Whistler Wave Generation by Continuous HF Heating of the F-region Ionosphere

Aram Vartanyan[1]

G. M. Milikh[1], B. Eliasson[1,2], A. C. Najmi[1], M. Parrot[3], K. Papadopoulos[1]

[1] Departments of Physics and Astronomy, University of Maryland, College Park, Maryland, USA

[2] Department of Physics, University of Strathclyde, 16 Richmond Street, Glasgow G1 1XQ, UK

[3] Laboratoire de Physique et Chimie de l'Environnement, CNRS, Orleans, France.

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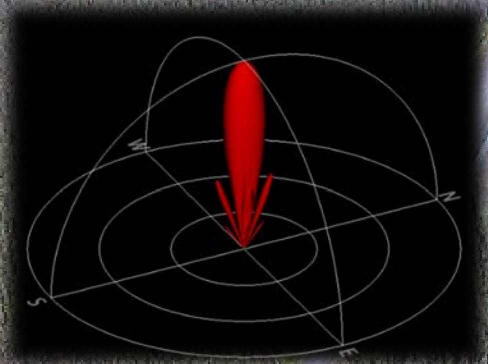
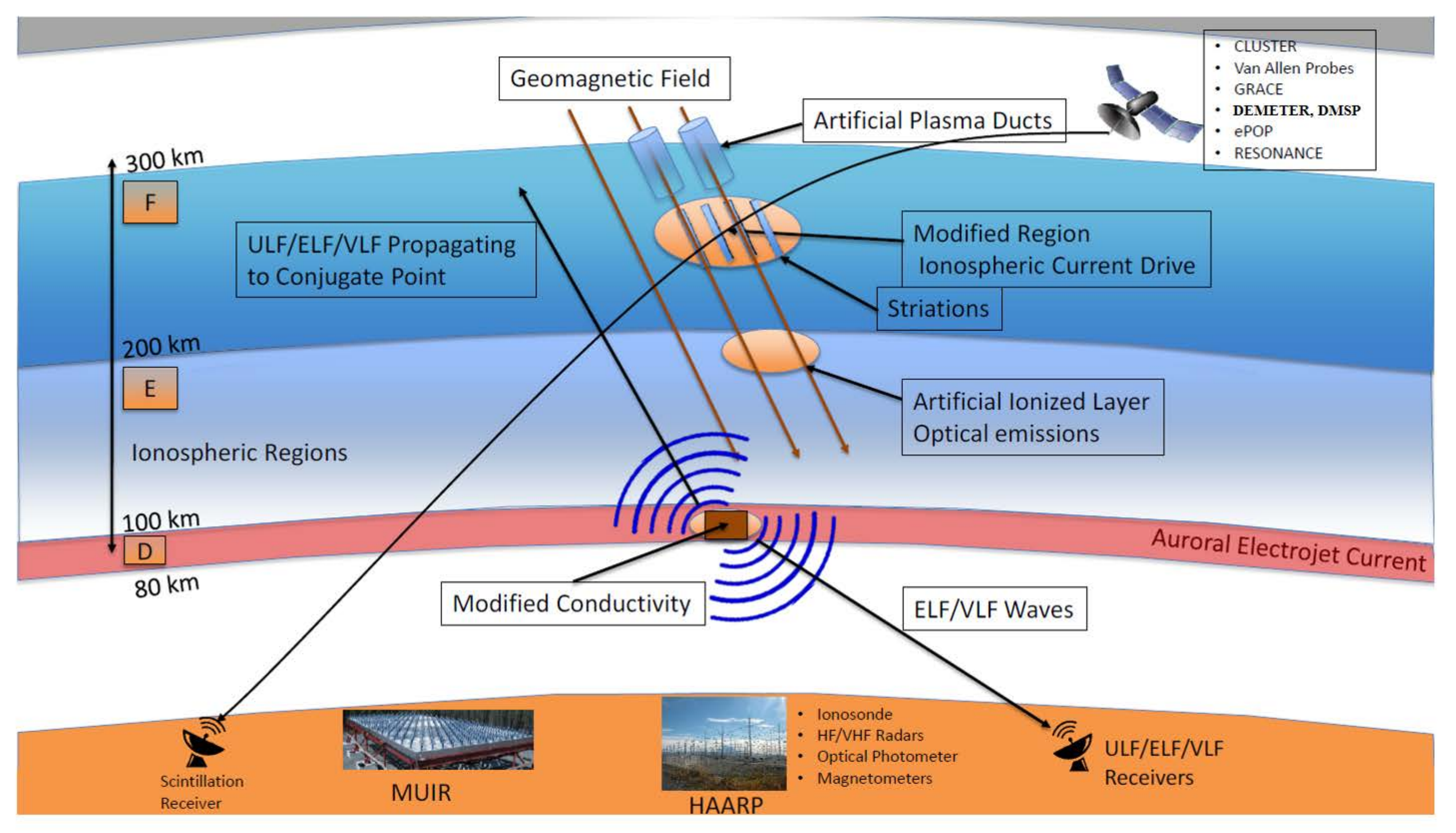
The HAARP facility

- Currently the most powerful HF heater in the world
- Located in Gakona, Alaska
- Consists of a 12 x 15 crossed dipole antenna array, with independent phase and amplitude control
- 3.6 MW of power, with ERP of 5 GW

