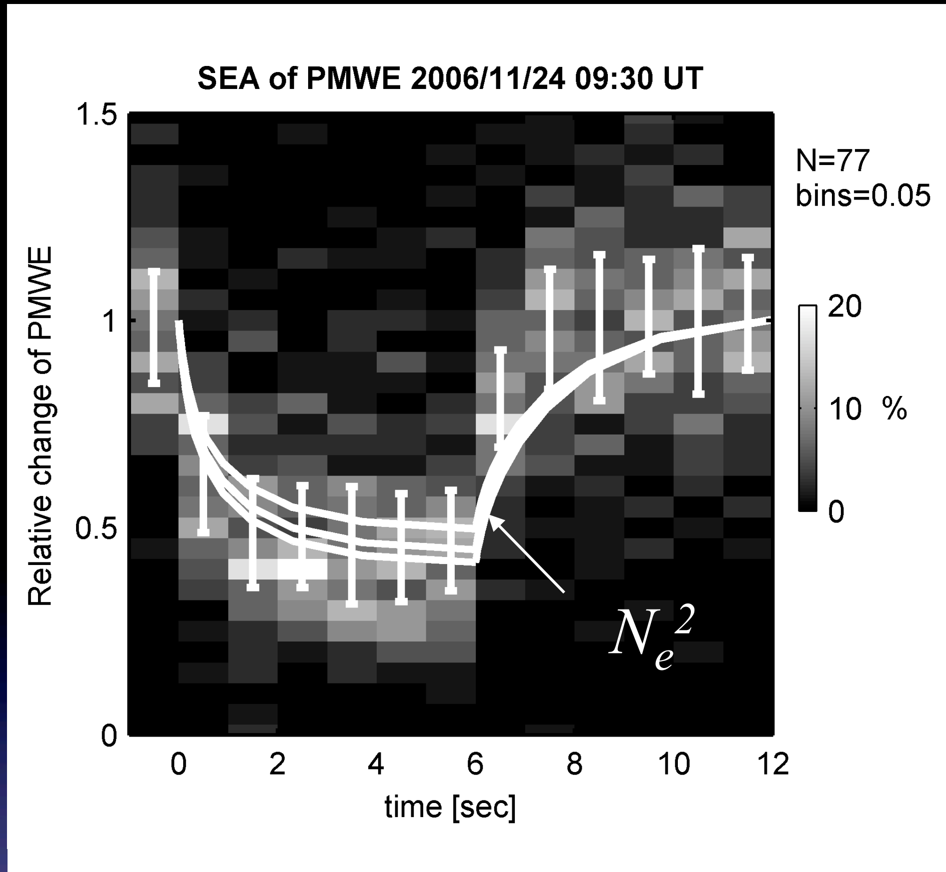
Input

- MSIS
- solar flux
- proton and electron precipitation
- cosmic rays

PMWE modulation

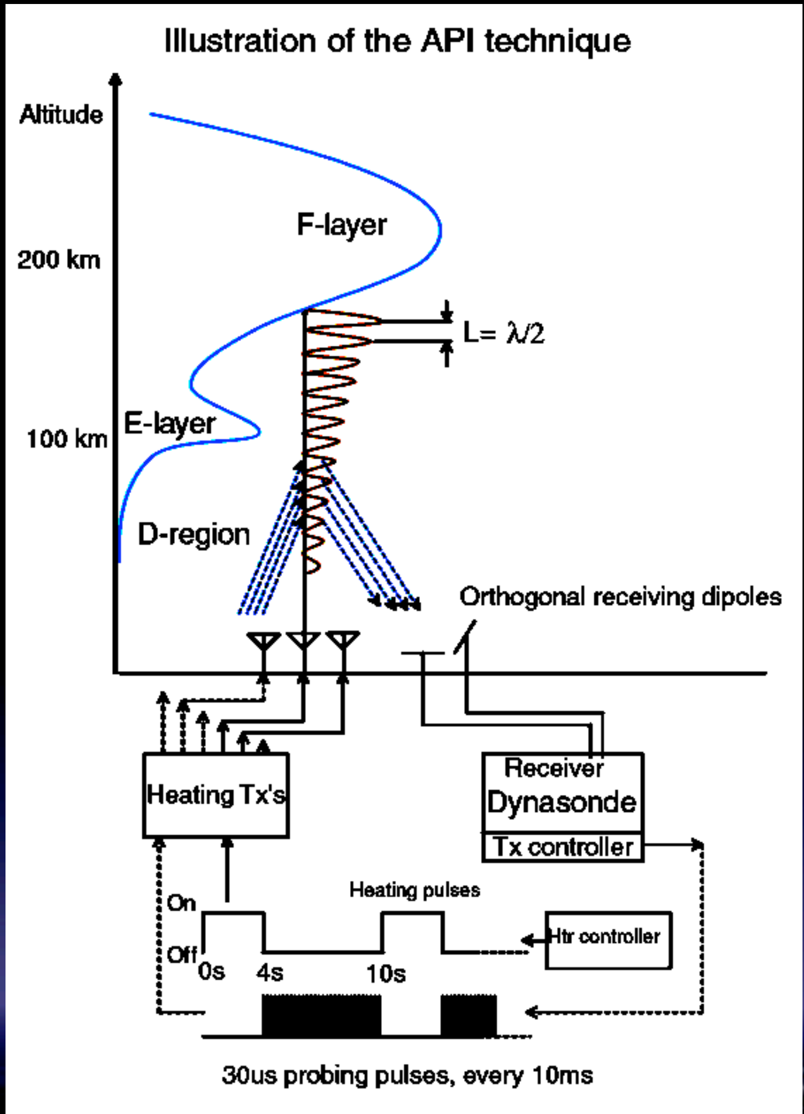
24th November 2006

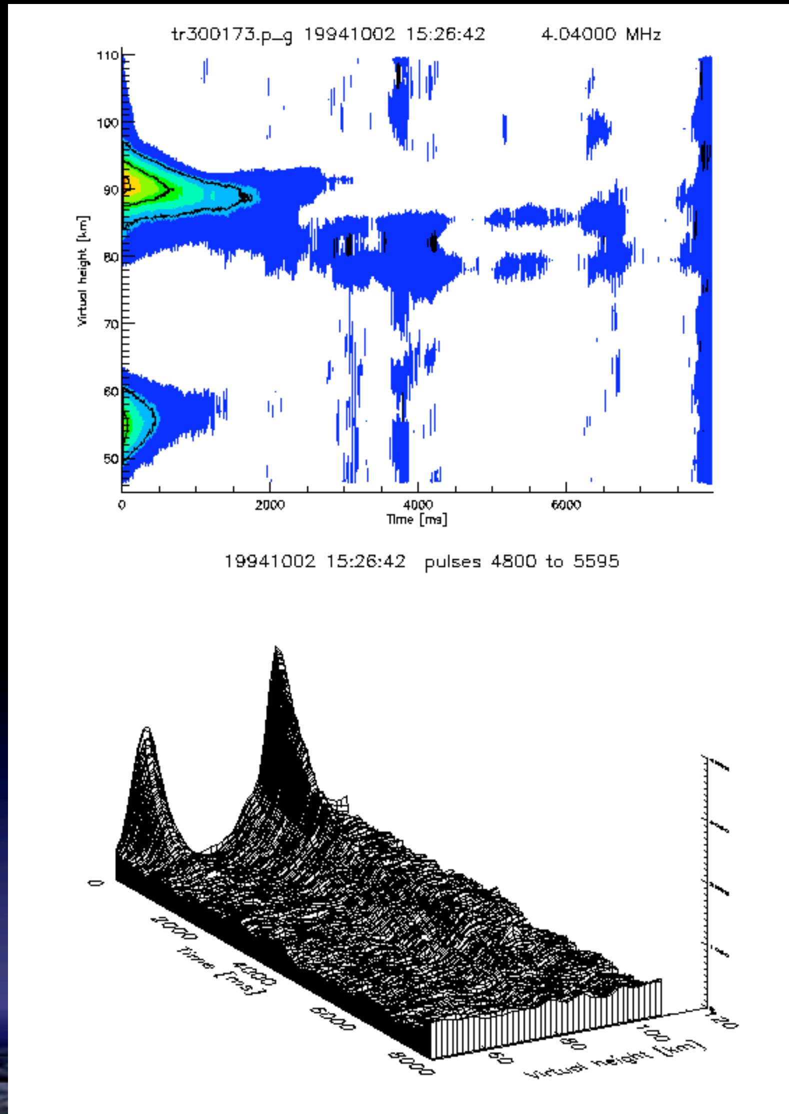




Kero et al., GRL 2008

Artificial Periodic Irregularities (API)





