Introduction to HF heating experiments

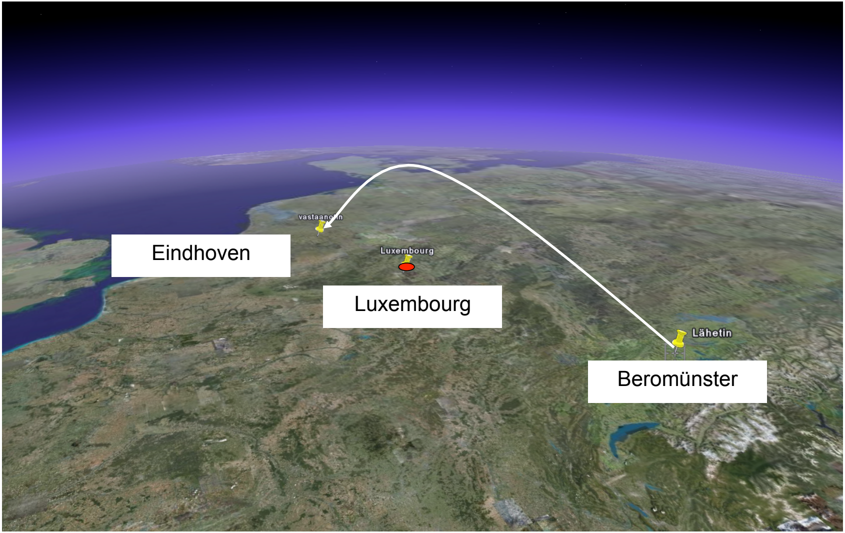
Antti Kero

Sodankylä Geophysical Observatory / University of Oulu, Finland

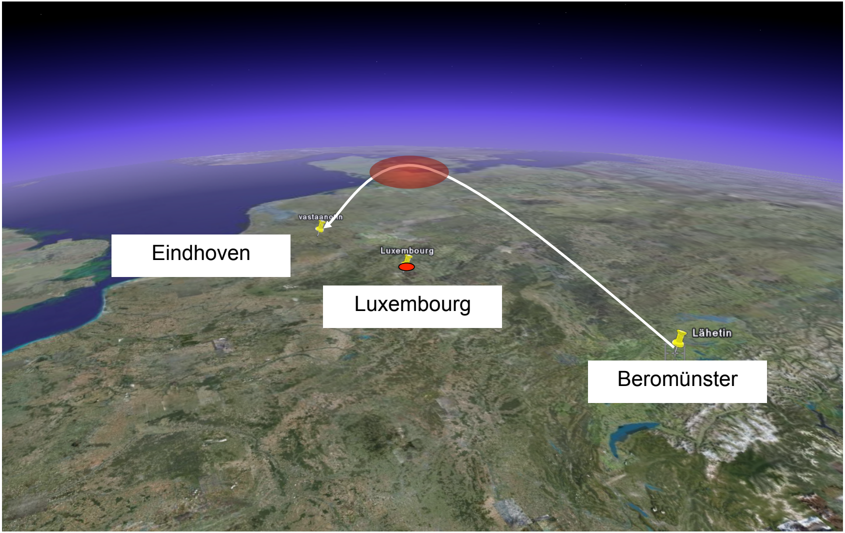
antti.kero@sgo.fi

ISR School, Syöte, Finland, 2019

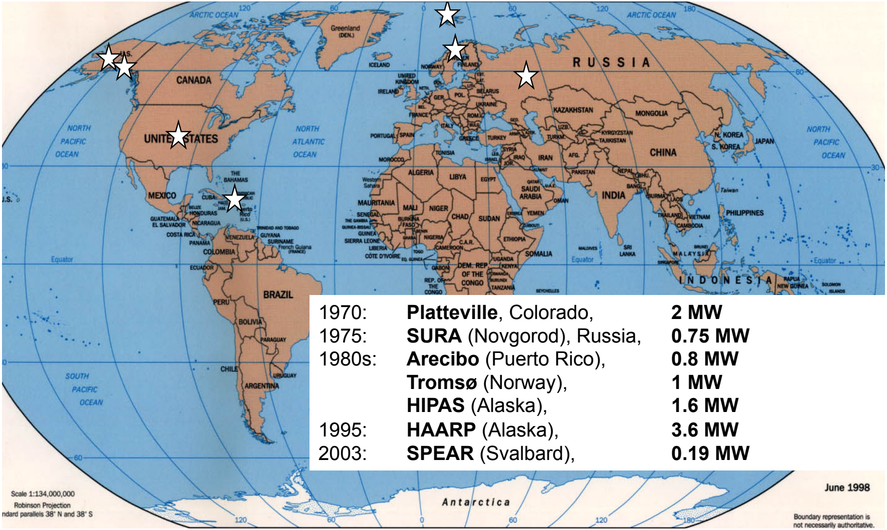
Early history: Luxembourg effect 1933



Early history: Luxembourg effect 1934

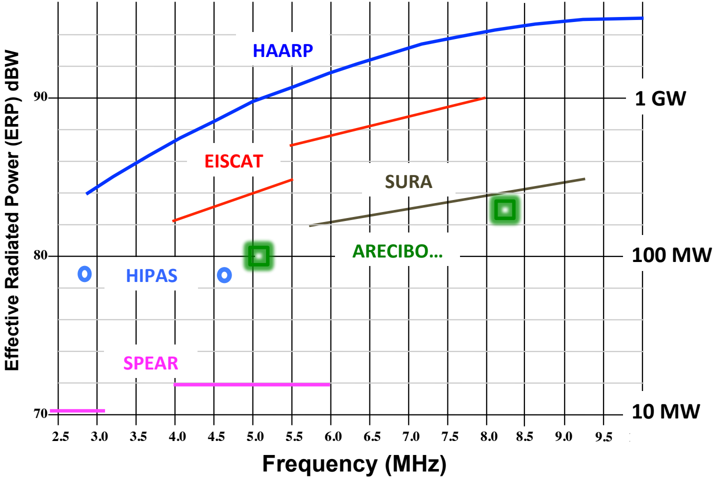


Heating facilities: POWER!



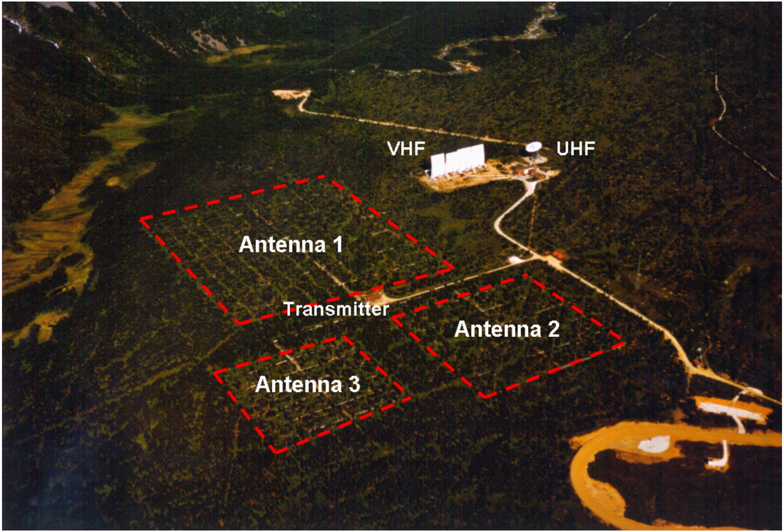
1970:	**Platteville**, Colorado,	**2 MW**
1975:	**SURA** (Novgorod), Russia,	**0.75 MW**
1980s:	**Arecibo** (Puerto Rico),	**0.8 MW**
	Tromsø (Norway),	**1 MW**
	HIPAS (Alaska),	**1.6 MW**