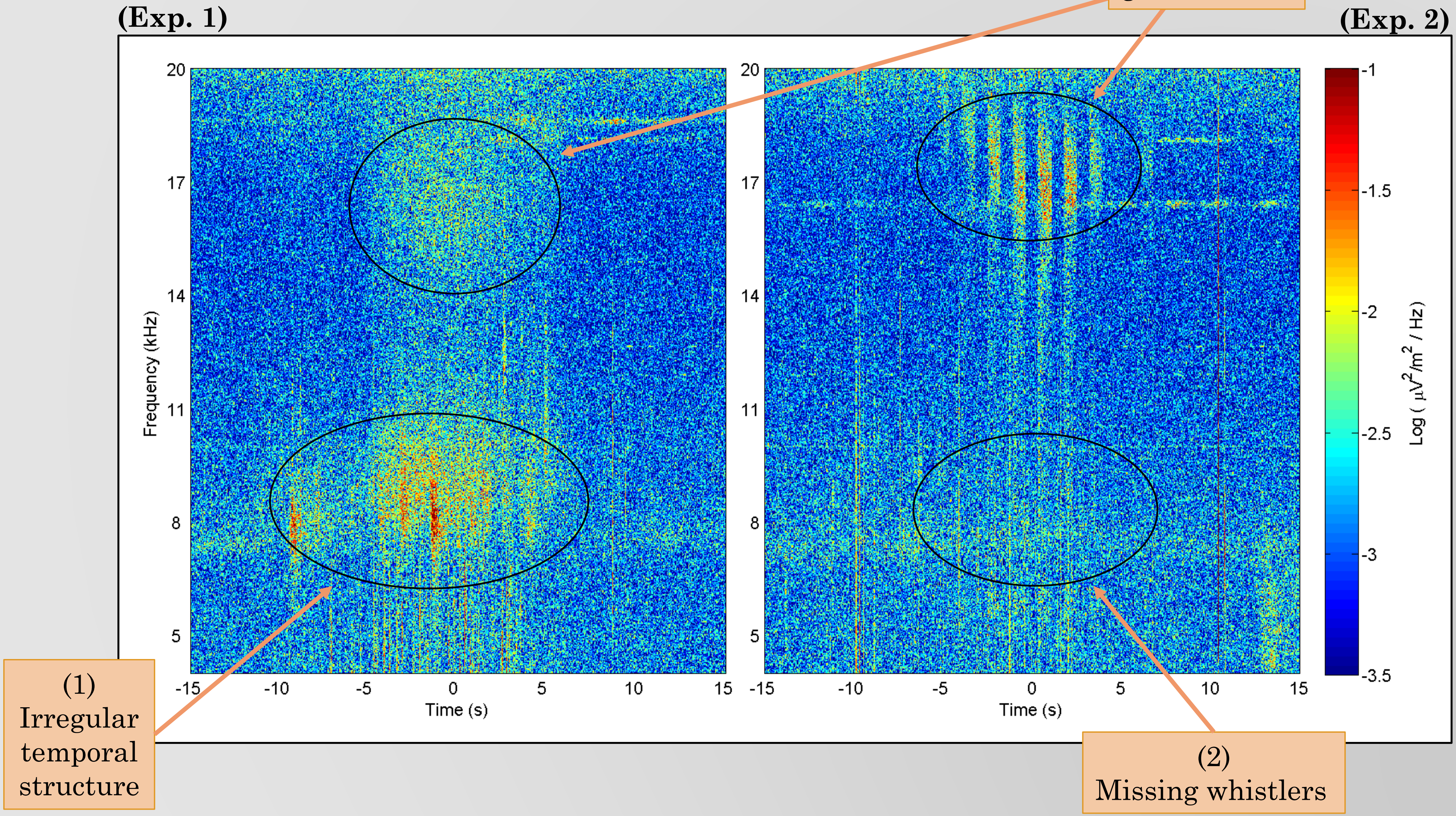


On-site diagnostics at HAARP



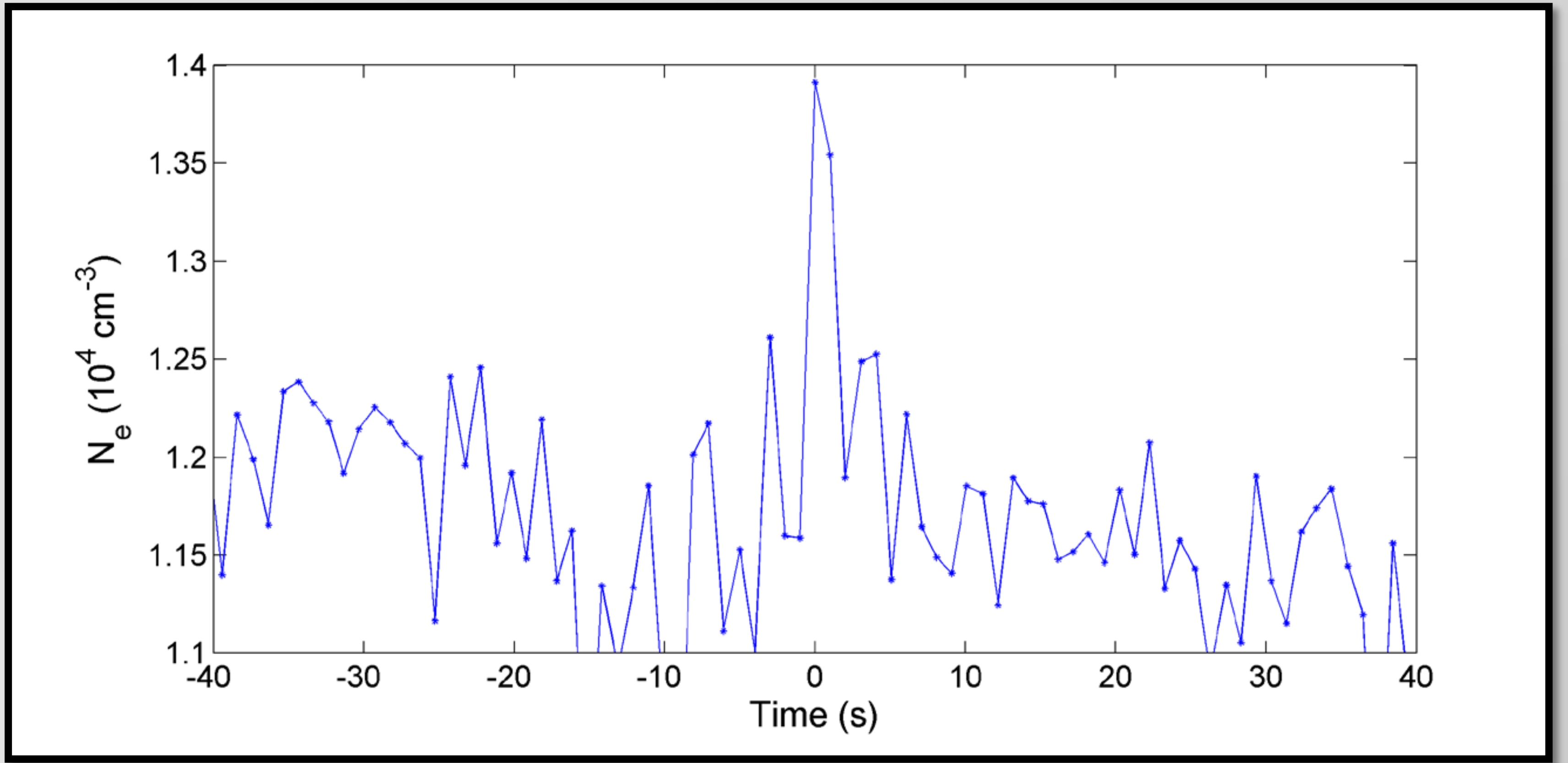
Courtesy Chris Najmi

DEMETER VLF observations



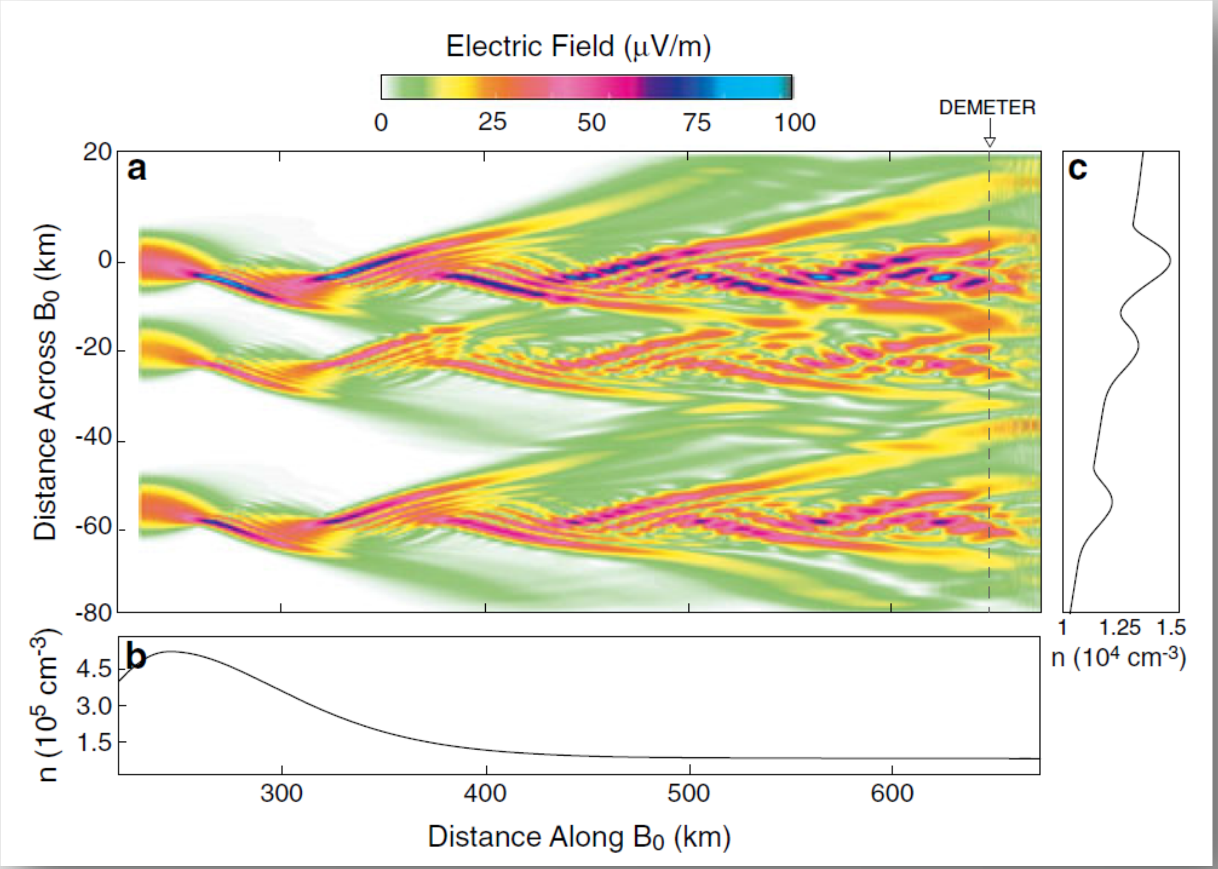
Plasma density measurement during Exp. 1

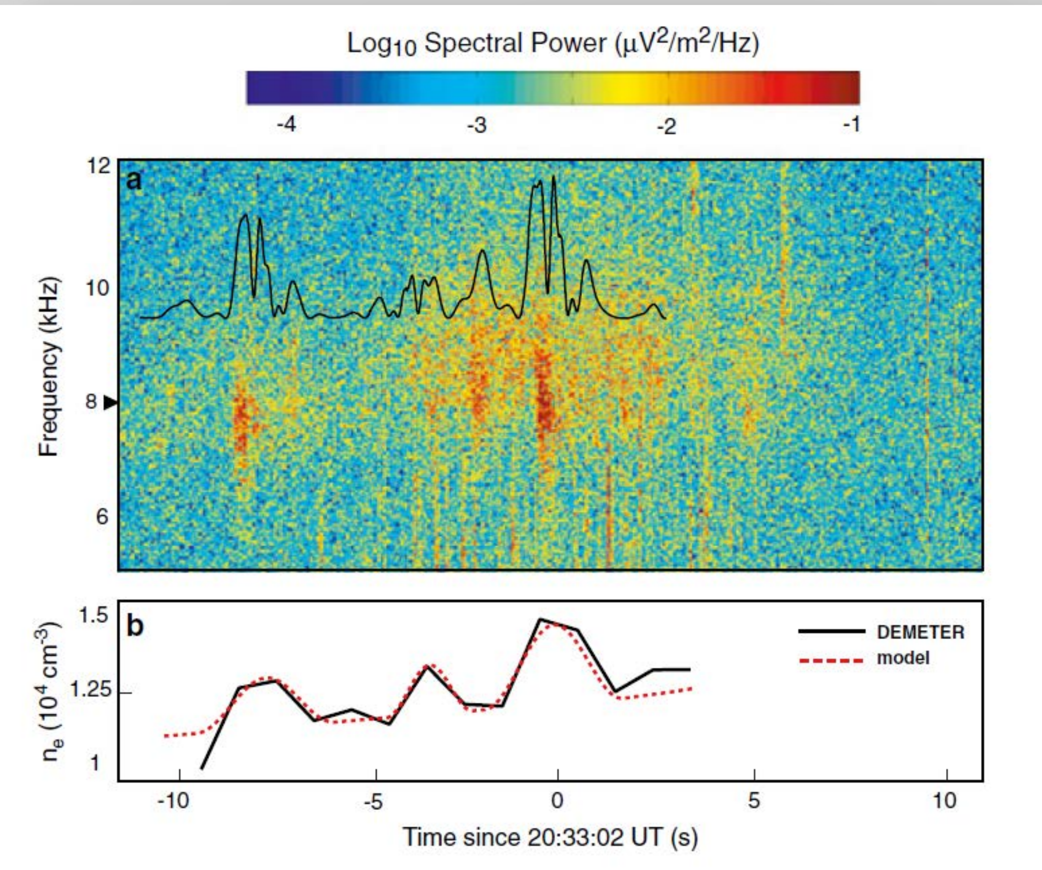
- Prominent artificial ionospheric duct was observed during Exp. 1
- Ducts can act as wave guides for whistler waves
- Thus we expect the presence of ducts to alter the spatial distribution of wave energy



Ducted whistler propagation simulation

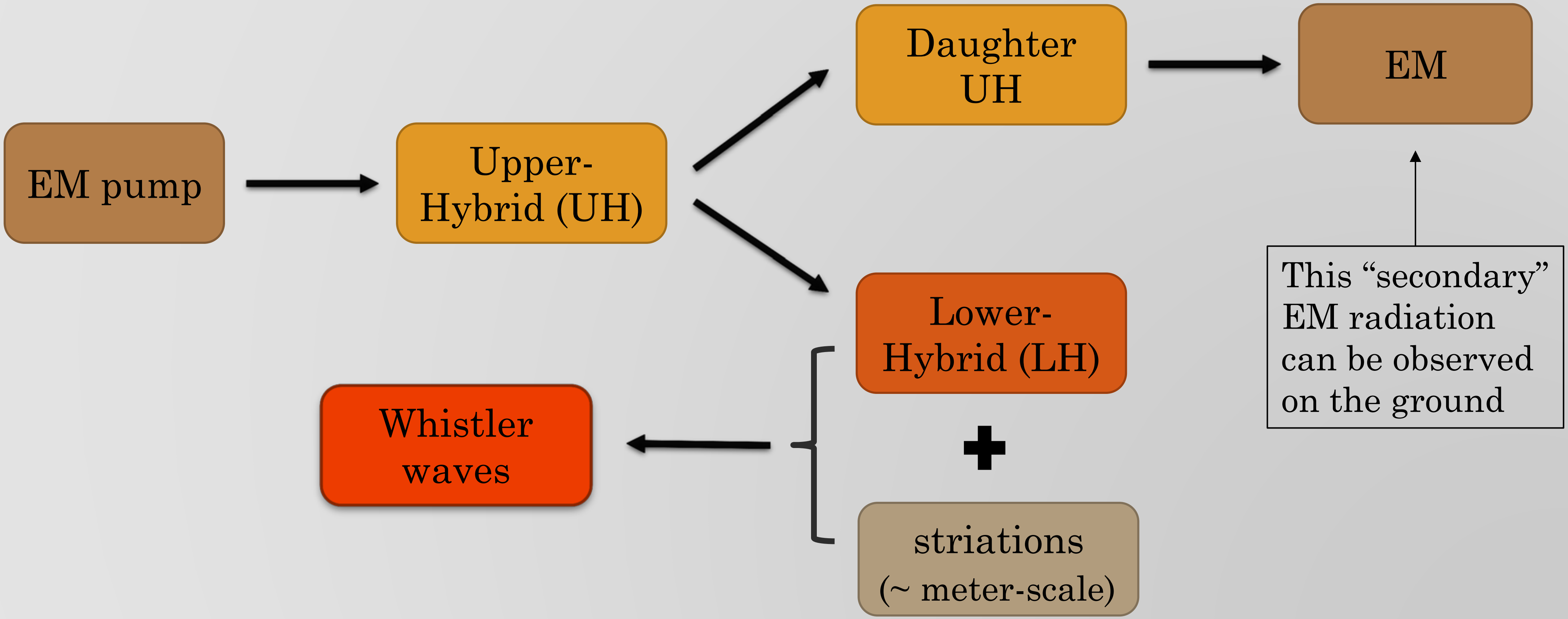
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \boldsymbol{E}, \quad \boldsymbol{\nabla} \times \boldsymbol{B} = -\mu_0 n e \boldsymbol{u}, \quad \lambda_e^2 \boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{E} + \boldsymbol{E} = -\frac{m_e \nu}{e}\boldsymbol{u} - \boldsymbol{u} \times \boldsymbol{B}_0 \quad \text{(EMHD)}$$





Woodroffe, Streltsov, Vartanyan, and Milikh, *J. Geophys. Res.*, 2013

Whistler wave generation mechanism



Stimulated Electromagnetic Emission (SEE)

