Introduction to heating experiments

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Luxembourg effect (1934)

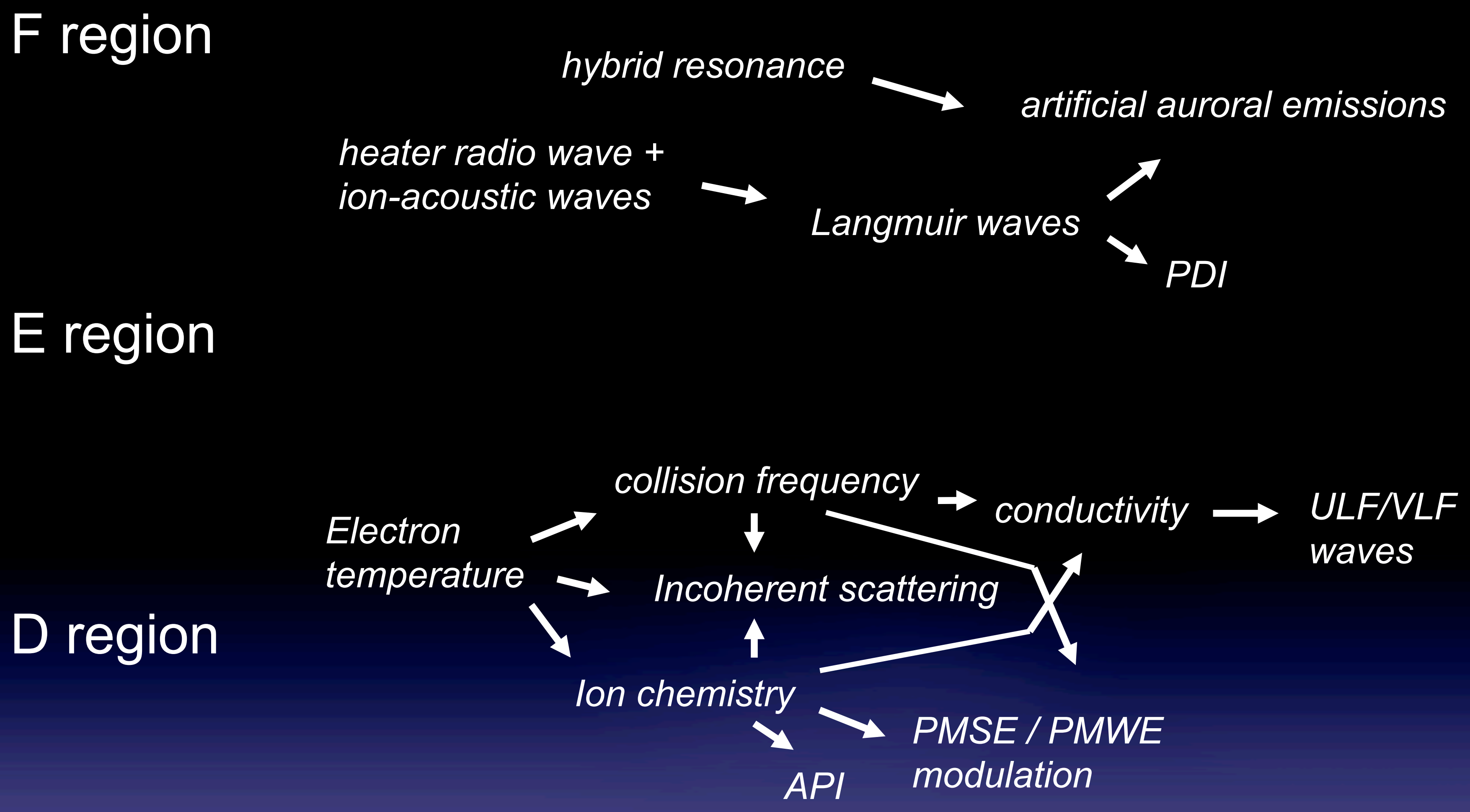
Eindhoven

Luxembourg

Beromünster

EISCAT site at Tromso, Norway

Some active HF heating effects



F region

hybrid resonance

artificial auroral emissions

heater radio wave +
ion-acoustic waves

Langmuir waves

PDI

E region

D region

collision frequency

conductivity

ULF/VLF
waves

Electron
temperature

Incoherent scattering

Ion chemistry

PMSE / PMWE
modulation

API

Outline

Intro

- Principle of active HF heating

Radio wave propagation in collisional plasma

- Magnetoionic theory
- Modelling the electron temperature

Observation techniques

- Incoherent scattering
- Riometer
- Coherent echoes (PMSE/PMWE)
- VLF/ULF waves

Summary

Appleton equation

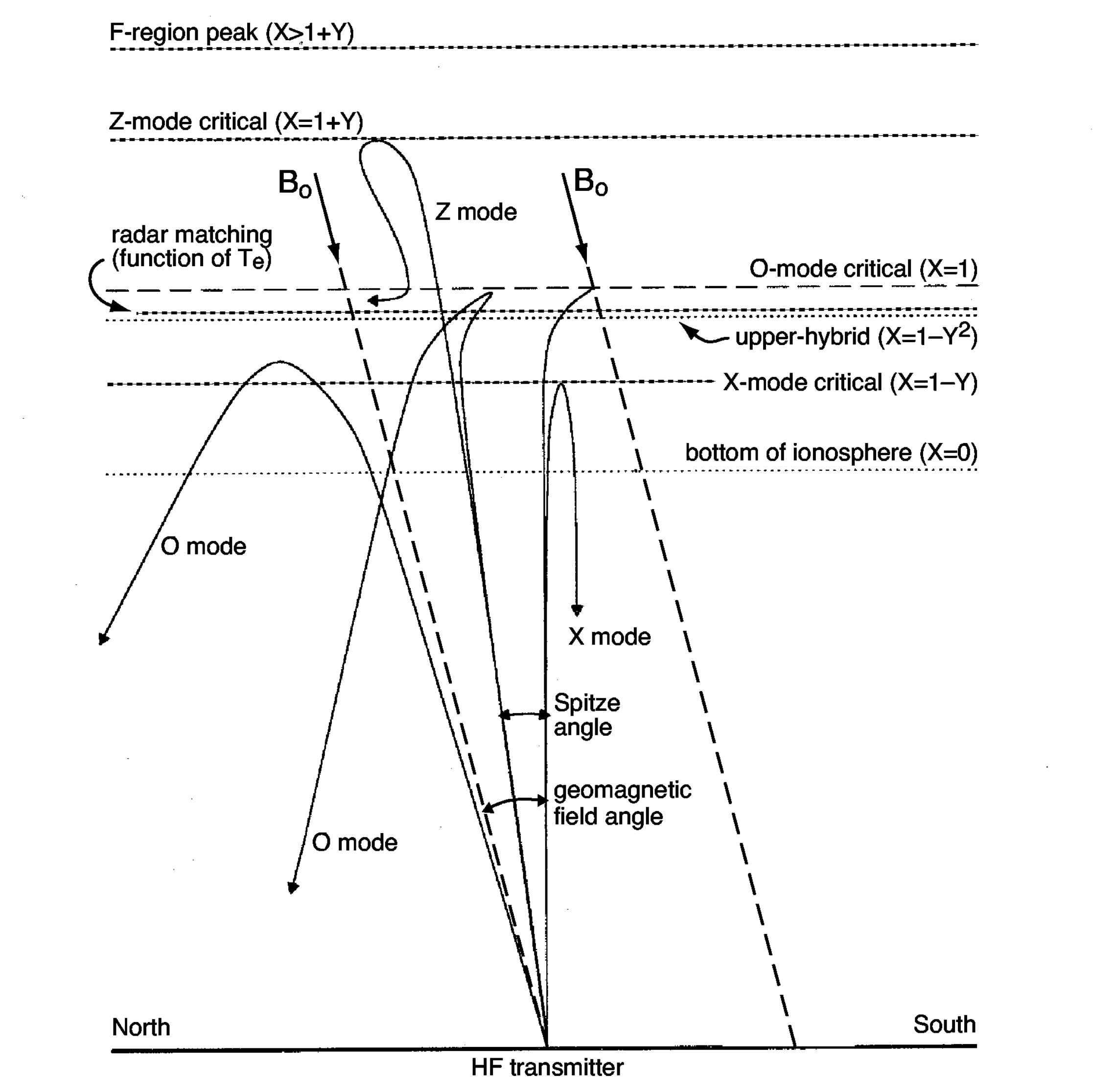
$$n^2 = 1 - \frac{X}{1 - iZ - \frac{(Y\sin\theta)^2}{2(1 - X - iZ)} \pm \sqrt{\frac{(Y\sin\theta)^4}{4(1 - X - iZ)^2} + (Y\cos\theta)^2}}$$

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

For detailed discussion, see K.G. Budden:

Radio Waves in the Ionosphere (1961)