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- History: Luxembourg effect
- Facilities around the world
- Two types of heating

Collisional heating

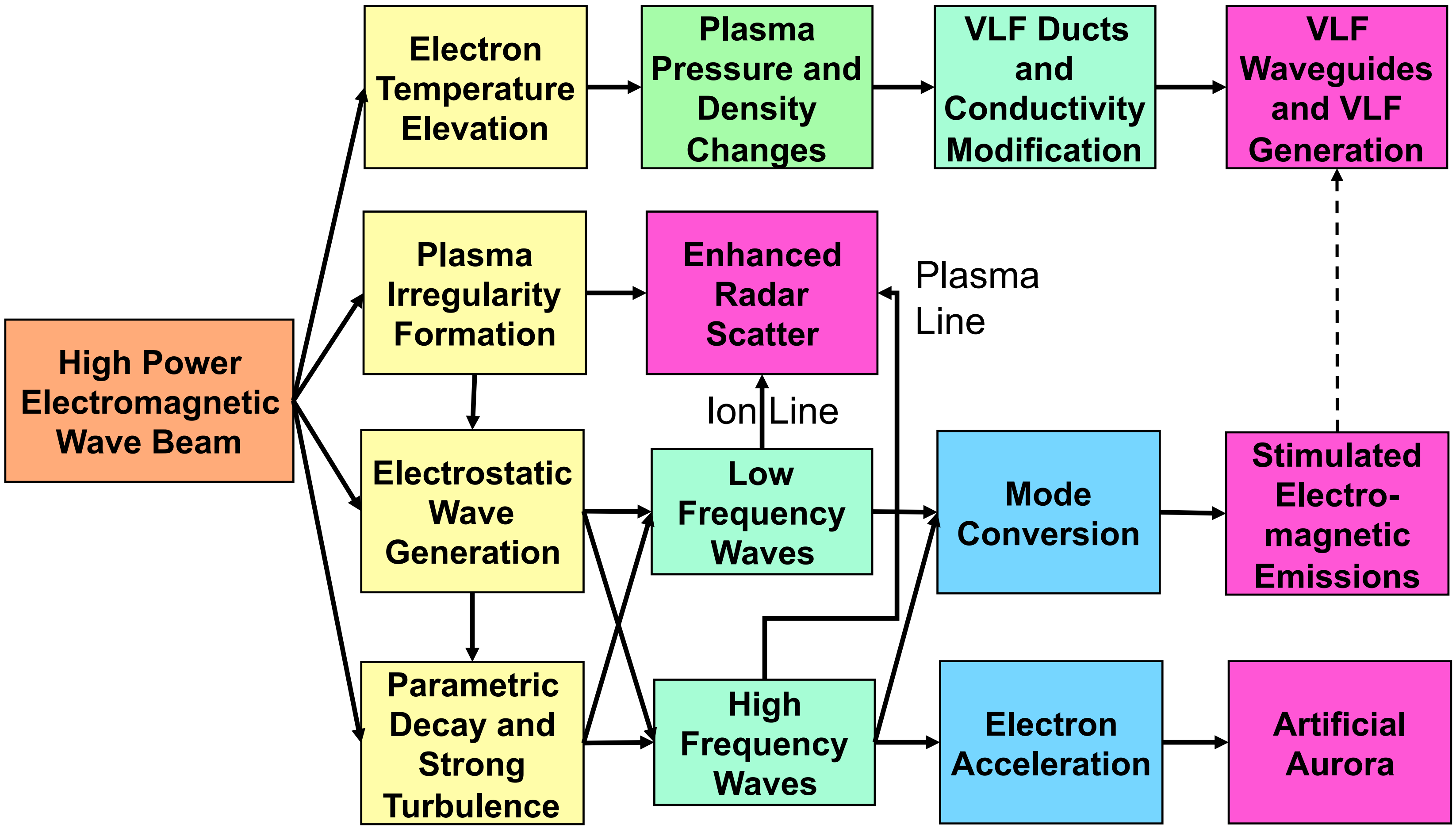
- Radio wave propagation theory
- Modeling the electron temperature
- Effects on incoherent scattering
- Coherent scattering: PMSE/PMWE, API