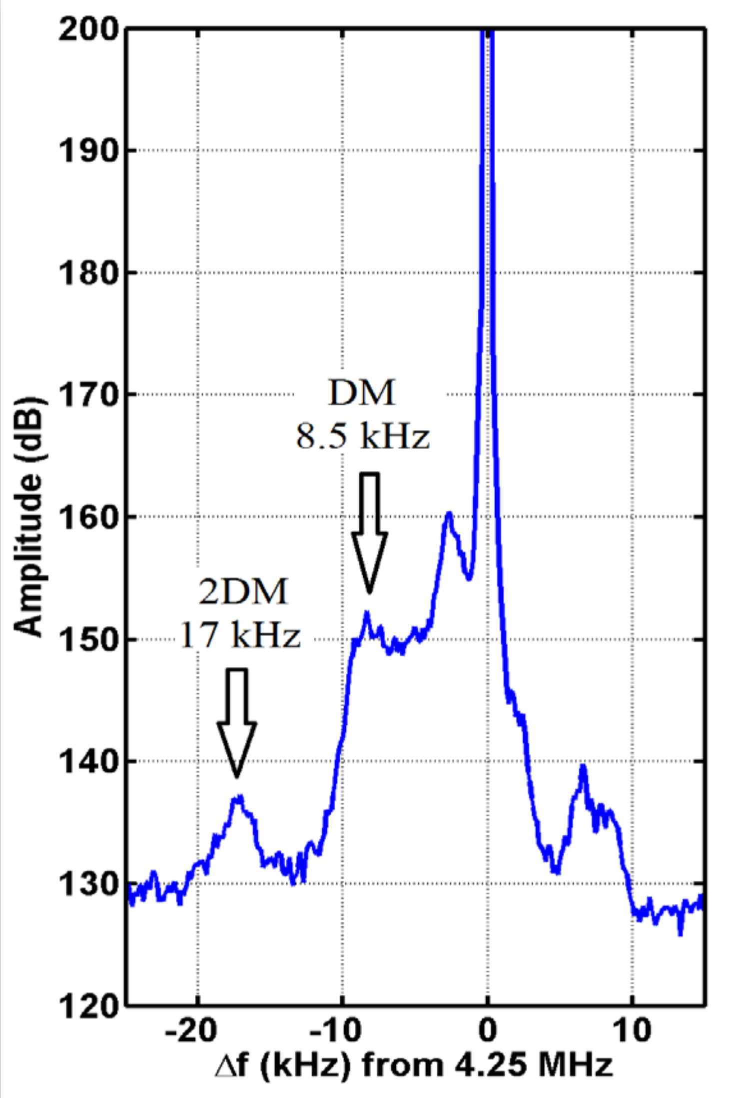
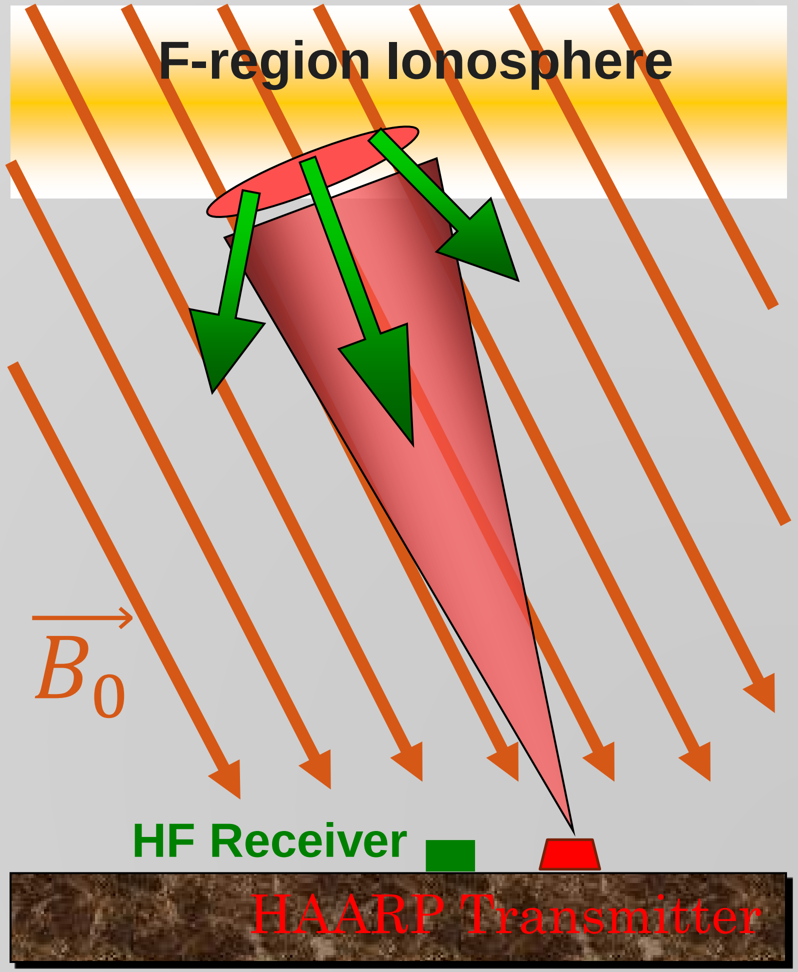


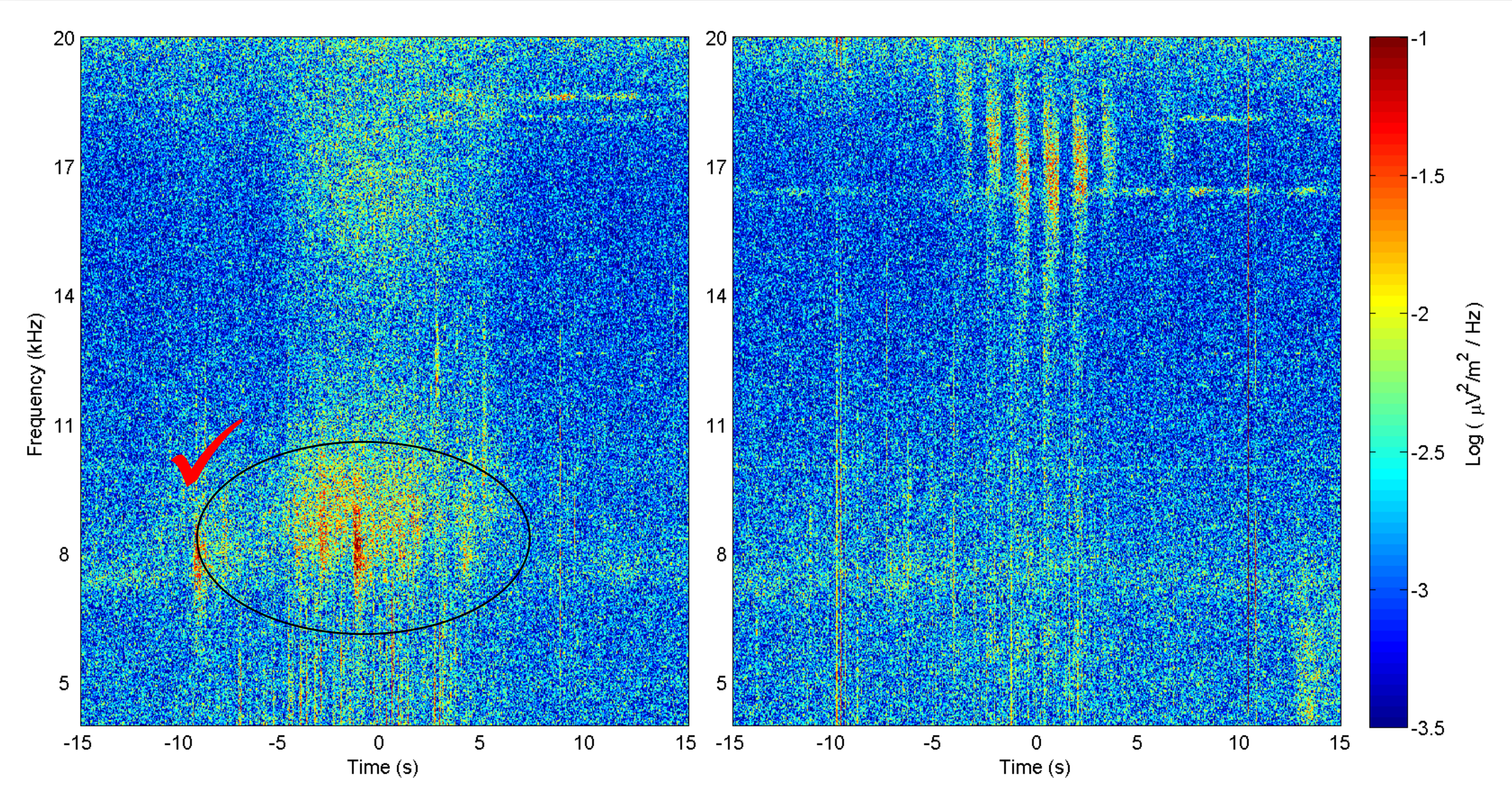
Figure: SEE during Exp. 2

- The "Downshifted Maximum" (DM) and 2DM are indicative of parametric processes involving Lower-Hybrid (LH) waves

- DM generation interaction:
  - $EM_{pump} \rightarrow UH$
  - $UH \rightarrow UH_1 + LH_1$
  - $UH_1 \rightarrow UH_2 + LH_2$
  - $UH_1 \rightarrow EM_{DM}$
  - $UH_2 \rightarrow EM_{2DM}$



(Exp. 1) **(Exp. 2)**



20
17
14
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Frequency (kHz)
-15
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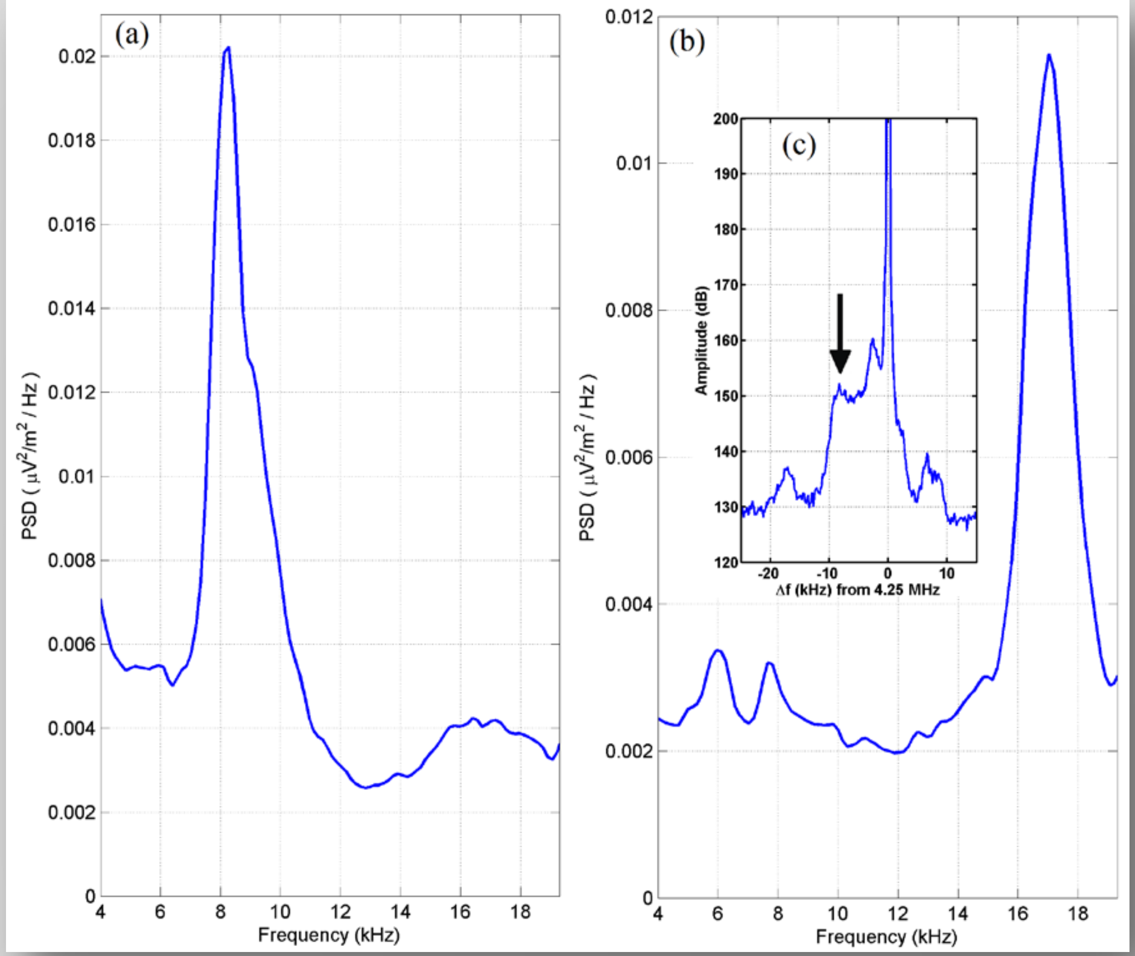
-5
0
5
10
15
Time (s)
-1
-1.5
-2
-2.5
-3
-3.5
Log ($\mu V^2/m^2$ / Hz)

The missing peak in Experiment 2

- Exp. 2 used square modulated heating with an on-time of about 0.7 seconds, while Exp. 1 used continuous (CW) heating
- The on-time in Exp. 2 is not enough time to develop the meter-scale striations necessary for LH-whistler conversion
- However, DM (and hence LH) generation time is less than 20 ms [*Sergeev et al.*, 2013]



