EXCITATION OF THE MAGNETOSPHERIC RESONANCES

Anatoly V. Streltsov[1,2]

[1]Embry-Riddle Aeronautical University, Daytona Beach, FL, USA

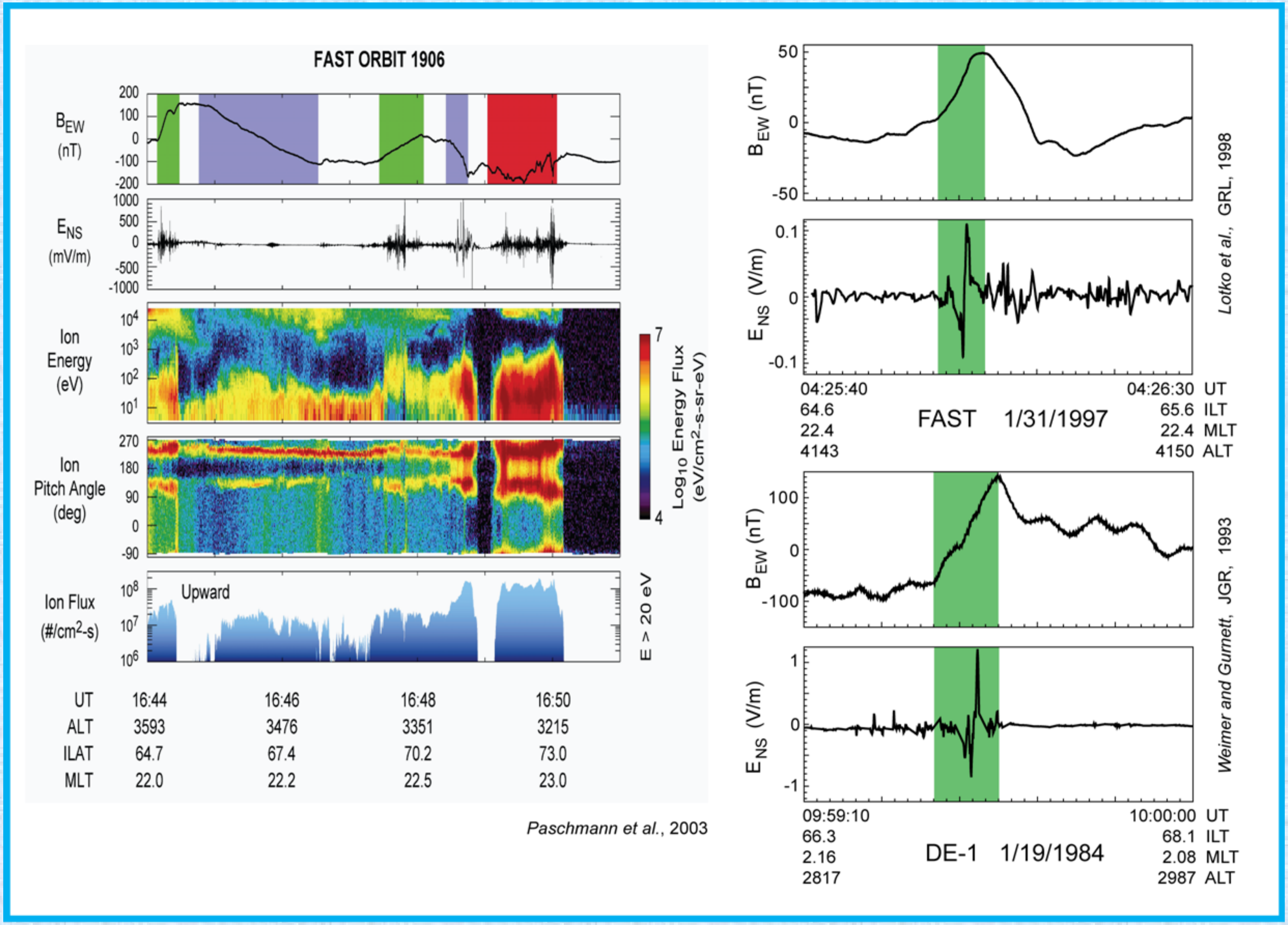
[2]Air Force Research Laboratory, RVBXC, Albuquerque, NM, USA

ULF Waves in the Magnetosphere

- Frequency is less than the ion cyclotron frequency (<30 Hz)
- Three ULF modes are:
  - a) fast (or compressible) waves
  - b) intermediate (or shear Alfven) waves
  - c) slow (or ion-acoustic) waves
- We focus on shear Alfven waves because they carry magnetic field-aligned currents (FACs), which can precipitate particle into the ionosphere, heat the ionospheric plasma, and cause density irregularities at low latitudes.
- Alfven waves propagate mostly along the ambient magnetic field and they can be trapped and amplified inside the magnetospheric resonator.