Radio wave propagation in collisional plasma



Radio wave propagation in collisional plasma

Appleton equation

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

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

Radio wave propagation in collisional plasma

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

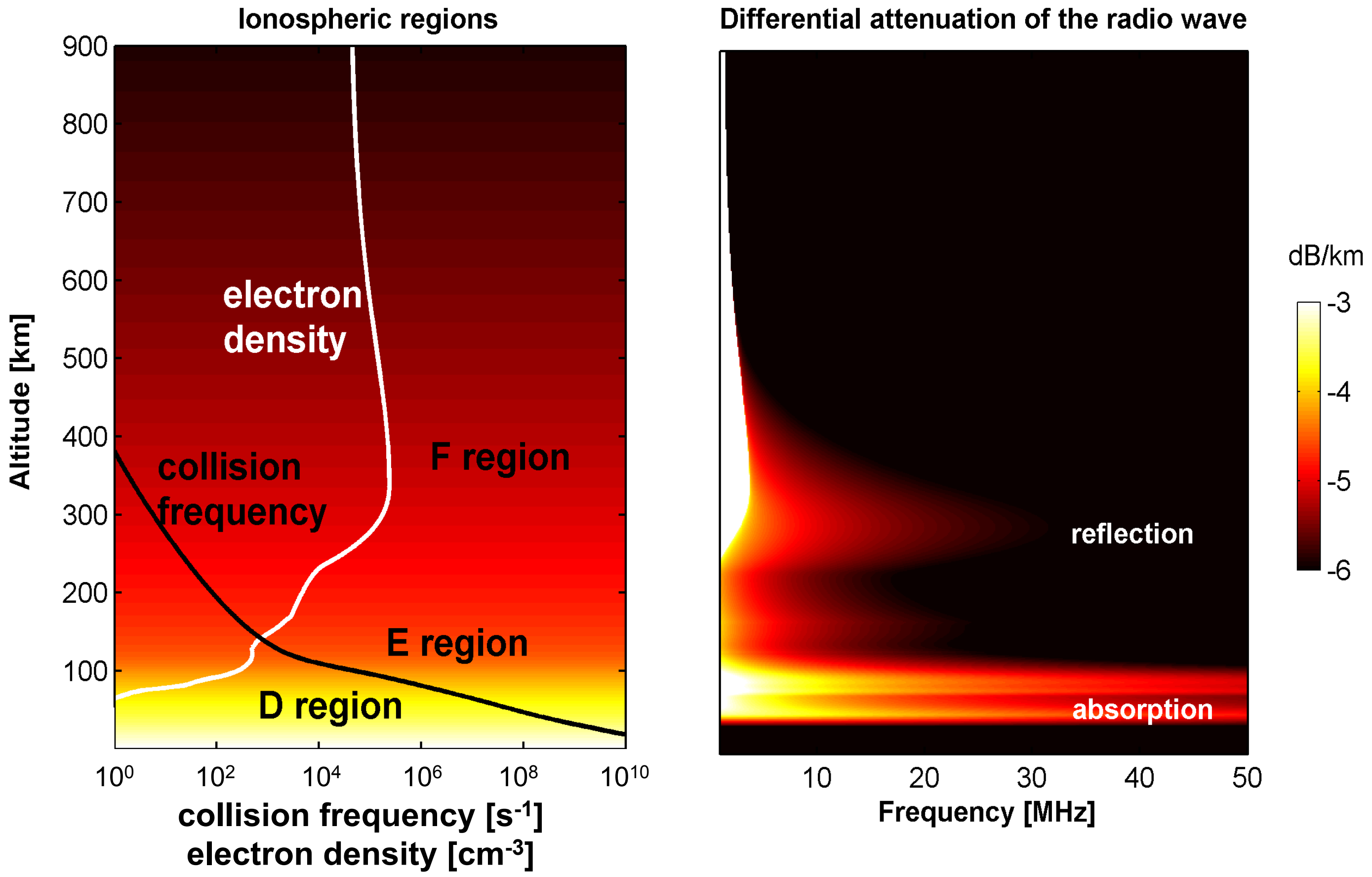
$$E(r,t) = E_0 \exp\left(i\omega(t - \frac{n}{c} r) \right)$$

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

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

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

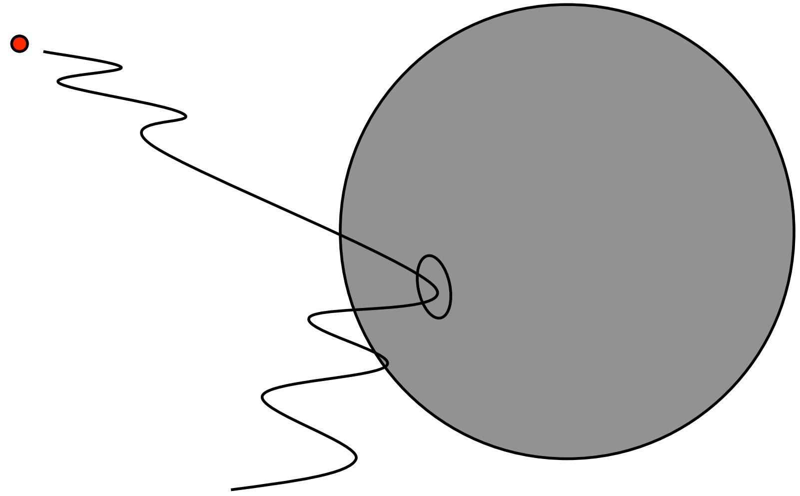
Radio wave propagation in collisional plasma



Radio wave propagation in collisional plasma

Physical interpretation of the absorption via collisions

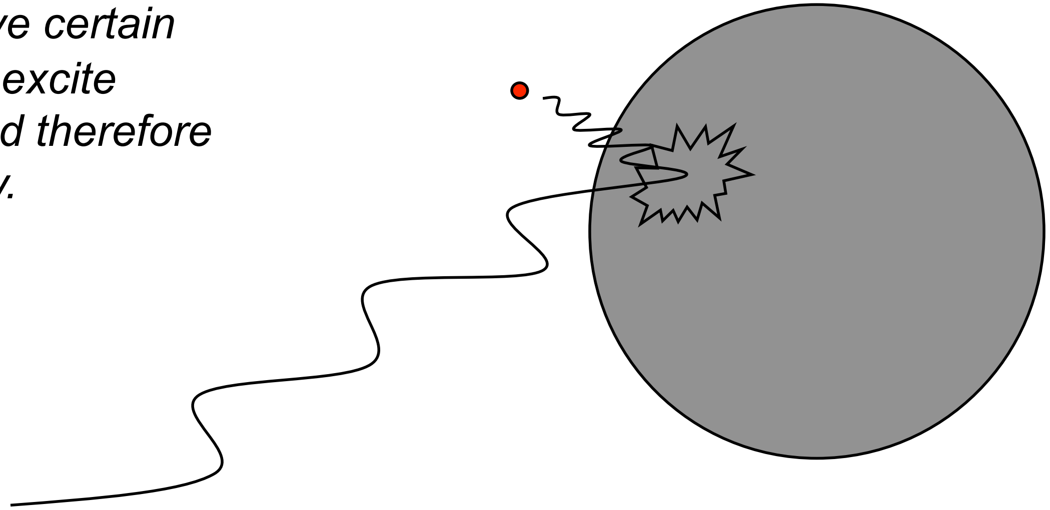
Electric field of the radio wave makes electrons as charged particles oscillate. A part of electron energy associated to the oscillation motion is transformed into random kinetic motion in collisions.



Radio wave propagation in collisional plasma

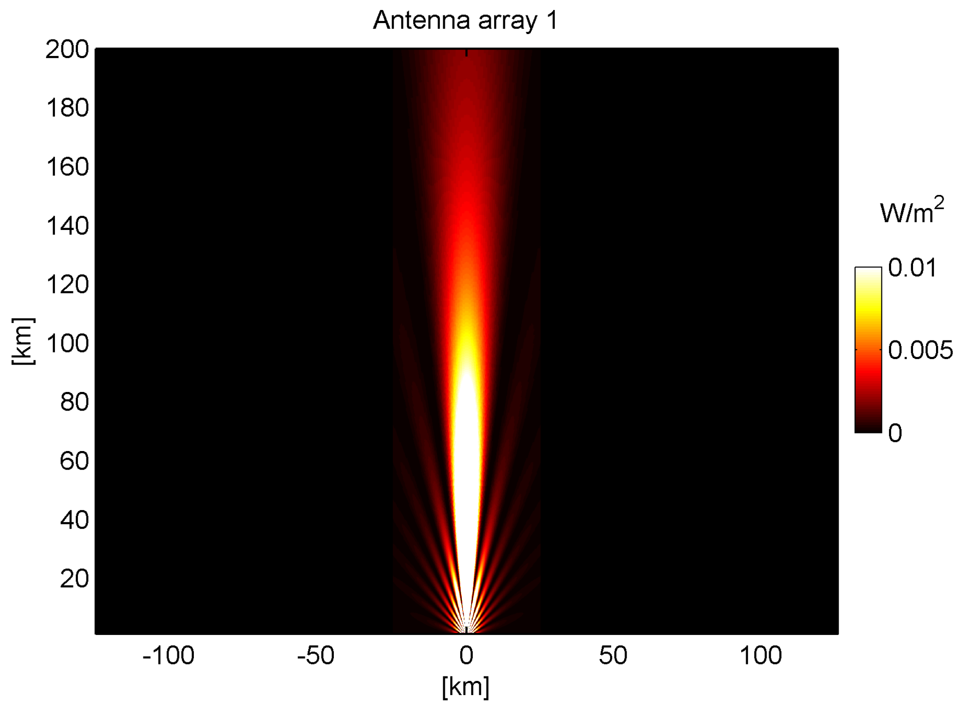
Physical interpretation of the absorption via collisions