1995:	**HAARP** (Alaska),	**3.6 MW**
2003:	**SPEAR** (Svalbard),	**0.19 MW**

Heating facilities: ERP



Intensity of a point source at distance r is $I(r) = \mathrm{ERP}/(4\pi r^2)$.

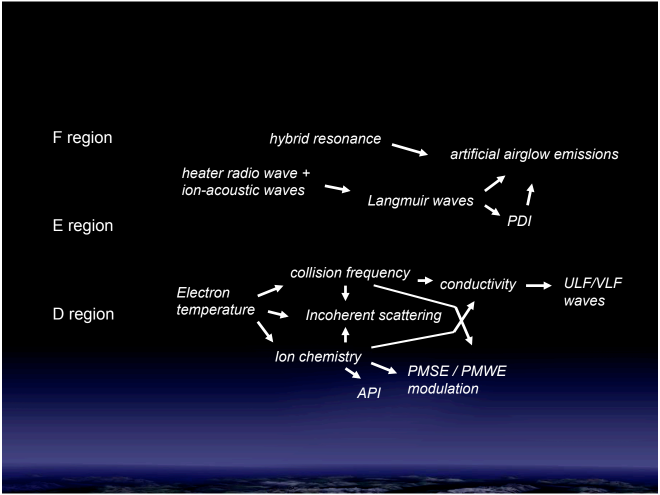
Heating facilities: EISCAT, Norway



Heating facilities: Arecibo, Puerto Rico

Heating facilities: HAARP, Alaska

Some science applications*



*For a comprehensive review, see Streltsov et al.: Present and Future of Active Radio Frequency Experiments in Space, Space Science Reviews, 2018

Heating effect in collisional plasma: Appleton equation

Refractive index n of the plasma for the radio wave is given by the Appleton equation