Wave excitation

- Plasma waves in principle
- Artificial aurora
- VLF/ULF waves

Summary

Ionospheric Modification with High Power Radio Waves



Plasma Waves from Linearized Equations

Ref: Swanson, Plasma Waves, 1989

Goedbloed and Poedts, Magnetohydrodynamics, 2004

Electrons

$$\frac{\partial \tilde{n}_e}{\partial t} + n_e \nabla \cdot \tilde{\mathbf{u}}_e = 0$$

$$\frac{\partial \tilde{\mathbf{u}}_e}{\partial t} + \nabla \tilde{p}_e + \frac{e}{m_e}(\tilde{\mathbf{E}} + \tilde{\mathbf{u}}_e \times \mathbf{B}) = -\nu_e(\tilde{\mathbf{u}}_e - \tilde{\mathbf{u}}_i)$$

$$\tilde{p}_e = \lambda_e k T_e \tilde{n}_e$$

Ions

$$\frac{\partial \tilde{n}_i}{\partial t} + n_i \nabla \cdot \tilde{\mathbf{u}}_i = 0$$

$$\frac{\partial \tilde{\mathbf{u}}_i}{\partial t} + \nabla \tilde{p}_i - \frac{e}{m_i}(\tilde{\mathbf{E}} + \tilde{\mathbf{u}}_e \times \mathbf{B}) = -\nu_i(\tilde{\mathbf{u}}_i - \tilde{\mathbf{u}}_e)$$

$$\tilde{p}_i = \lambda_i k T_i \tilde{n}_i$$

Fields

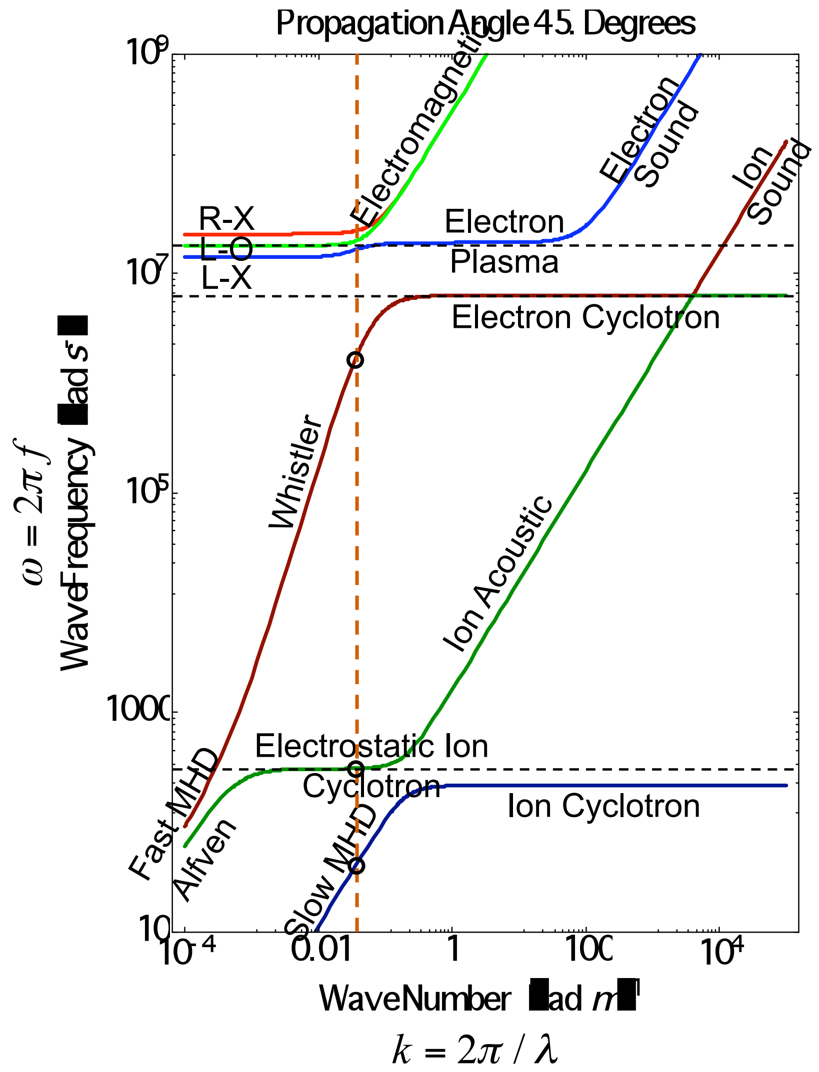
$$\frac{\partial \tilde{\mathbf{B}}}{\partial t} + \nabla \times \tilde{\mathbf{E}} = 0, \quad \nabla \cdot \tilde{\mathbf{B}} = 0$$

$$\frac{\partial \tilde{\mathbf{E}}}{\partial t} - c^2 \nabla \times \tilde{\mathbf{B}} = \frac{e}{\varepsilon_0} n_e(\tilde{\mathbf{u}}_e - \tilde{\mathbf{u}}_i), \quad \nabla \cdot \tilde{\mathbf{E}} = -\frac{e}{\varepsilon_0}(\tilde{n}_e - \tilde{n}_i)$$

$$\tilde{n}_e(\mathbf{r},t) = \tilde{n}_e \exp[i(\mathbf{k}\cdot\mathbf{r} - \omega t)] \quad \nabla \rightarrow -\mathbf{k}, \quad \partial/\partial t \rightarrow -i\omega$$