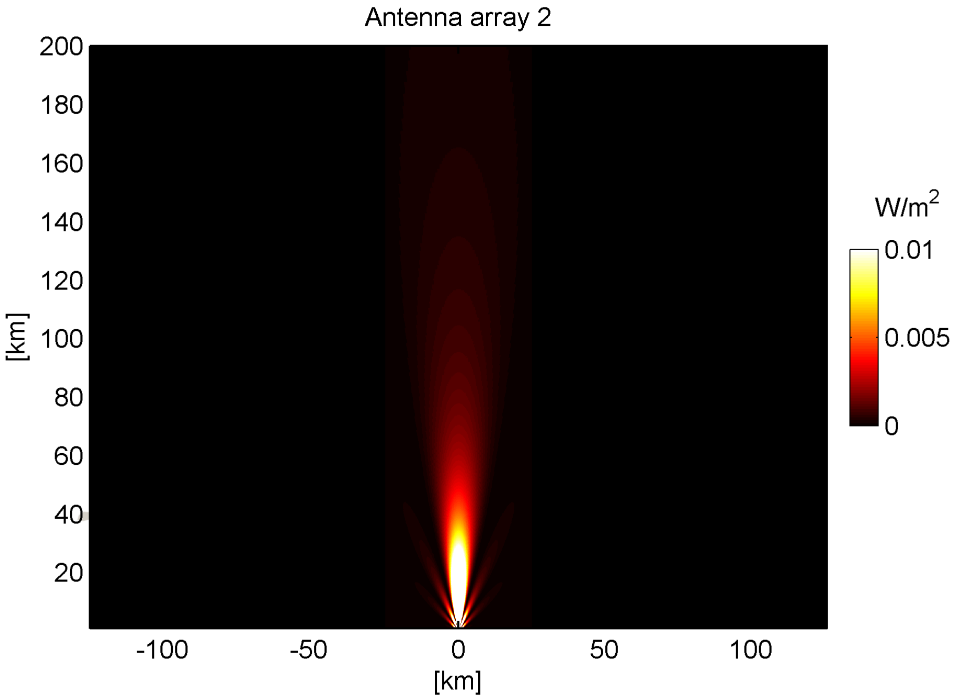
However, when the electron kinetic energy grows above certain level it can excite neutrals and therefore lose energy.



Intensities of the heater beams 1 & 2

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





Radio wave propagation in collisional plasma

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

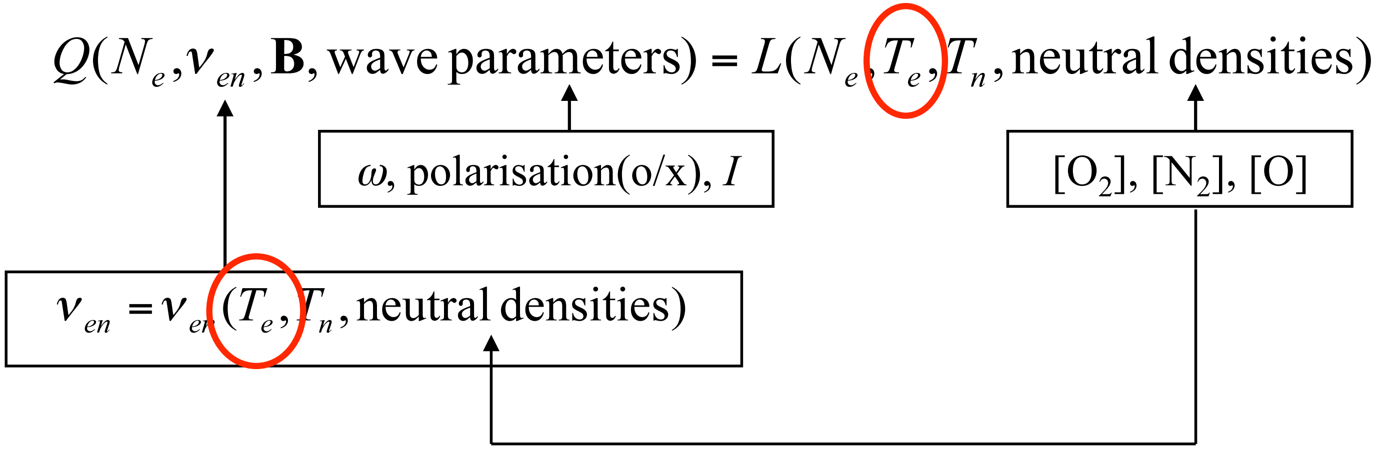
- *Vibrational and rotational excitation of O_2 and N_2 (Pavlov, 1998)*

- *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

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

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

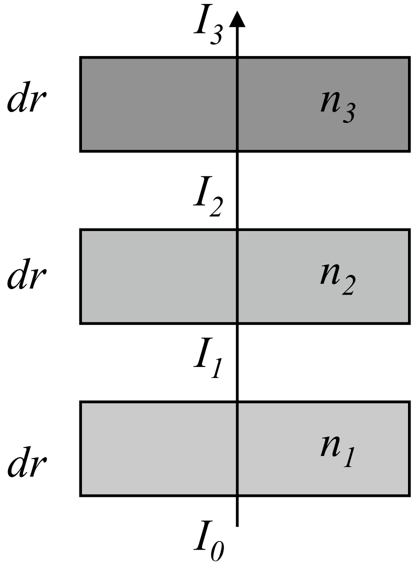
Radio wave propagation in collisional plasma

The electron temperature is calculated in dr layers:

- *Calculate the intensity below*

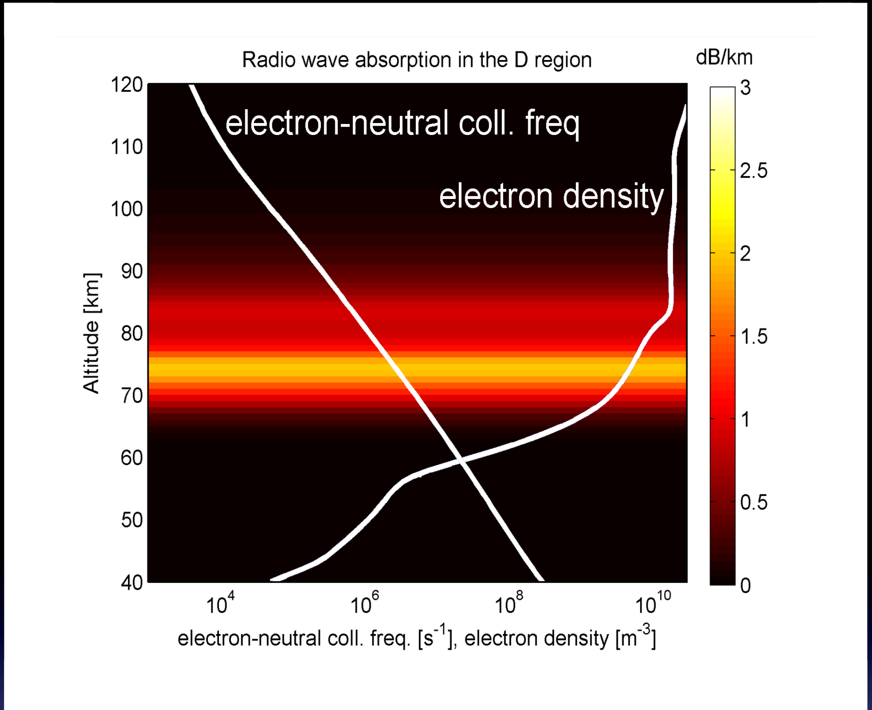
$$I = \frac{PG}{4\pi r^2}\exp\left(\frac{2\omega}{c}\int_0^r \Im(n)dr\right)$$

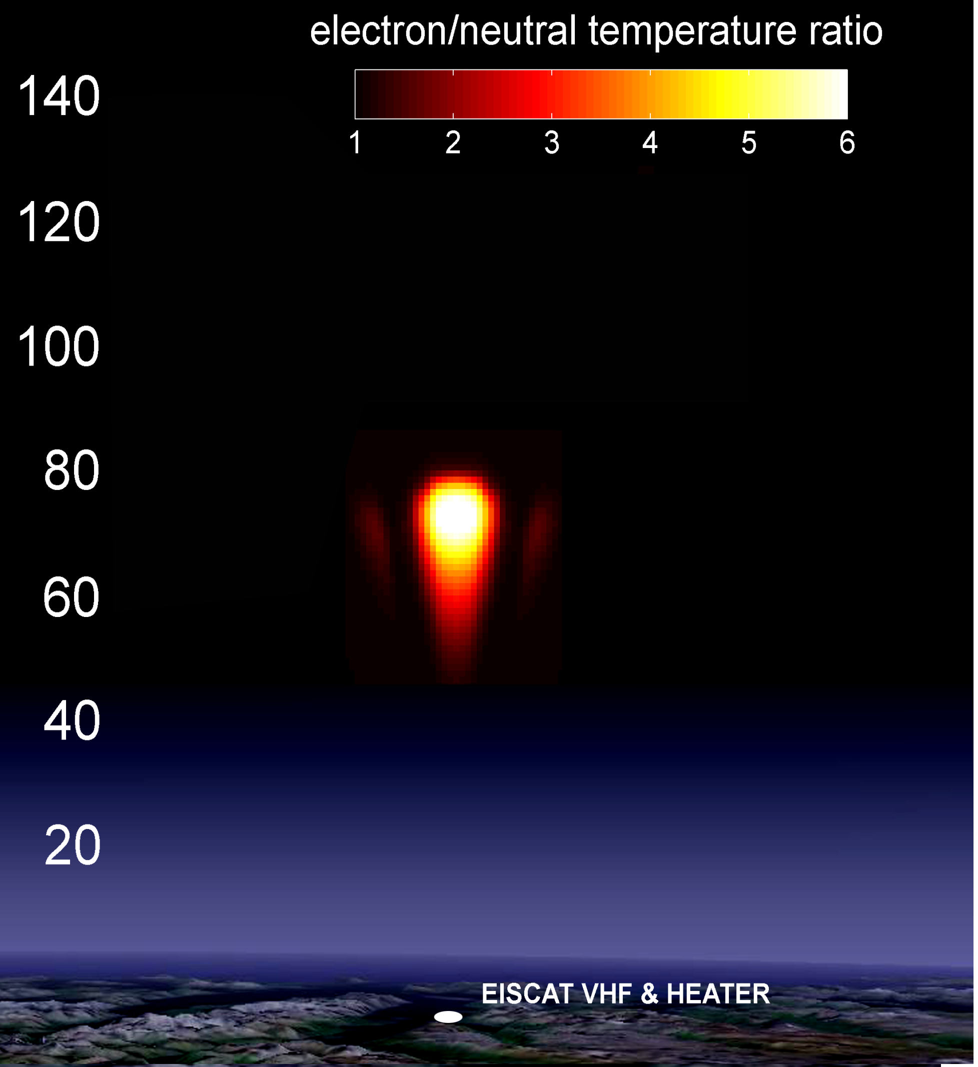
- *Find T_e which obeys the energy balance $Q=L$*
- *recalculate the refractive index in this T_e*