ULF waves observed by satellites in the magnetosphere.

DE-1 and FAST



Generation of ULF waves

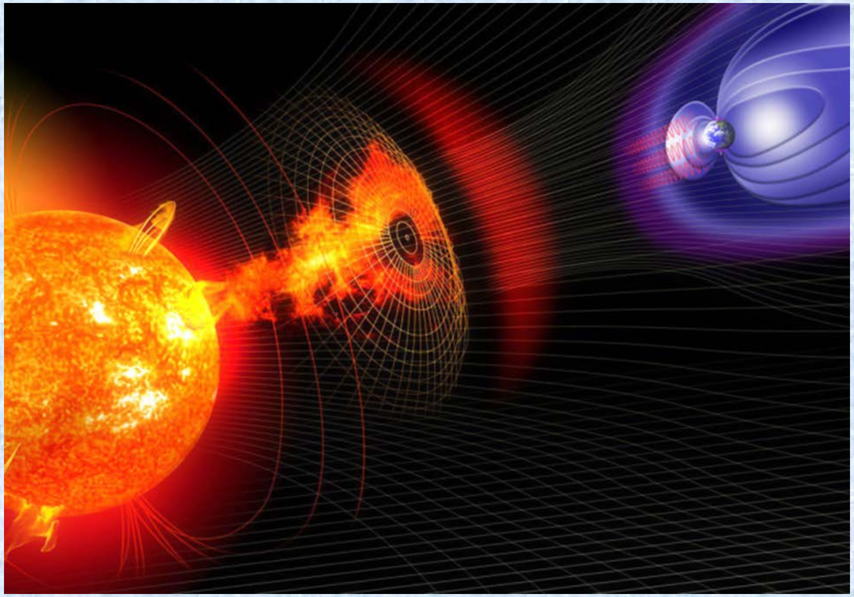
Natural