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

where the normalised frequencies are

$$X = \frac{\omega_{pe}^2}{\omega^2} = \frac{N_e e^2}{\epsilon_0 m_e \omega^2}, Y = \frac{\omega_{ge}}{\omega} = \frac{eB}{m_e\omega} \text{and } Z = \frac{\nu_{en}}{\omega}.$$

Heating effect in collisional plasma: energy absorption

When the complex refractive index $n = \Re(n) + i\Im(n)$, given by the Appleton equation, is applied to the plane wave equation

$$E(r,t) = E_0 \exp\left[i\omega\left(t - nr/c\right)\right]$$

we get a decaying wave in a case of $\Im(n) < 0$:

$$E(r,t) = E_0 \exp\left[i\omega\left(t - \Re(n)r/c\right)\right] \exp\left(\omega\Im(n)r/c\right).$$

Heating effect in collisional plasma: energy absorption

Since the intensity of the wave $I \propto E^2$,

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

and the absorbed energy per time unit and per volume is

$$Q = -\frac{dI_{abs}}{dr} = -2\omega\Im(n)I/c.$$

This is the energy gain from the wave to the plasma due to collisions between electrons (accelerated by the wave) and neutrals.

Heating effect in collisional plasma: electron energy budget

In the ideal gas, the mean electron energy is

$$E = \frac{3}{2} k_B T_e.$$

By differentiating this with respect to volume and time, we get

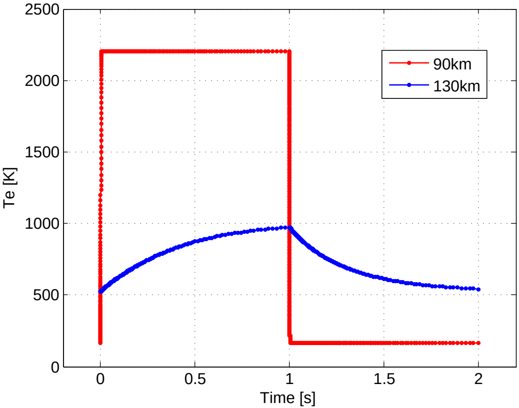
$$\frac{dT_e}{dt} = \frac{2}{3k_B N_e}(Q - L) = \frac{2}{3k_B N_e}\left(\frac{-2\omega\Im(n)I}{c} - L\right).$$

Here $L = \sum L_X\left([X], N_e, T_n, T_e\right)$ denotes the sum of electron energy loss processes by excitations of $\mathrm{O_2}$, $\mathrm{N_2}$ and O (Stubbe ja Varnum, 1972), such as:

$$L_{\mathrm{rotO_2}} = 7.0 \cdot 10^{-14} \times N_e N_{\mathrm{O_2}} \left(\frac{T_e - T_n}{\sqrt{T_e}}\right)$$