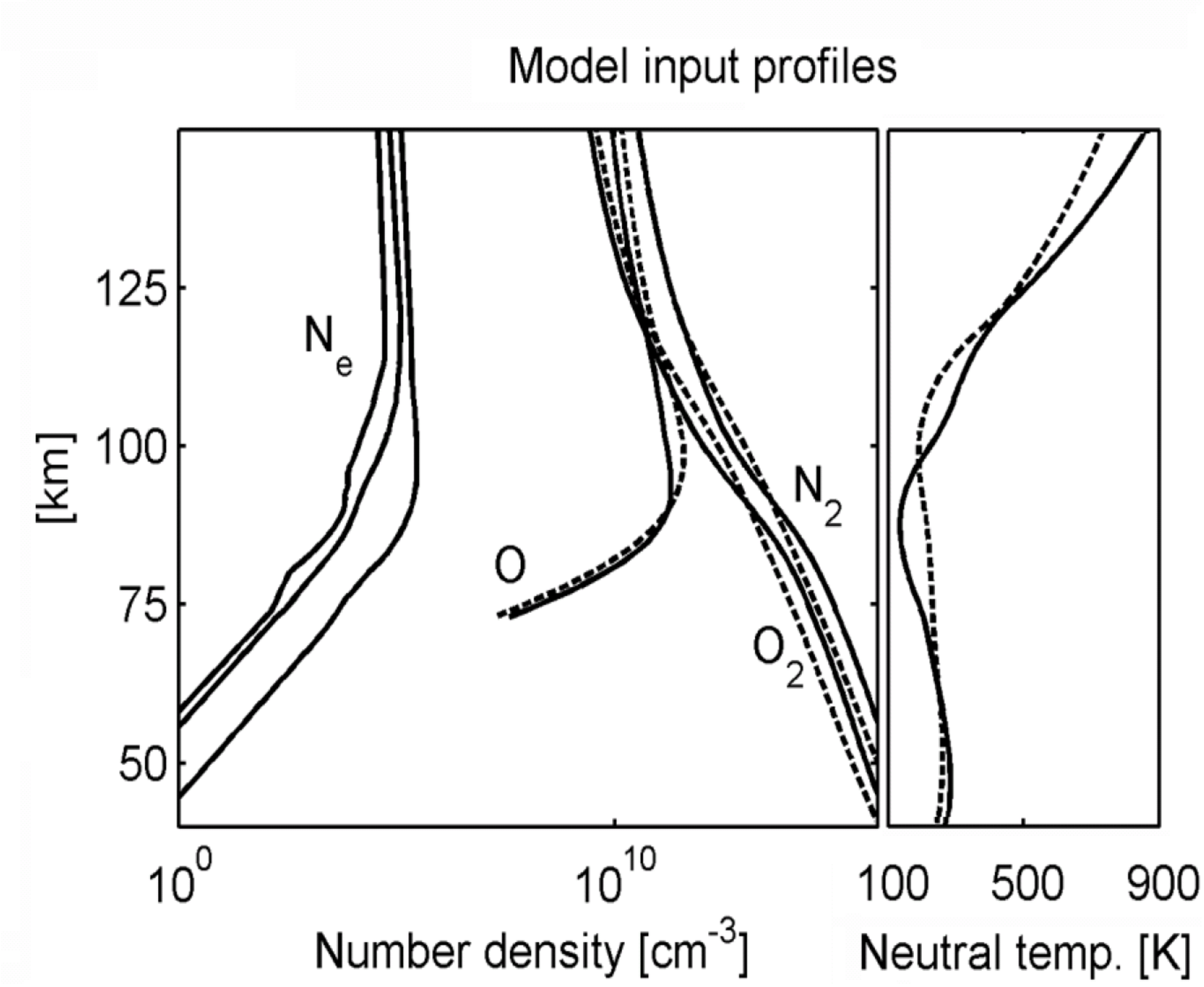
Radio wave propagation in collisional plasma