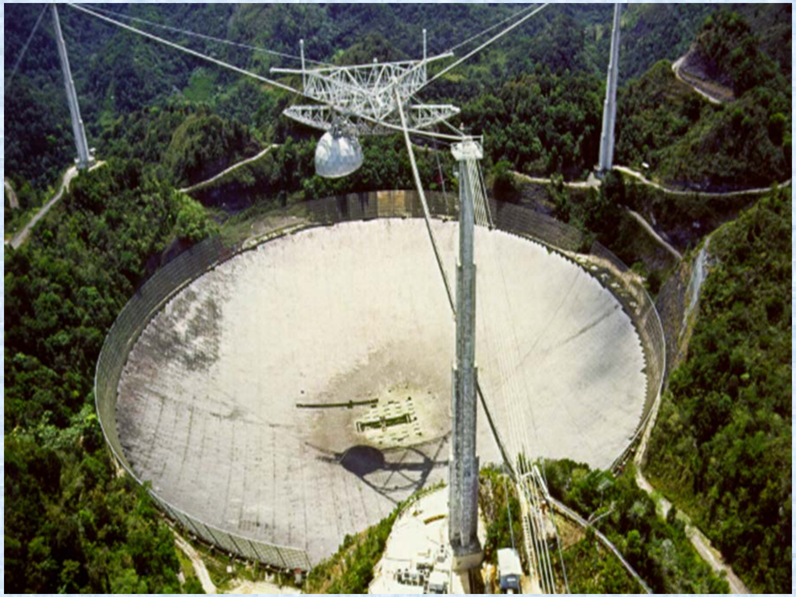
- Storms
- Substorms

Artificial

- Active Experiments

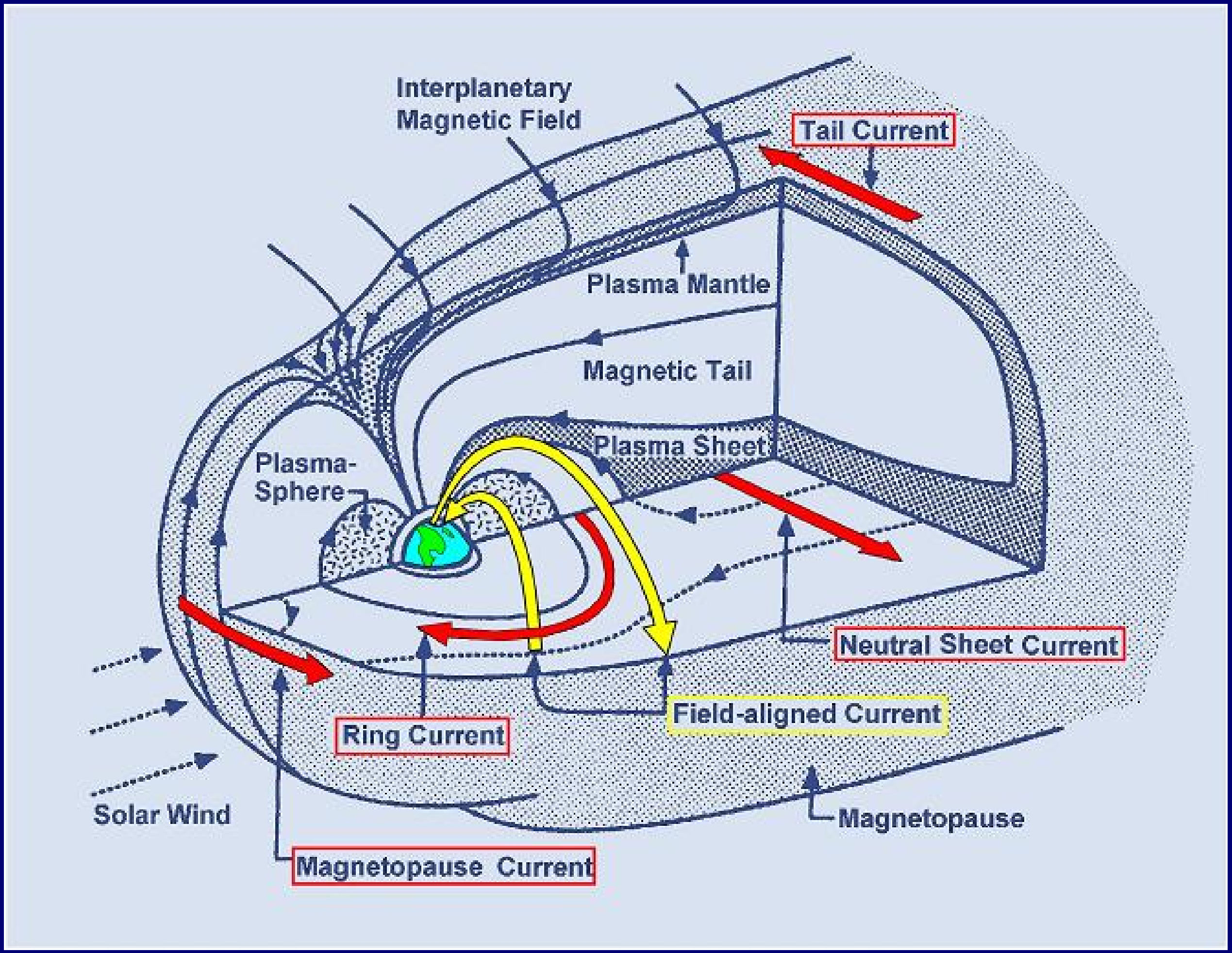
(for example, Arecibo)