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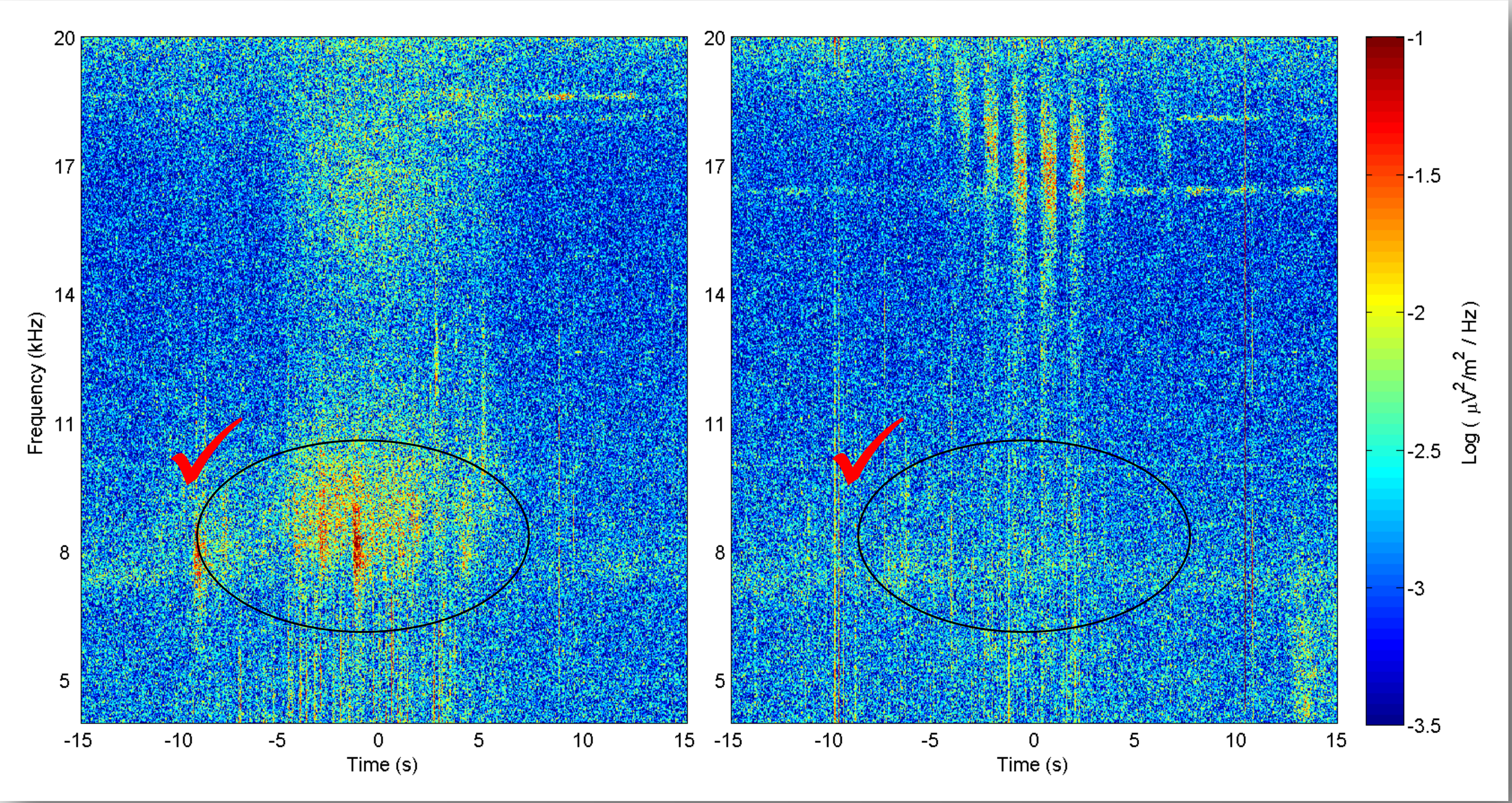

Frequency (kHz)
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Time (s)
Log (μV²/m² / Hz)
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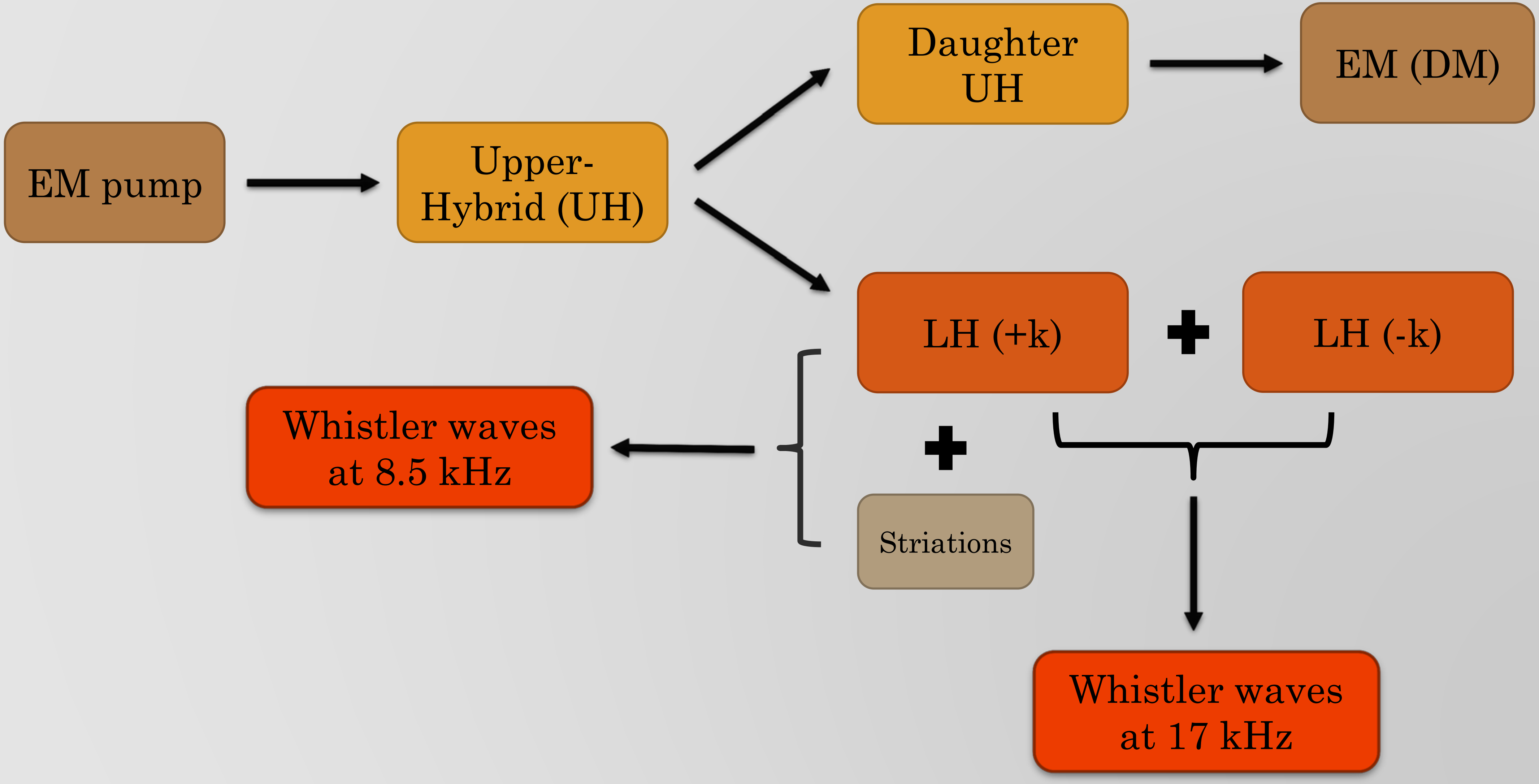
What about whistler waves at LH harmonic?



Model of LH-whistler conversion

This is based on the model of *Eliasson and Papadopoulos* [2008]

$$\frac{\partial \mathbf{j}_w}{\partial t} = -\frac{e\lambda_e^2}{m_e}(1-\lambda_e^2\nabla^2)^{-1}\nabla\times[\nabla\times((n_{str}+n_{LH})\mathbf{E}_{LH}+\mathbf{j}_w\times\mathbf{B}_0)]$$

$$\frac{\partial \mathbf{j}_{LH}}{\partial t} = \nabla^{-2}\left\{\frac{\mathrm{e}}{\mathrm{m_e}}\nabla\times[\nabla\times(n_{str}\mathbf{E}_W+\mathbf{j}_{LH}\times\mathbf{B}_0)]-\frac{e}{m_i}\nabla[\nabla\cdot(\mathbf{j}_{LH}\times\mathbf{B}_0)]\right\}$$

$$\mathbf{E}_W = -(\mathbf{j}_W\times\mathbf{B}_0)/n_0$$

$$\mathbf{E}_{LH} = -\nabla\nabla^{-2}[\nabla\cdot(\mathbf{j}_{LH}\times\mathbf{B}_0)]/n_0$$