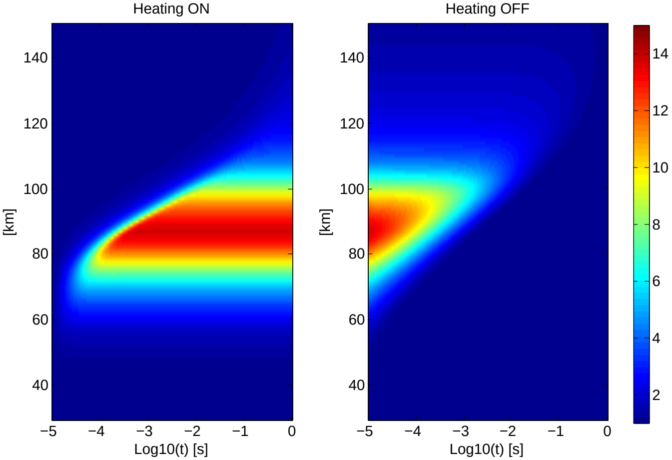
Model example: 1s on/off heating, T_e

ERP=600 MW, $f = 5.423$ MHz, O-mode



Model example: 1s on/off heating, T_e/T_i

ERP=600 MW, $f = 5.423$ MHz, O-mode



Incoherent scatter spectrum

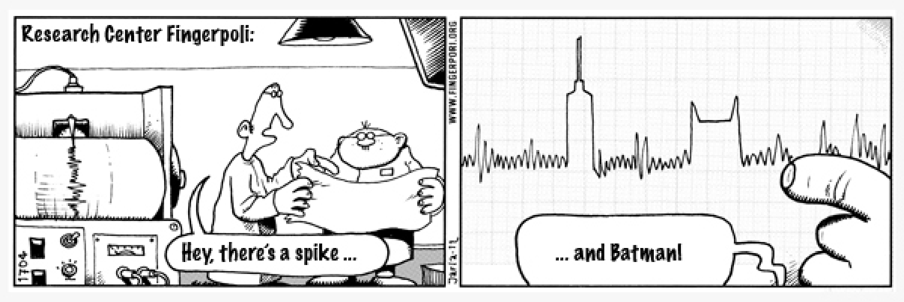


Figure: Fingerpori, HS, 7 September 2012

Incoherent scatter spectrum

The spectral density of the incoherent scattering is

$$\sigma(\omega_0+\omega)d\omega = \frac{N_e r_e^2 d\omega}{\pi} \frac{\left(\left|y_e\right|^2 \frac{\sum_j n_j \Re(y_j)}{\omega - \mathbf{k}\cdot\mathbf{v}_{dj}} \left| \sum_j \mu_j y_j + i\lambda_D^2 k^2 \right|^2 \frac{\Re(y_e)}{\omega - \mathbf{k}\cdot\mathbf{v}_{de}} \right)}{\left(\left| y_e + \sum_j \mu_j y_j + i\lambda_D^2 k^2 \right|^2 \right)}.$$

Here

- $n_j = N_j/N_e$ and $\mu_j = n_j T_e/T_j$ (densities and temperatures),
- $\lambda_D = (\epsilon_0 k_B T_e/N_e e^2)^{1/2}$ (Debye length)
- $k = 2\pi/\lambda$ (wave number).
- y_j (admittance function ... the next slide)

Incoherent scatter spectrum: Admittance function y_j

The admittance functions for the species j are

$$y_j = \frac{i + (\theta_j - i\psi G_j)}{1 - \psi G_j}.$$

Here the Gordeyev integral (asymptotic expansion) can be written as

$$G_j(\theta_j - i\psi_j, \phi_j, \alpha) = \int_0^\infty e^{-i(\theta - i\psi))t' - \phi^{-2}\sin^2 0.5\phi t' - 0.25t'^2\cos^2\alpha} dt',$$

where α is the angle to the **B** and ...

$$\theta_j = \omega\zeta_j, \phi_j = \frac{eB}{m_j c}\zeta_j, \psi_j = \nu_j\zeta_j, t' = t/\zeta_j, \zeta_j = \frac{1}{k}(m_j/2k_B T_j)^{1/2}.$$

Incoherent scatter spectrum: Inputs

What is needed for calculating the IS spectrum?

- Radio wave parameters: ω, $\mathbf{k}$
- Plasma composition, temperatures, ion masses, coll. frequencies and drift velocities: N_j, T_j, m_j, ν_j and $\mathbf{v_j}$
- Magnetic field $\mathbf{B}$

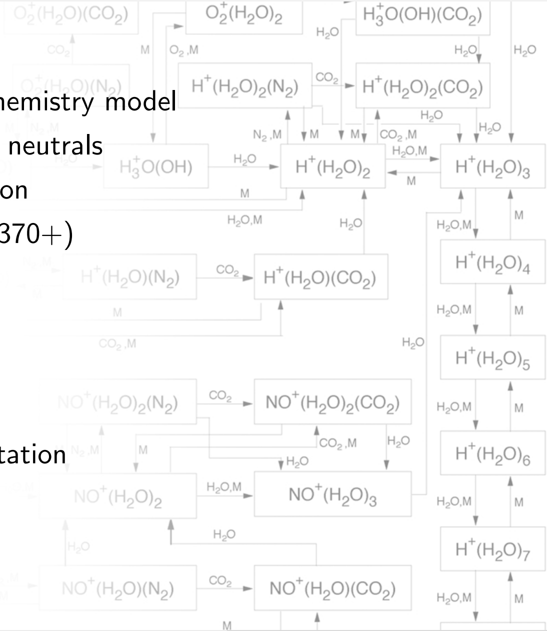
Sodankylä Ion (and neutral) Chemistry model (SIC)

Detailed 1-D time dependend chemistry model

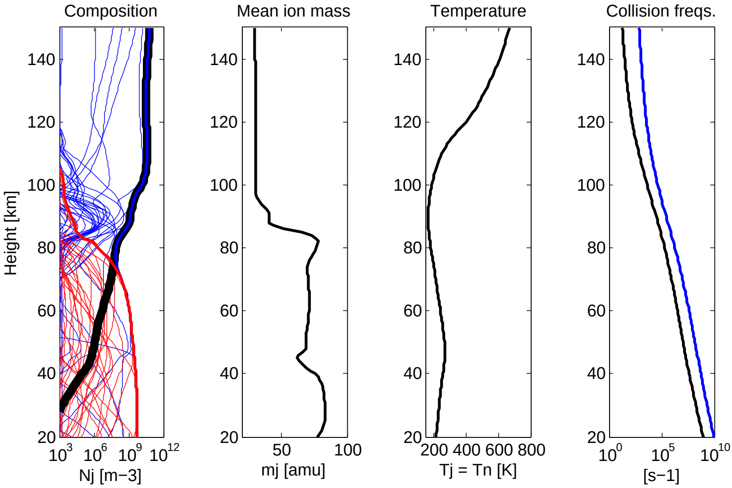
- 63 ions (27 negative) & 13 neutrals
- 20-150 km in 1 km resolution
- several hundred reactions (370+)
- vertical transport