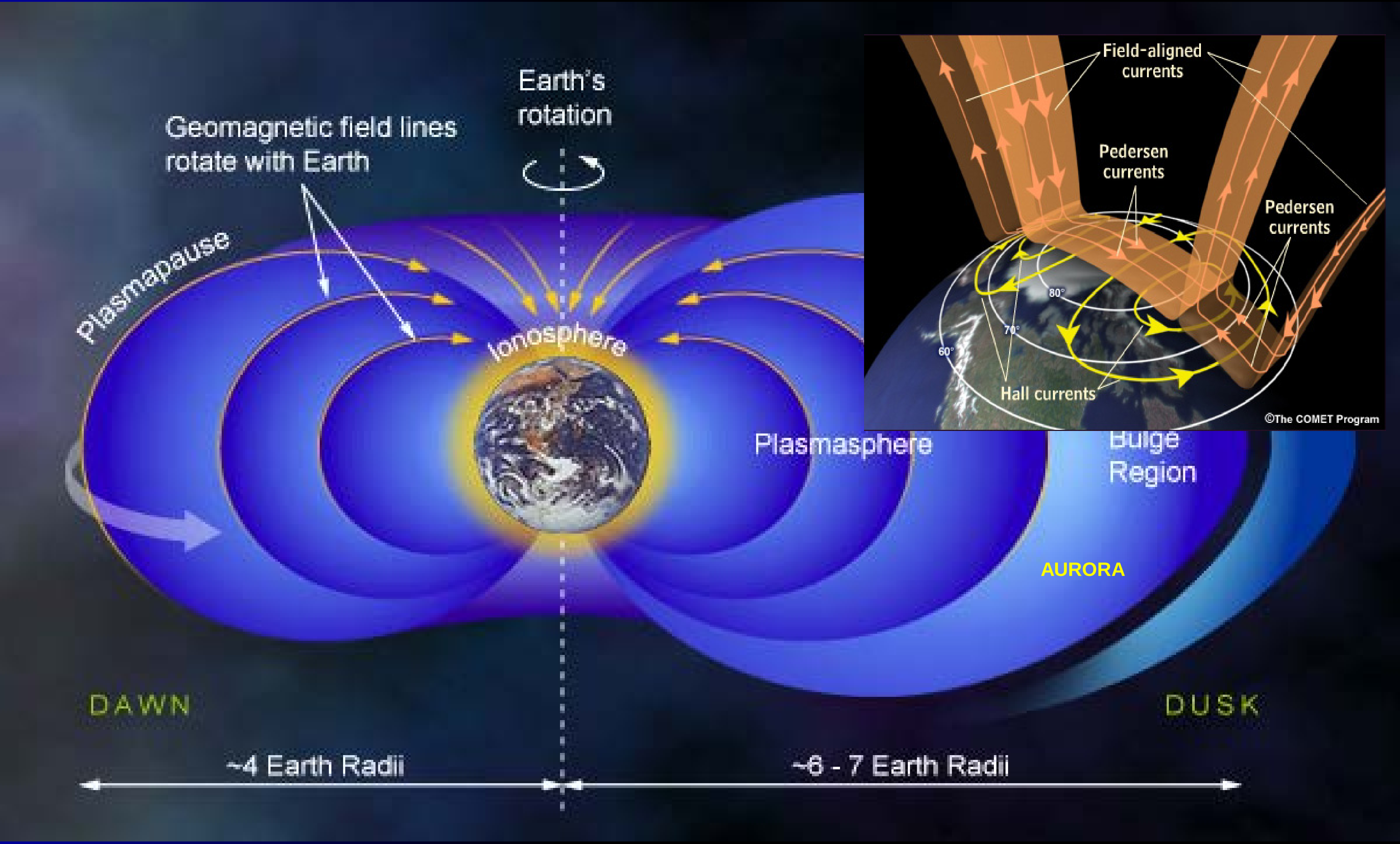
Artificial Generation of ULF waves.

To generate these waves we need a very big antenna.
Let's consider the magnetospheric current system…