The modelled heating effect

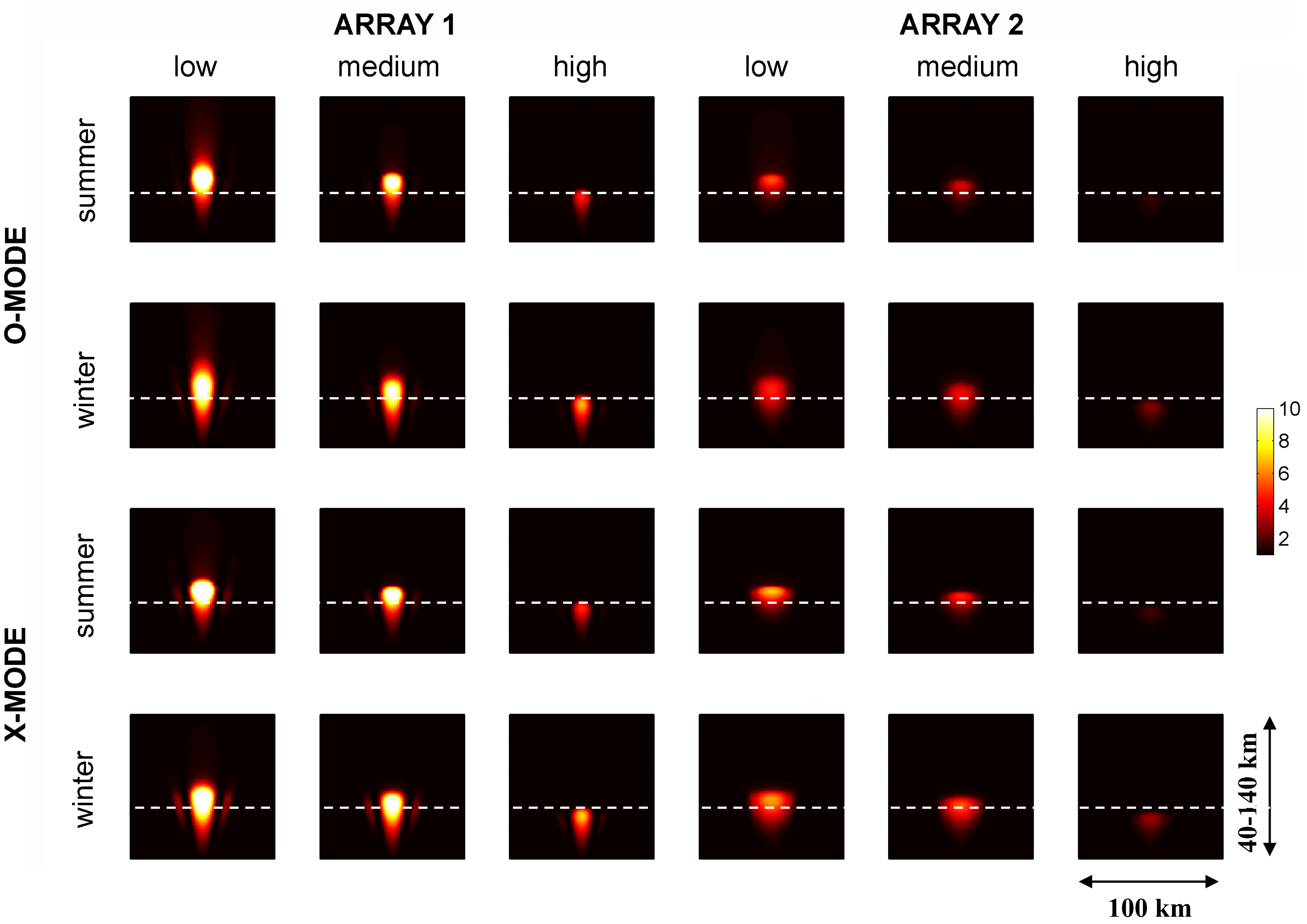




Radio wave propagation in collisional plasma



Modelled heating effect in the D region



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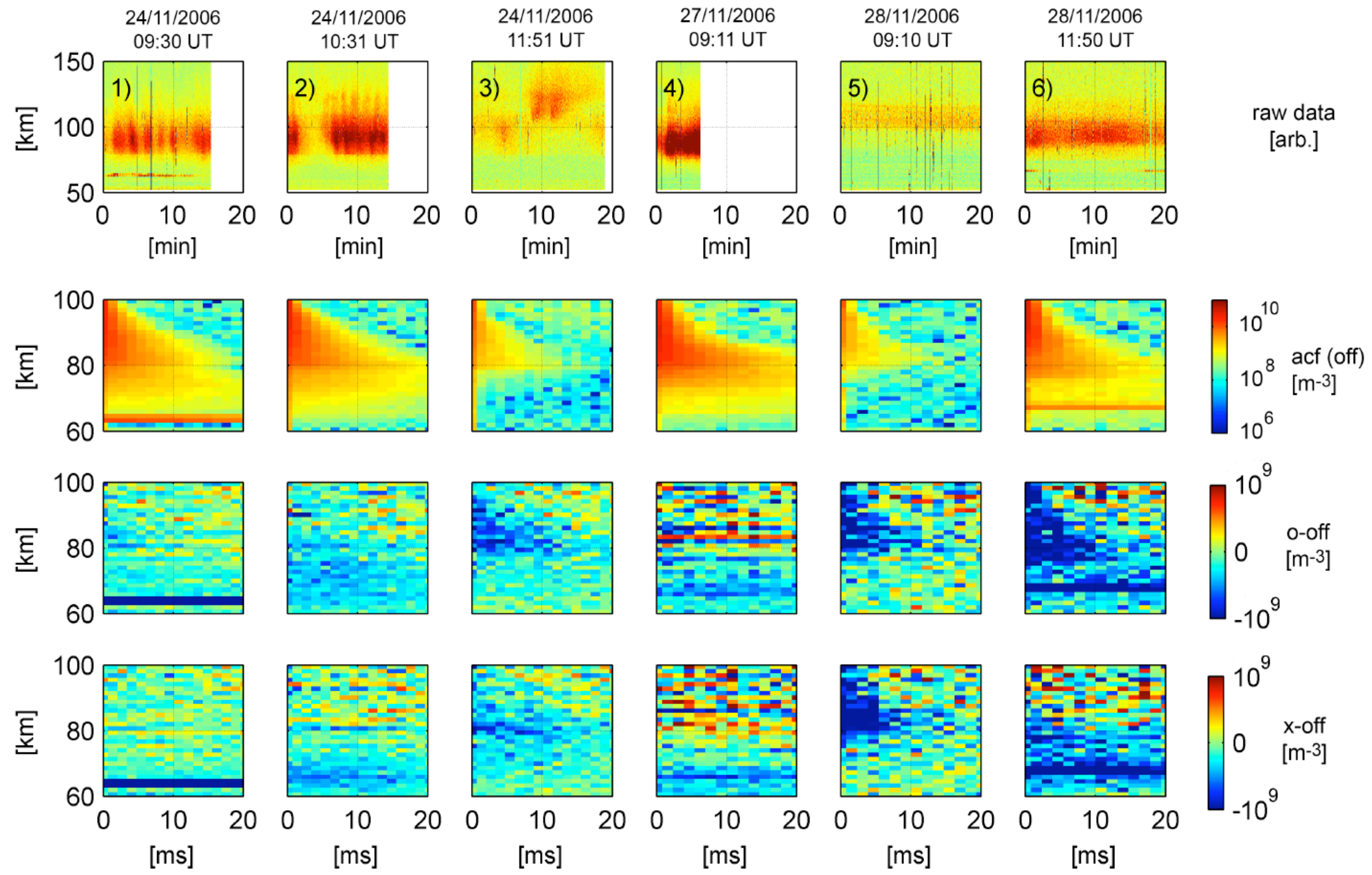
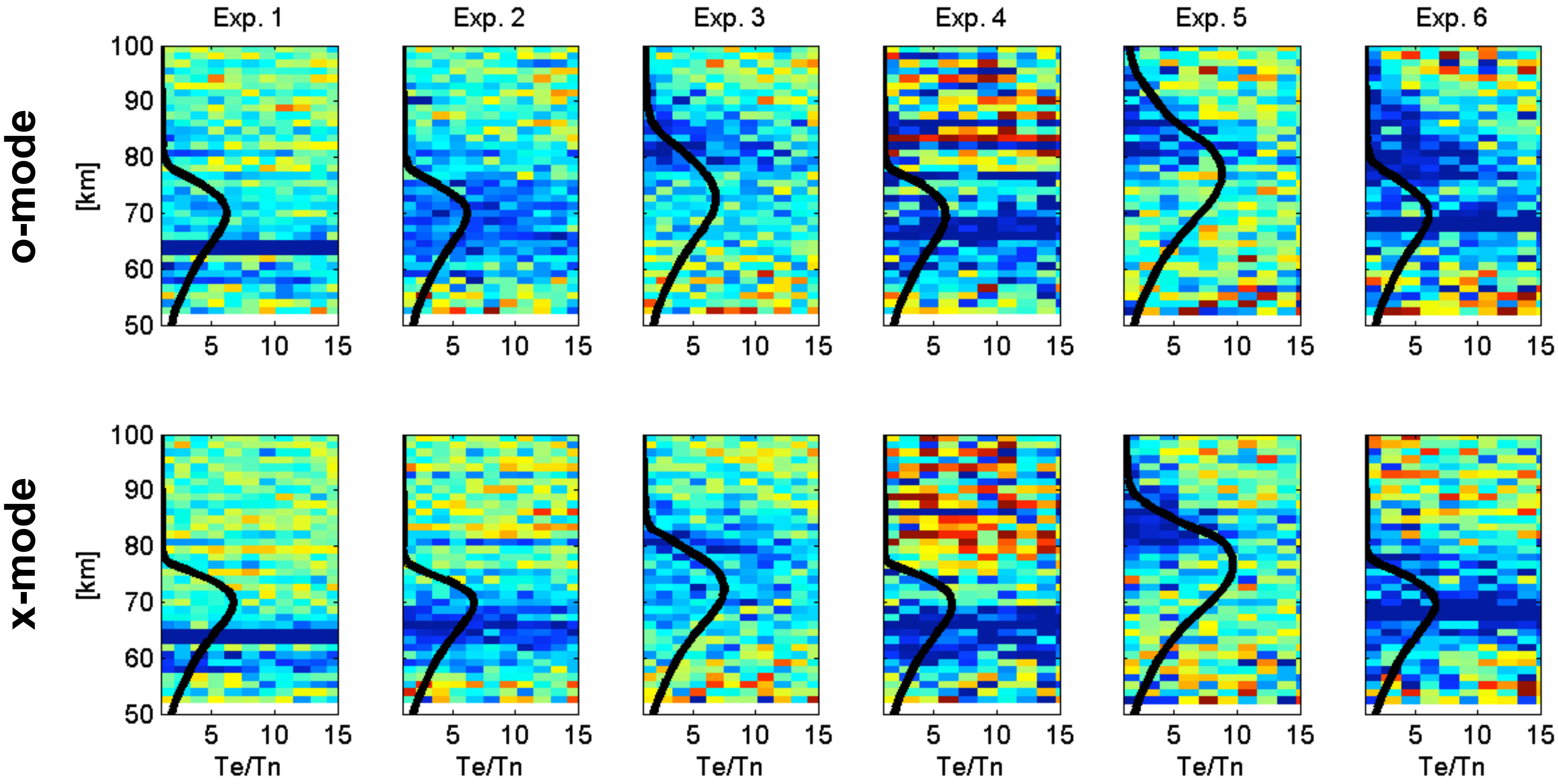
Summary

Heating signature in the IS signal (2006)



Model vs. data for the 2006 experiments



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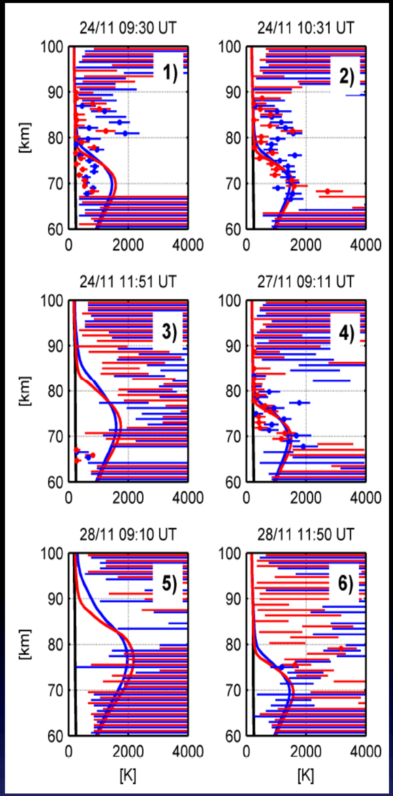
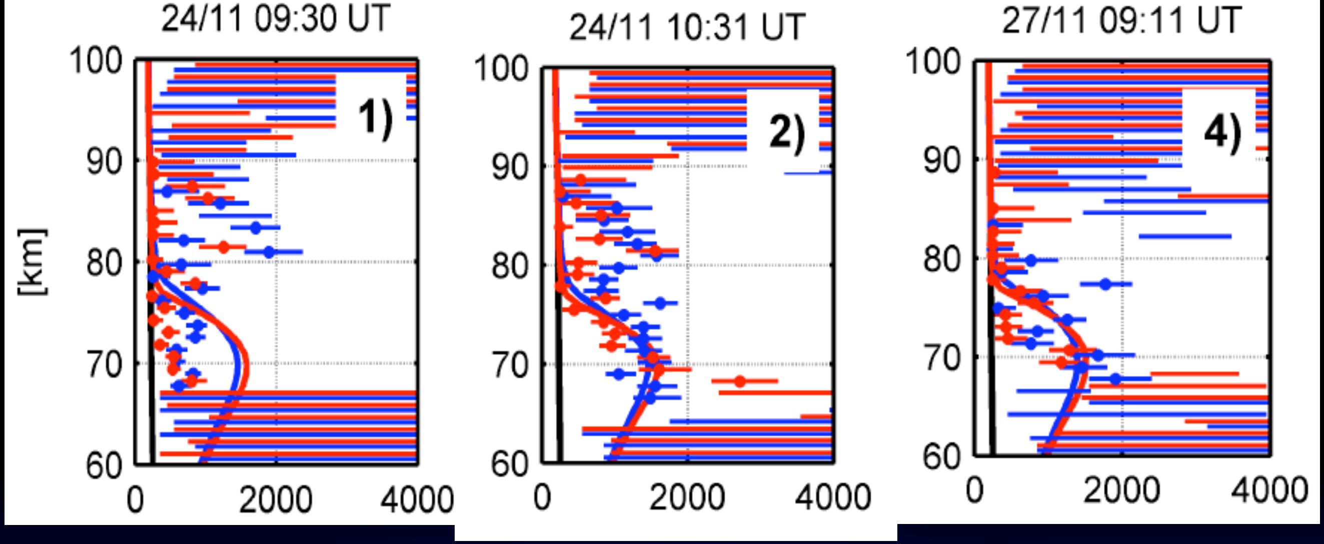
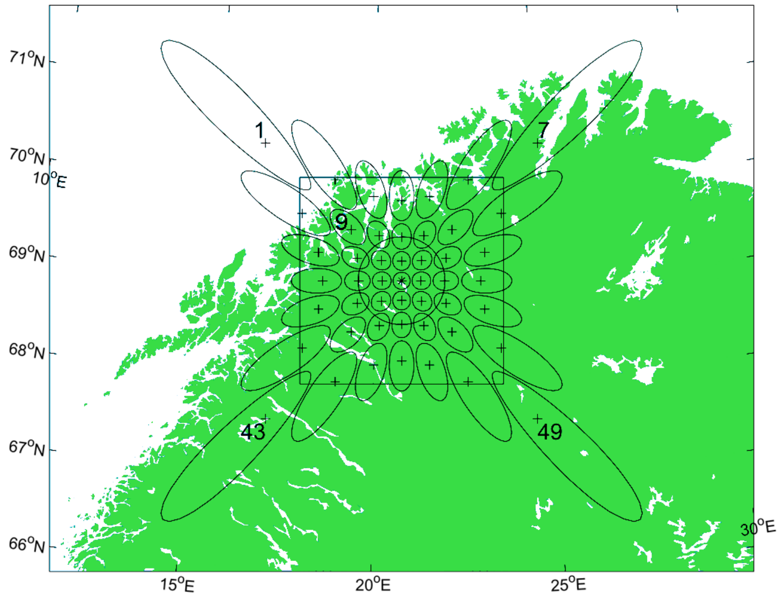




