Introduction to heating experiments

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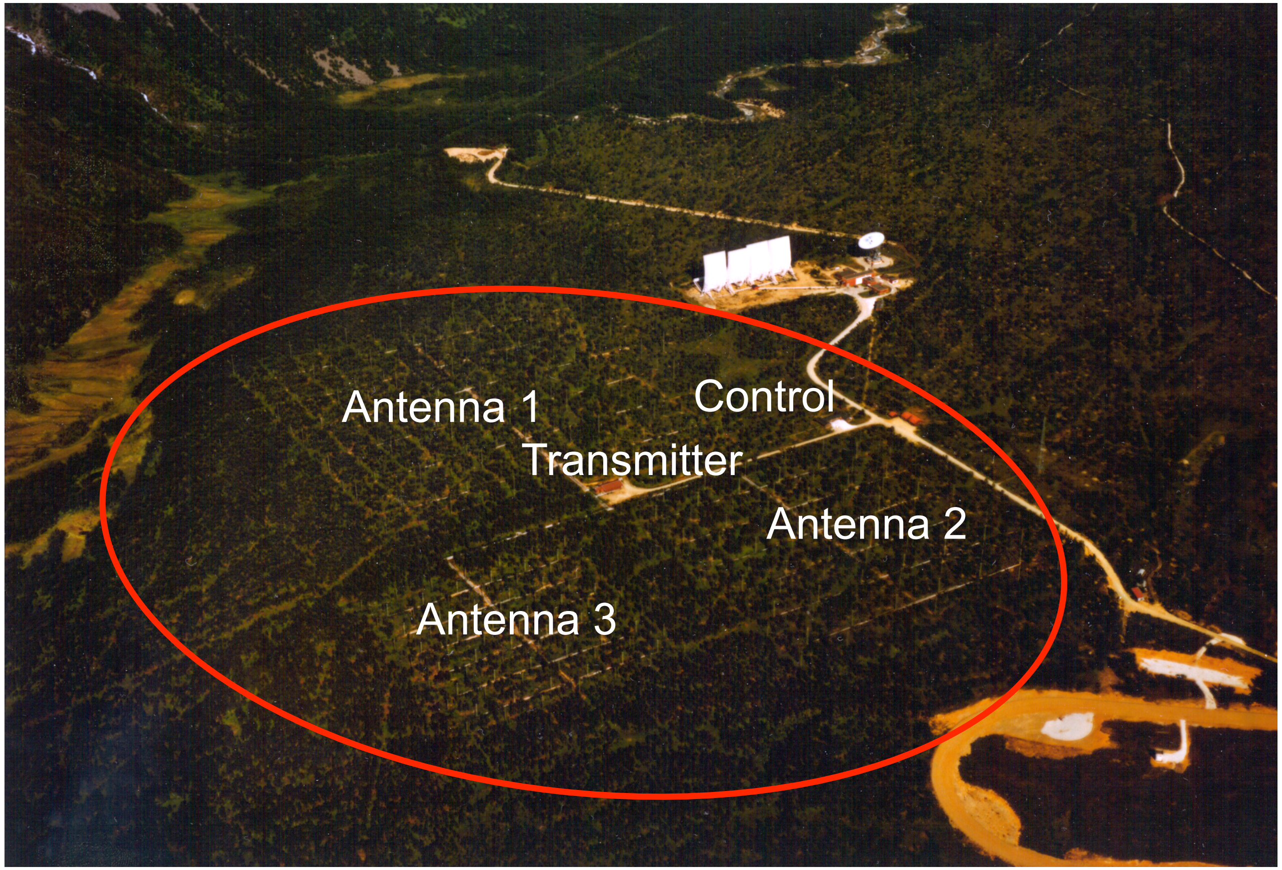
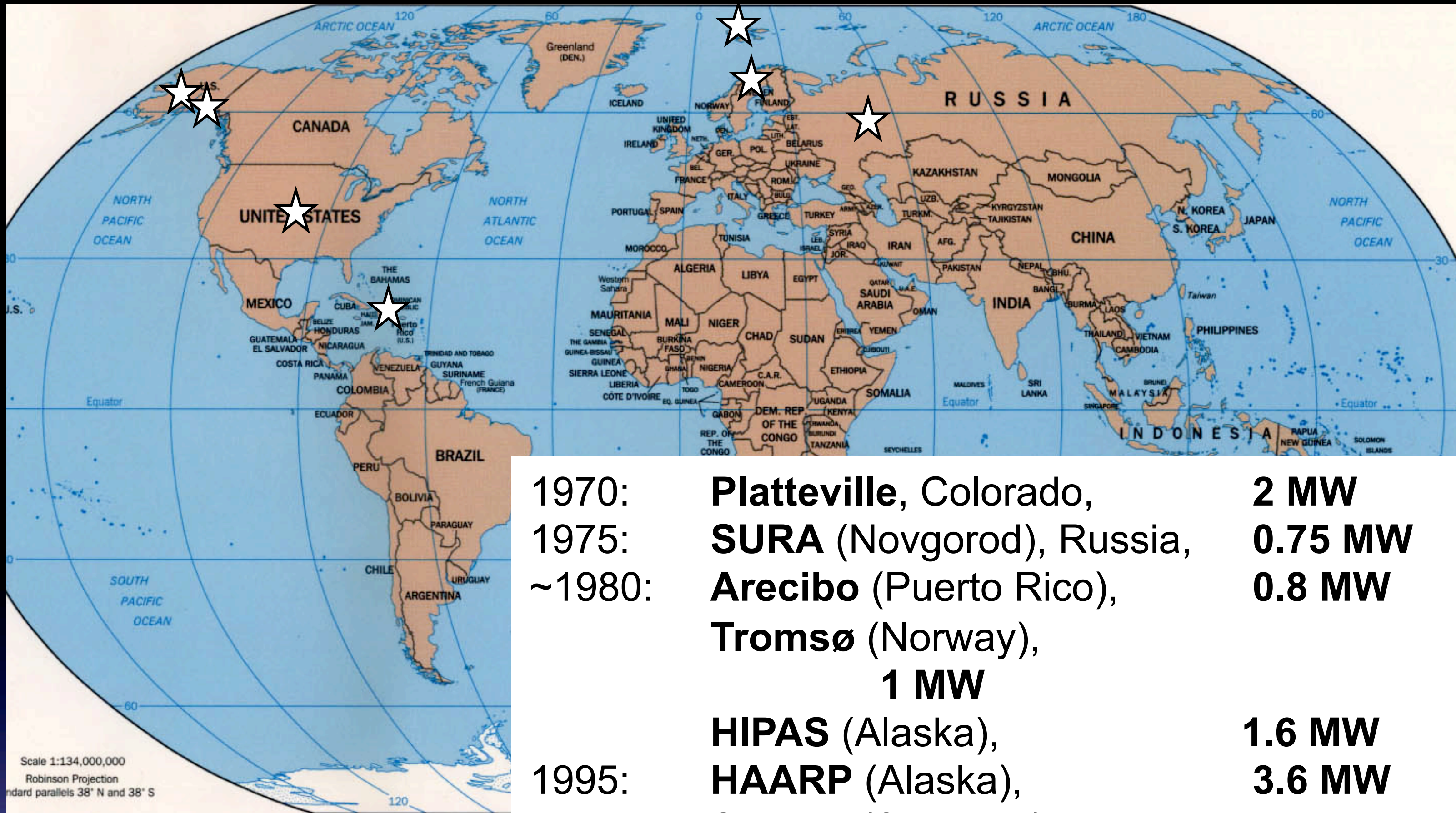
Luxembourg effect (1934)

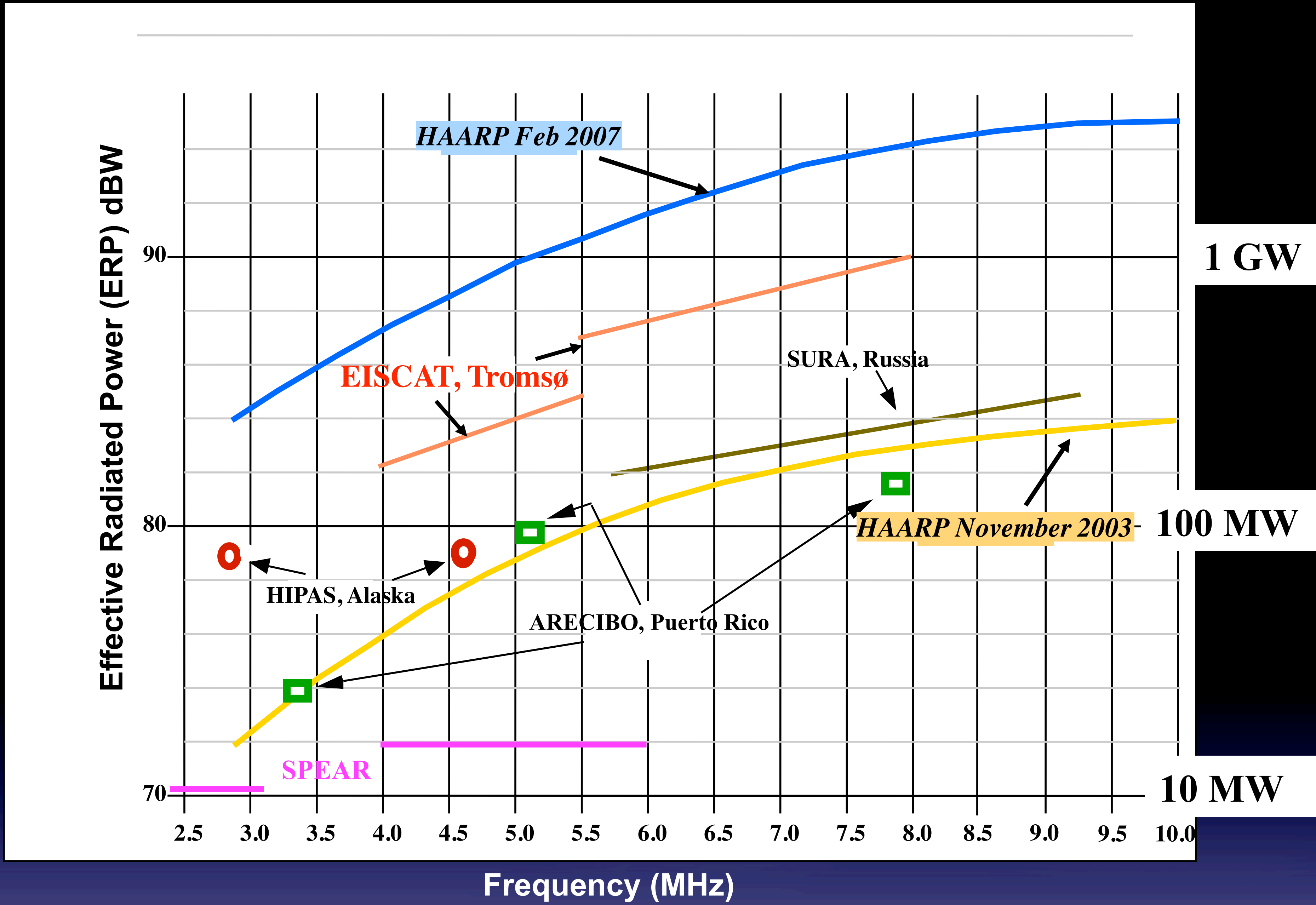
EISCAT site at Tromso, Norway



Heating facilities since 1970



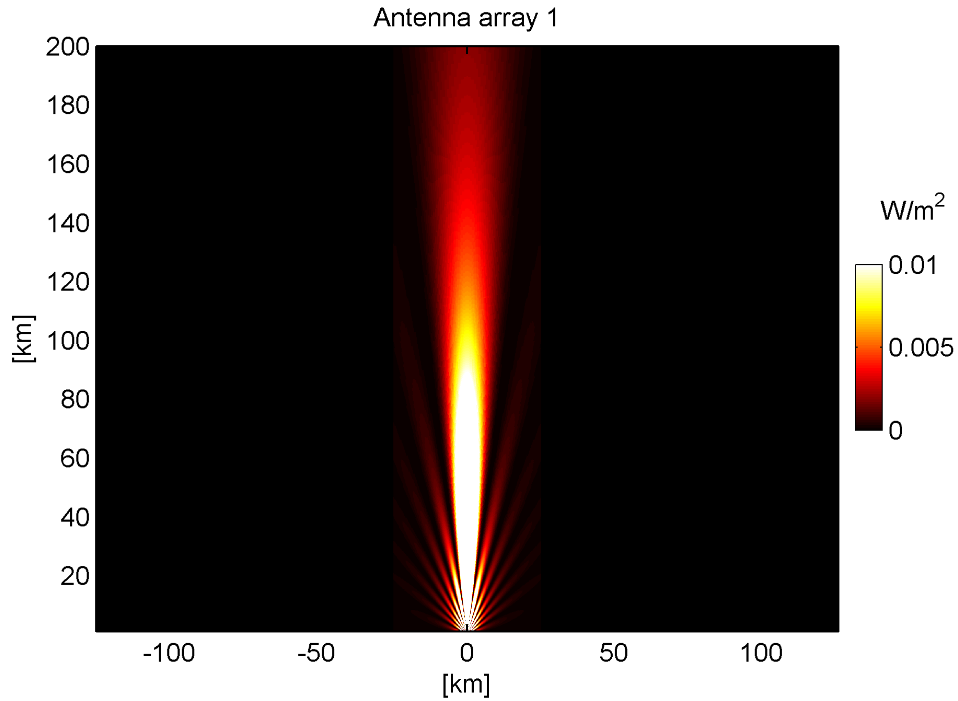
1970: **Platteville**, Colorado, **2 MW**
1975: **SURA** (Novgorod), Russia, **0.75 MW**
~1980: **Arecibo** (Puerto Rico), **0.8 MW**
Tromsø (Norway), **1 MW**
HIPAS (Alaska), **1.6 MW**
1995: **HAARP** (Alaska), **3.6 MW**
2003: **SPEAR** (Svalbard), **0.19 MW**

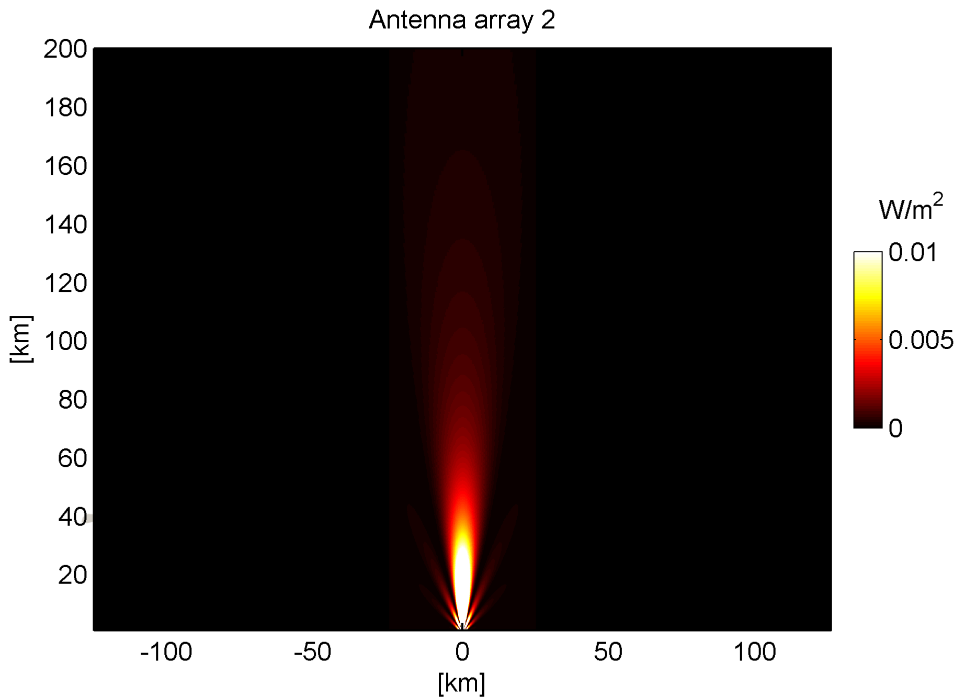


HAARP Feb 2007
EISCAT, Tromsø
SURA, Russia
HAARP November 2003
HIPAS, Alaska
ARECIBO, Puerto Rico
SPEAR
1 GW
100 MW
10 MW
90
80
70
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Effective Radiated Power (ERP) dBW
Frequency (MHz)