Input

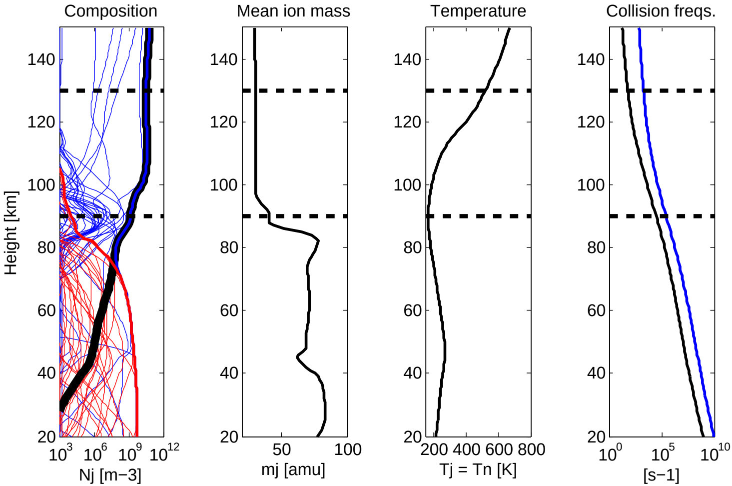
- MSIS
- solar EM flux
- proton and electron precipitation
- cosmic rays



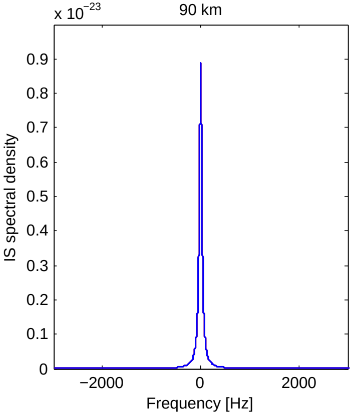
Input profiles



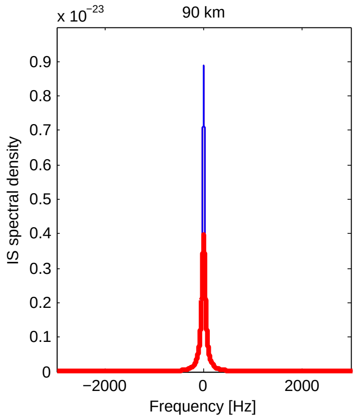
Input profiles



Incoherent scatter ion line: 90 and 130 km

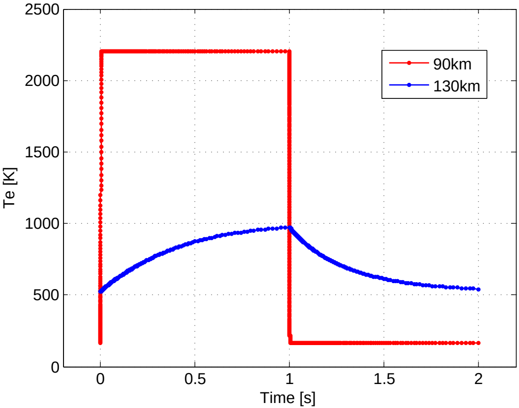


Incoherent scatter ion line: 90 and 130 km, $T_e = 2T_i$



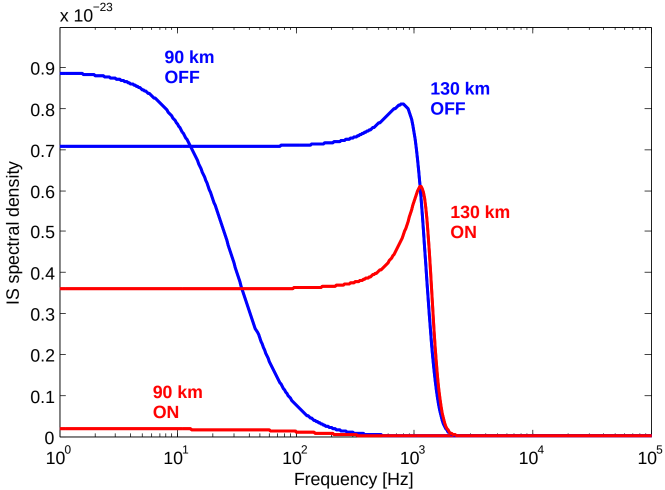
Model example: 1s on/off heating, T_e

ERP=600 MW, $f = 5.423$ MHz, O-mode



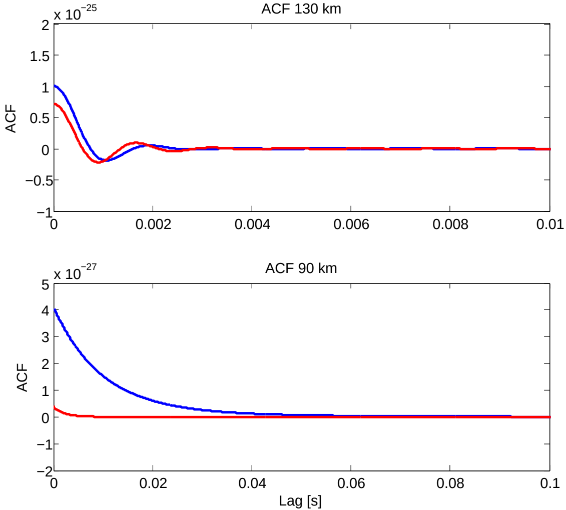
Model example: 1s on/off heating, the IS spectra