$$\frac{\partial n_{LH}}{\partial t}+\nabla\cdot\mathbf{j}_{LH}=0.$$

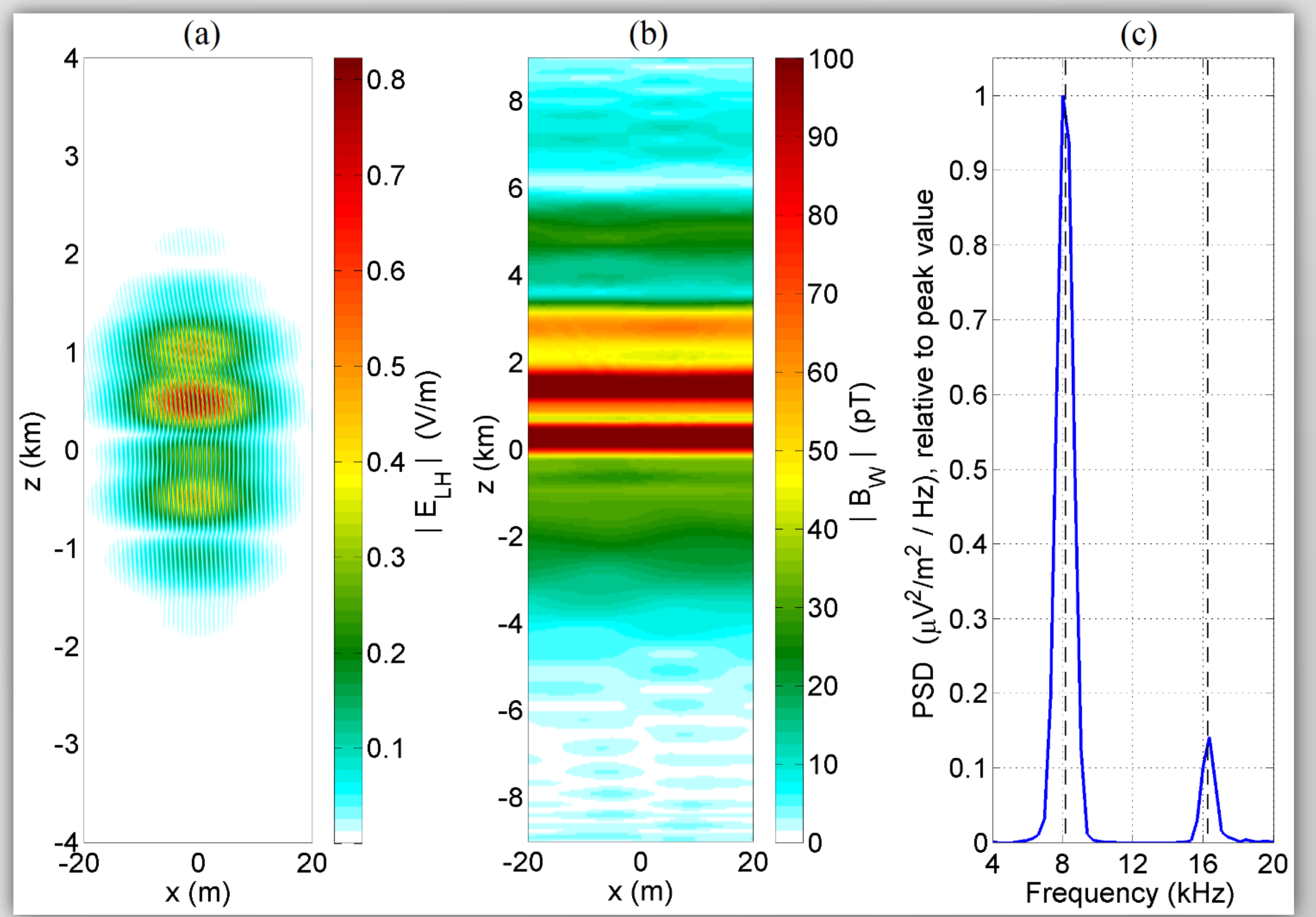
Non-linear coupling

Linear coupling

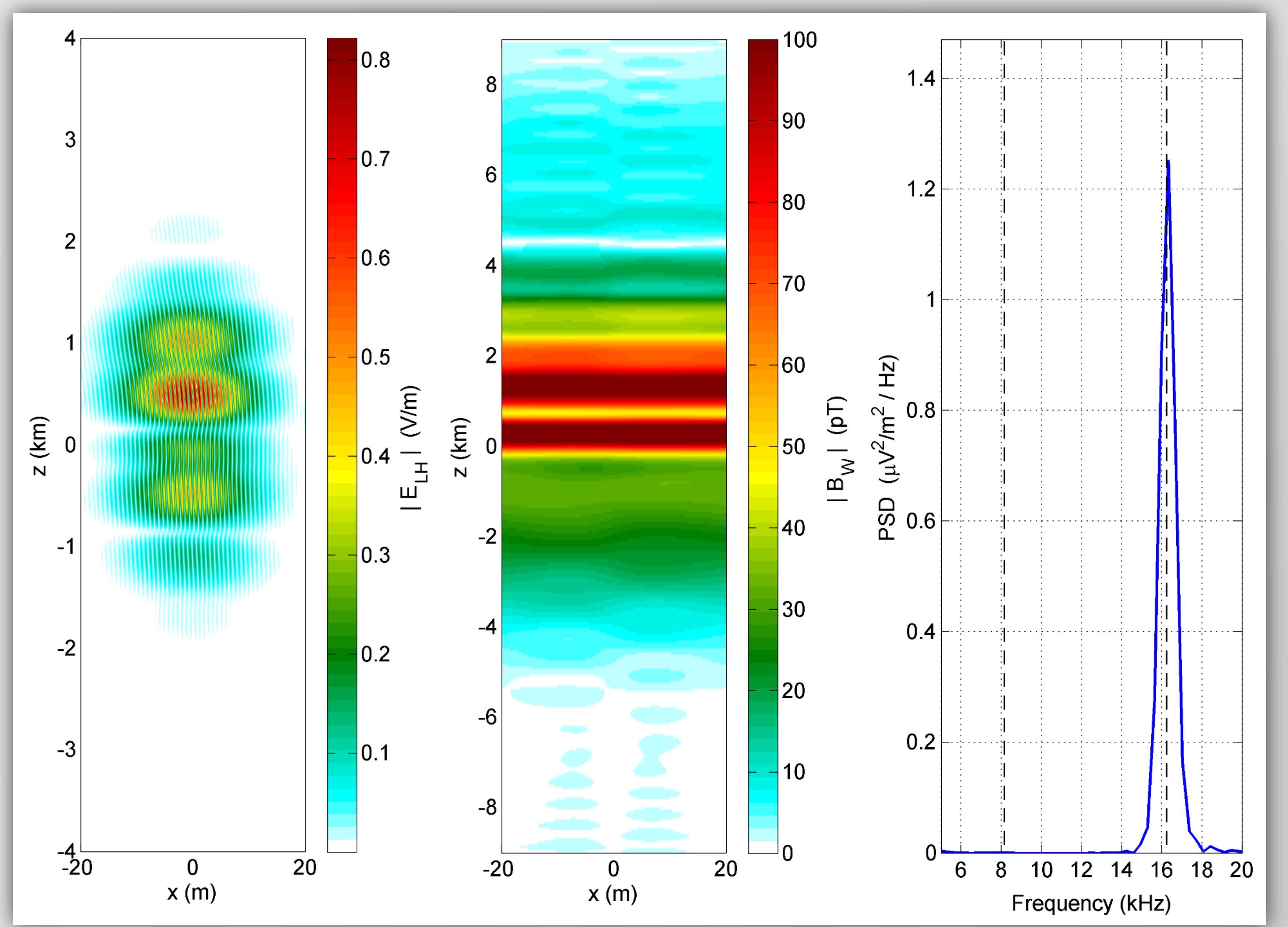
- Pseudo-spectral derivatives in space
- Runge-Kutta 4th order time integration

→ Wrote (2D) code for the model, added nonlinear coupling

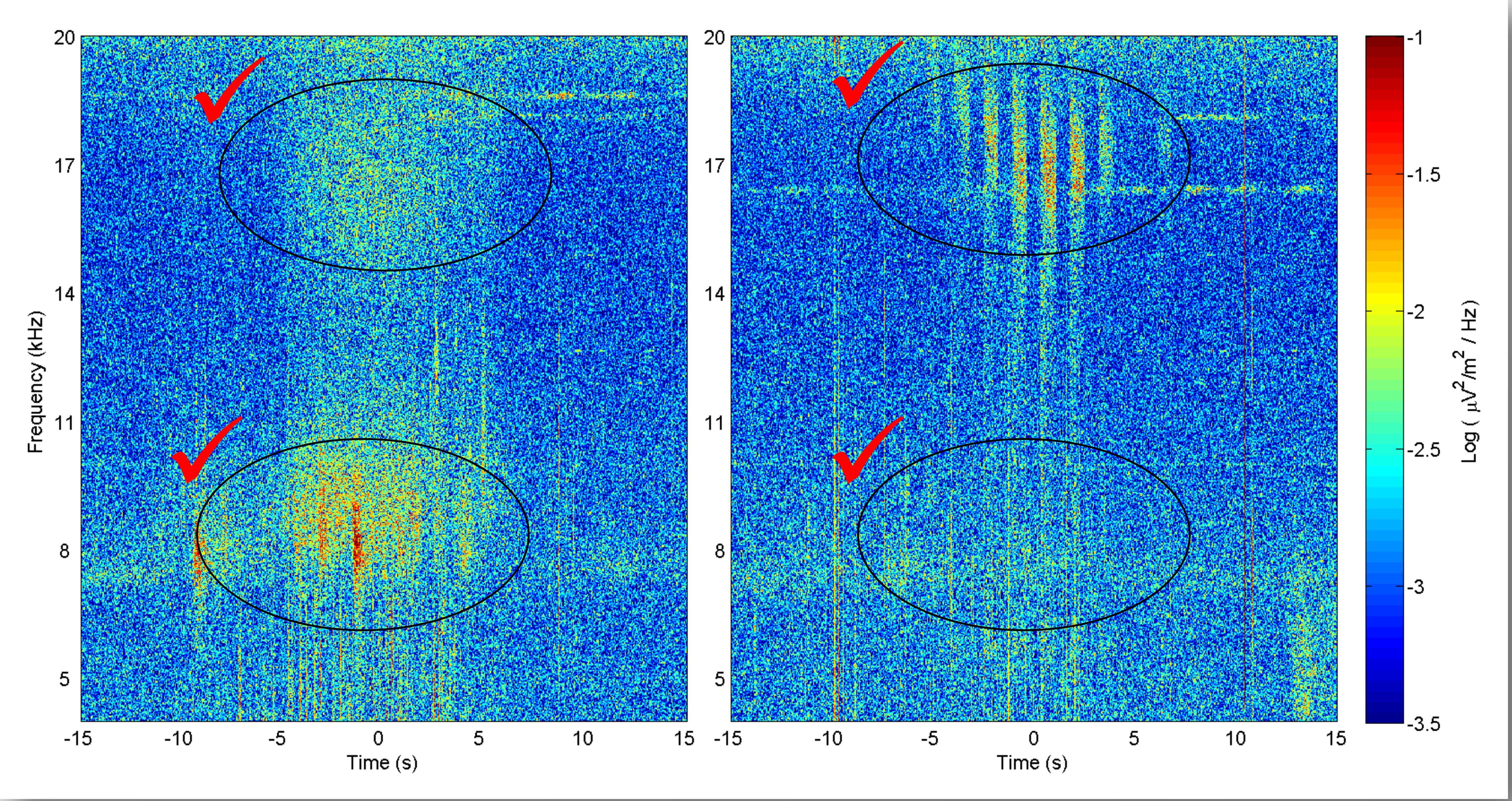
Simulation snapshot (with nonlinear coupling included)



Nonlinear coupling only (striation turned off)



(Exp. 1) **(Exp. 2)**



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Log (µV²/m² / Hz)

Conclusion

- DEMETER VLF observations were reported from two different experiments.
- The observations are consistent with whistler waves that were mode converted from parametrically excited LH waves in the heated region.
- Simulation results of LH-whistler conversion, with the nonlinear coupling term, show good agreement with the observed whistler spectrum.
- The discussed mode conversion techniques could be a source for VLF generation in regions where the electrojet is absent, and be used for subsequent injection to the radiation belts in order to trigger particle precipitation.

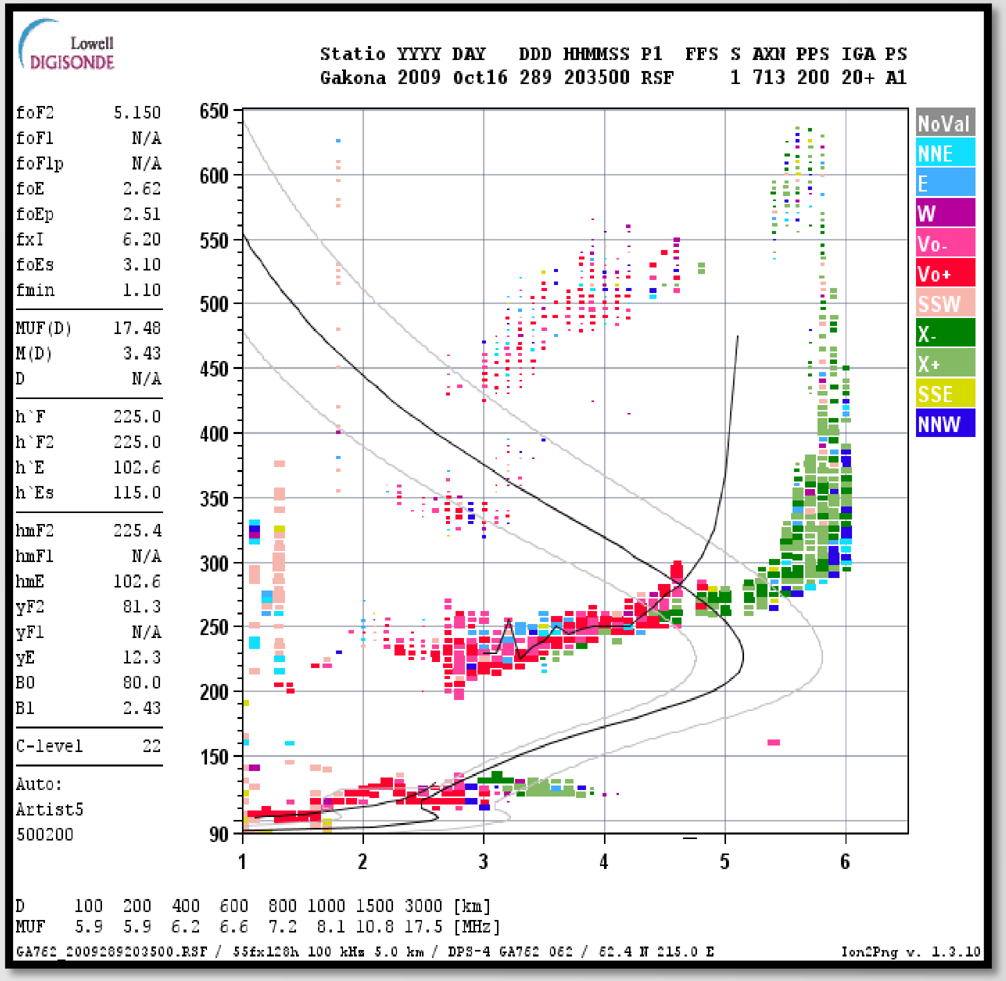
Description of experiments

	HF heating time	f_H(MHz)/ h_r(km)	f_0F_2(MHz)/ h_mF_2(km)	ΔR(km)/ L_{EW}(km)	Ionospheric condition	HF heating regime
1	10/16/2009 20:15-20:45	5.1 / 220	5.15 / 225	69 / 32	very quiet	CW, O-mode, MZ
2	02/10/2010 20:15-20:34	4.25 / 200	5.5 / 230	40 / 39	very quiet	Modulated at 0.7 Hz, O-mode, MZ