Intensity of the EISCAT heater beams

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





Some active HF heating effects

F region

hybrid resonance

artificial auroral emissions

heater radio wave +
ion-acoustic waves

Langmuir waves

PDI

E region

collision frequency

conductivity

ULF/VLF waves

Electron temperature

Incoherent scattering

D region

Ion chemistry

PMSE / PMWE modulation

API

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

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

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

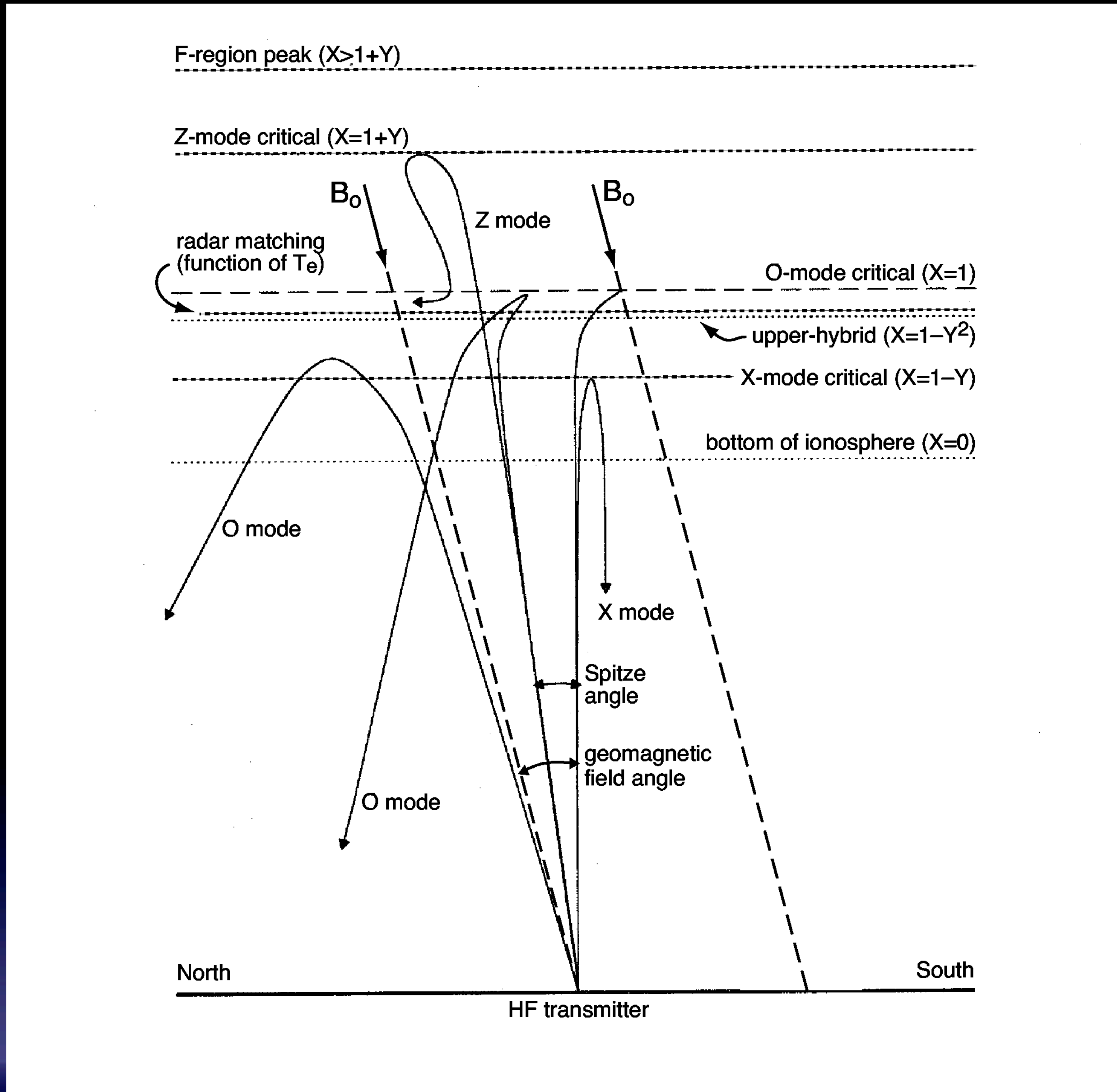
For detailed discussion, see K.G. Budden:

Radio Waves in the Ionosphere (1961)

Appleton equation

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

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



F-region peak (X>1+Y)
Z-mode critical (X=1+Y)
B_o
Z mode
B_o
radar matching (function of T_e)
O-mode critical (X=1)
upper-hybrid ($X=1-Y^2$)
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

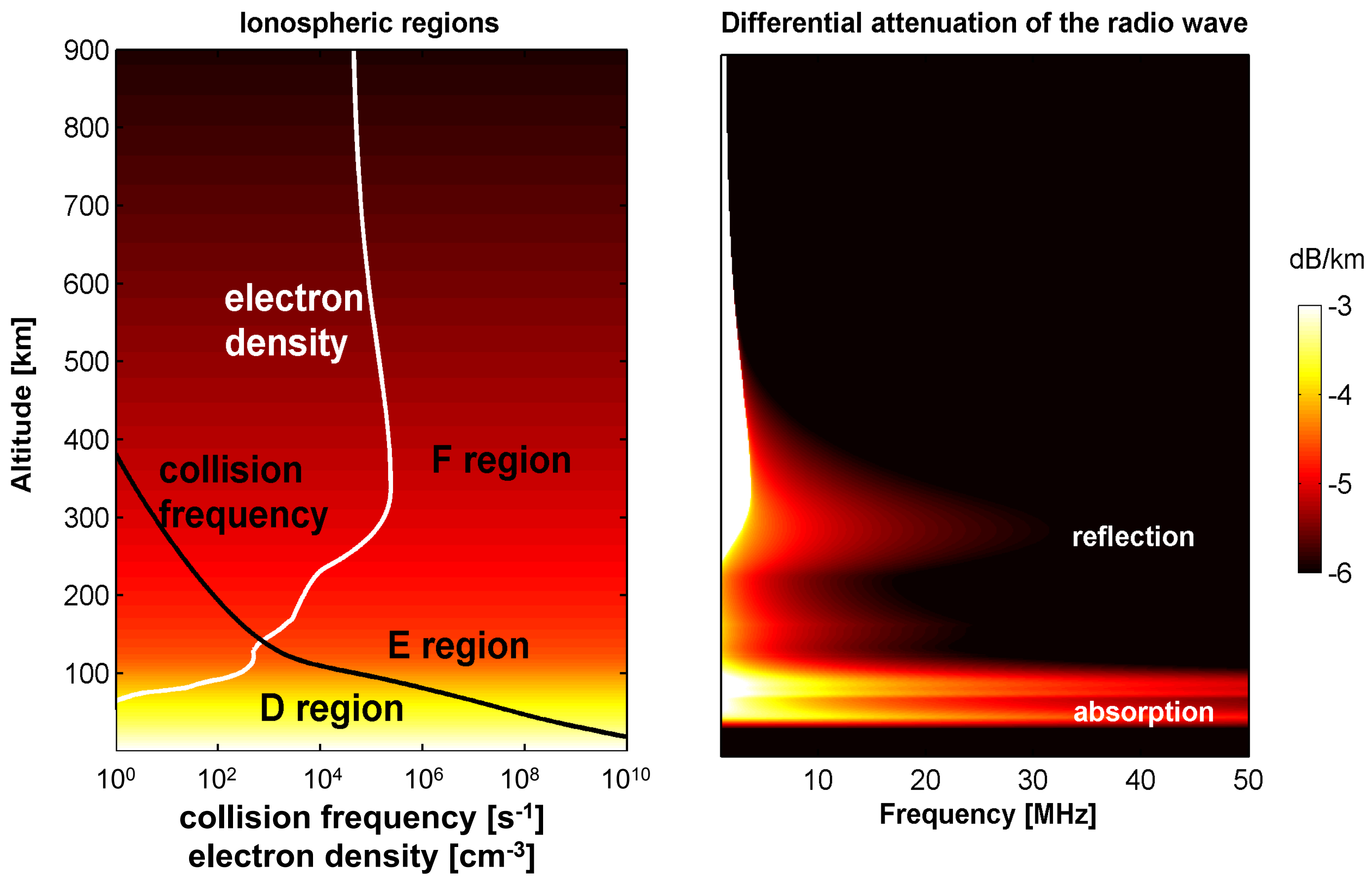
Consider a radio wave propagating in medium described by a complex refractive index $n = \Re(n) + i\Im(n)$. Apply it to the plane wave equation along path r

$$
\begin{aligned}
E(r,t) &= E_0 \exp\left(i\omega(t - \frac{n}{c} r) \right) \\
&= E_0 \exp\left(i\omega(t - \frac{\Re(n) + i\Im(n)}{c} r) \right) \\
&= E_0 \exp\left(i\omega\left(t - \frac{\Re(n)}{c} r \right) \right) \exp\left(\frac{\omega\Im(n)}{c} r \right)
\end{aligned}
$$

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

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

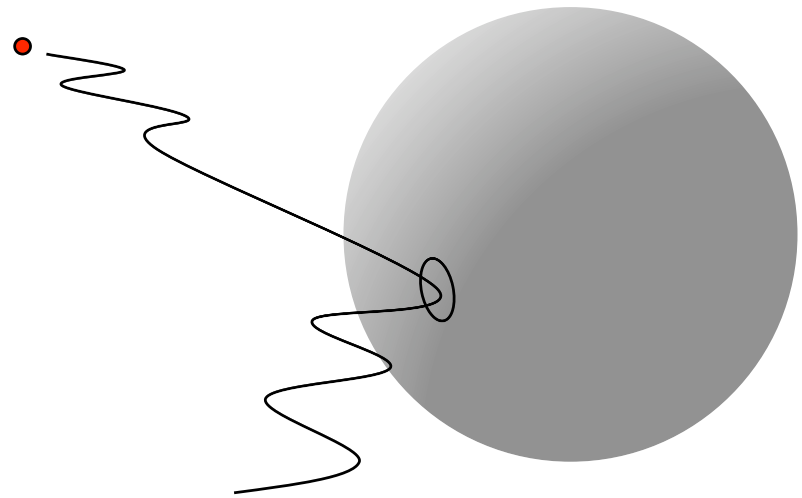
$$
E(r) = E'_0 \exp\left(\frac{\omega\Im(n)}{c} r \right) \xrightarrow{I \propto E^2} I(r) = I_0 \exp\left(\frac{2\omega\Im(n)}{c} r \right)
$$



Ionospheric regions
900
800
700
600
500
400
300
200
100
Altitude [km]
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

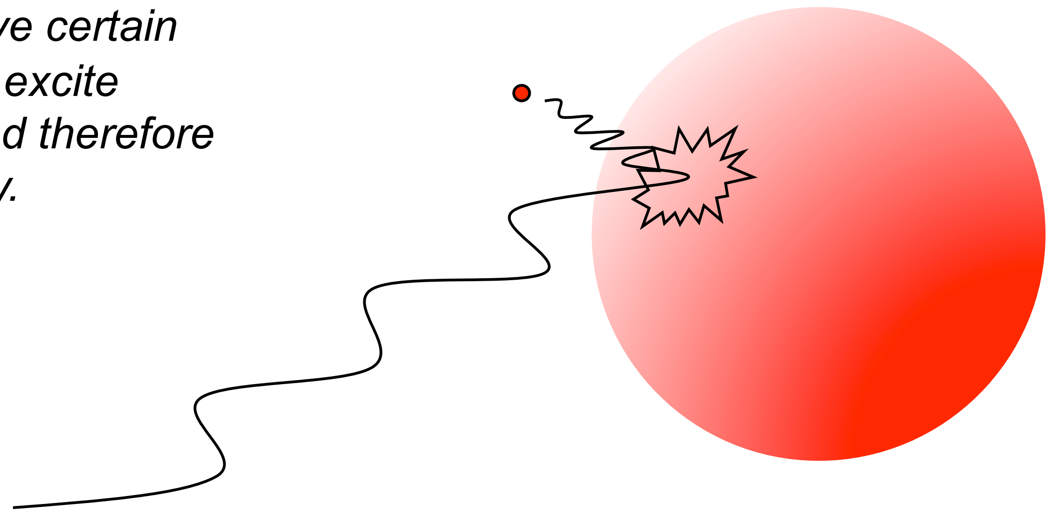
Physical interpretation of the absorption via collisions

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

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

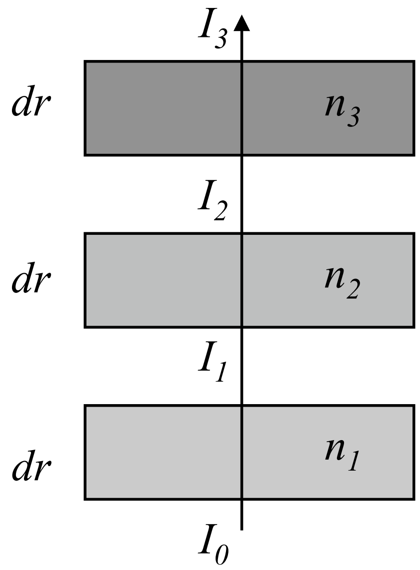
$$\nu_{en} = \nu_{en}(T_e, T_n, \text{neutral densities})$$

The electron temperature is calculated in dr layers:

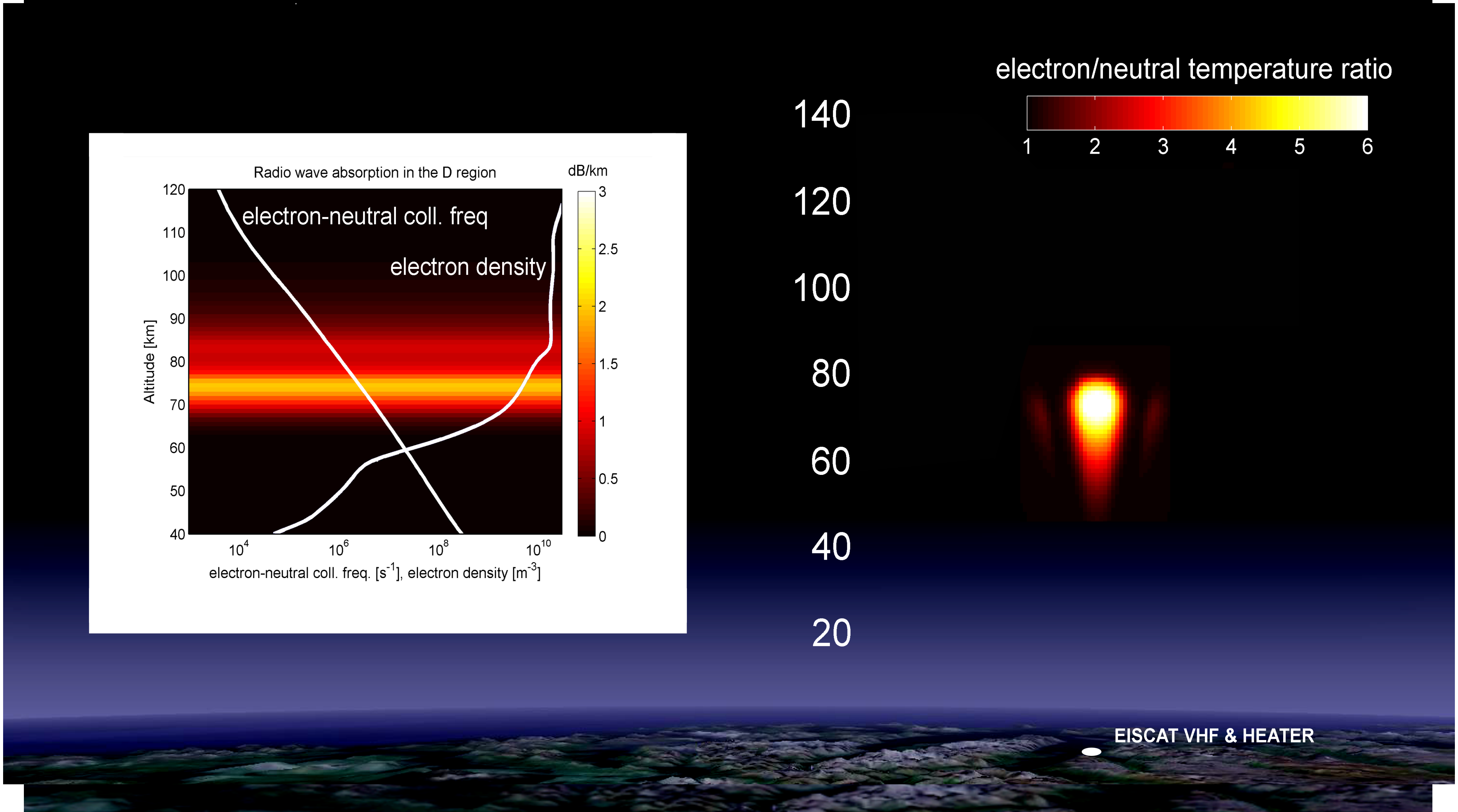
- *Calculate the intensity below*

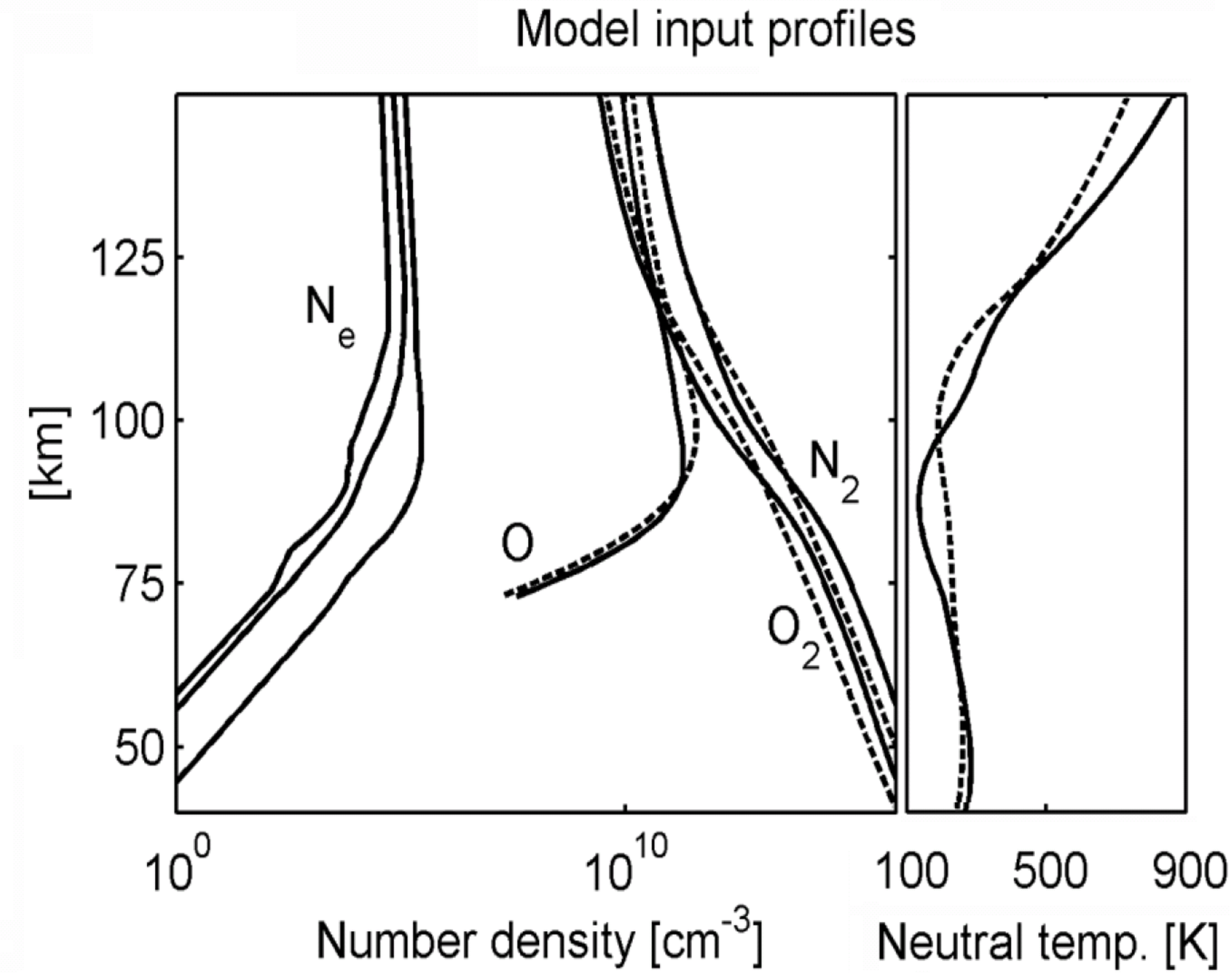
$$I = \frac{PG}{4\pi r^2}\exp\left(\frac{2\omega}{c}\int_0^r \Im(n)\,dr\right)$$

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



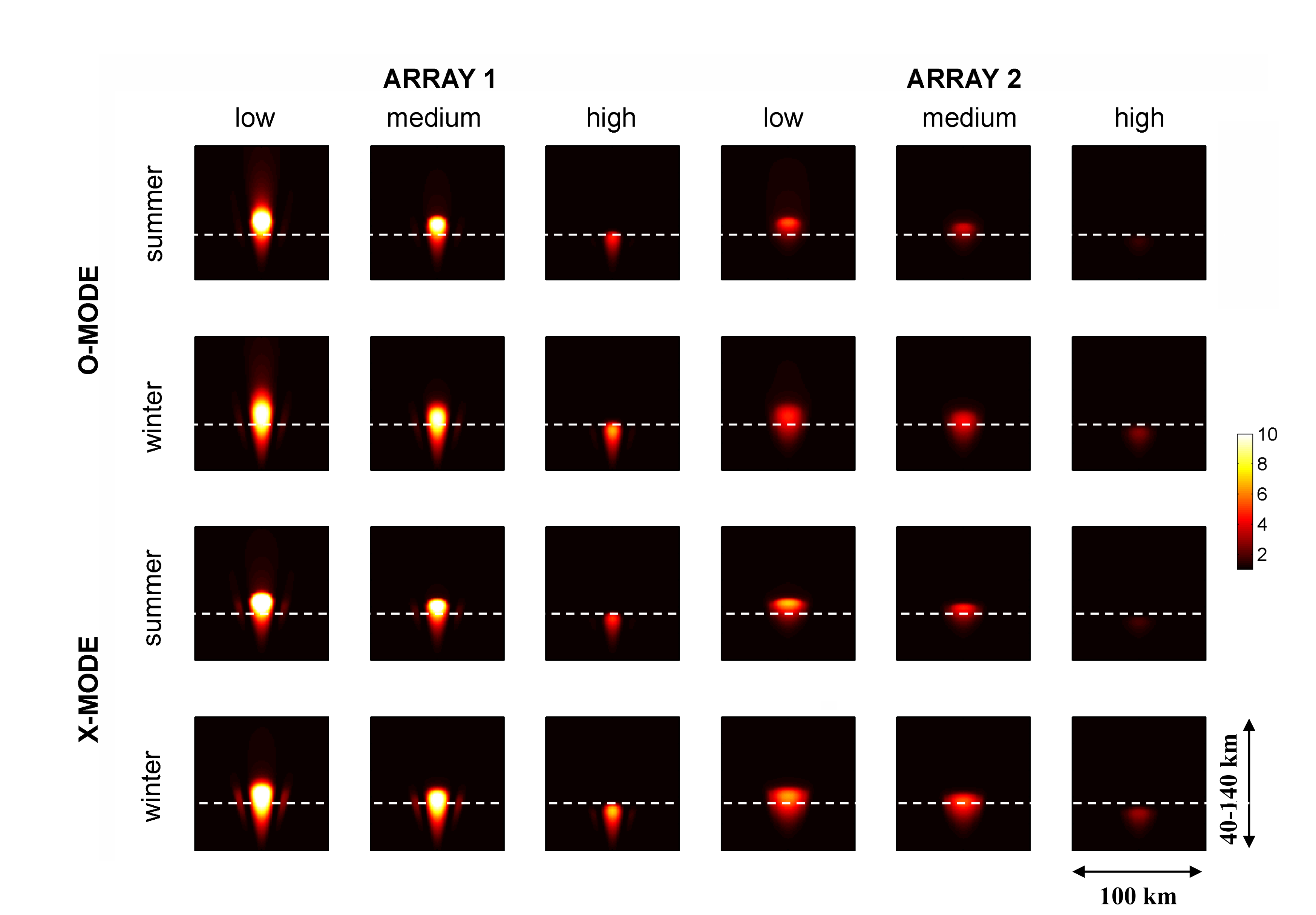
The modelled heating effect



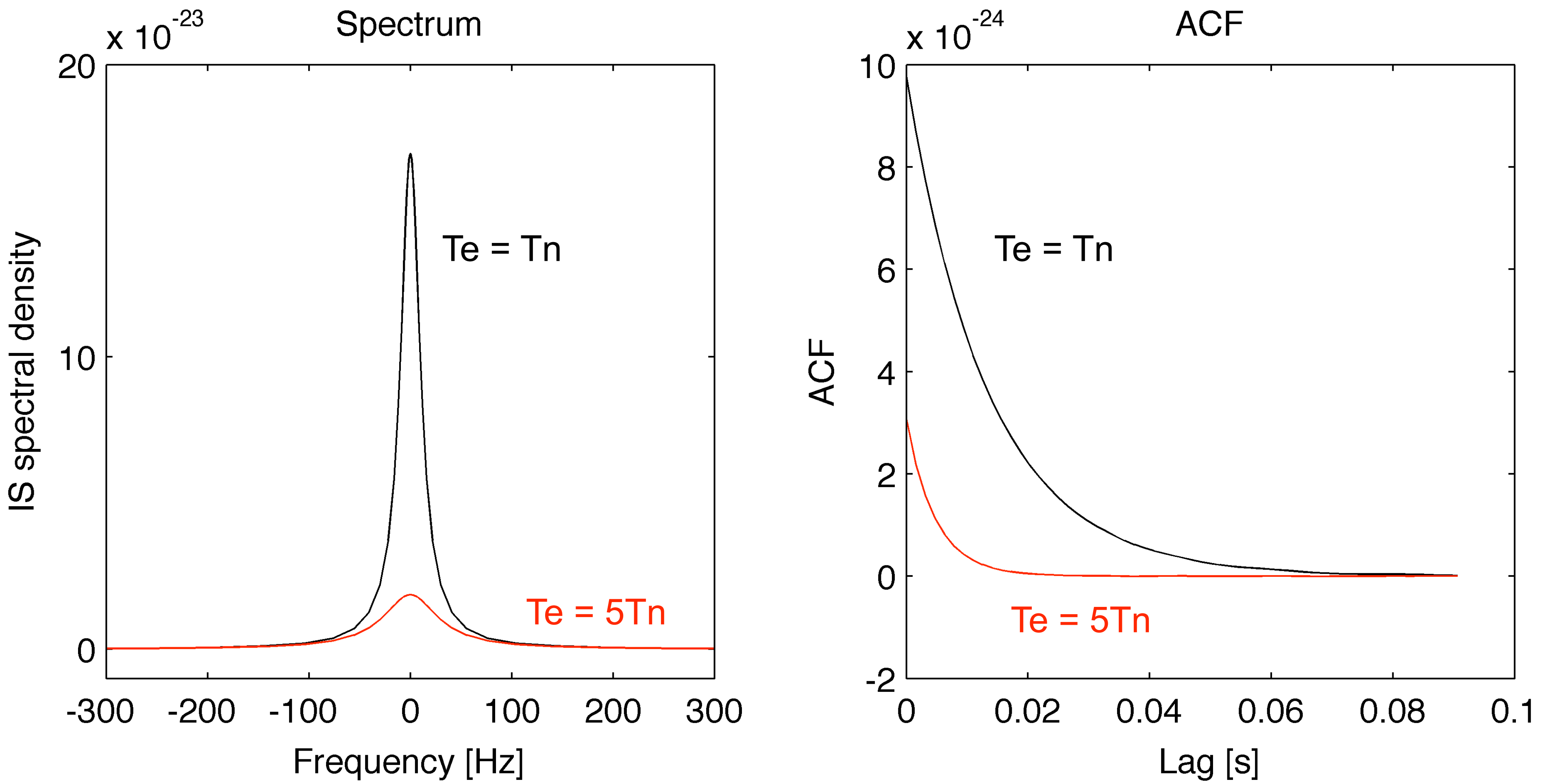


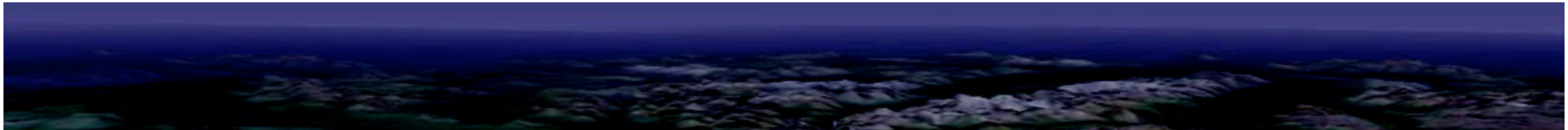
Model input profiles
125
100
75
50
[km]
N_e
O
N_2
O_2
10^0
10^{10}
Number density [cm^{-3}]
100
500
900
Neutral temp. [K]