- 12 Unknowns
  - 4 Electron Variables
  - 4 Ion Variables
  - 2 Electric Fields
  - 2 Magnetic Fields
- Dispersion Equation
  - 12^{th} Order in ω
  - 8^{th} order in k
- Solutions
  - 6 Branches
  - 2 Propagation Directions
  - Cutoffs ($k^2 \rightarrow 0$, $\lambda^2 \rightarrow \infty$)
  - Resonances ($k^2 \rightarrow \infty$, $\lambda^2 \rightarrow 0$)
  - MHD
    - $k^2 \rightarrow 0$, $\omega^2 \rightarrow 0$
    - Finite Phase Velocity (ω/k)
  - High Frequency
    - $k^2 \rightarrow \infty$, $\omega^2 \rightarrow \infty$
    - Finite Phase Velocity (ω/k)

Waves in a Fluid Plasma for Oblique Propagation



Plasma Wave Mode Characteristic Branches for Typical Ionospheric Parameters

Stringer (1963) Diagram

$\Omega_e = (2\pi)\ 1.43\ 10^6\ Rad / s$

$\omega_{pe} = 2\ \Omega_e Rad / s = (2\pi)\ 2.86\ 10^6\ Rad / s$

$\omega_{UH} = (2\pi)\ 3.2\ 10^6\ Rad / s$

$\omega_{LH} = (2\pi)\ 7460\ Rad / s$

$\Omega_i = (2\pi)\ 48.7\ Rad / s$

$n_e = 1.01\ 10^{11}\ m^{-3}$

$T_e = 2500K$

$T_i = 800K$

$V_A = 8.75\ 10^5\ m / s$

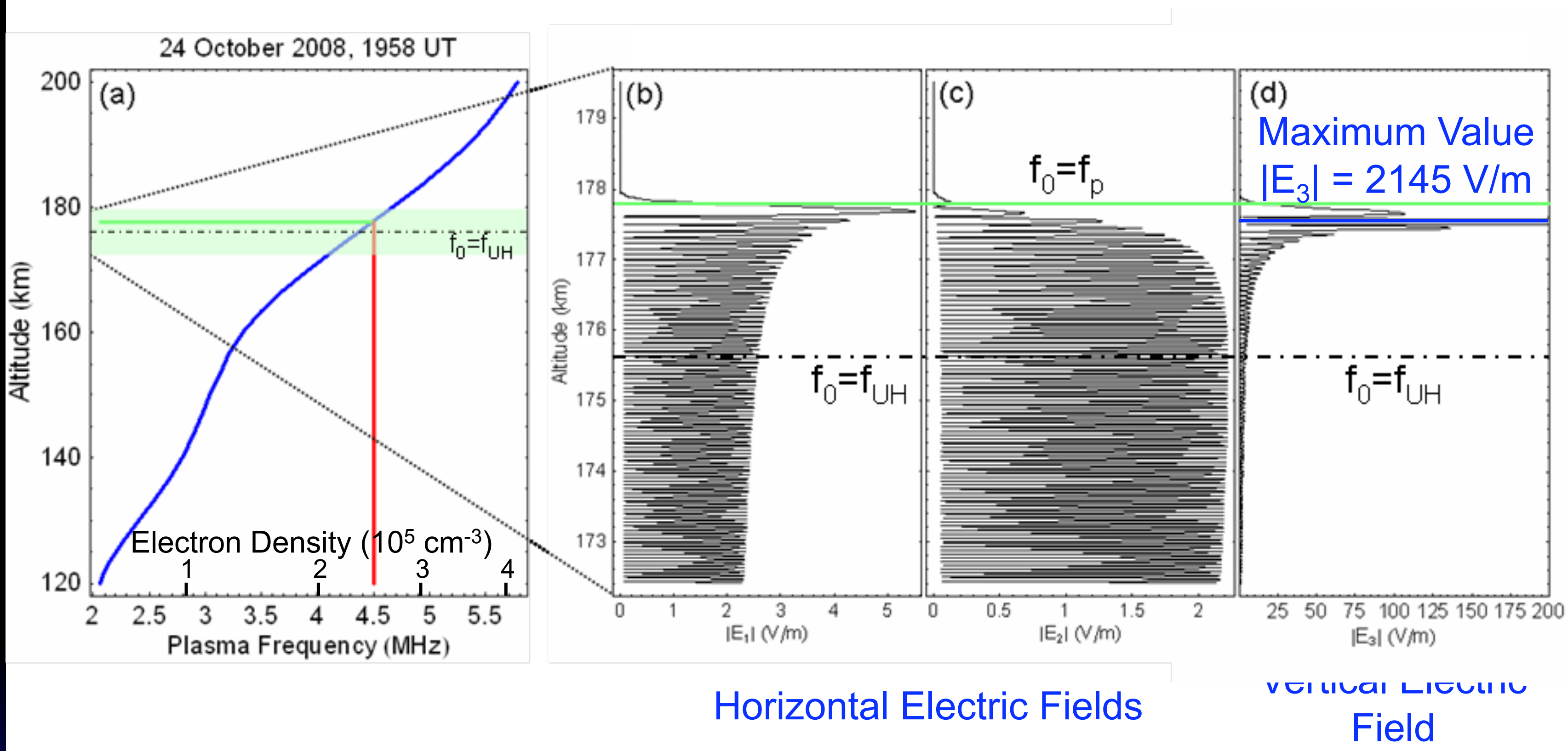
$c_s = 1590\ m / s$

$\rho_e = 0.022\ m$

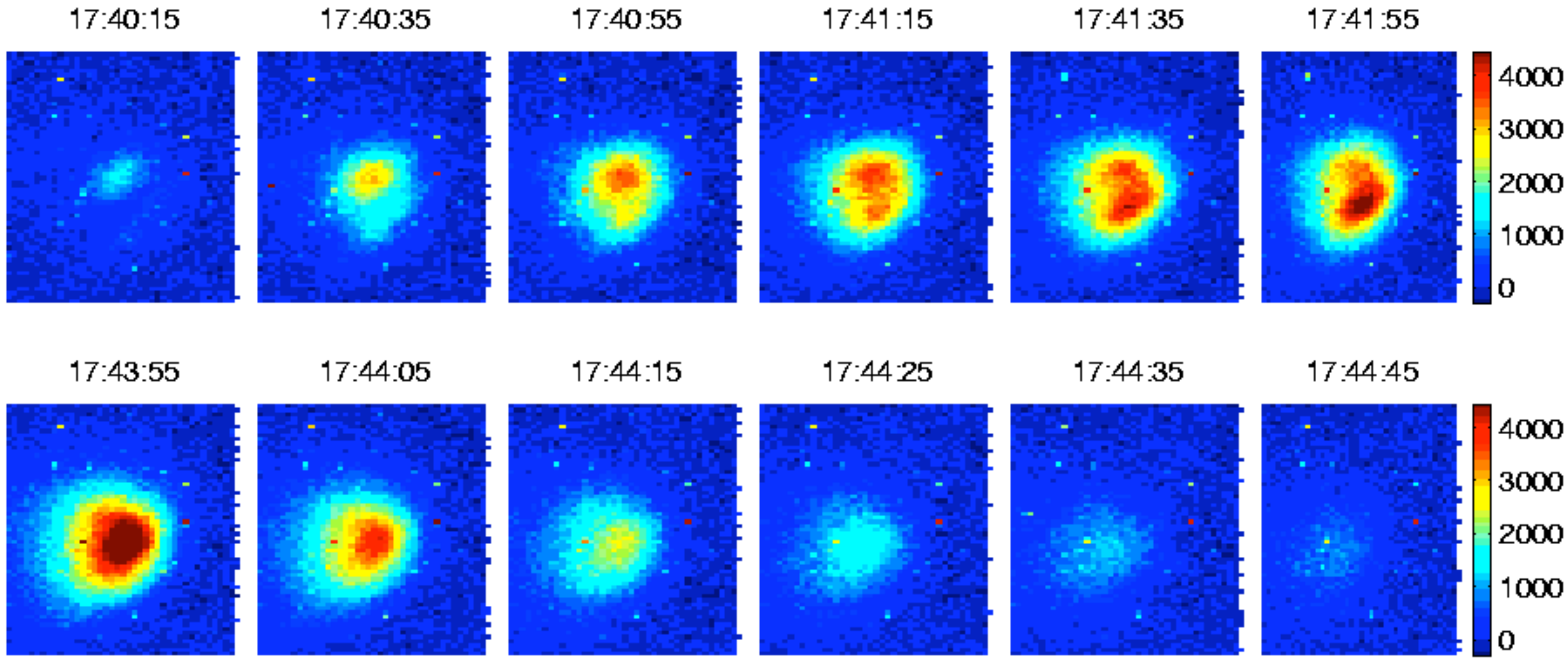
$\rho_i = 3.64\ m$

$\theta = \pi / 4$

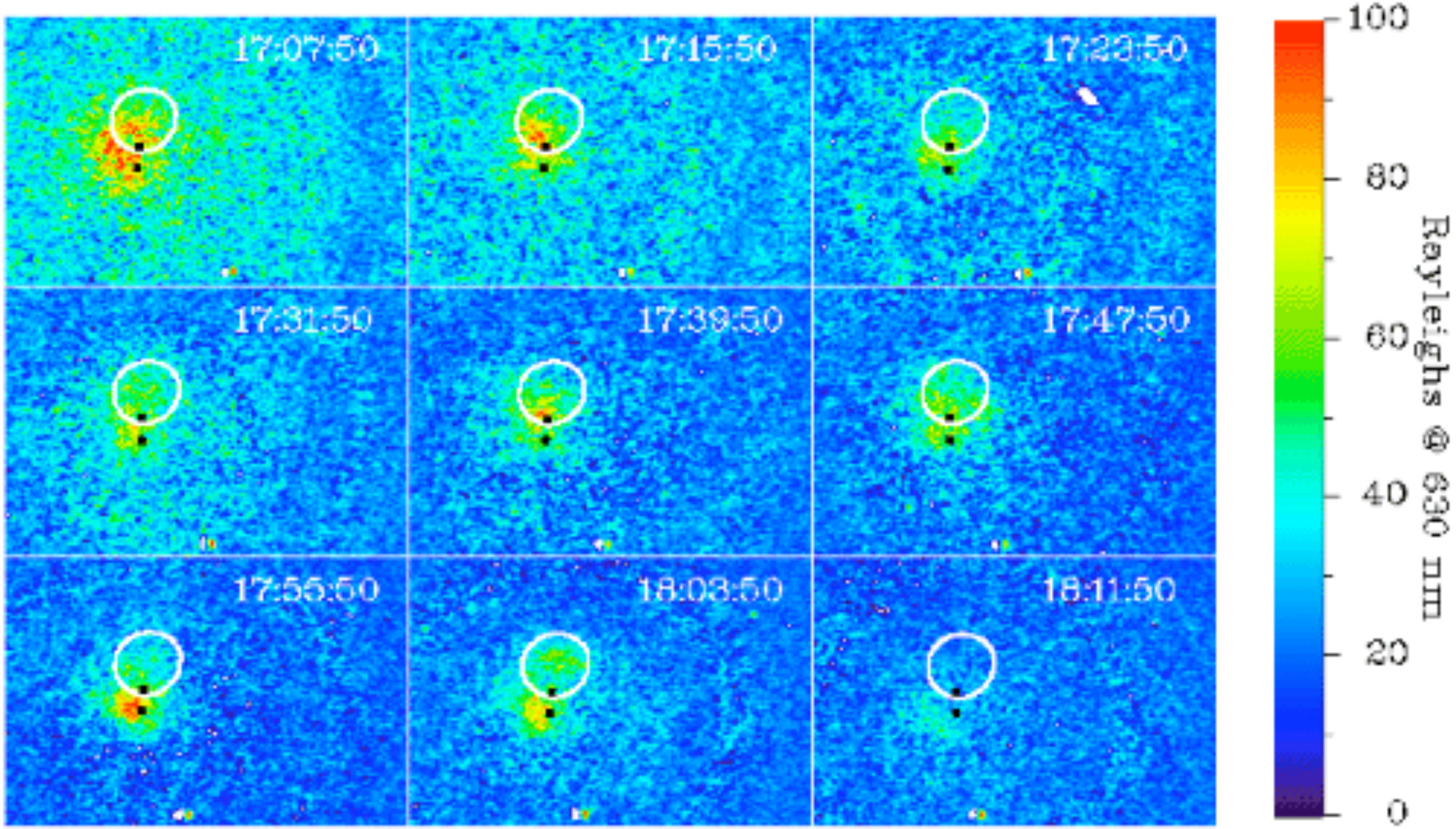
Full Wave Solution for EM Pump Wave at 4.5 MHz in the Ionosphere Over HAARP