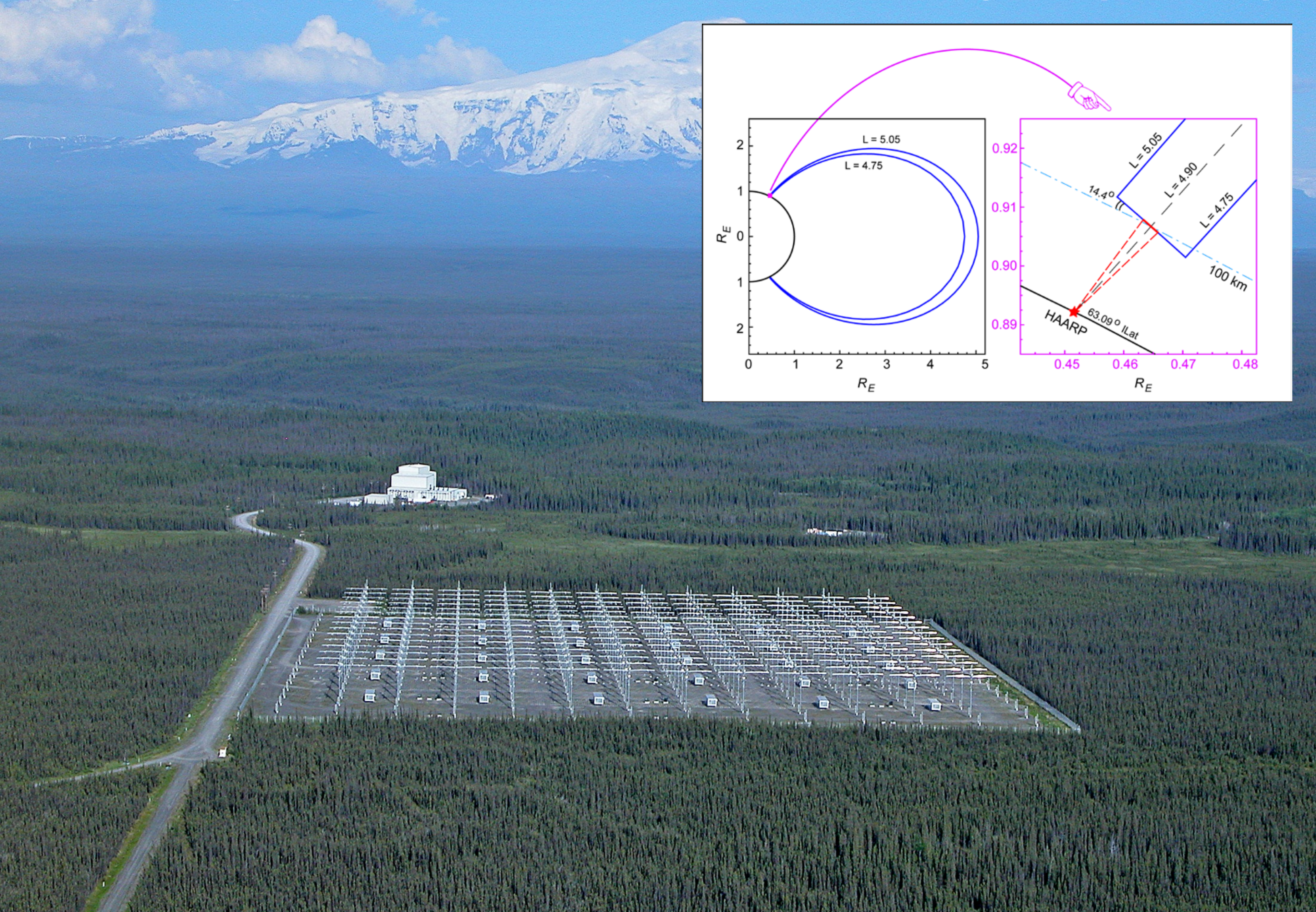


adapted from Kivelson and Russel [1995]