Modelled heating effect in the D region

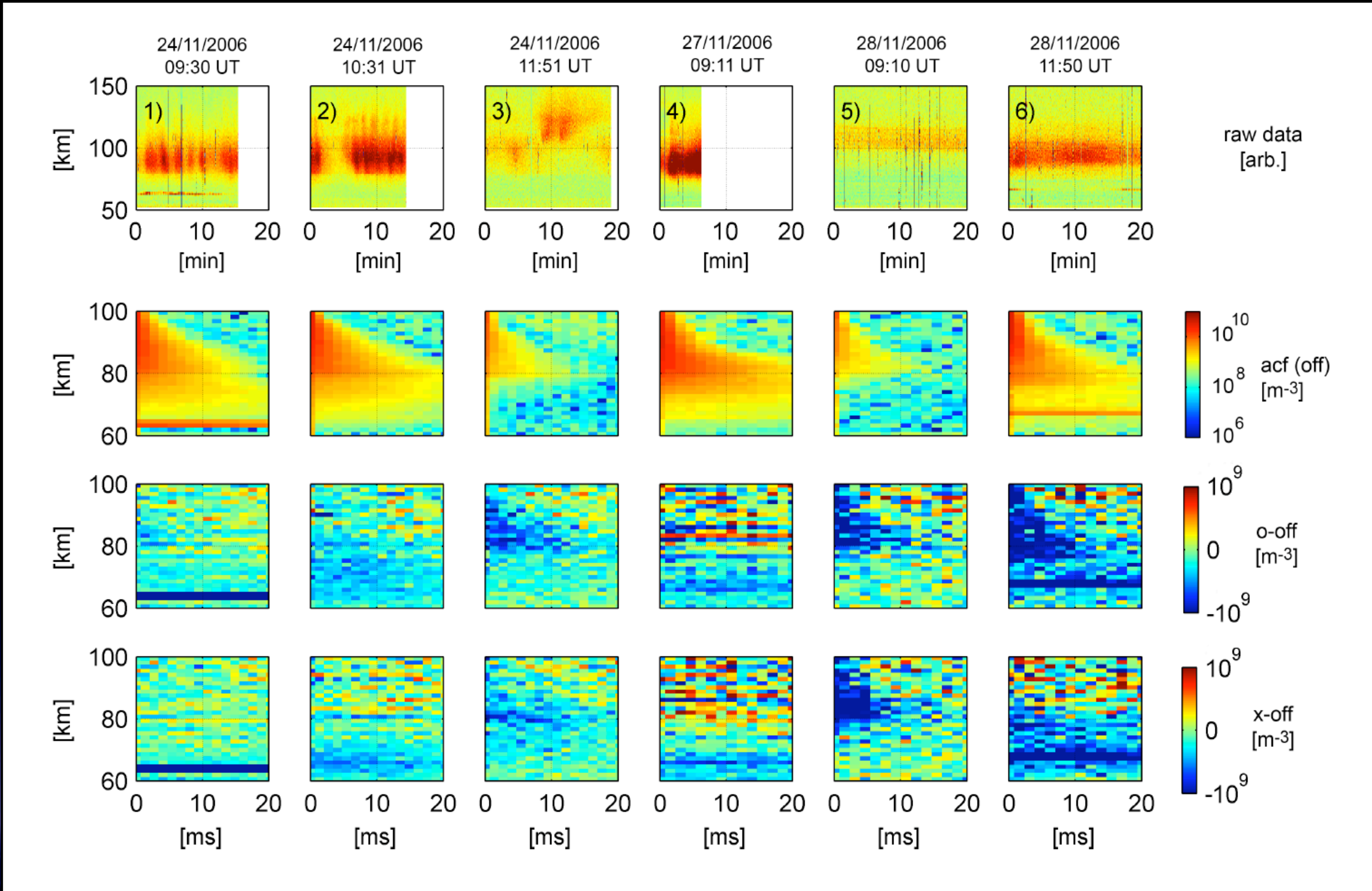


Heating effect on IS spectrum

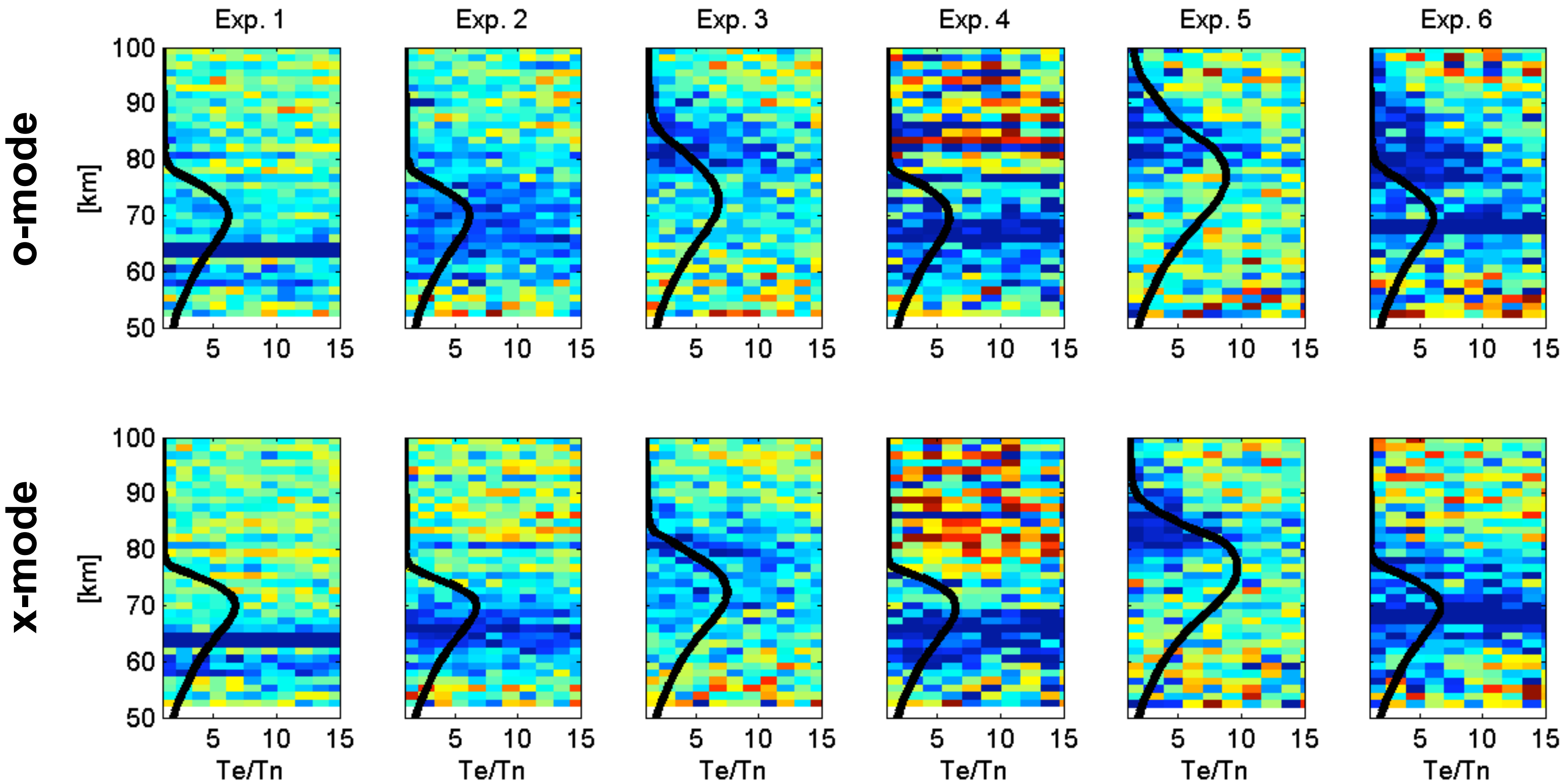




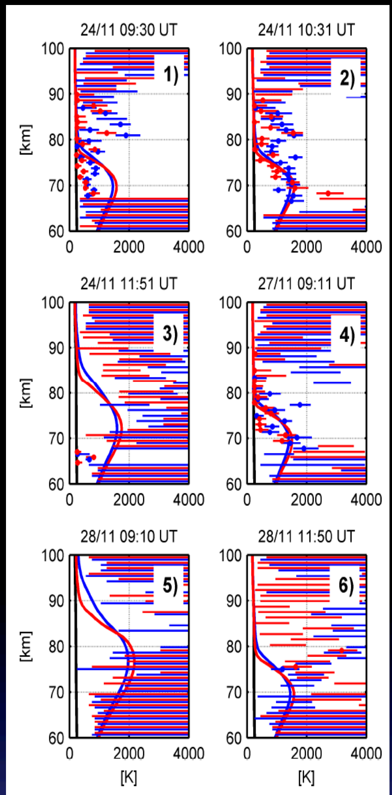
Heating signature in the IS signal (2006)