Large Increase in Electric Field Just Below Reflection Altitude where EM Wave Frequency = Plasma Frequency



(Brändström et al., Geophys. Res. Lett., 1999)


17:07:50
17:15:50
17:23:50
17:31:50
17:39:50
17:47:50
17:55:50
18:03:50
18:11:50
100
80
60
40
20
0
Rayleighs @ 630 nm

Heating effect on the conductivities

$$\mathbf{j} = \sigma_P \mathbf{E}_\perp - \sigma_H \frac{\mathbf{E} \times \mathbf{B}}{B} + \sigma_\parallel \mathbf{E}_\parallel$$

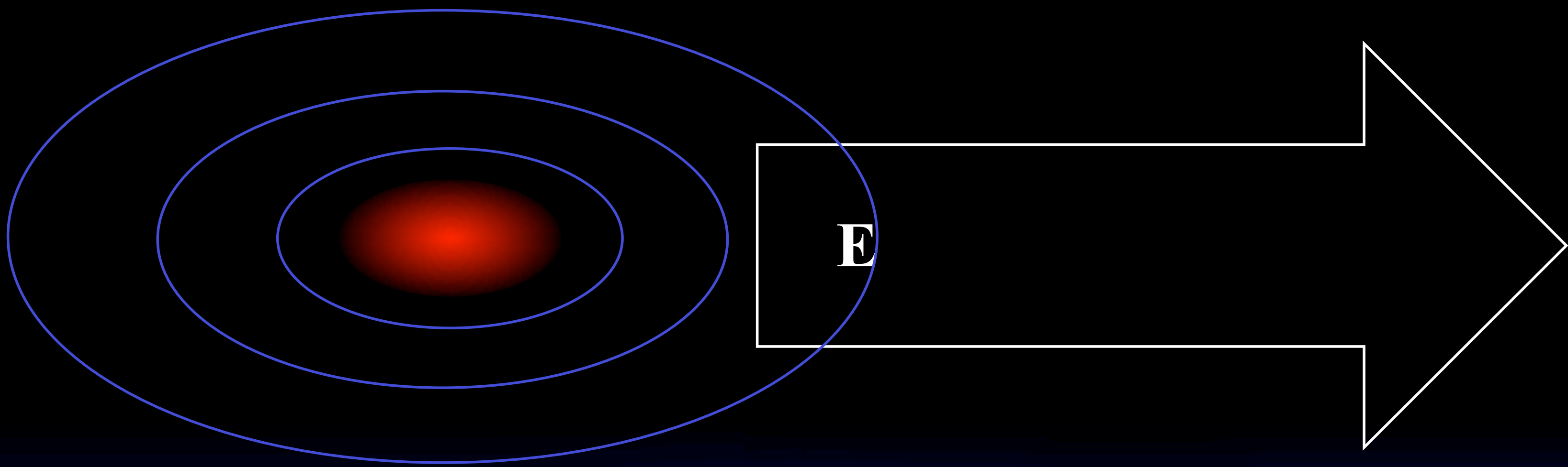
$$\sigma_P = \frac{ne}{B}\left(\frac{k_i}{1+k_i^2} + \frac{k_e}{1+k_e^2}\right)$$

$$\sigma_H = \frac{ne}{B}\left(-\frac{k_i^2}{1+k_i^2} + \frac{k_e^2}{1+k_e^2}\right)$$