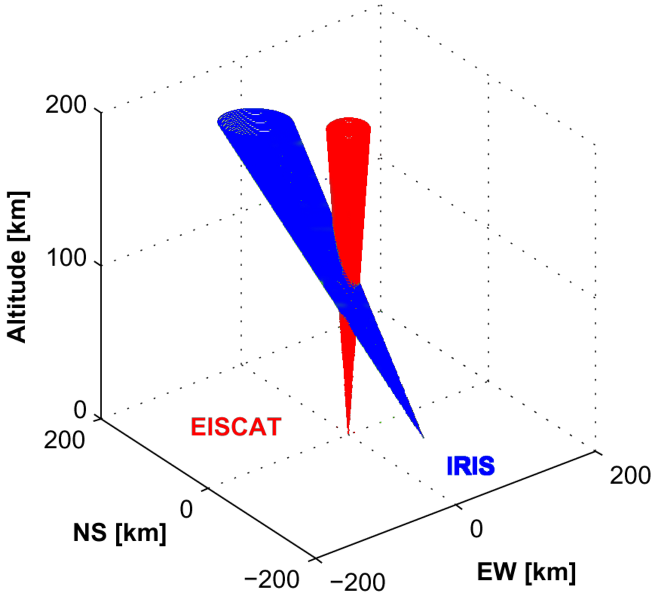
Kero et al., Ann Geophys, 2008

Observation techniques: riometer

IRIS riometer vs. EISCAT heater



EISCAT heater array 1 and
IRIS riometer beam 9



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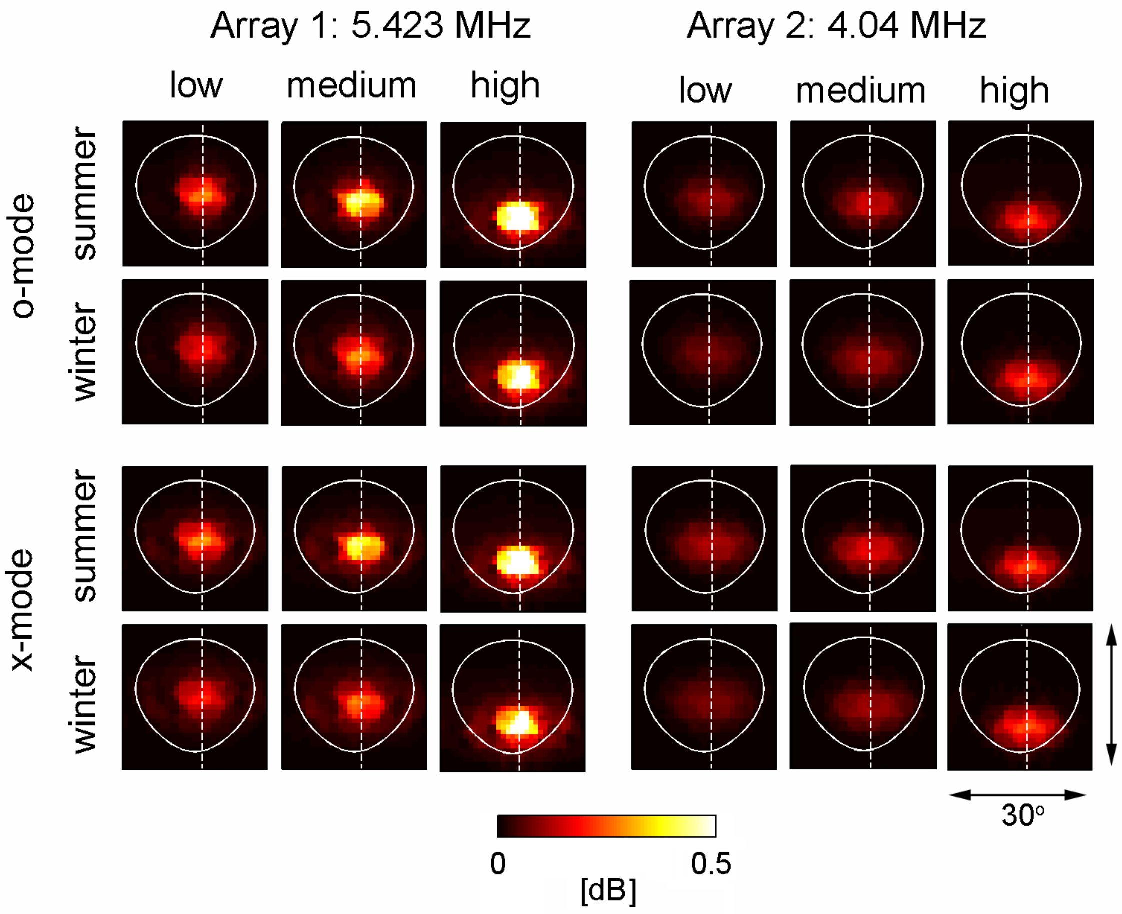
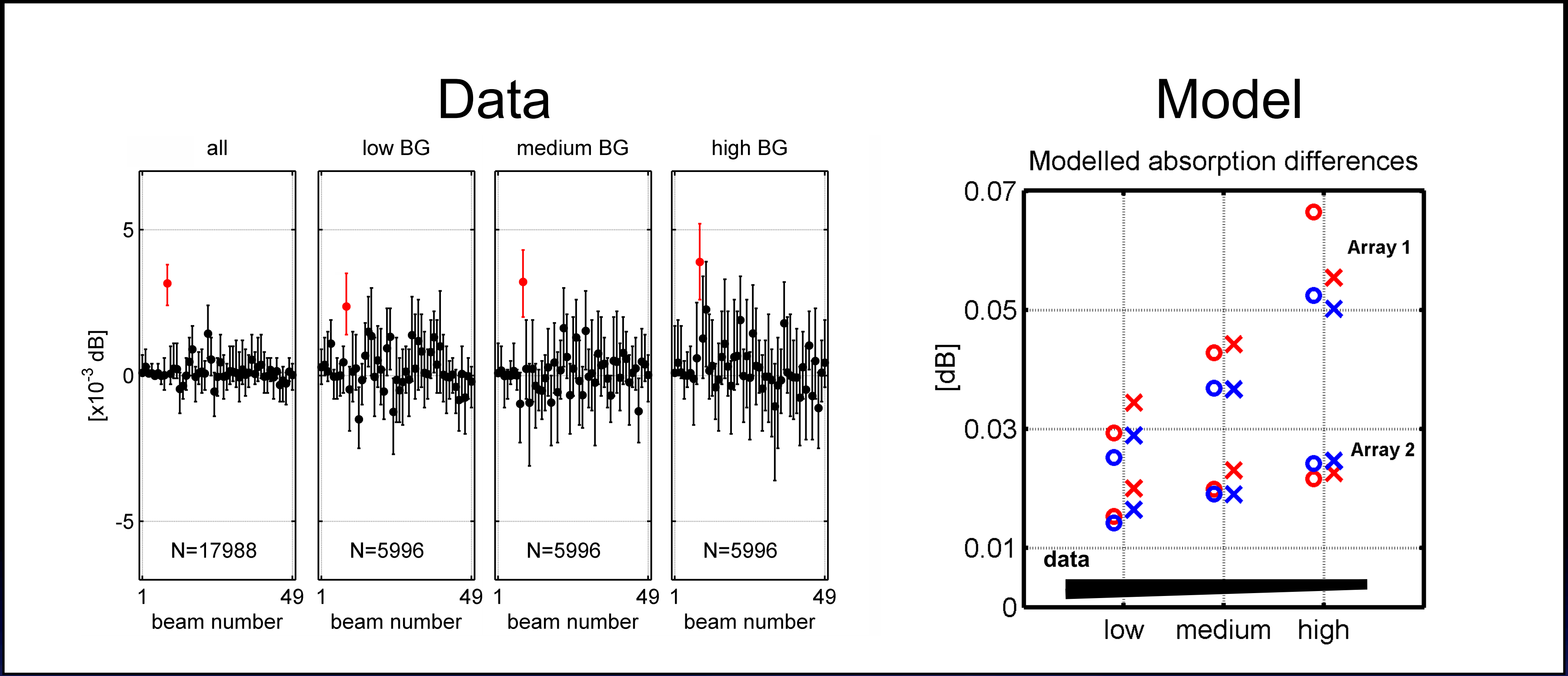