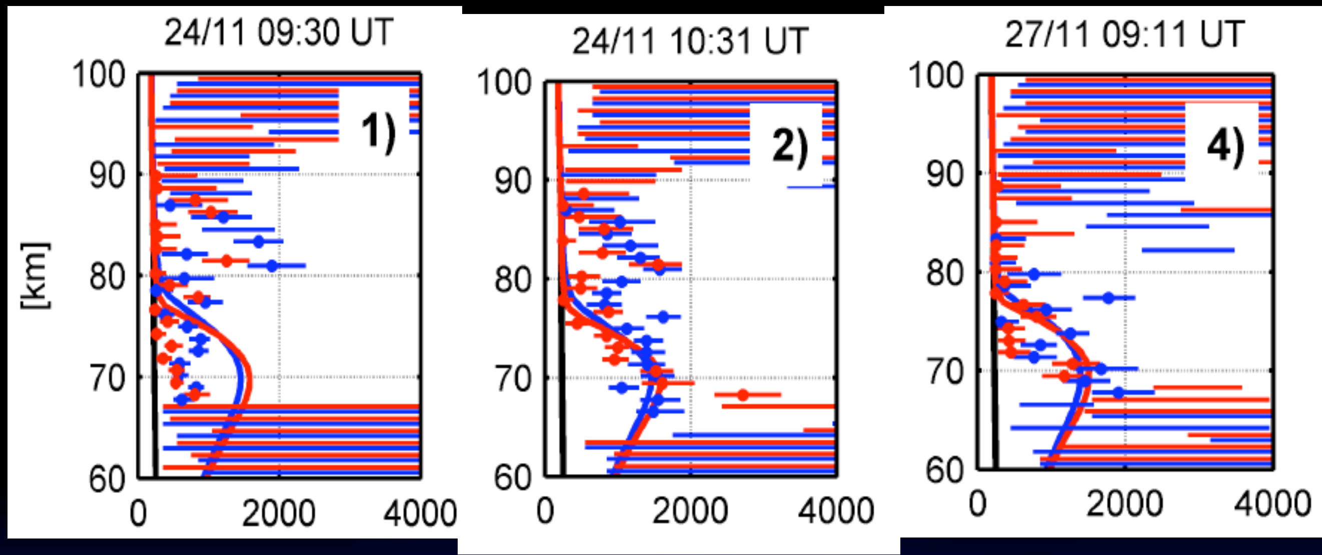


Model vs. data for the 2006 experiments



Model vs. data for the 2006 experiments

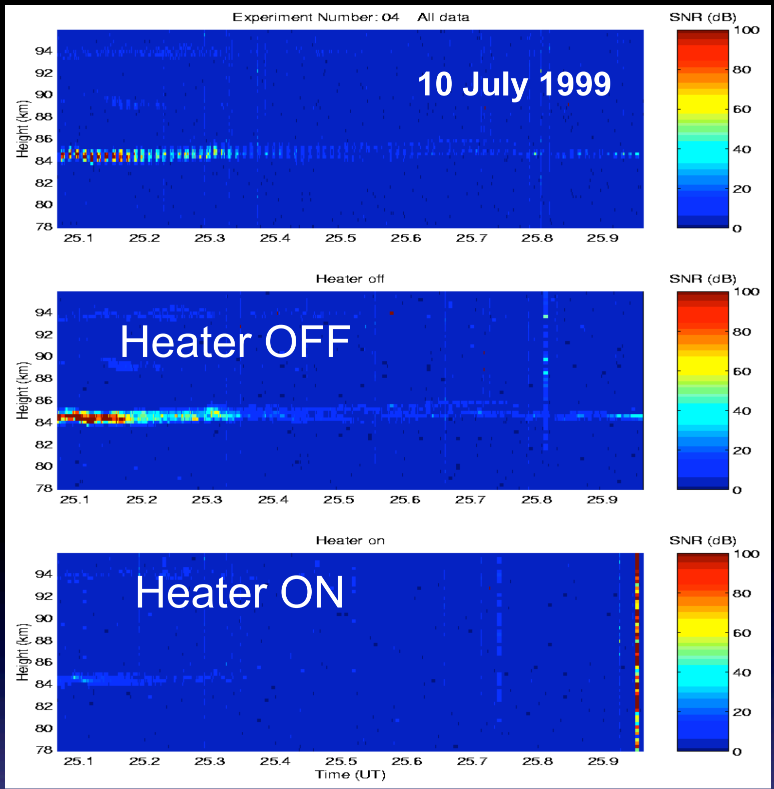




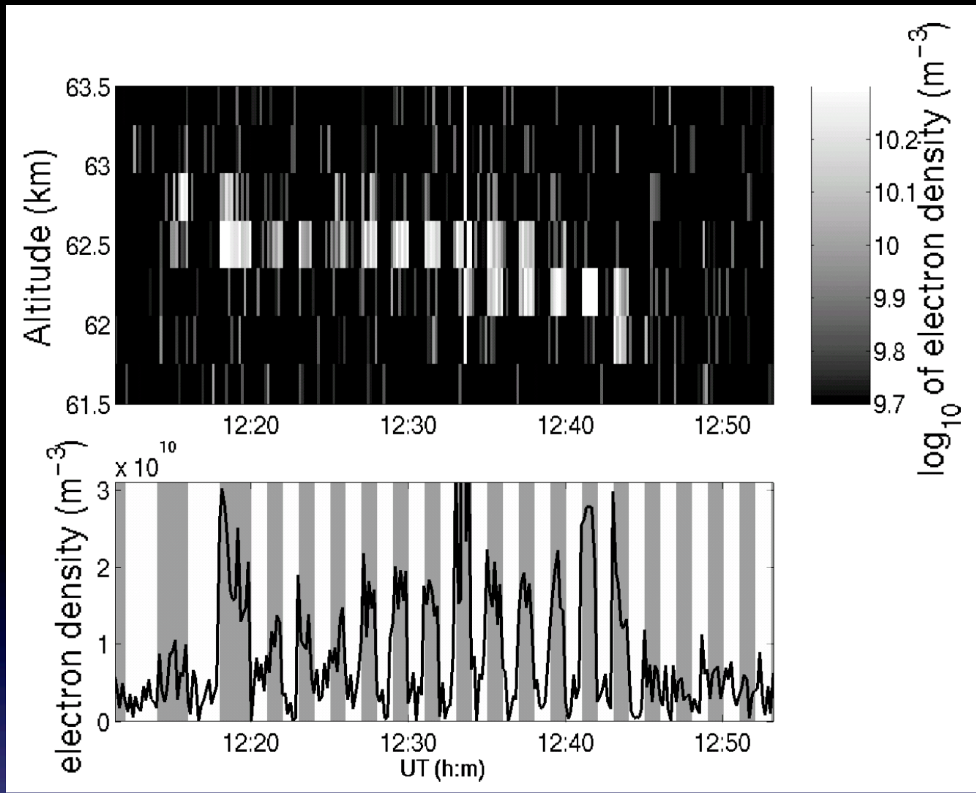
Kero et al., Ann Geophys, 2008

PMSE & PMWE

PMSE at 85 km

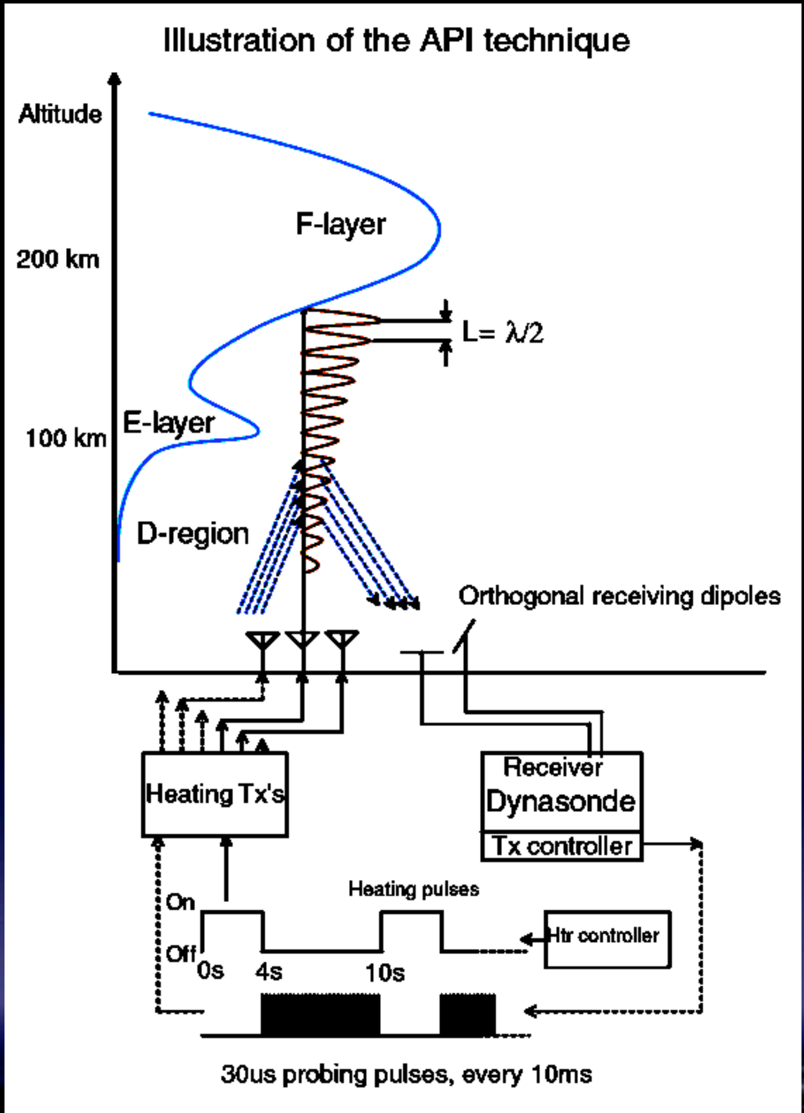


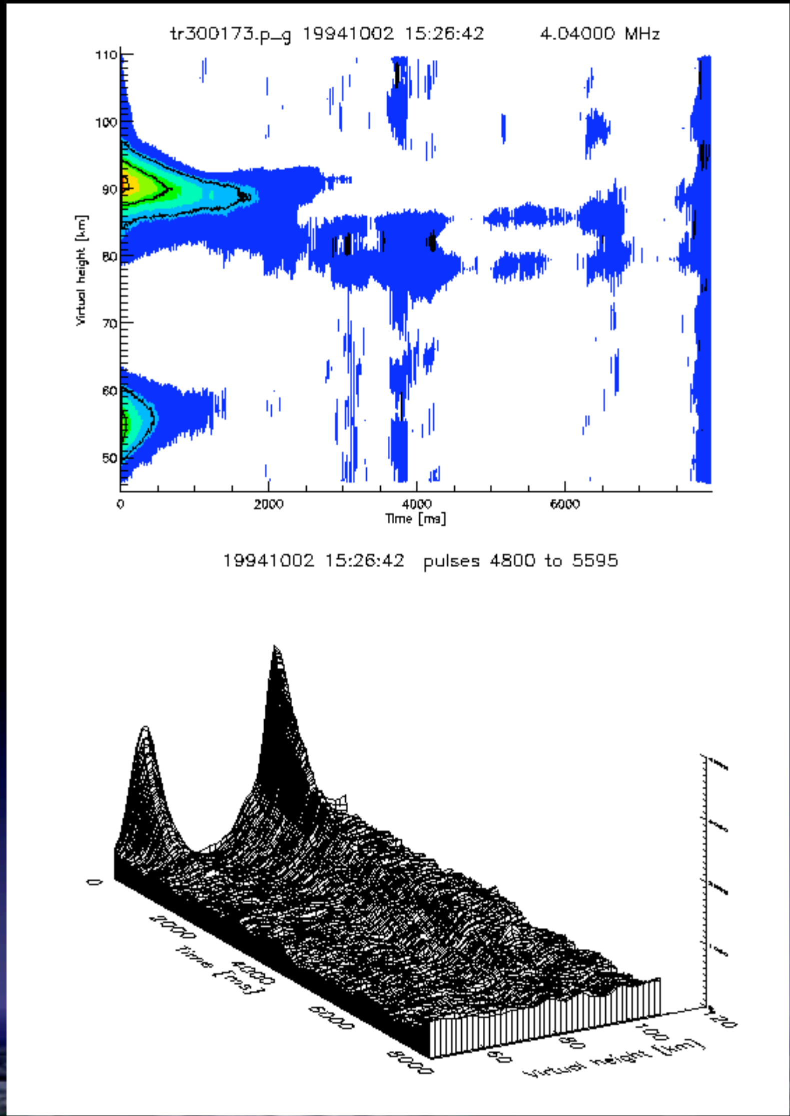
PMWE at 63 km



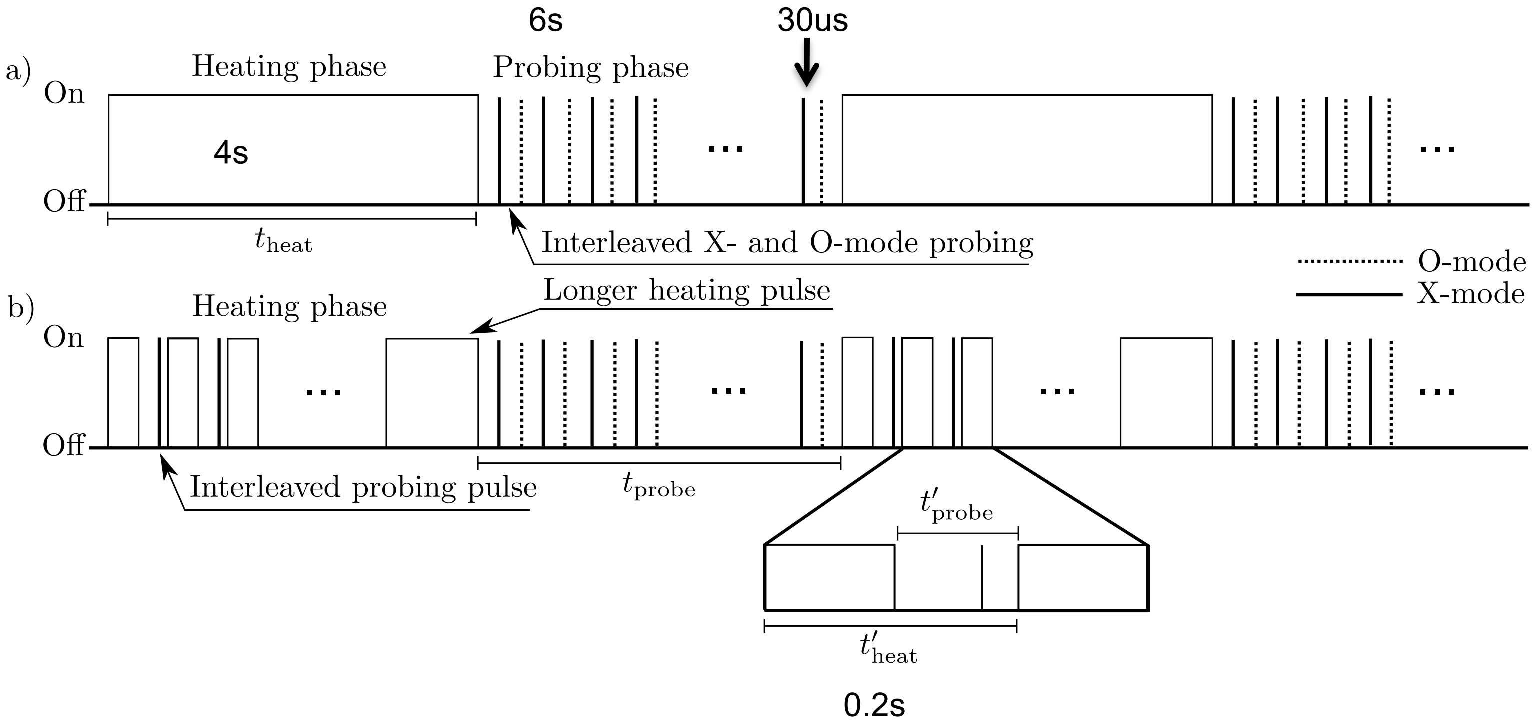
Kavanagh et al., GRL, 2006

Artificial Periodic Irregularities (API)