ERP=600 MW, $f = 5.423$ MHz, O-mode

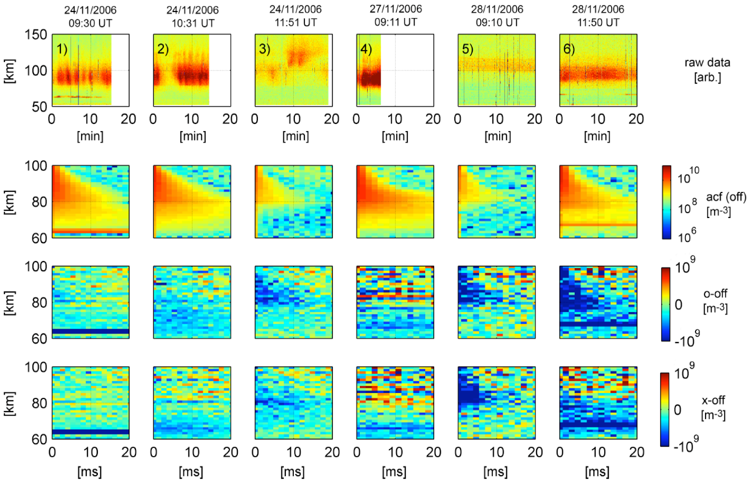


Model example: 1s on/off heating, the ACFs

ERP=600 MW, $f = 5.423$ MHz, O-mode



ISR detection of the HF heating



ISR detection of the HF heating

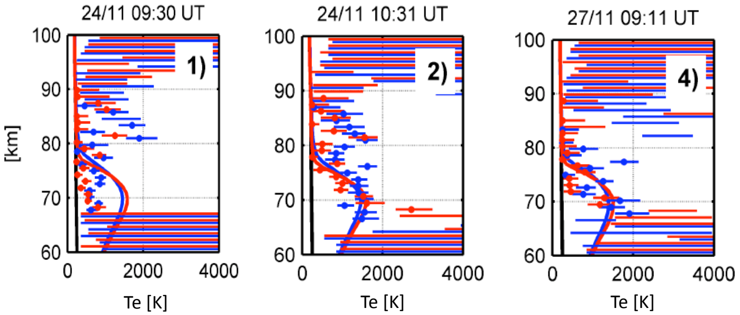
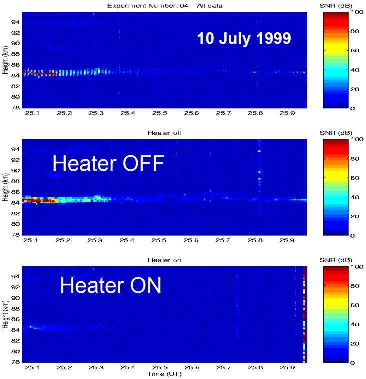


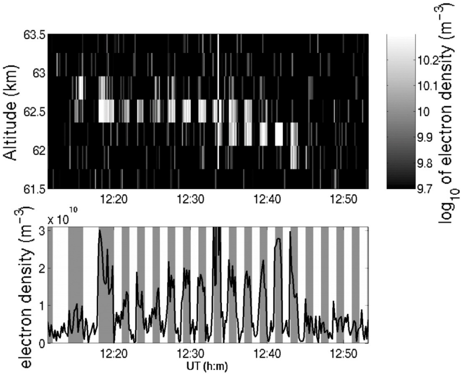
Figure: Kero et al., ANN GEOPHYS, 2008

Coherent scattering: PMSE and PMWE

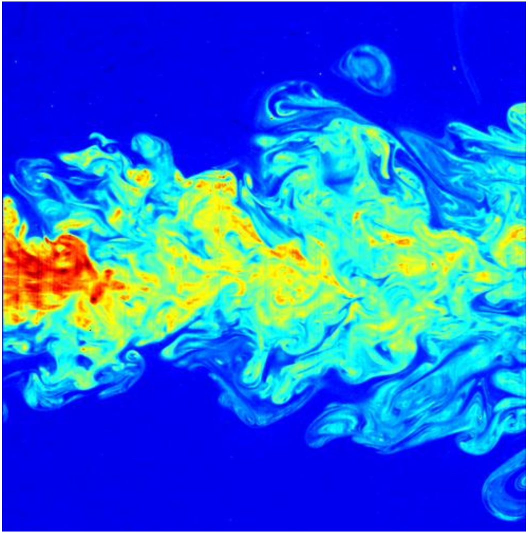
PMSE at 85 km



PMWE at 63 km



Coherent scattering: turbulence (photo: Wikipedia)