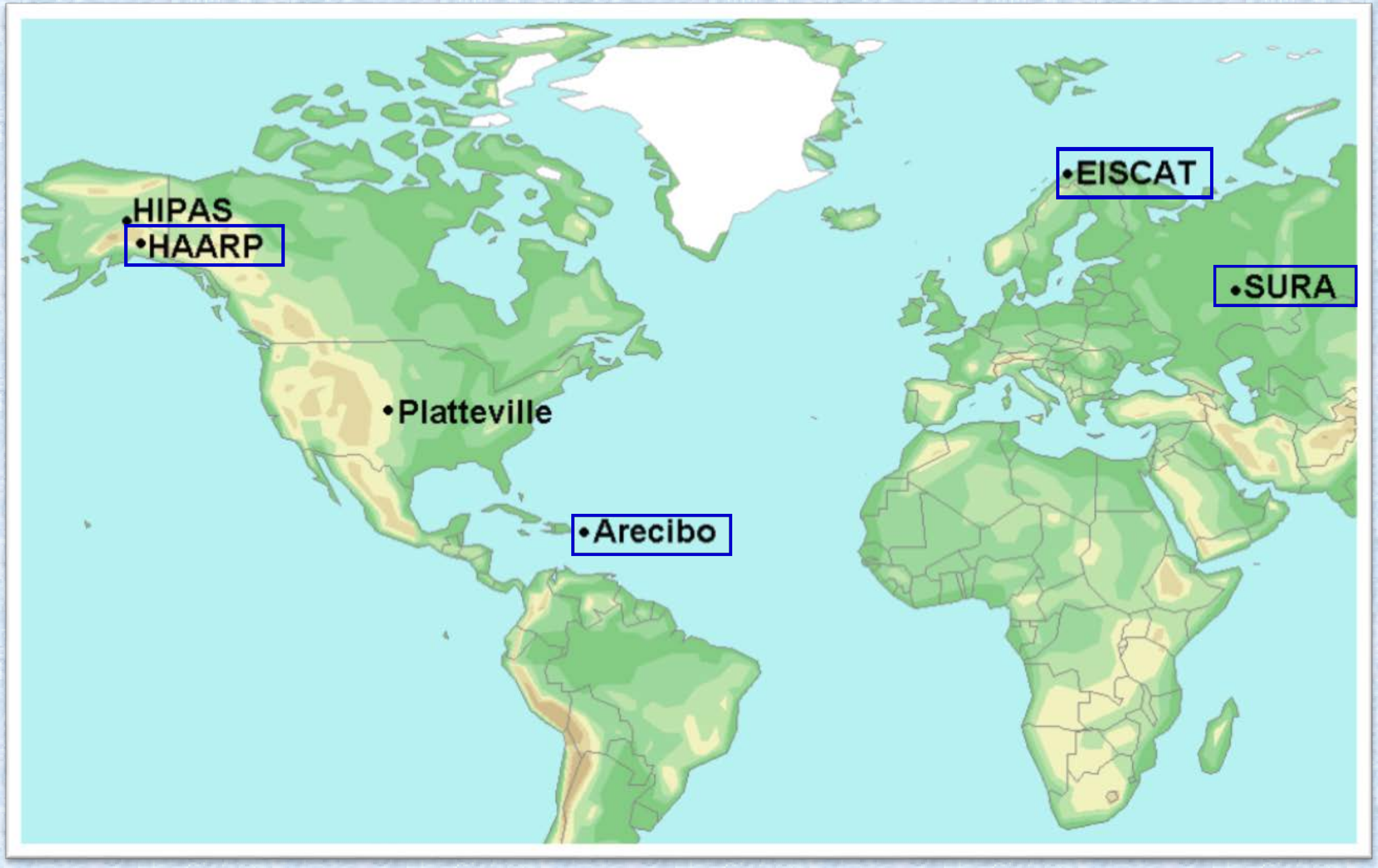
Magnetosphere-Ionosphere System



High Frequency Active Auroral Research Program (HAARP)