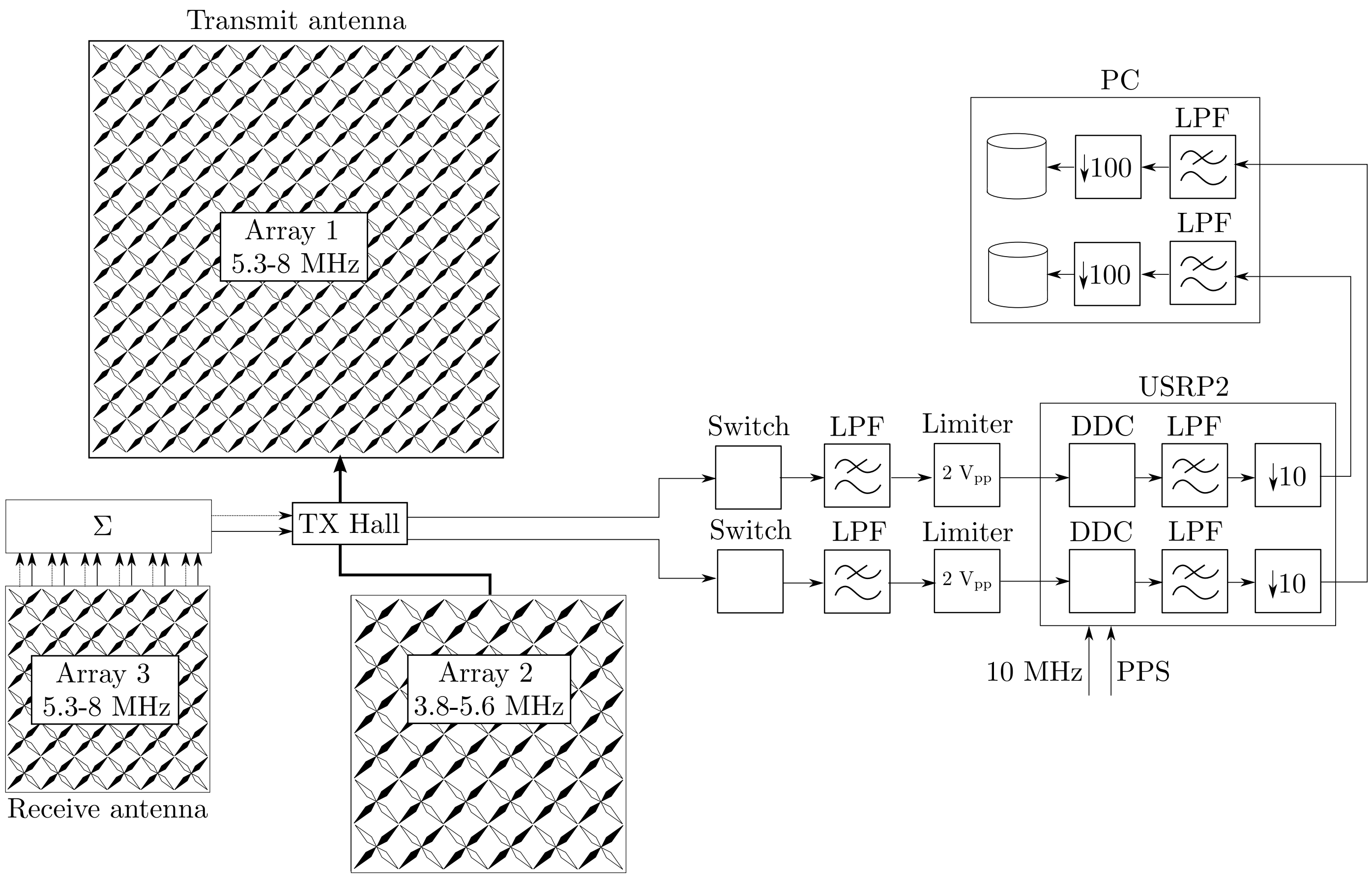


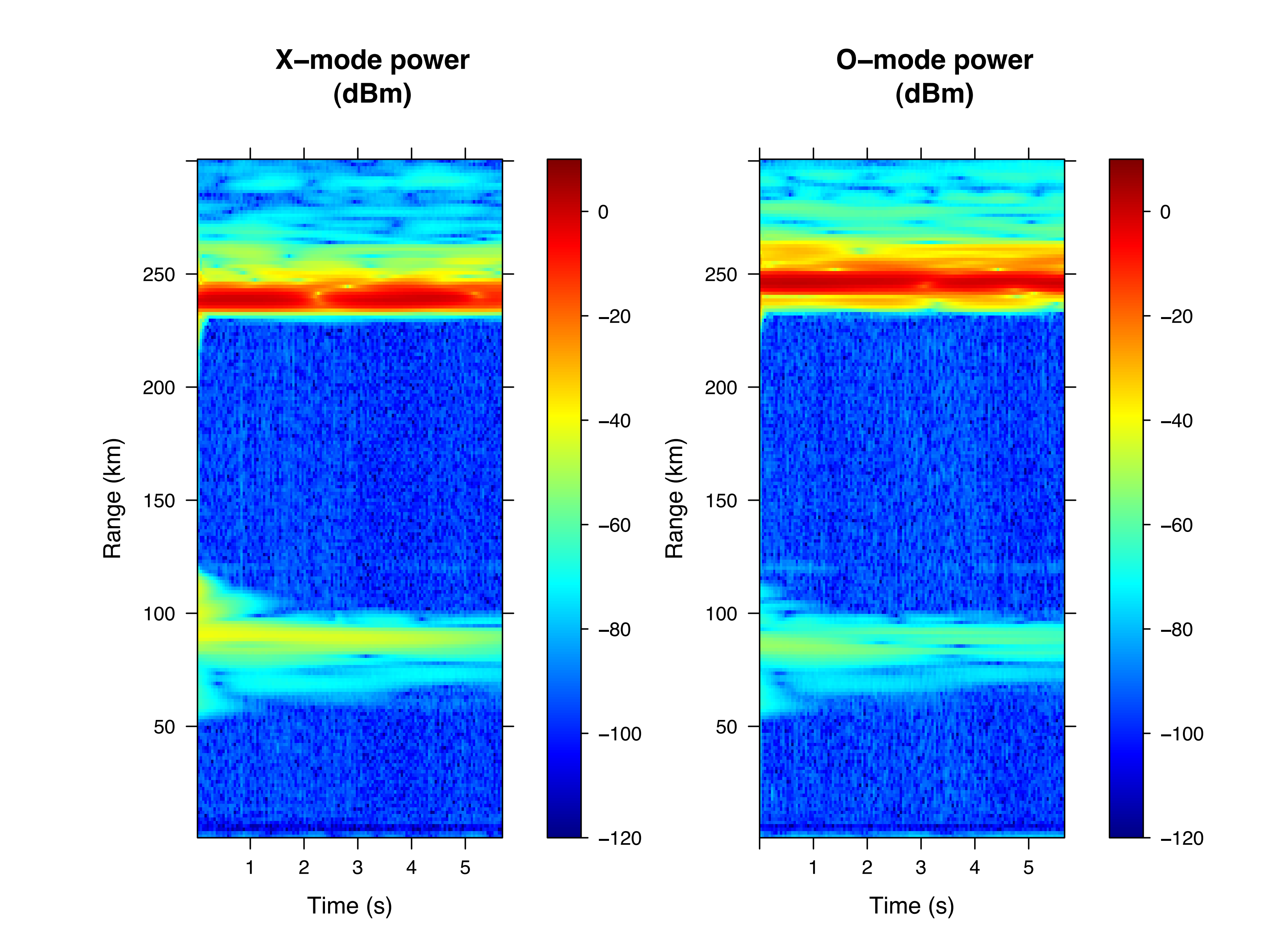


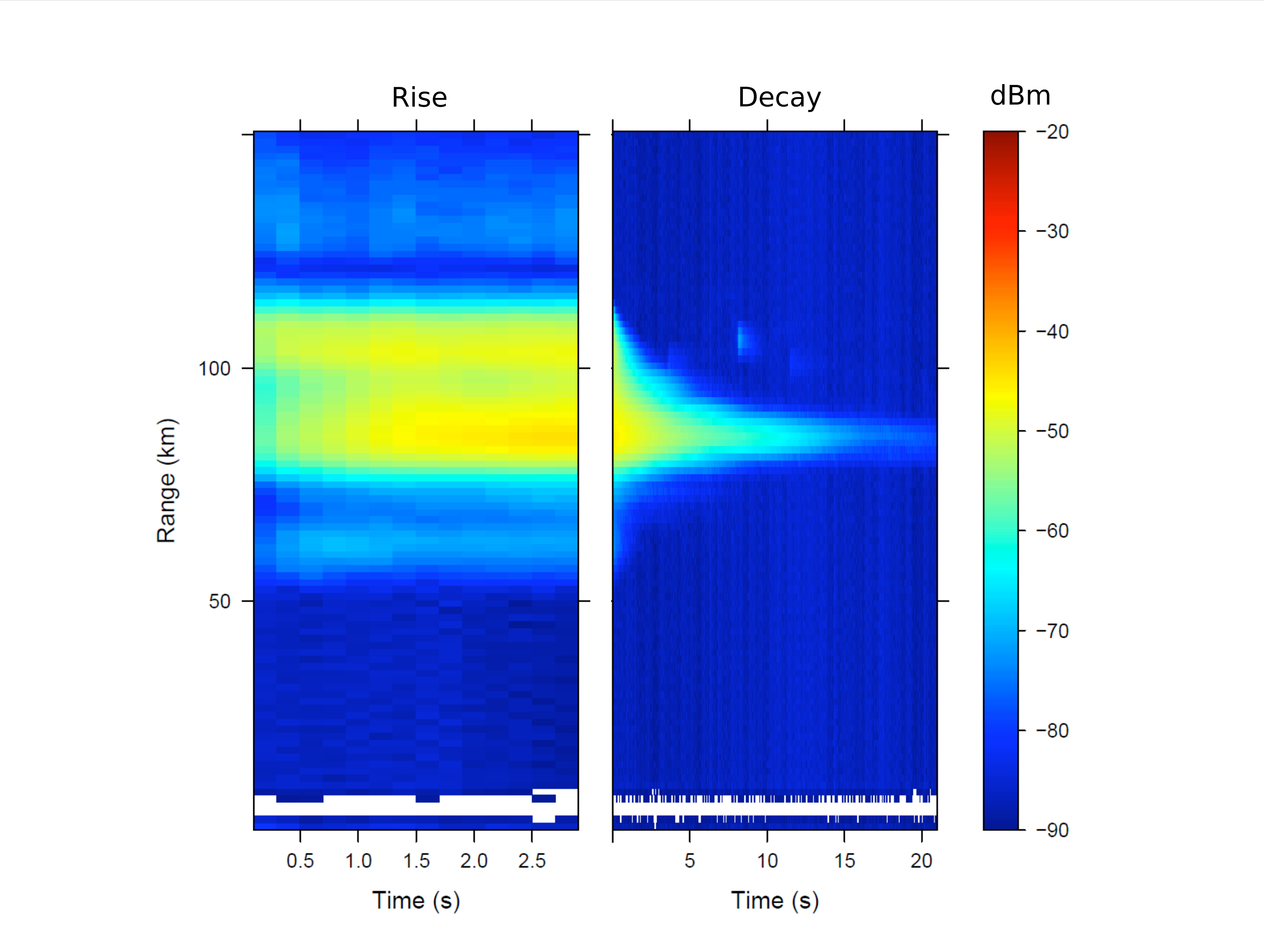
API modulation schemes



Technical implementation




X–mode power
(dBm)
O–mode power
(dBm)
Range (km)
250
200
150
100
50
1
2
3
4
5
Time (s)
0
–20
–40
–60
–80
–100
–120

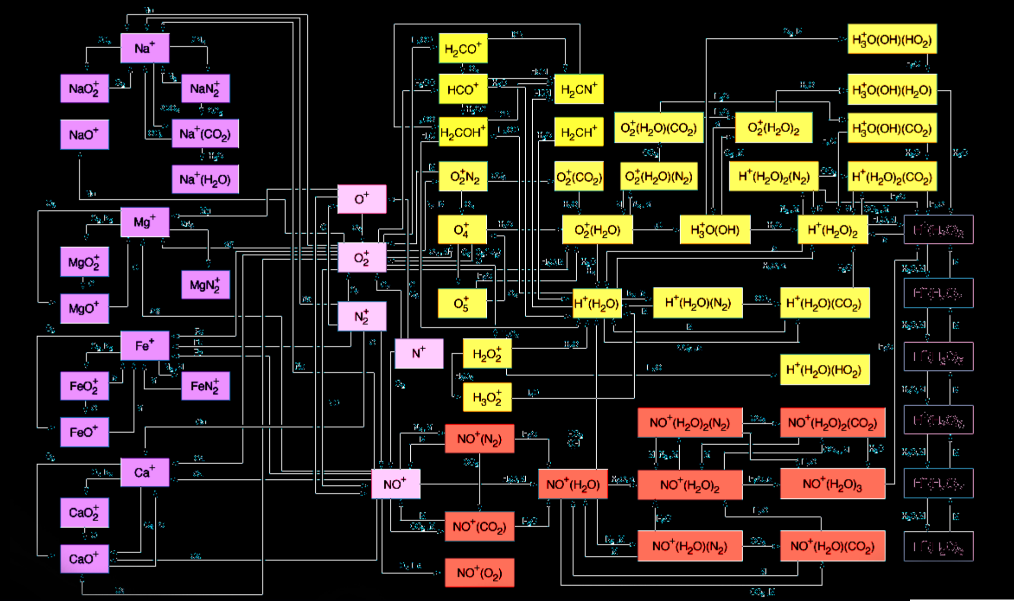


Rise
Decay
dBm
Range (km)
100
50
0.5
1.0
1.5
2.0
2.5
Time (s)
5
10
15
20
Time (s)
-20
-30
-40
-50
-60
-70
-80
-90

Sodankylä Ion Chemistry model (SIC)

Detailed 1-D time dependend chemistry

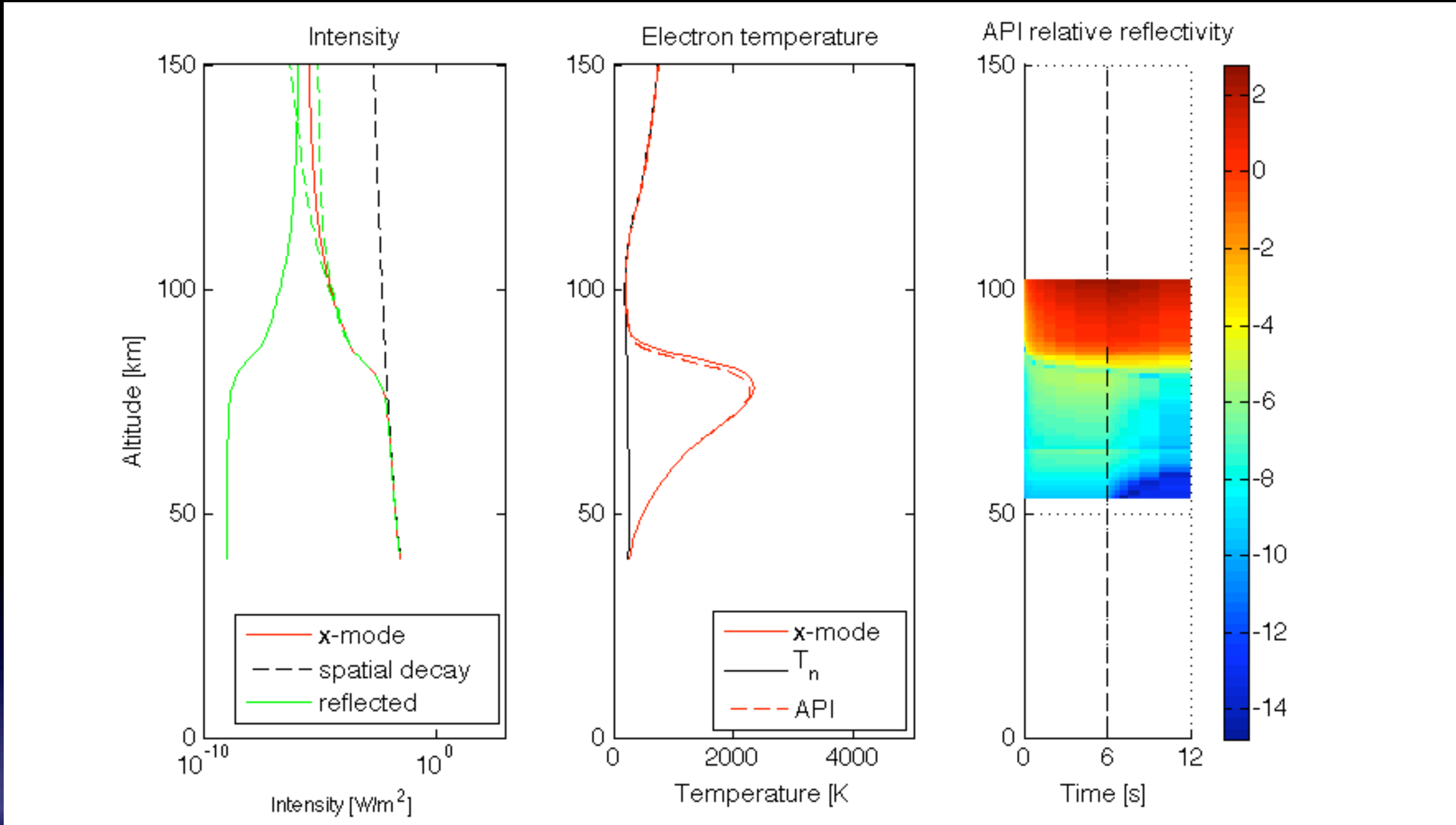
- 63 ions (27 negative) & 13 neutrals
- 20-150 km in 1 km resolution
- several hundred reactions
- vertical transport



Input

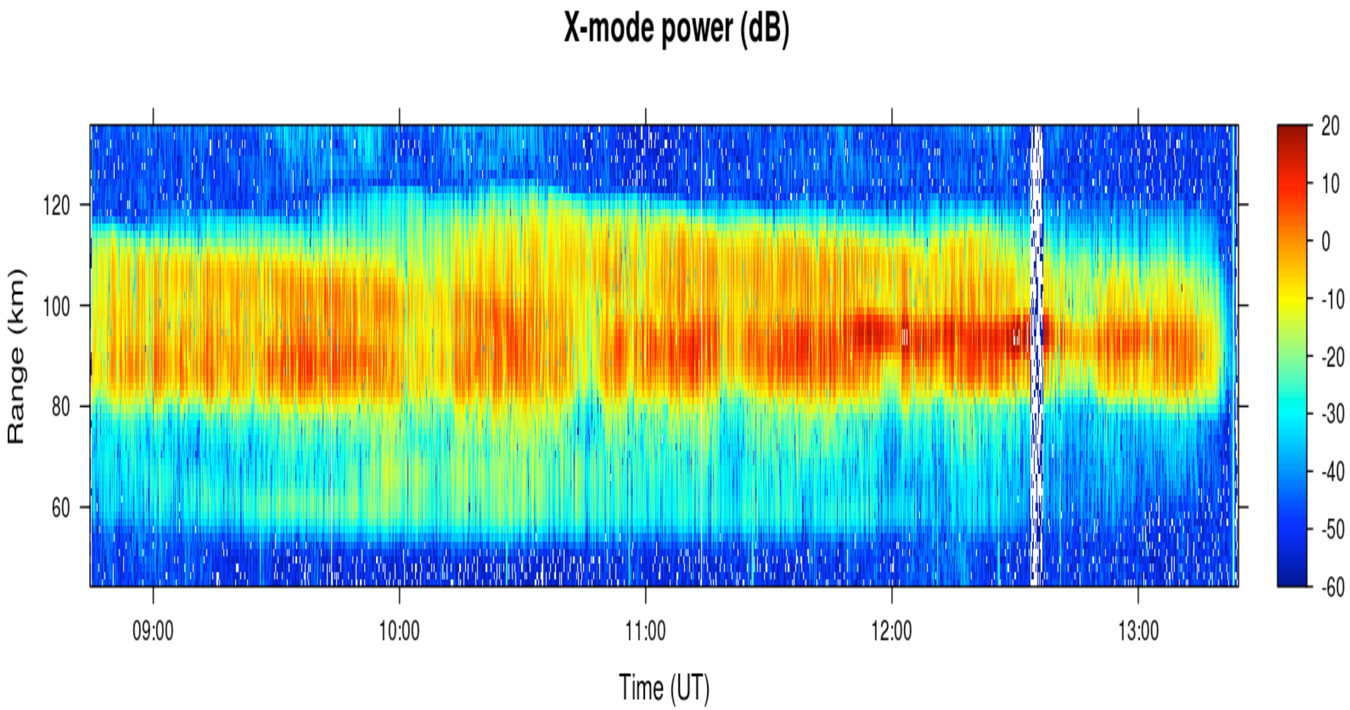
- MSIS
- solar flux
- proton and electron precipitation
- cosmic rays