$$\sigma_\parallel = \frac{ne}{B}(k_i + k_e)$$

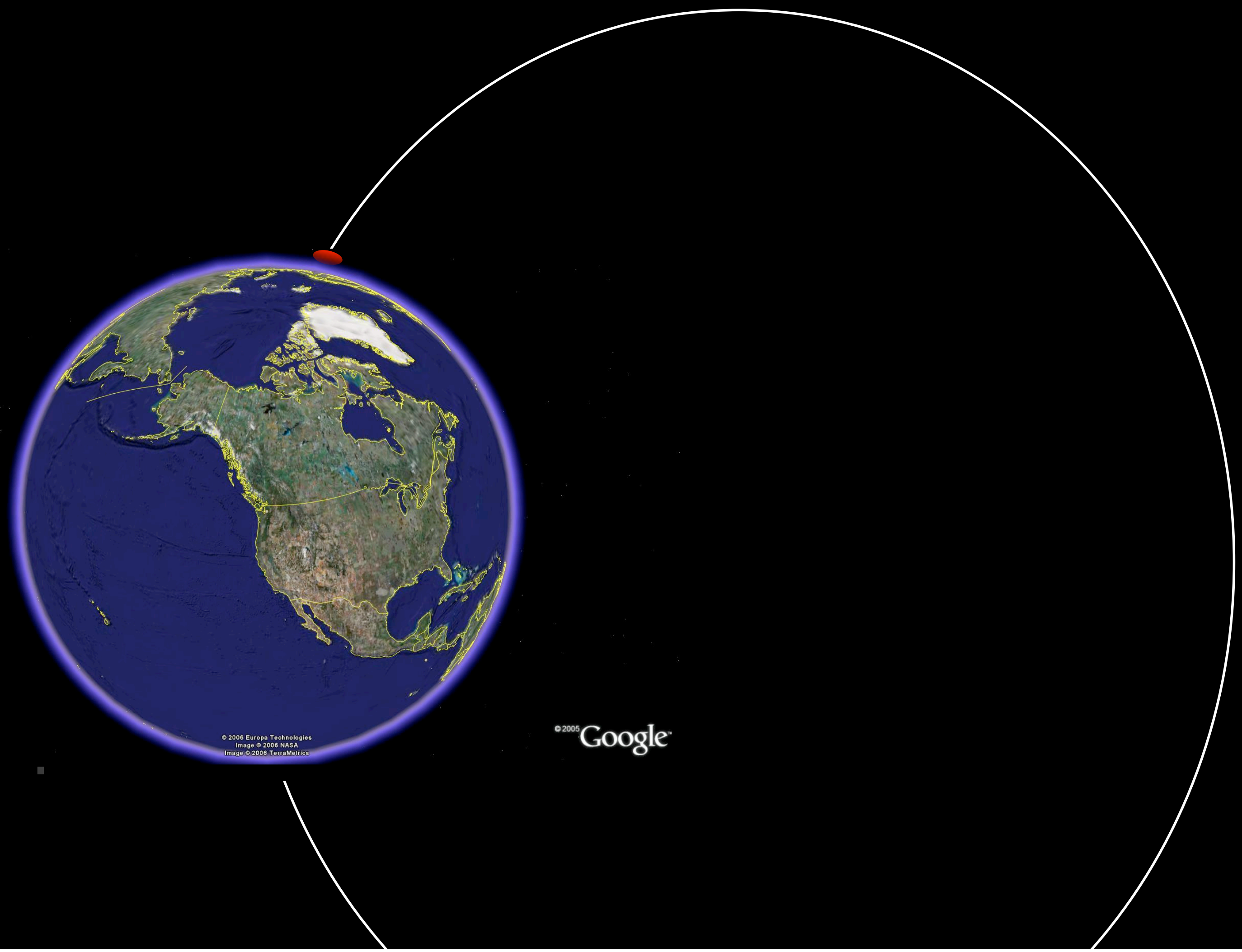
$$k_i = \frac{\omega_i}{\nu_{in}} \qquad k_e = \frac{\omega_e}{\nu_{en}}$$

Heating effect on the conductivities: generation of ULF/VLF waves

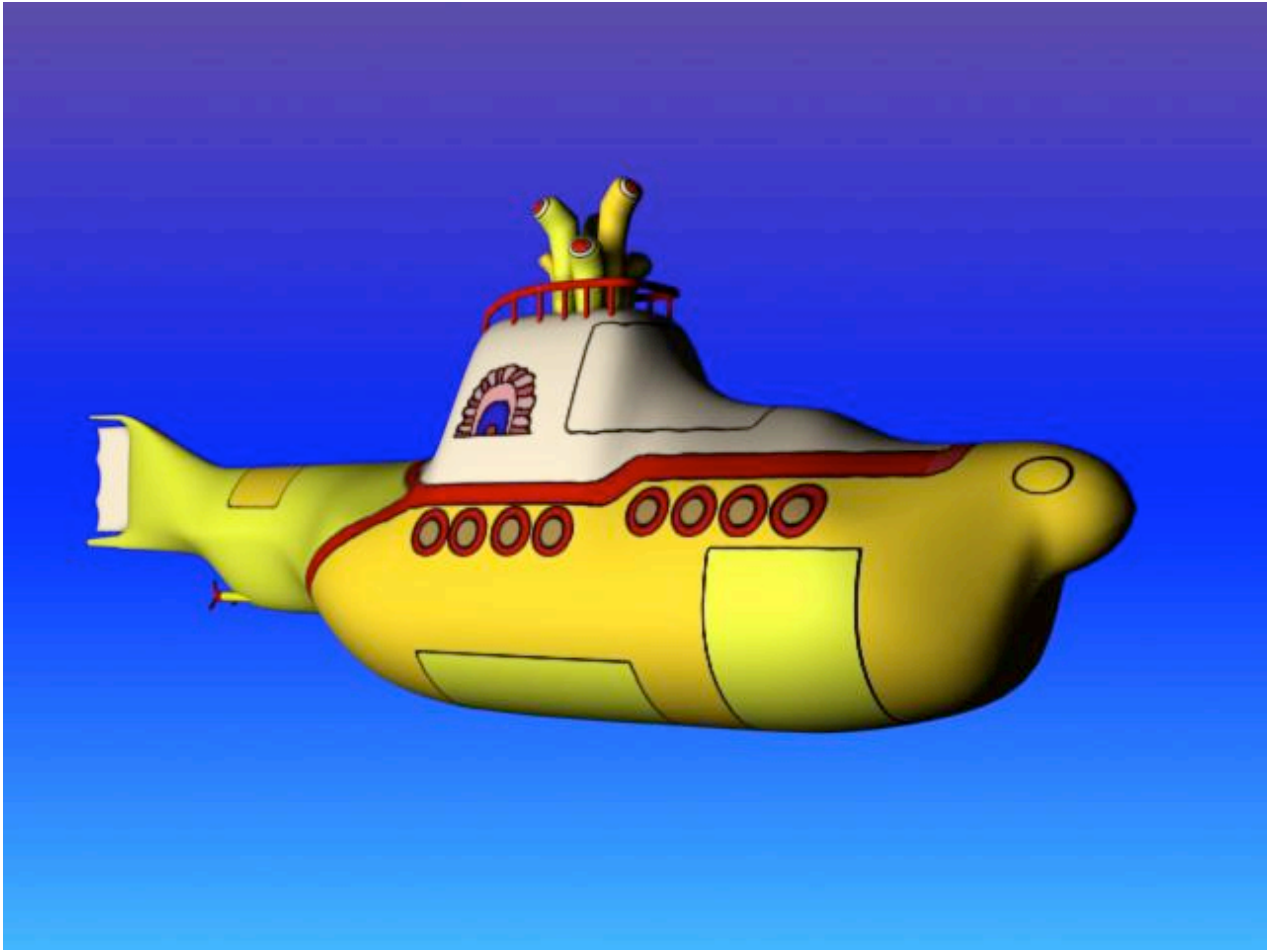


Heating effect on the conductivities:

ducted VLF waves



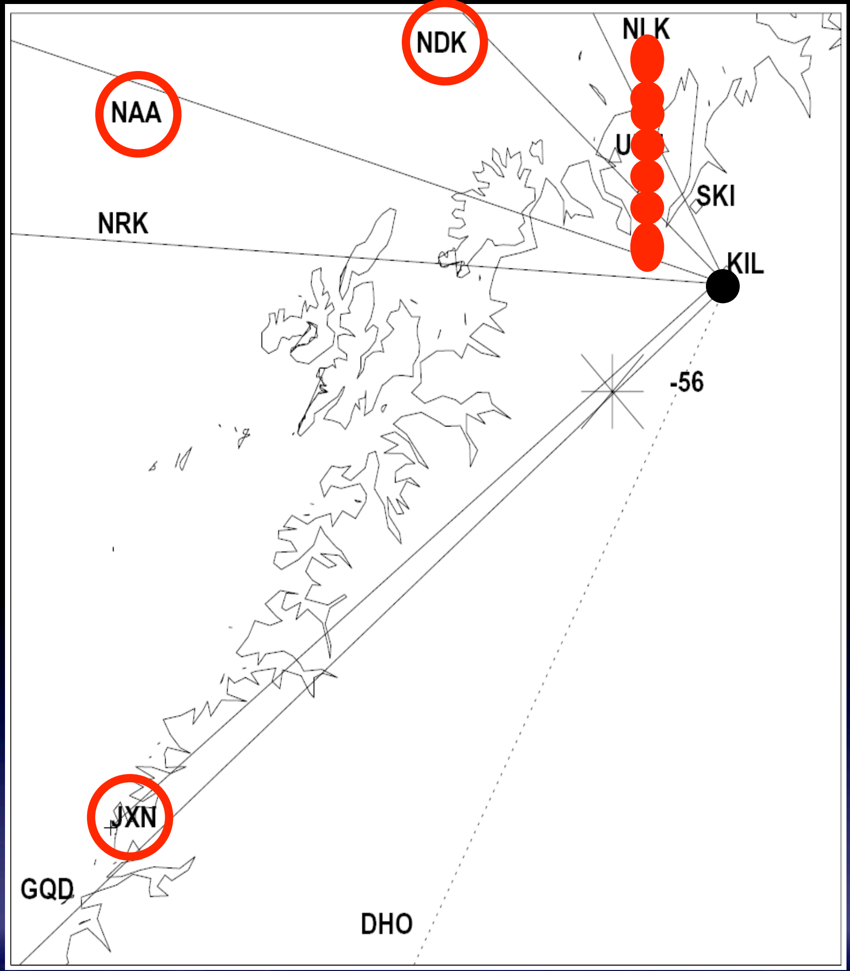
Heating effect on the conductivities: propagation path of VLF waves

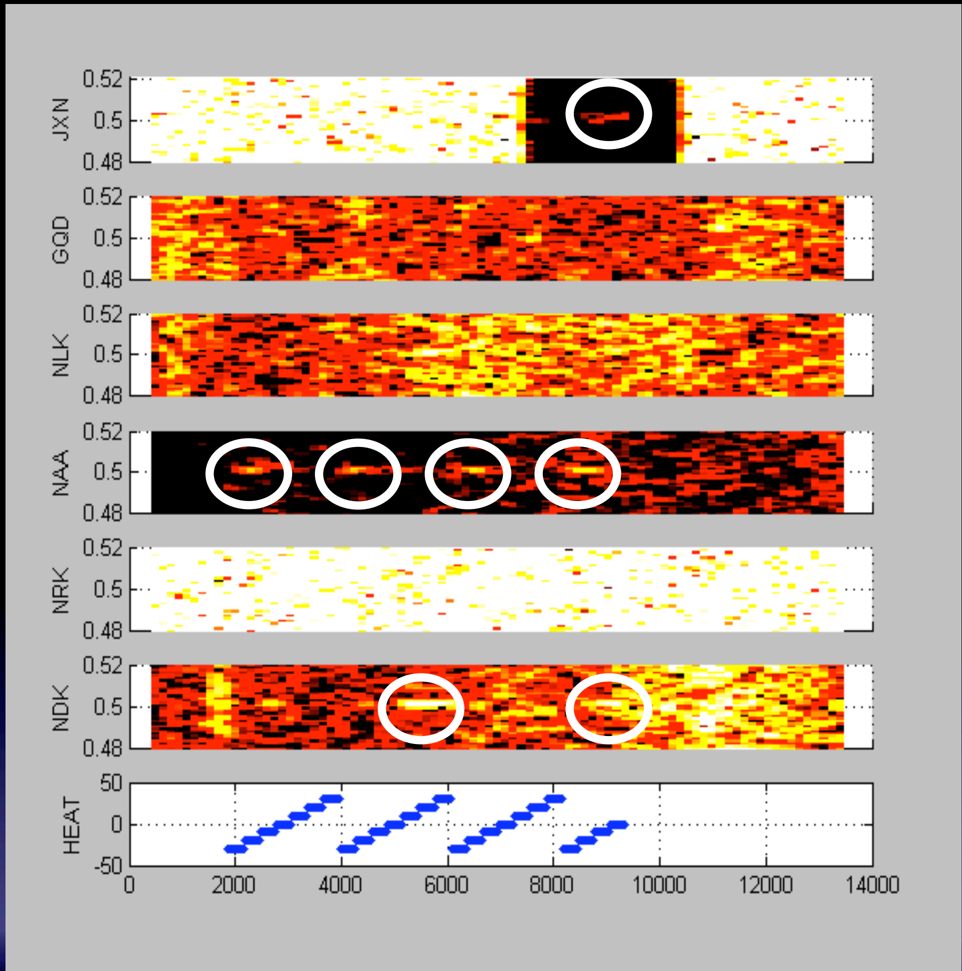


Heating effect on the conductivities: propagation path of VLF waves

Heating effect on the conductivities:

propagation path of VLF waves





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- Modeling the electron temperature
- Effects on incoherent scattering
- Coherent scattering: PMSE/PMWE, API

Wave excitation

- Plasma waves in principle
- Artificial aurora
- VLF/ULF waves

Summary