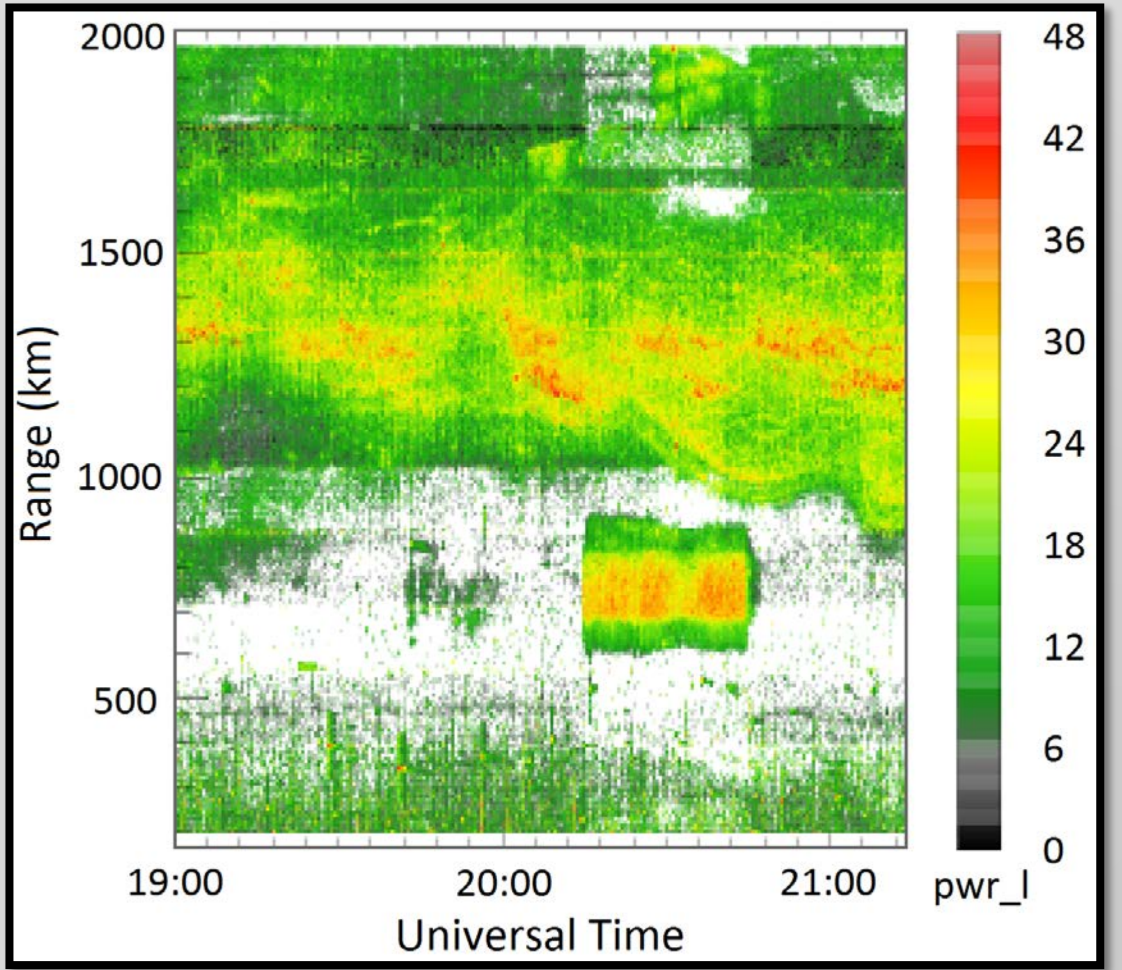
Table 1. Key experimental information, from left to right: HF heating frequency (f_H) and reflection height (h_r); critical frequency (f_oF_2) and critical height (h_mF_2); closest approach to the HAARP MZ (ΔR) and the E-W half-power beam width at the heating altitude (L_{EW}); ionospheric conditions; and heating beam details.