Measured vs. modelled absorption

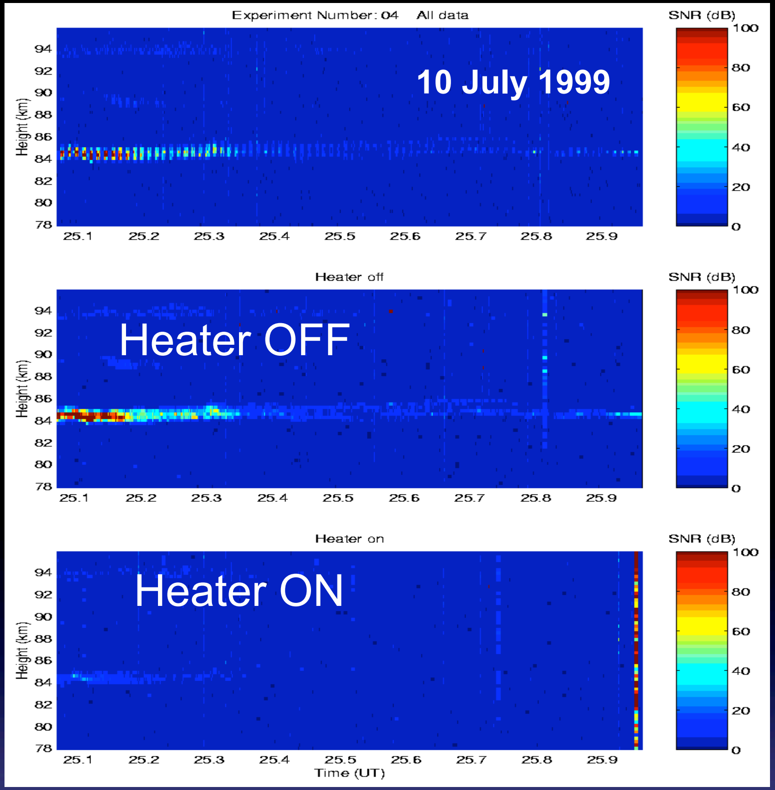


Kero, A., C.-F. Enell, Th. Ulich, E. Turunen, M. T. Rietveld, and F. H. Honary. Statistical signature of active D-region HF heating in IRIS riometer data from 1994-2004, *Ann. Geophys.*, *25*, 407-415, 2007.

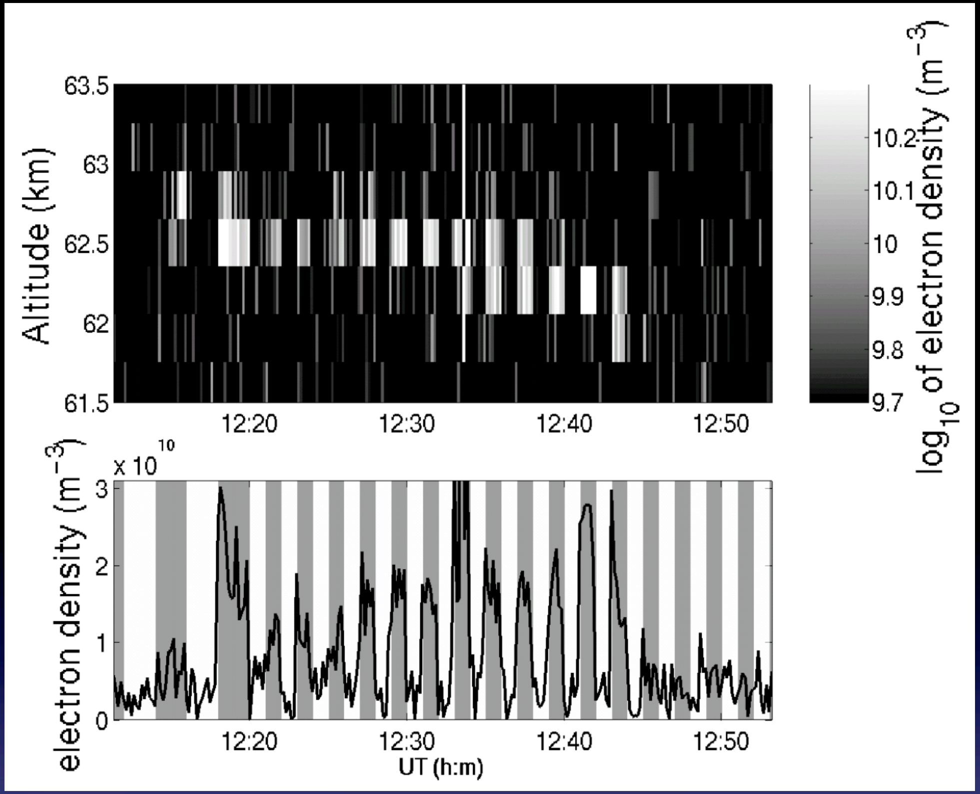
Observation techniques: coherent radar echoes