Modelling the API

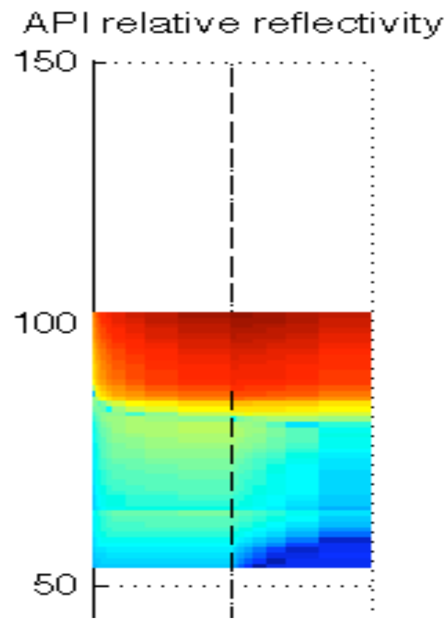


API “brightness”, data vs. model

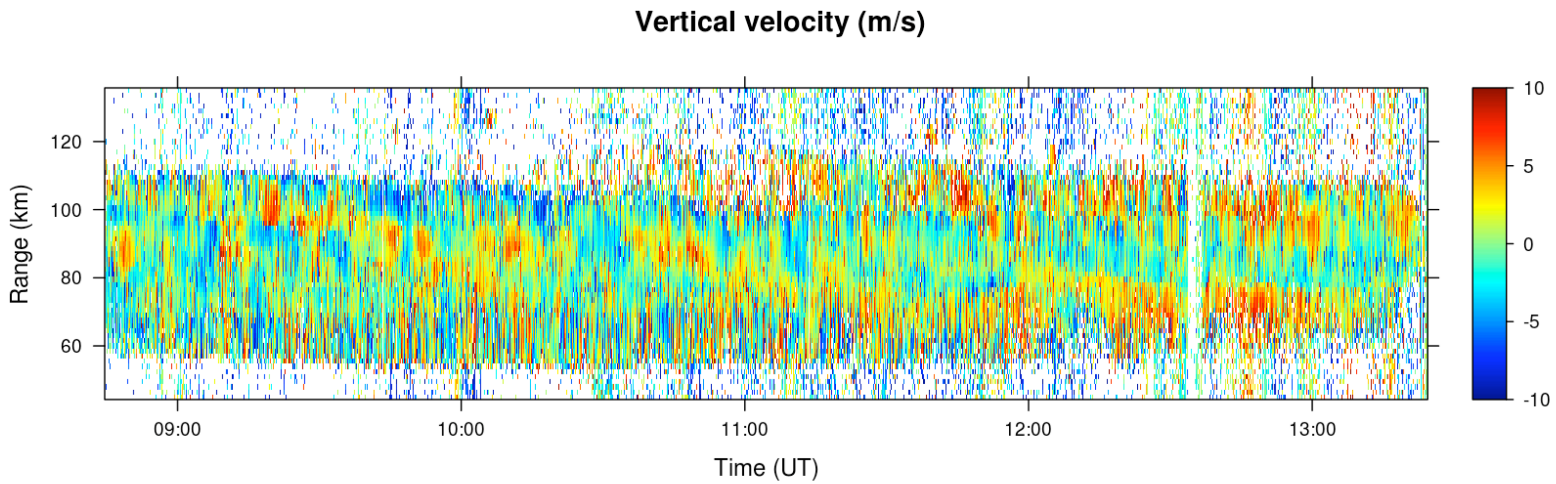
Data, 9th December 2011

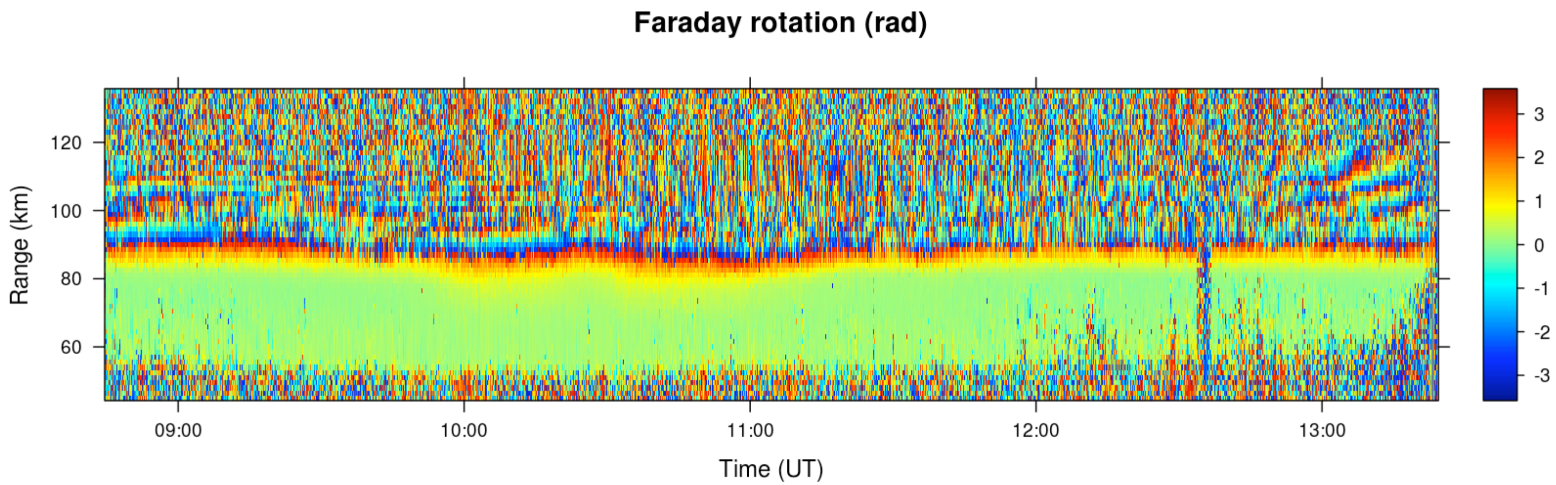


Model



Other parameters …





API vs. PMSE/PMWE in the mesosphere

	API	PMSE/PMWE
Production	• standing wave • negative ion prod. • (dust charging?)	• turbulence • dust/ice charging • (negative ions?)
Loss	• detachment • (dust de-charging) • (diffusion)	• diffusion • dust de-charging • (detachment)
Heating	Forms the irregularities in the first place	Makes the echo *weaker* (+ builds the overshoot)
Lambda	55.3 m	0.32/1.34/5.35 m

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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

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

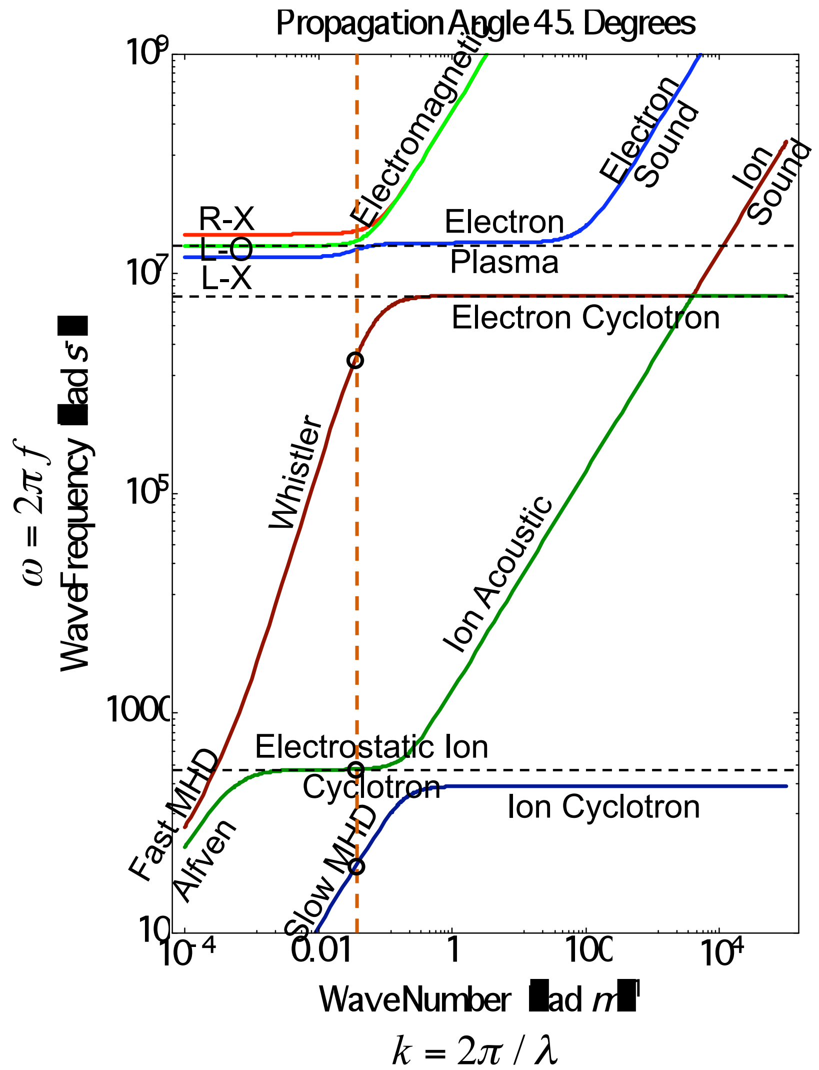
$$\frac{\partial \tilde{\mathbf{B}}}{\partial t} + \nabla \times \tilde{\mathbf{E}} = 0, \quad \nabla \cdot \tilde{\mathbf{B}} = 0$$

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

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

- 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 ($k^2 \to 0$, $\lambda^2 \to \infty$)
  - Resonances ($k^2 \to \infty$, $\lambda^2 \to 0$)
  - MHD
    - $k^2 \to 0$, $\omega^2 \to 0$
    - Finite Phase Velocity (ω/k)
  - High Frequency
    - $k^2 \to \infty$, $\omega^2 \to \infty$
    - 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