Experiment 1, 10/16/2009

Ionogram for Exp. 1



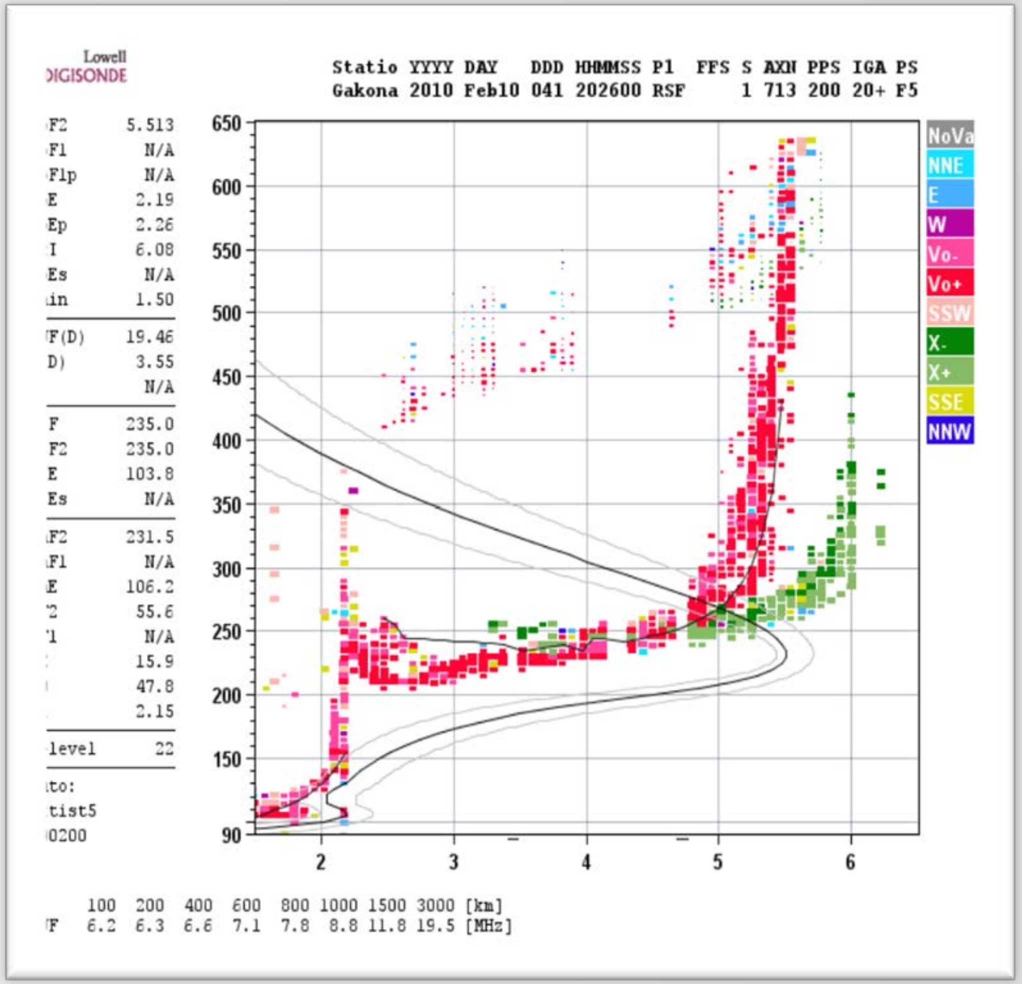
Kodiak radar diagnostics

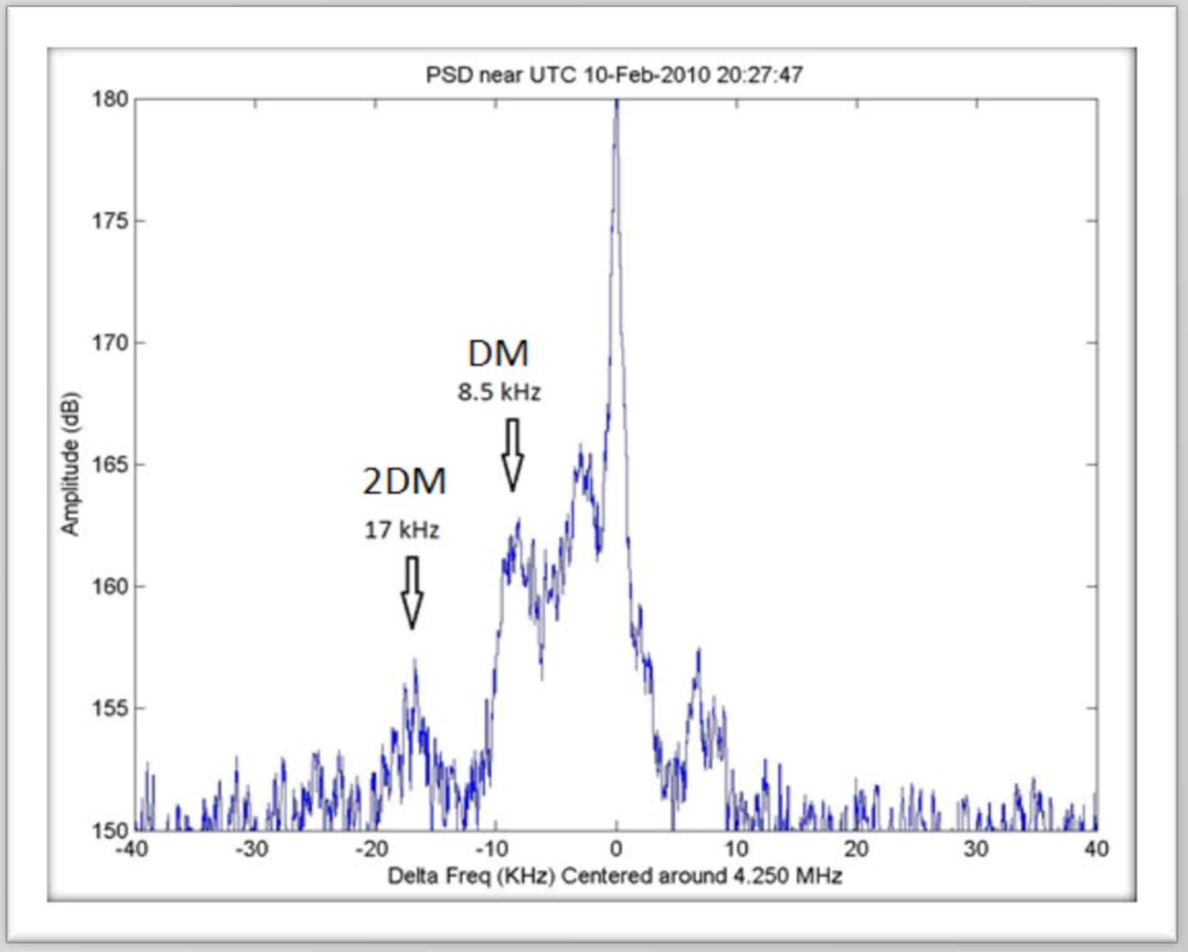


Experiment 2, 02/10/2010

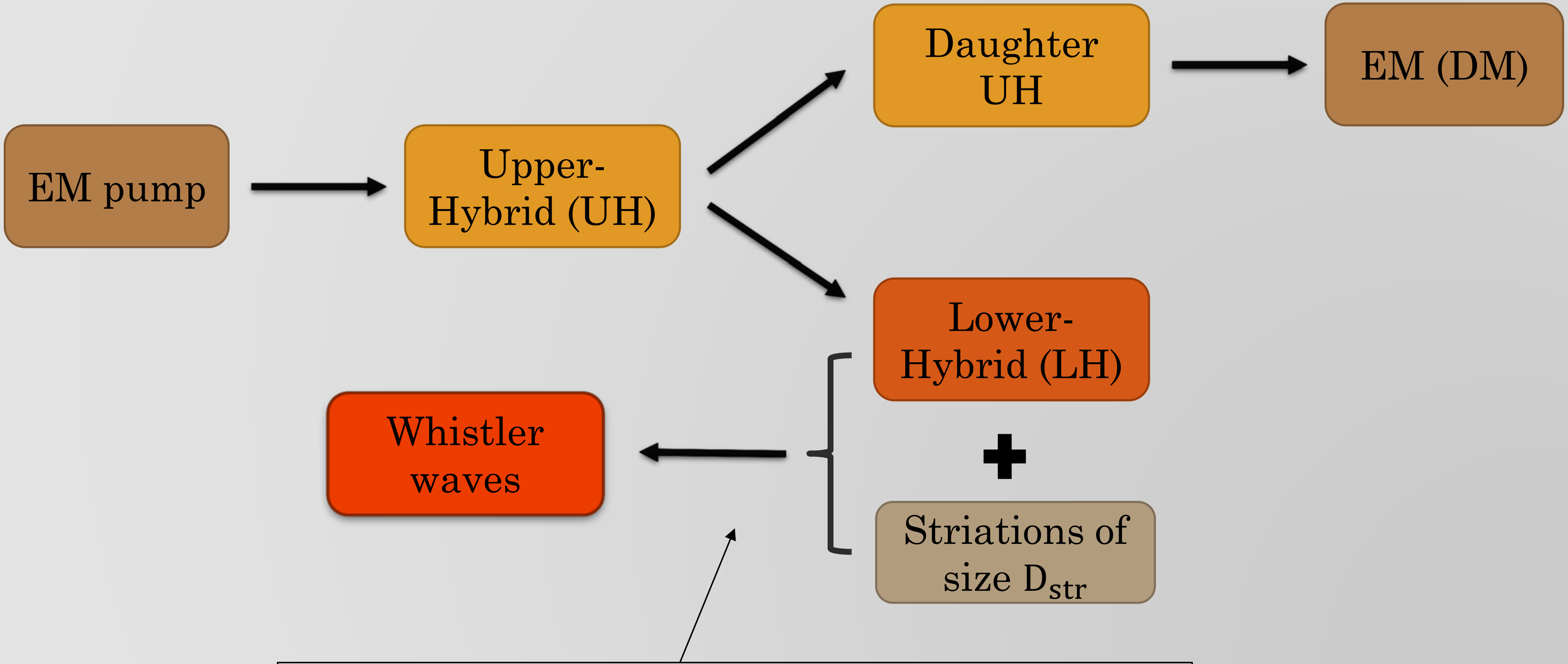
Ionogram for Exp. 2

Stimulated Electromagnetic Emission (SEE)





Necessary striation size



Resonant LH-whistler mode conversion when $D_{str} \approx \pi / k_{\perp,LH}$
[*Eliasson and Papadopoulos*, 2008]

Striation size estimate

- Matching conditions for resonant mode conversion:
  - $\omega_{LH} = \omega_{w} = \omega$
  - $k_{\parallel,LH} = k_{\parallel,w} = k_{\parallel}$
  - $k_{\perp,w} = 0$
- Using the above and LH/whistler dispersion relations give us:

$$\omega_{LH}^2 = \omega^2 = \frac{\omega_{LH,0}^2 k_{\perp,LH}^2 + \omega_{ce}^2 k_{\parallel}^2}{k_{\perp,LH}^2 + k_{\parallel}^2} \approx \frac{\omega_{LH,0}^2 k_{\perp,LH}^2 + \omega_{ce}^2 k_{\parallel}^2}{k_{\perp,LH}^2}$$

$$\omega_{w}^2 = \omega^2 = \lambda_e^4 k_{\parallel}^2 \left(k_{\perp,w}^2 + k_{\parallel}^2\right) \omega_{ce}^2$$

- Eliminating $k_{\parallel}^2$ above, we obtain:

$$k_{\perp,LH}^2 = \frac{\omega_{ce}\omega}{\lambda_e^2\left(\omega^2 - \omega_{LH,0}^2\right)} = \frac{\sqrt{m_i/m_e}\; f/f_{LH,0}}{\lambda_e^2\left(\left(f/f_{LH,0}\right)^2 - 1\right)}$$

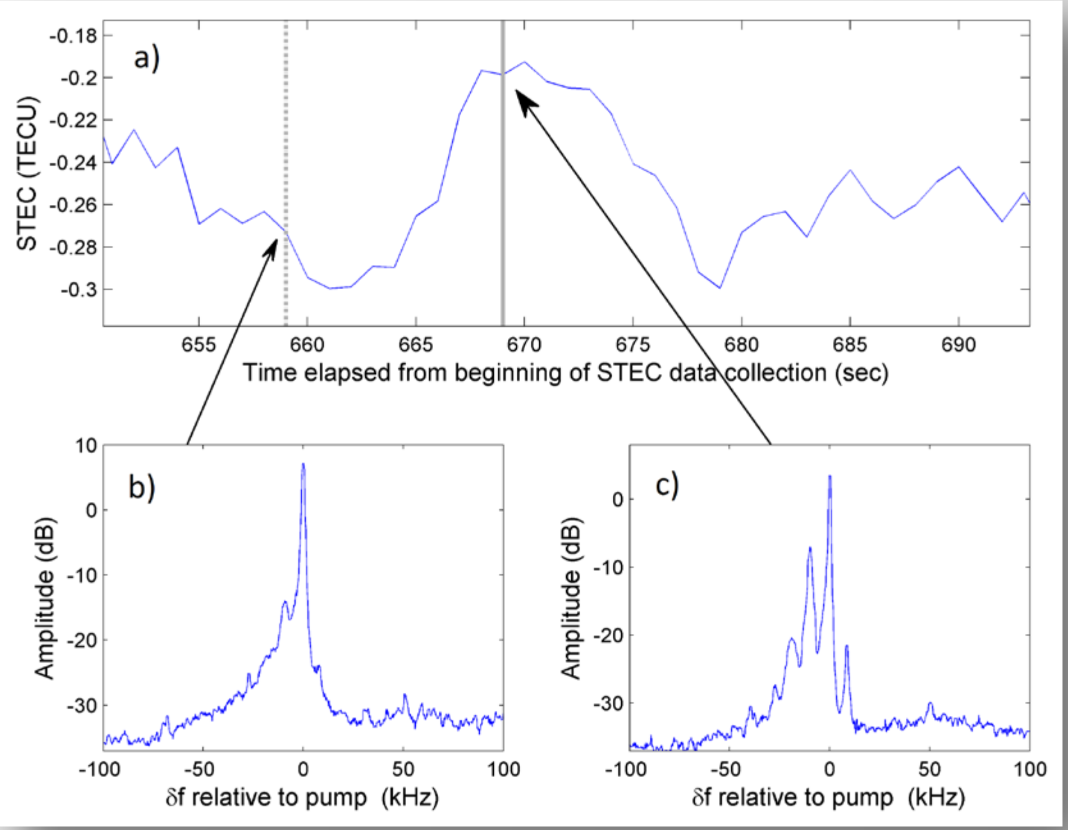
- Plugging ionospheric parameters above gives a striation width estimate:

$D_{str} \sim \pi/k_{\perp,LH} \sim 1$ m → Need meter-scale striations for LH-whistler conversion

One more diagnostic: Slant Total Electron Content (STEC)

- Heating experiments are carried out during the flyby of a GPS satellite
- The propagation of the GPS signals is affected by HF-driven plasma density irregularities
- This manifests itself as a relative phase delay between two GPS signals
- Since the phase difference is related to the (change in) height integrated plasma density, an increased phase difference indicates plasma density irregularities (striations)

Example of striation build-up time scale using STEC



- (a) Measurements of STEC using GPS satellite data during an HF heating experiment
- (b) Simultaneously, SEE was measured on the ground a small fraction of a second after the start of heating, showing signs of DM development.
- (c) SEE after 10 s of heating reveals a very well developed DM, along with a 2DM and 3DM

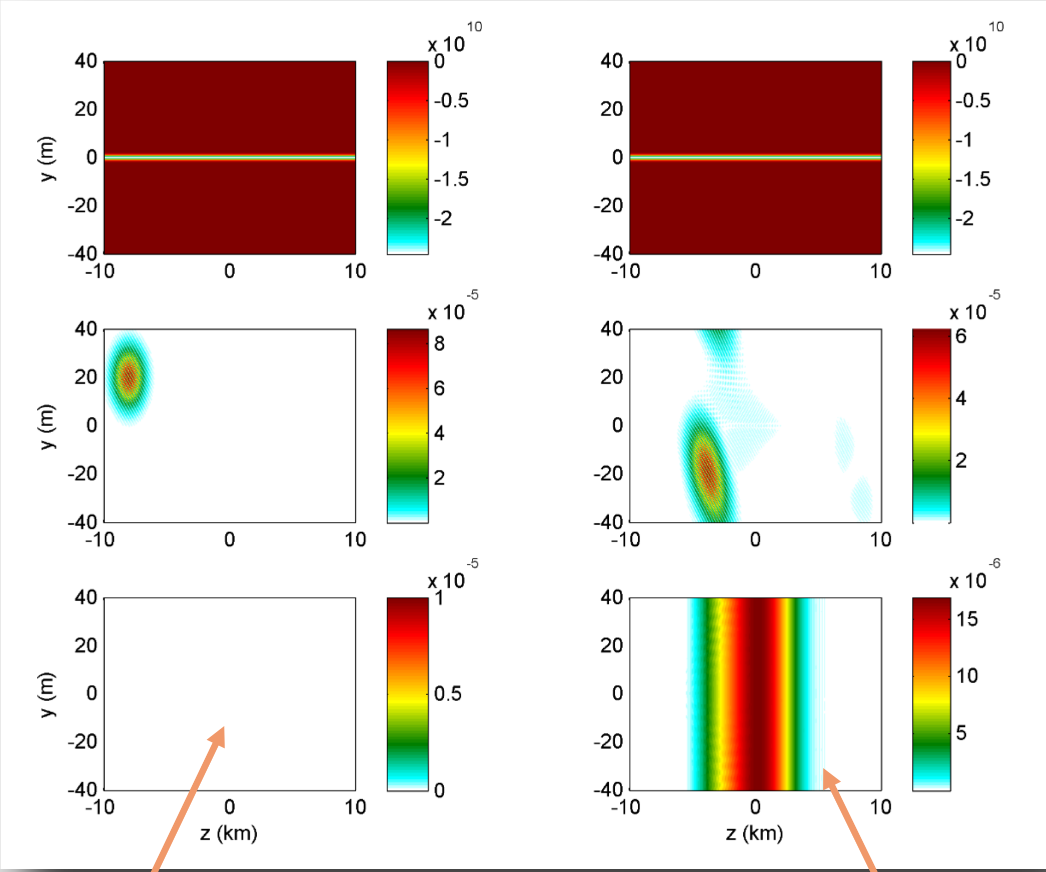
Conditions for experiment: daytime, quiet ionosphere, $f_H = 5.75\ MHZ \approx 4f_{ce}, h_r = 200\ km$

SEE/STEC data and processing courtesy Amir Najmi, Paul Bernhardt, Stan Briczinski and Carl Siefring