A recent paper on PMWE by Mahmoudian et al.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2016JA023388

Remote sensing of mesospheric dust layers using active modulation of PMWE by high-power radio waves

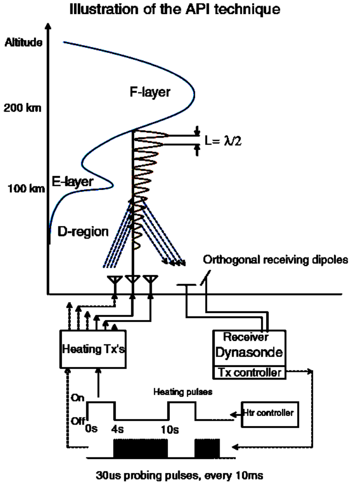
A. Mahmoudian[1], A. R. Mohebalhojeh[1], M. M. Farahani[1], W. A. Scales[2], and M. Kosch[3,4,5]

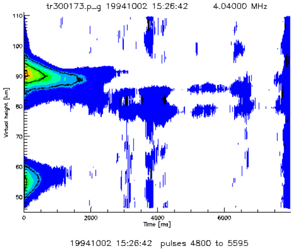
[1]Institute of Geophysics, University of Tehran, Tehran, Iran, [2]Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, [3]South African National Space Agency, Hermanus, South Africa, [4]Physics Department, Lancaster University, Lancaster, UK, [5]Physics Department, University of Western Cape, Bellville, South Africa

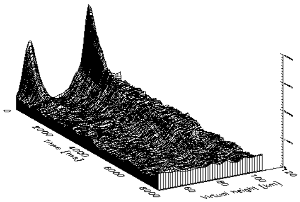
Key Points:

- First study of HF PMWE heating and predicted turn-on overshoot effect
- First comprehensive comparison of PMWE heating observations with computational model
- Two-frequency radar measurements can lead to estimate dust density and radius

Coherent scattering: Artifical Periodic Irregularities (API)







Coherent scattering: Artifical Periodic Irregularities (API)

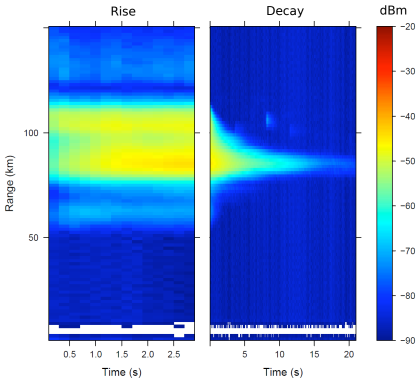
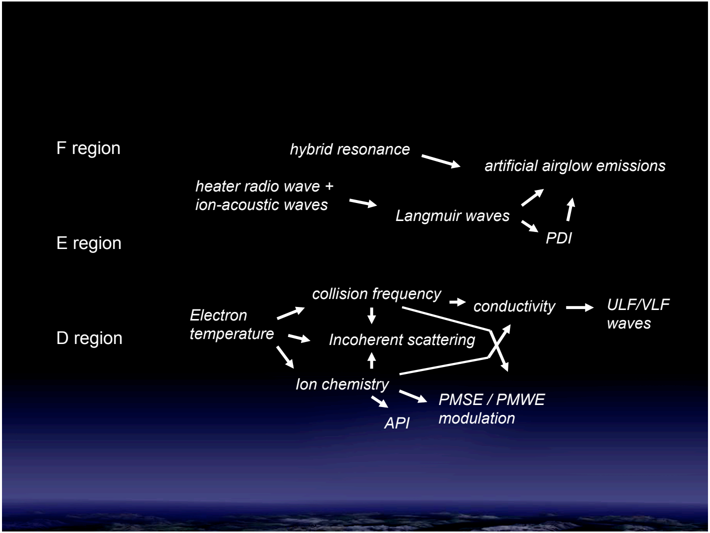