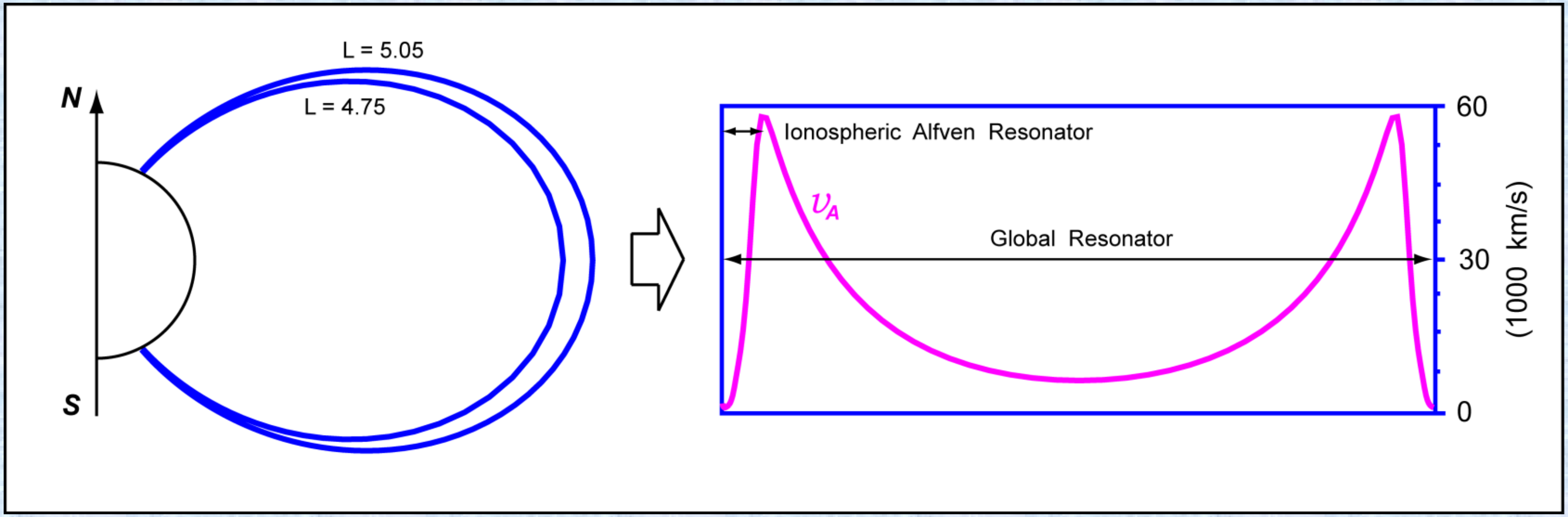
Active Experiment Facilities



Amplification of ULF waves in the magnetospheric resonators

1) Global Magnetospheric Resonator (FLR) , frequency 0.001 – 0.010 Hz

2) Ionospheric Alfven Resonator (IAR), frequency 0.1 – 10.0 Hz



Mechanism of the wave generation is changing of the ionospheric conductivity with HF waves when the electric field exists in the ionosphere. **The frequency of the heater should match the eigenfrequency of the resonator !**

Magnetospheric Resonator

1) Classical approach: The eigenfrequencies of the resonator are defined by the parameters of the magnetosphere only (namely, by the length of the magnetic field line and Alfven speed along it).

In reality, the eigenfrequencies of the resonator also depend on the parameters of the ionosphere (conductivity).

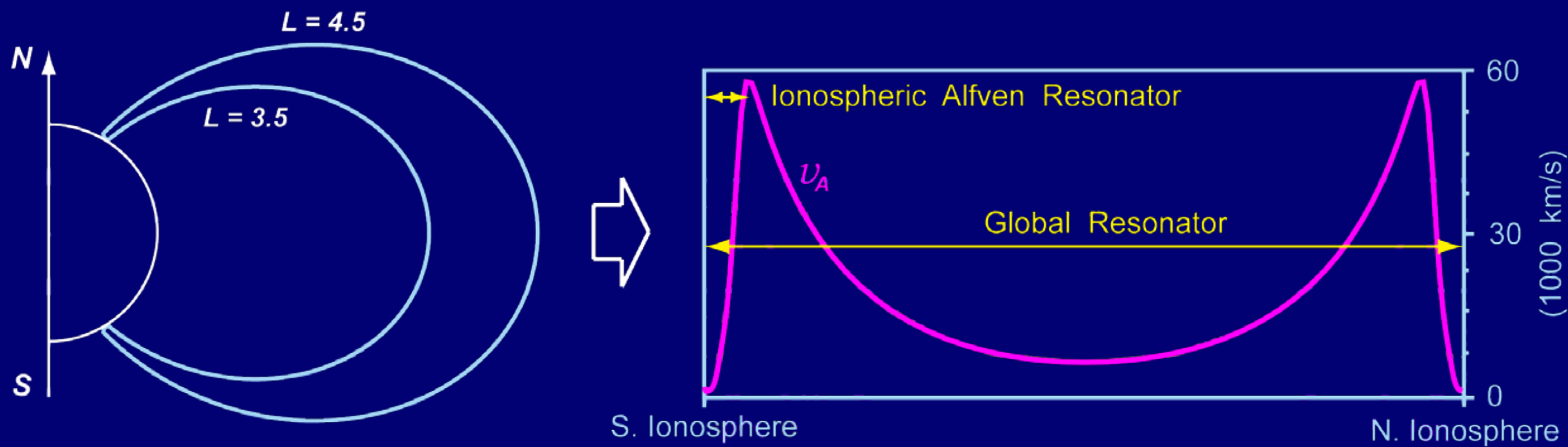
2) “New” approach: The eigenfrequencies of the resonator are ***mostly*** defined by the parameters of the ionosphere (electric field, ion mobility/temperature, and plasma density).