Benchmarking (without nonlinearity)

t = 0

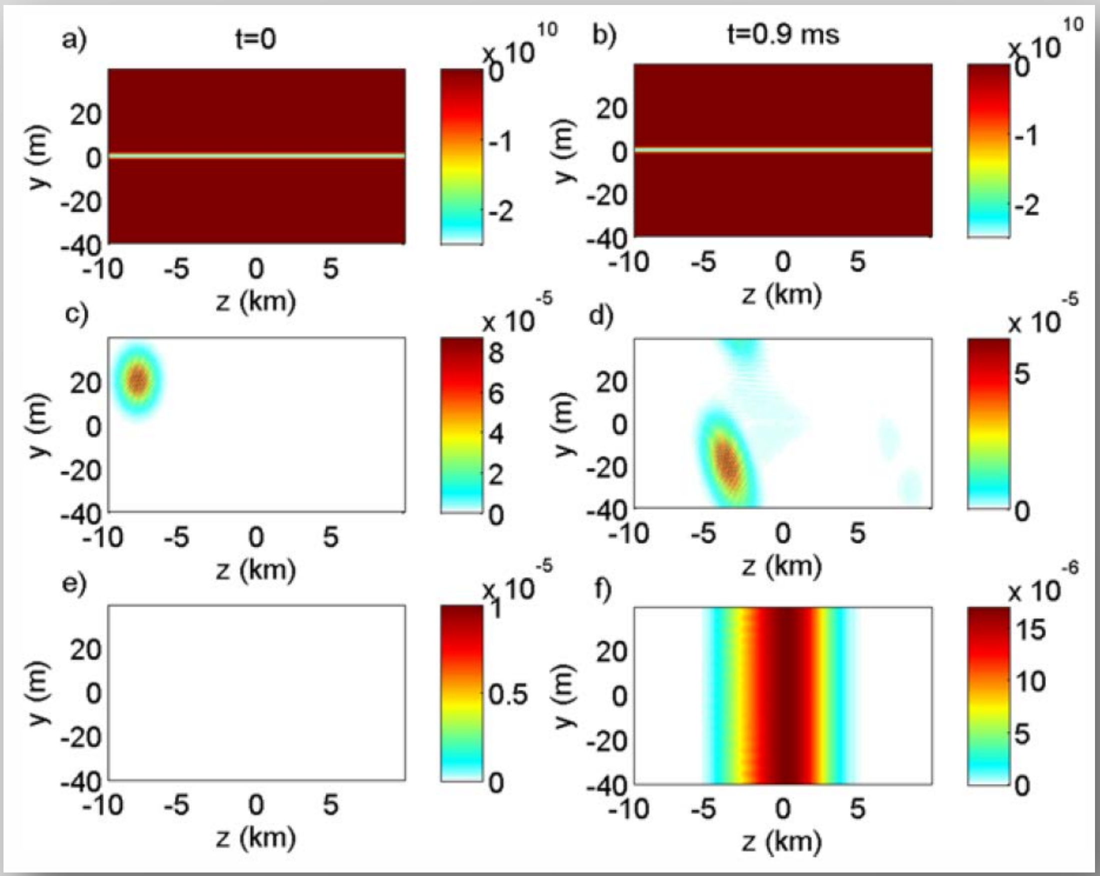
t = 0.9 ms



Nothing

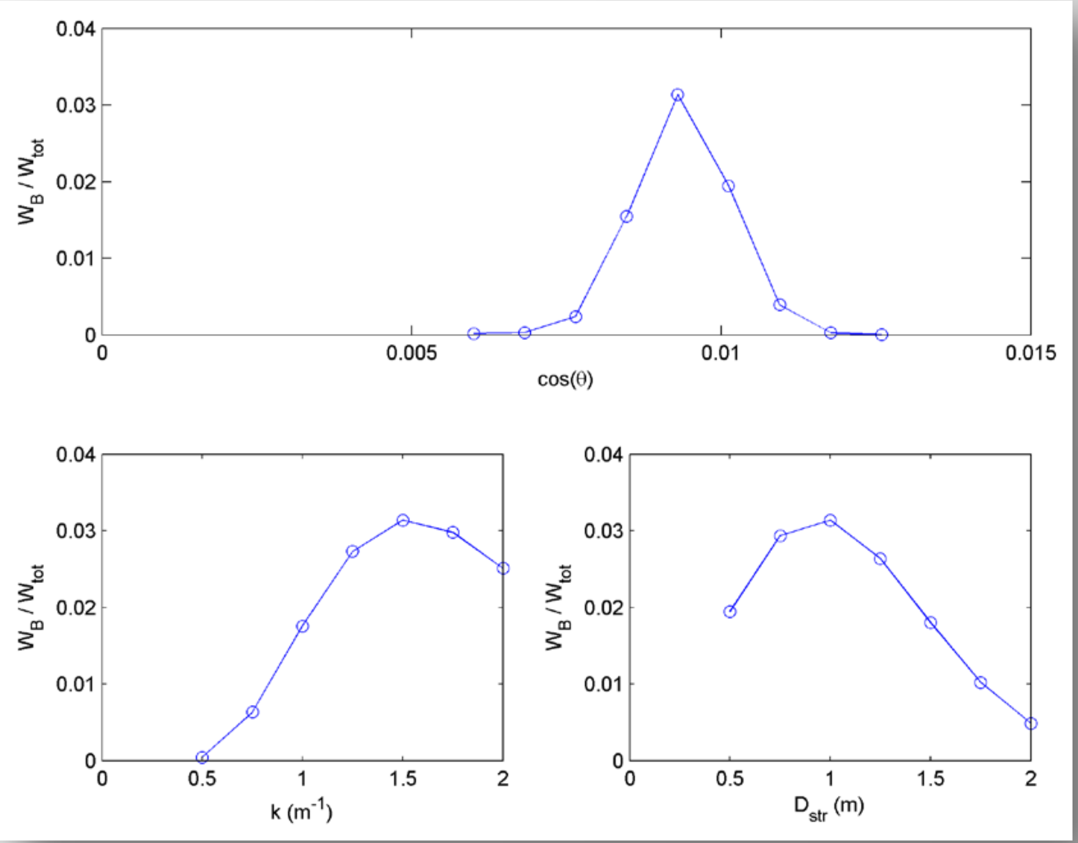
My code

Whistler waves!

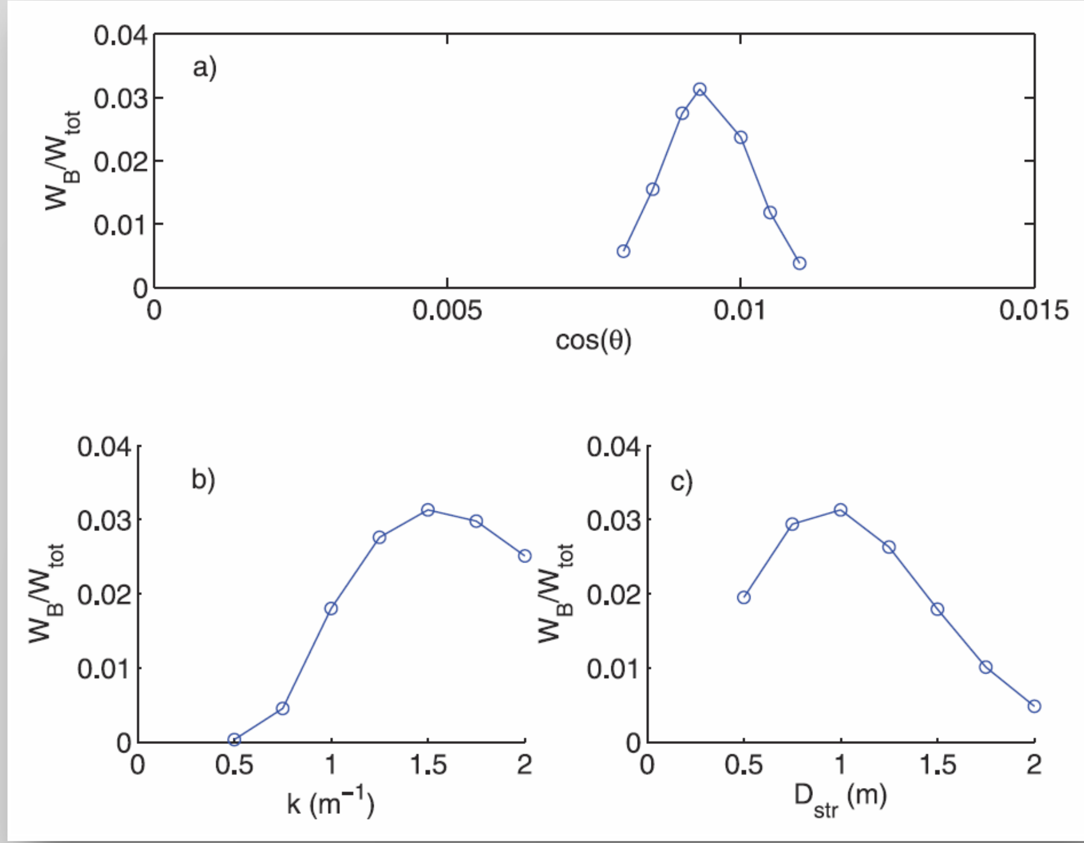


Eliasson and Papadopoulos [2008]

Benchmarking (continue)



My code



Eliasson and Papadopoulos [2008]

Whistlers at LH harmonic

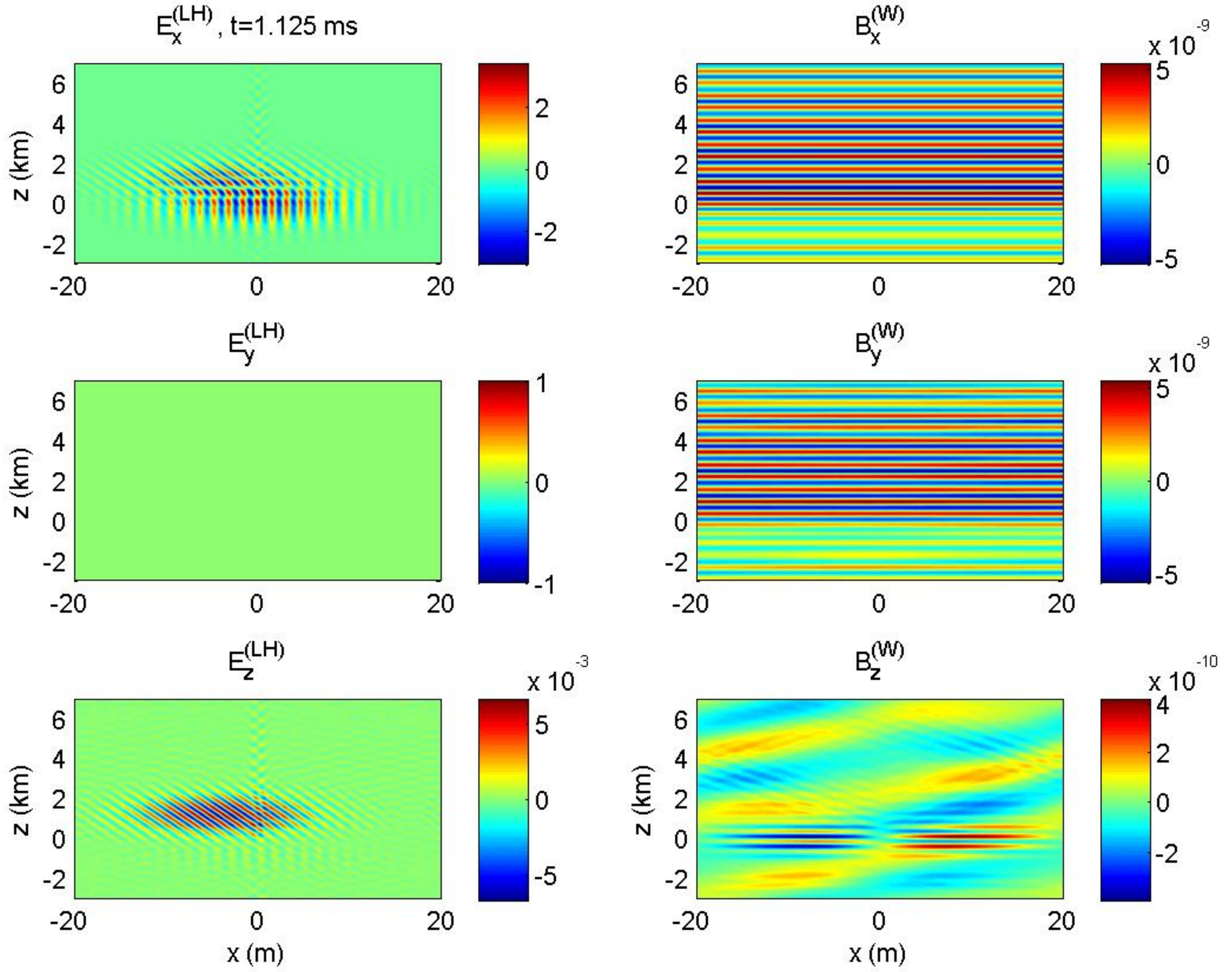
- Consider two oppositely traveling LH waves, one slightly oblique and one perpendicular to the magnetic field, with electric fields $E_1 \sim \exp\left(ik_{\perp,LH}y + ik_{\parallel,LH}z - i\omega_{LH}t\right)$ and $E_2 \sim \exp\left(-ik_{\perp,LH}y - i\omega_{LH}t\right)$, respectively.

- A nonlinear "beating" of these two waves gives $E_3 \sim E_1 E_2 \sim \exp\left(ik_{\parallel,LH}z - i2\omega_{LH}t\right)$, which can mode convert to parallel whistlers if $\omega_w = 2\omega_{LH}$ and $k_{\parallel,w} = k_{\parallel,LH}$.

- This suggests that a nonlinear interaction of LH waves can generate whistlers at twice the LH frequency, as observed in the DEMETER data

Simulation snapshot (with nonlinear coupling included)

LH electric field wave packet



Whistler magnetic field

References

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