Figure: Vierinen et al., JASTP, 2013

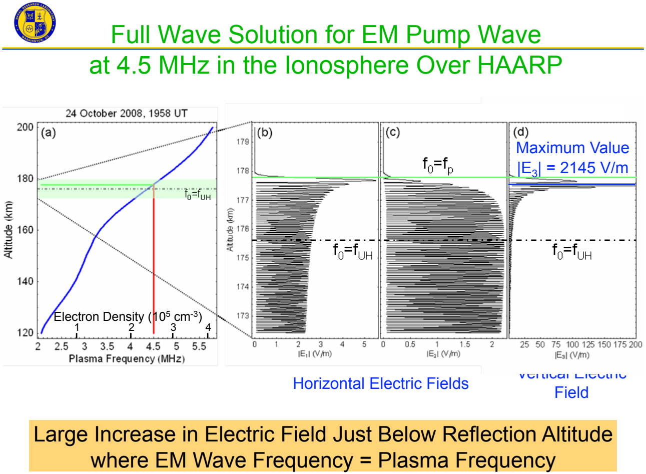
Coherent scattering: summary

	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

Some science applications

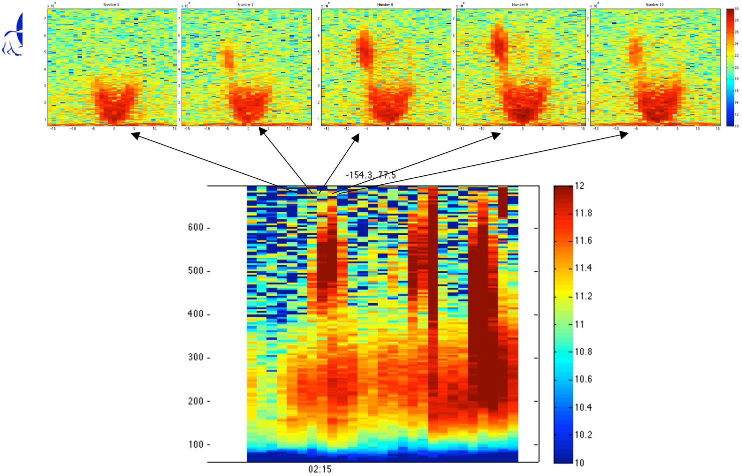


Resonance heating



Courtesy of Paul Bernhardt.

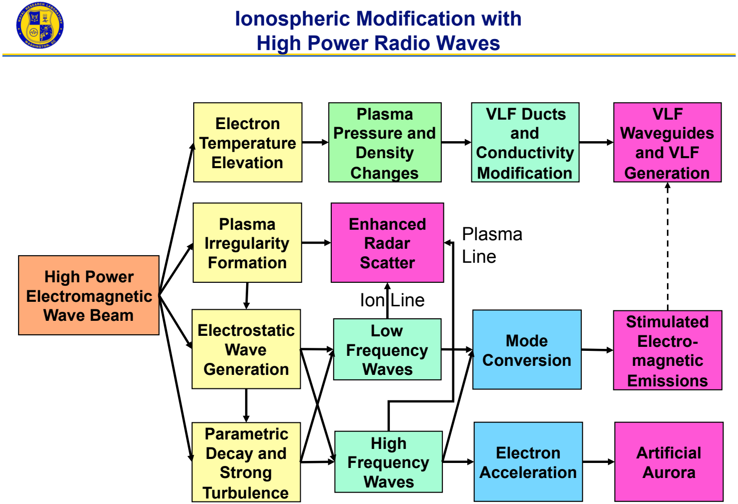
Resonance heating: (N)EIALs



The Ion Line Spectra are Enhanced and Asymmetric

EISCAT Radar School, Åland 1. August 2007 Anja Strømme

Resonance heating



A recent paper on heater excited LPIs by Wang and Zhou

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL074743

Aspect dependence of Langmuir parametric instability excitation observed by EISCAT

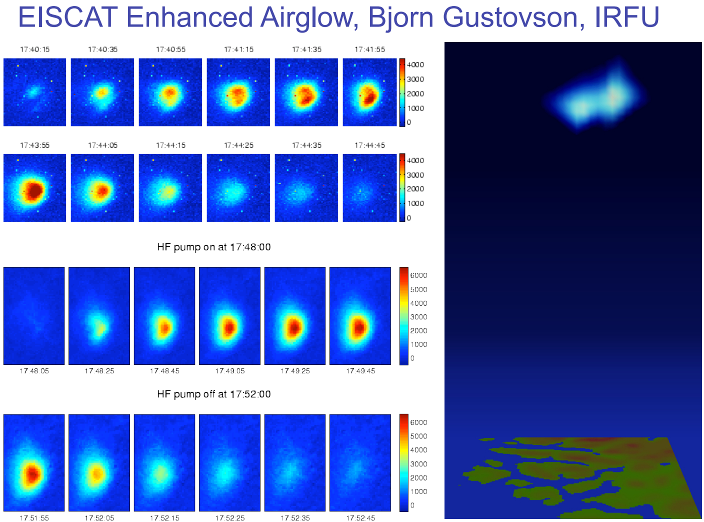
Xiang Wang[1] **and Chen Zhou**[1]

[1]Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan, China

Key Points:

- *X*-mode EM heating wave can excite the PI near its turning point with dependent on different propagation angles of the excited Langmuir wave
- The parallel electric field is crucial for

Resonance heating: artificial airglow



Conclusions