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

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

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

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

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

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

$T_e = 2500K$

$T_i = 800K$

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

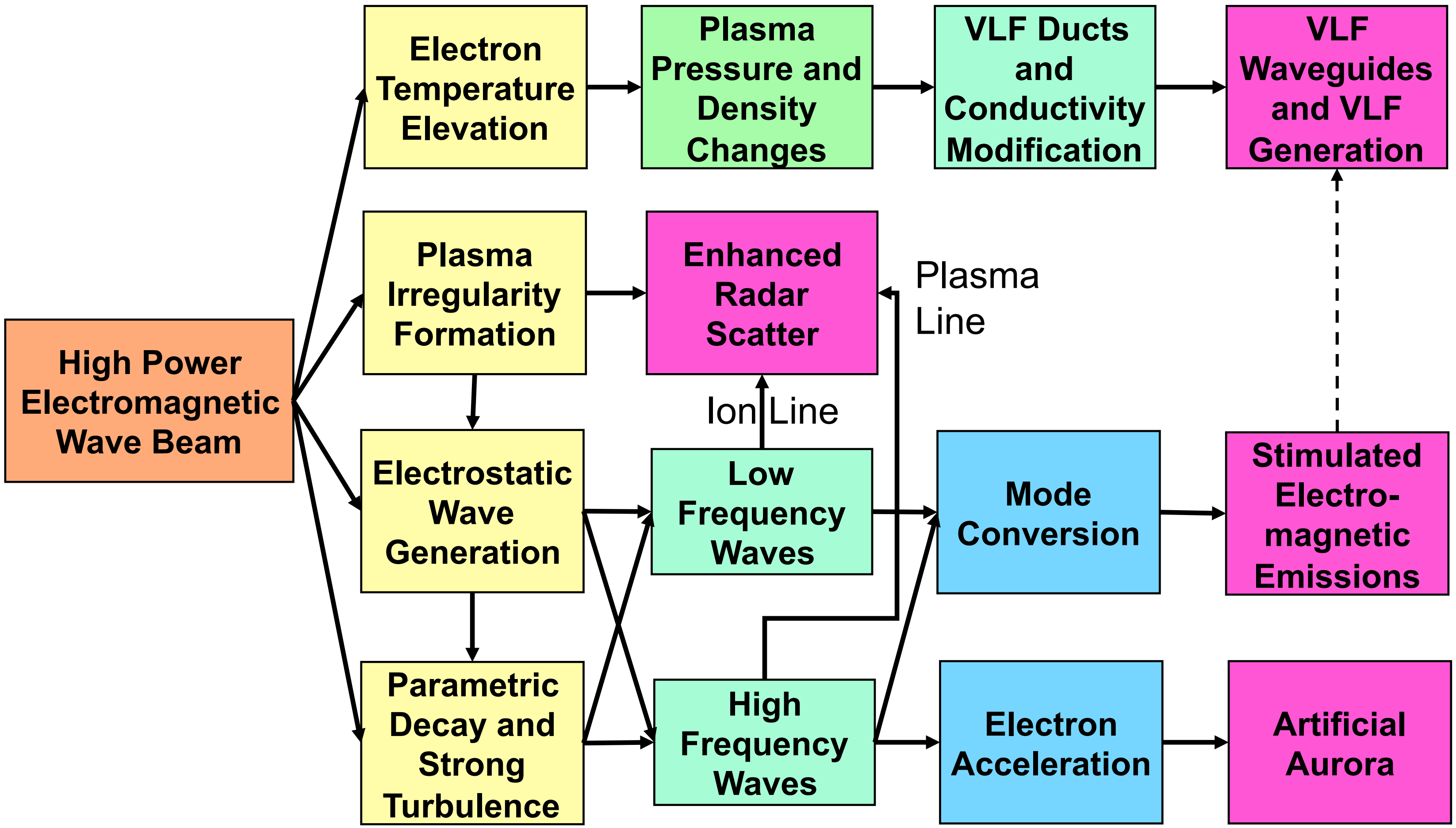
$c_s = 1590\ m/s$

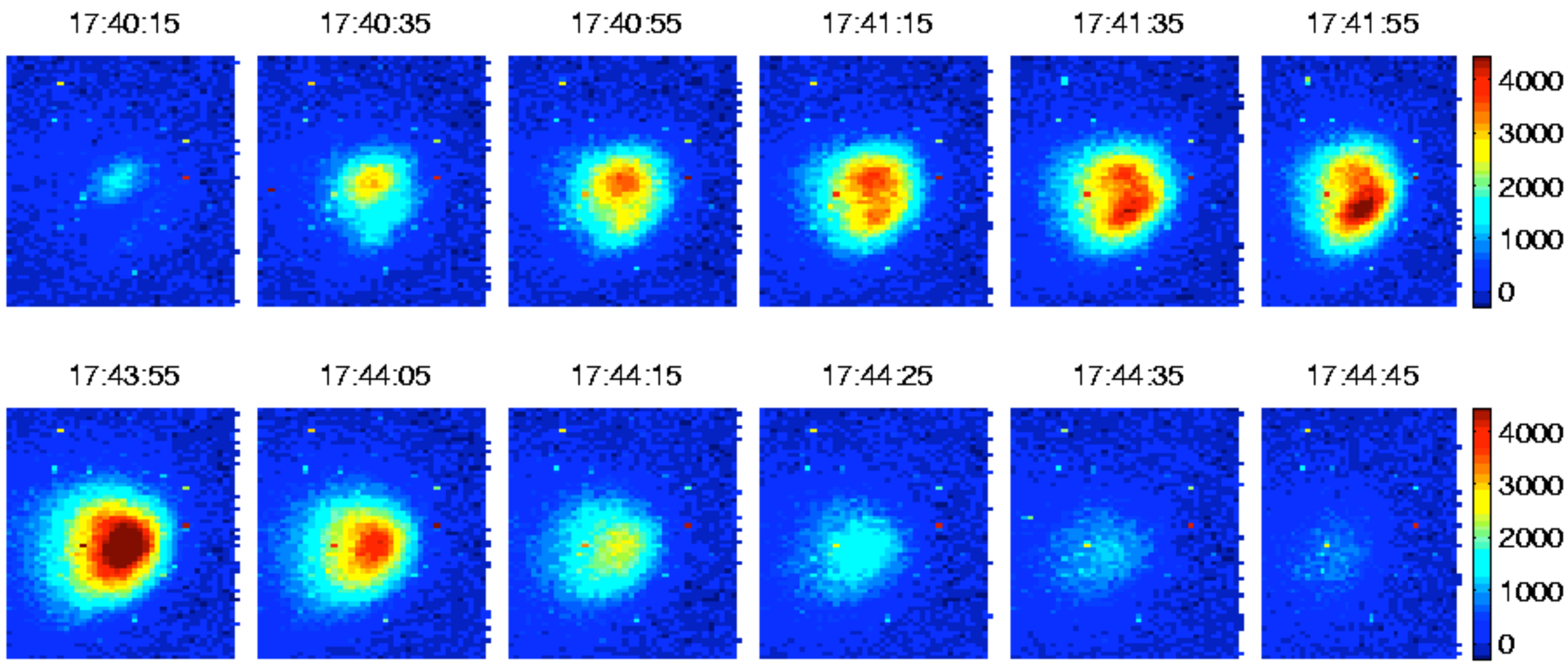
$\rho_e = 0.022\ m$

$\rho_i = 3.64\ m$

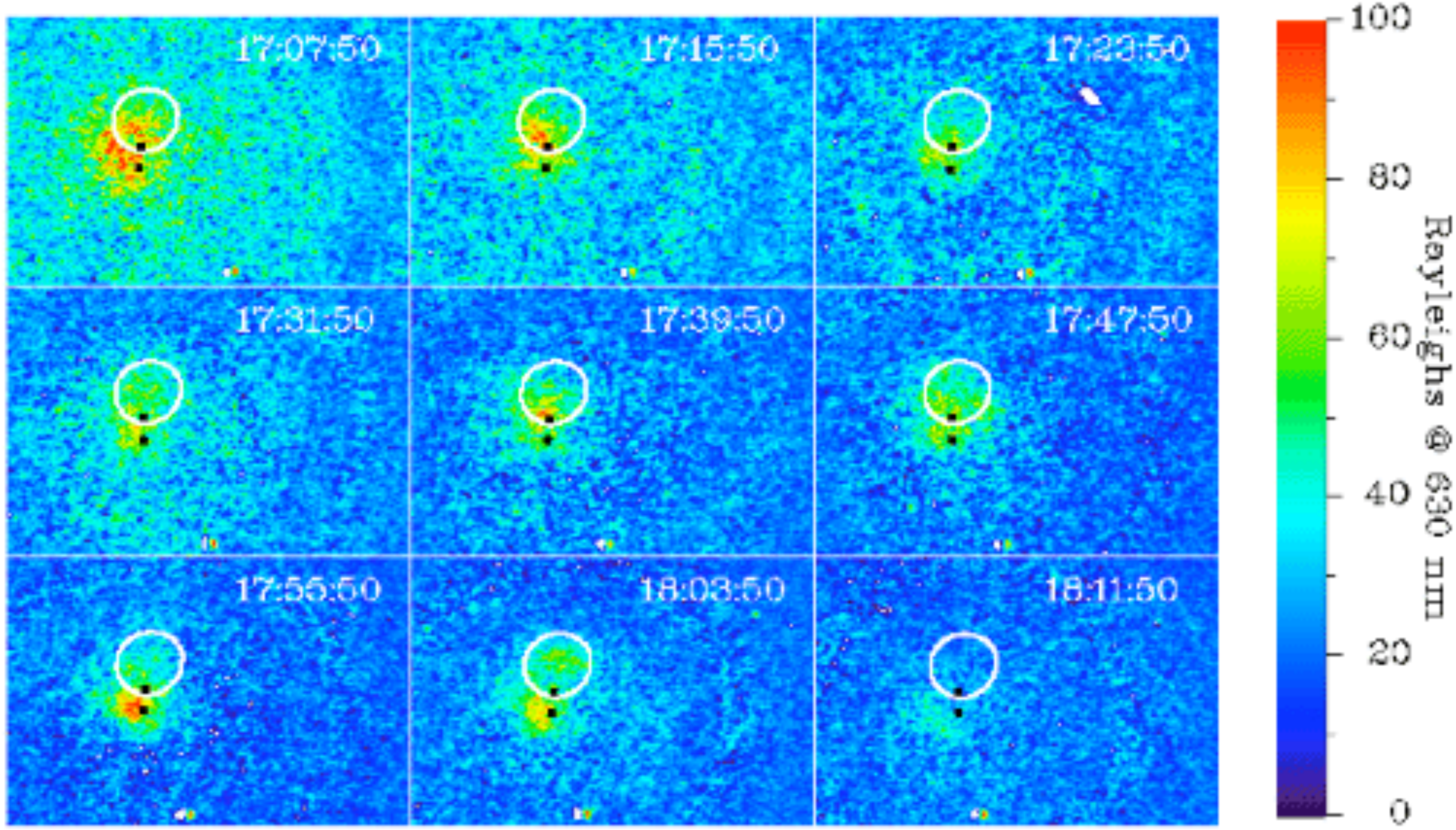
$\theta = \pi/4$

Ionospheric Modification with High Power Radio Waves





(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

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

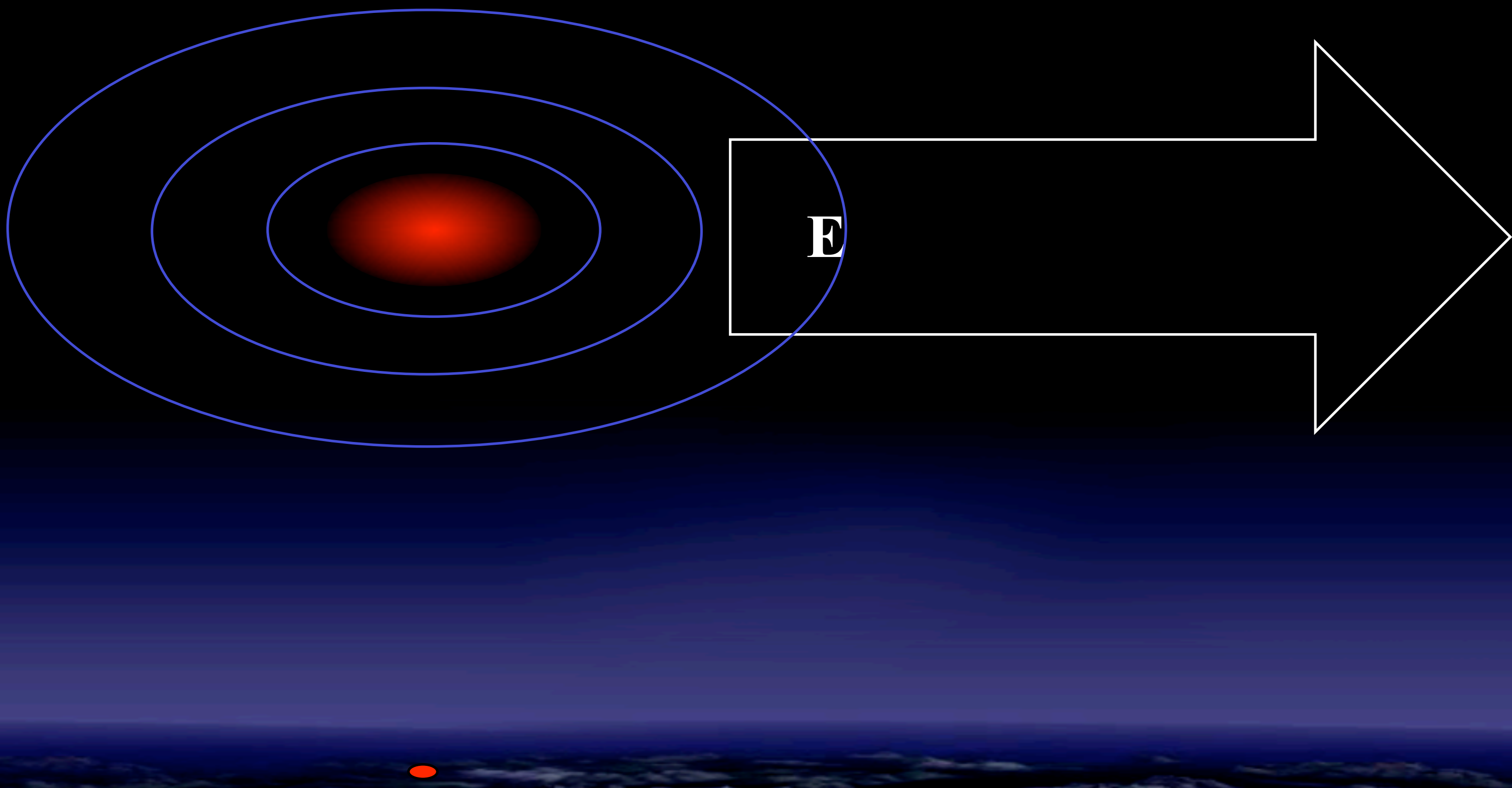
$$\sigma_P = \frac{ne}{B}\left(\frac{k_i}{1+k_i^2} + \frac{k_e}{1+k_e^2}\right)$$

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

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

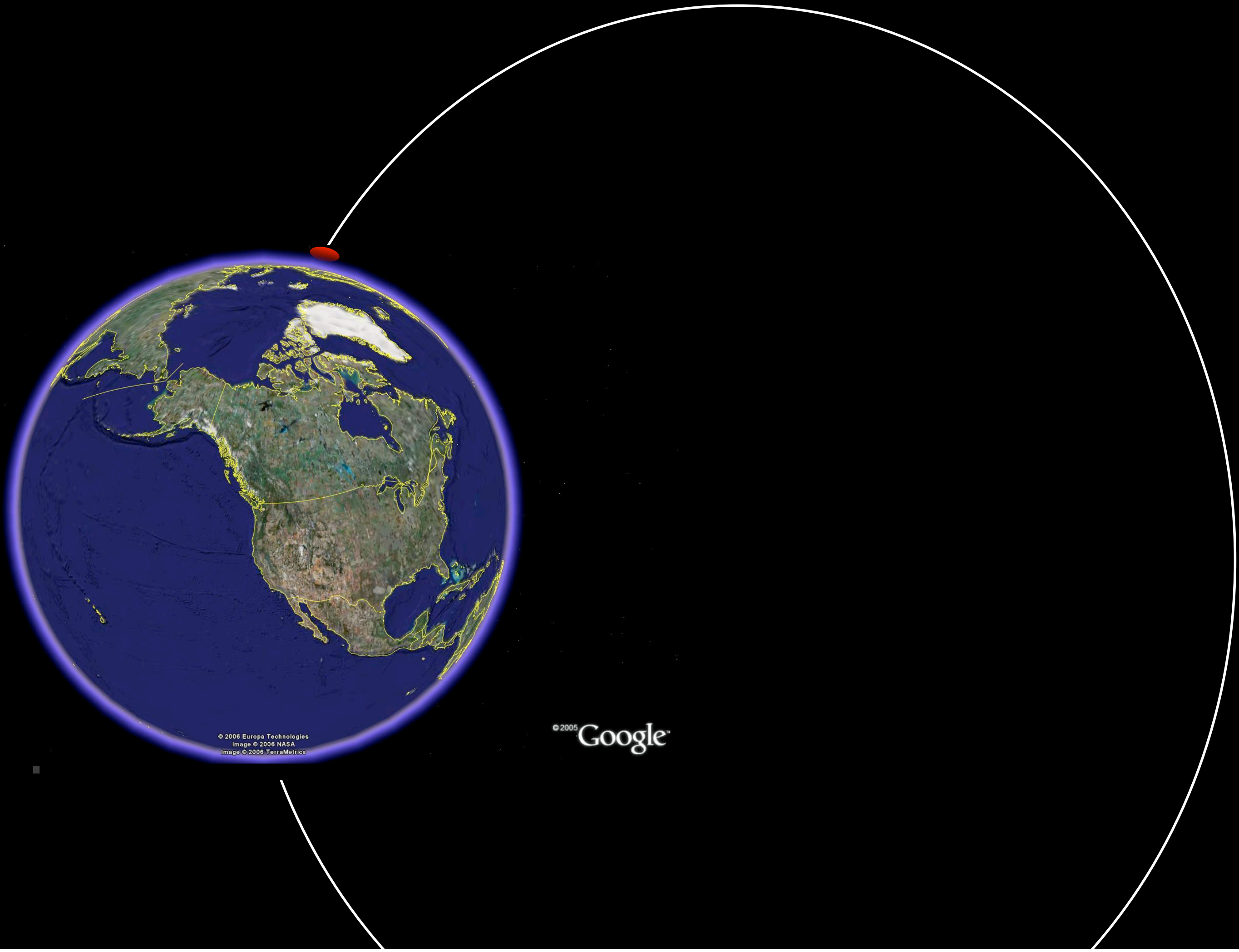
$$k_i = \frac{\omega_i}{\nu_{in}} \qquad k_e = \frac{\omega_e}{\nu_{en}}$$

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



Heating effect on the conductivities:

ducted VLF waves

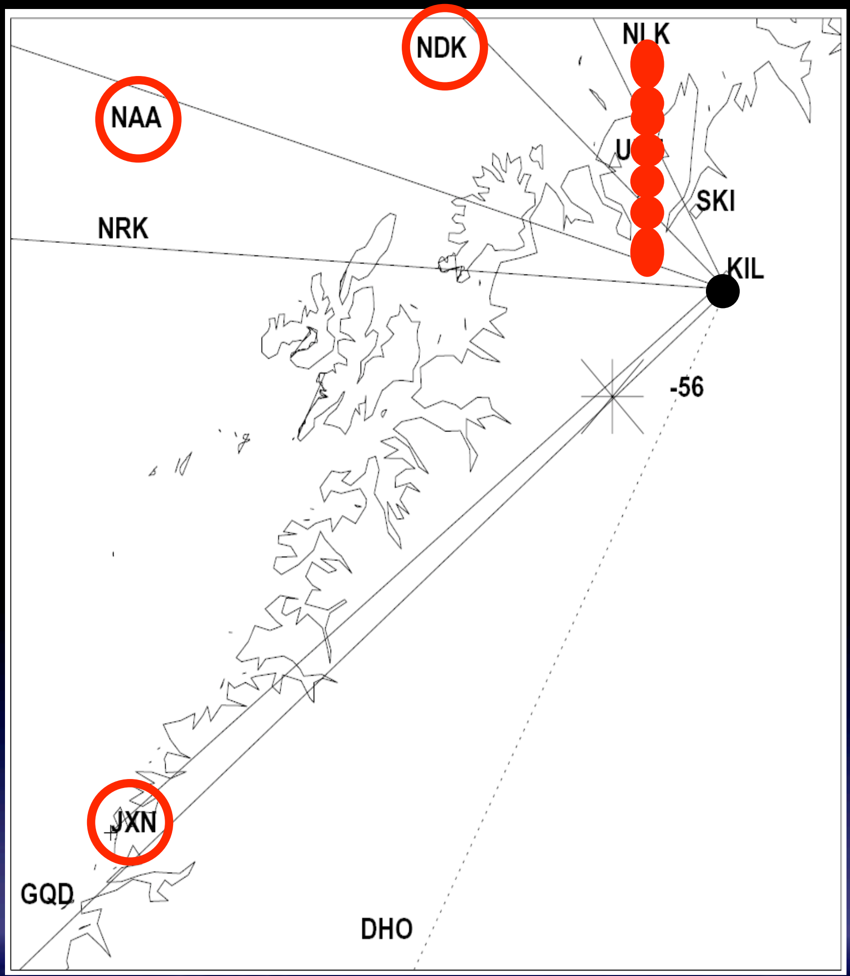


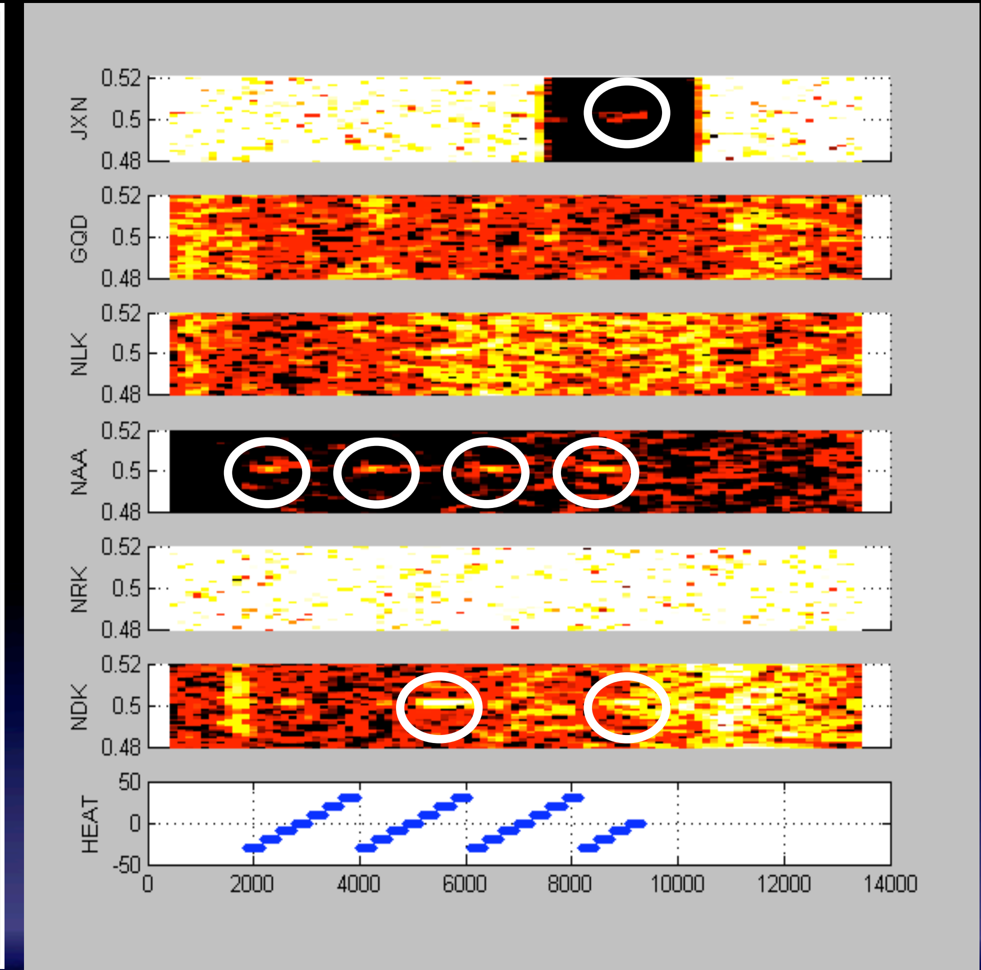
Heating effect on the conductivities:

propagation path of VLF waves

Heating effect on the conductivities:

propagation path of VLF waves





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