PMSE & PMWE

PMSE at 85 km

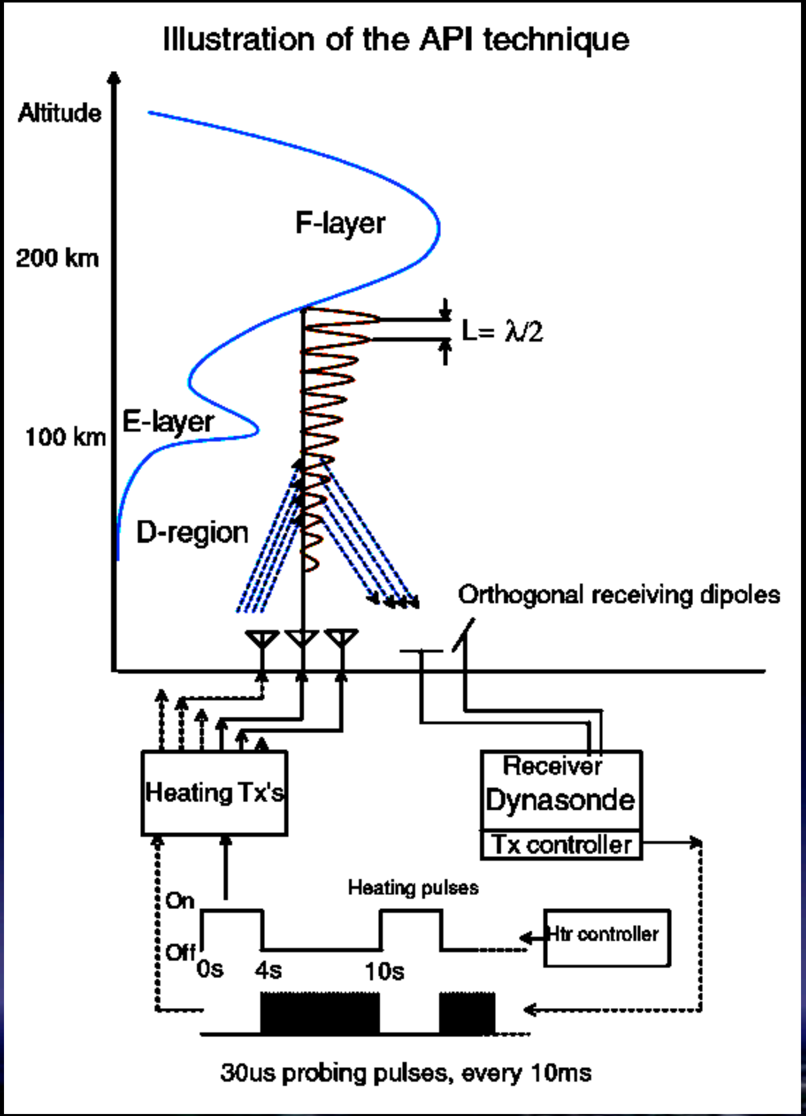


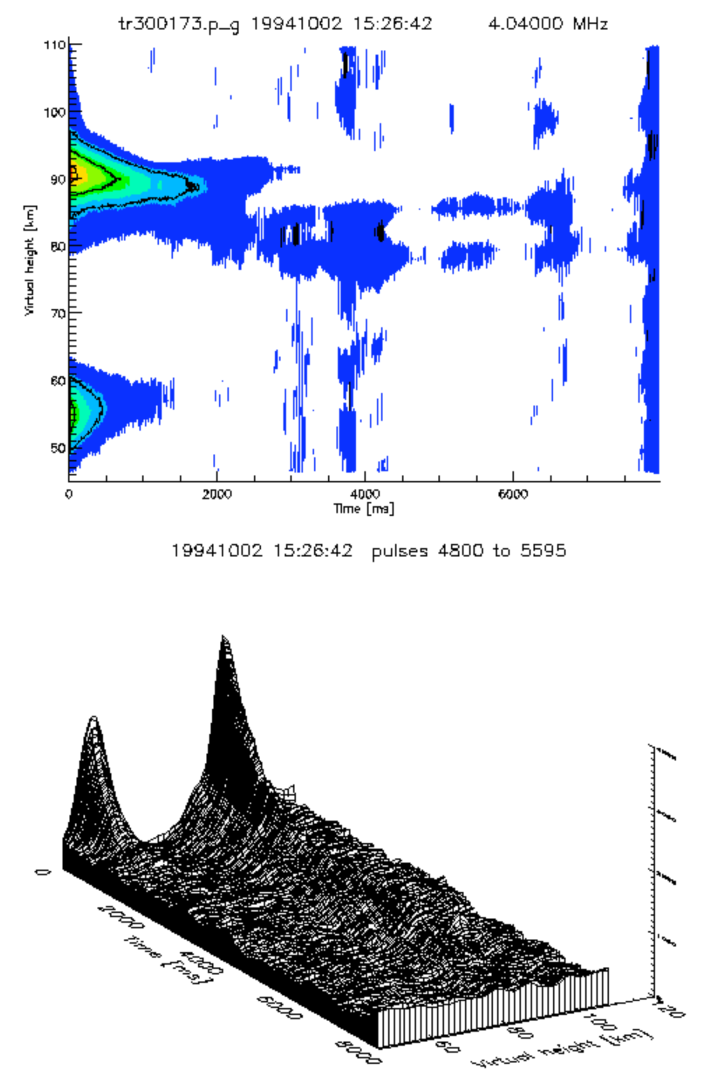
PMWE at 63 km



Kavanagh et al., GRL, 2006

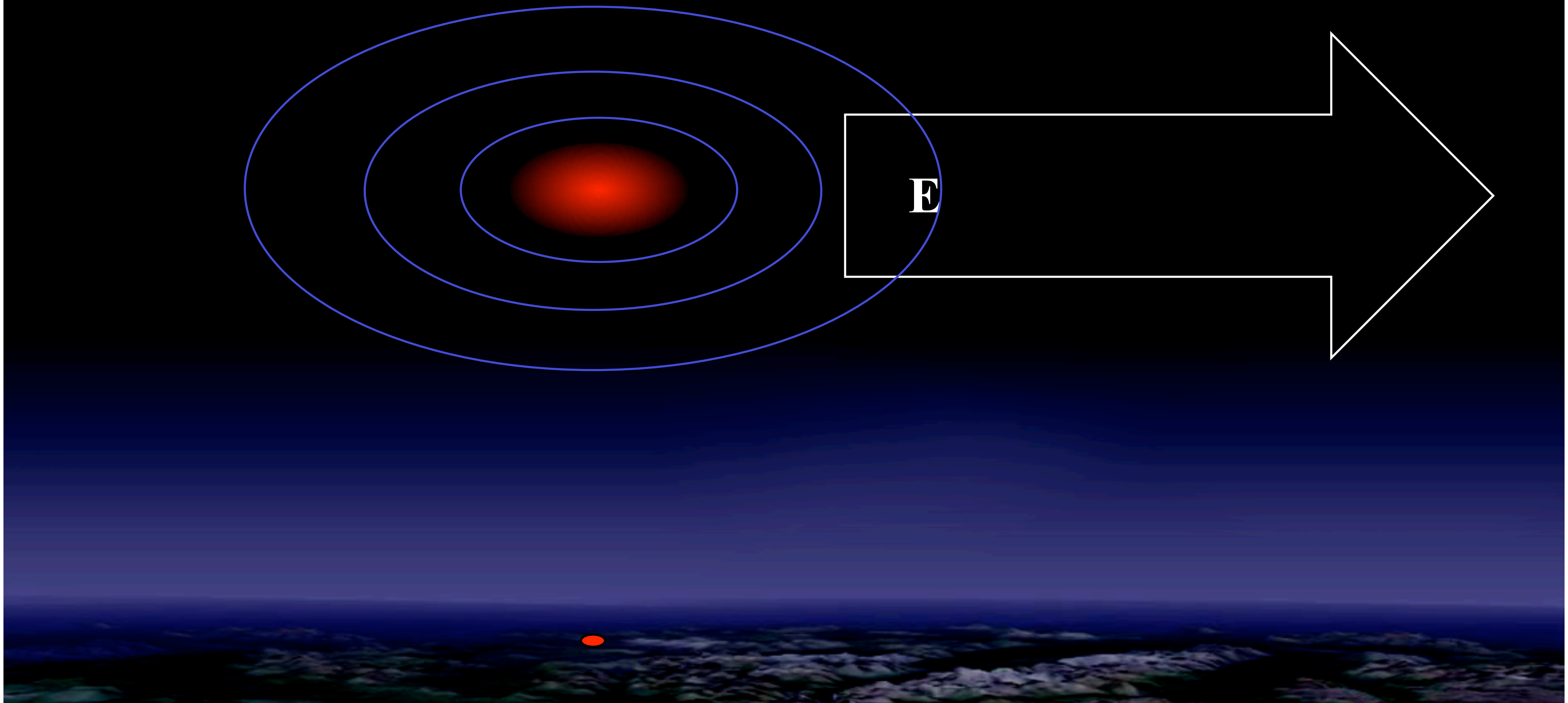
Artificial Periodic Irregularities (API)





Heating effect on the conductivities:

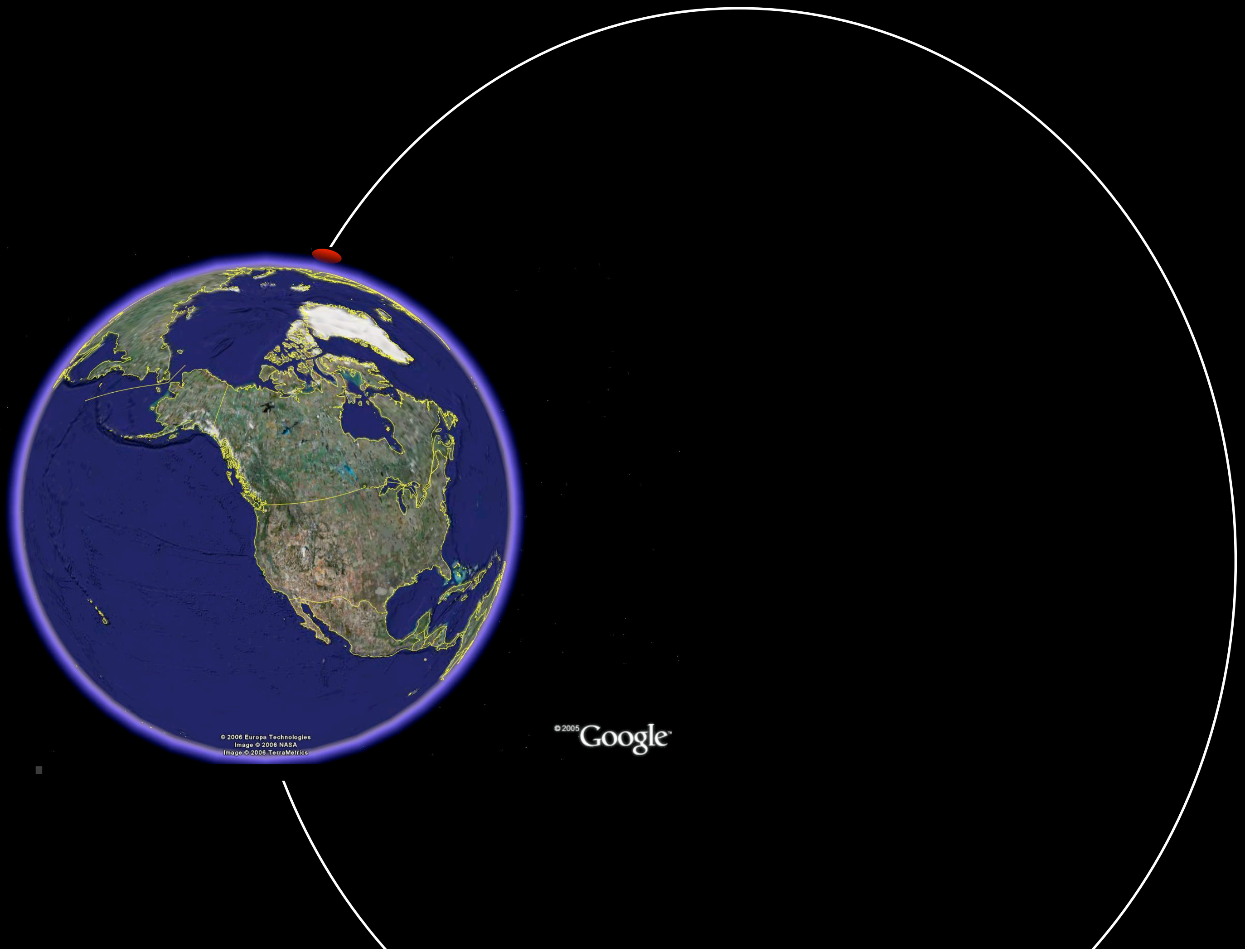
generation of ULF/VLF waves



Observation techniques: ULF/VLF waves

Heating effect on the conductivities:

ducted VLF waves



Observation techniques: ULF/VLF waves

Heating effect on the conductivities: propagation path of VLF waves

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