Ionospheric Feedback Mechanism (IFM)

$$\nabla\cdot(\Sigma_P \mathbf{E}_\perp) = -j_\parallel, \quad \text{where} \quad \Sigma_P \propto n$$

$$\frac{\partial n}{\partial t} = \frac{j_\parallel}{eh} + \alpha\,(n_0^2 - n^2)$$

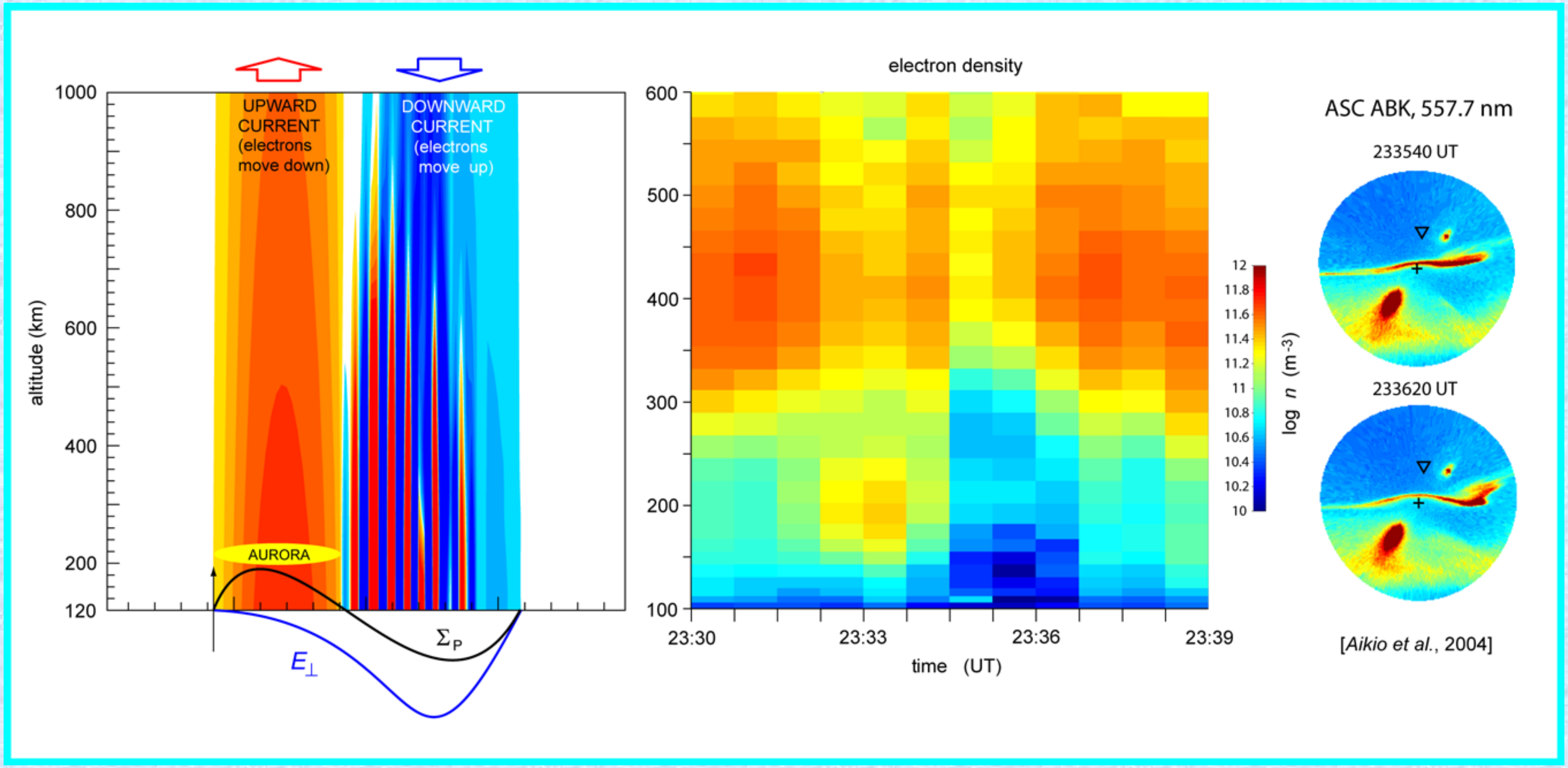
IFM + $E_\perp$ + cavity = Ionospheric Feedback Instability (IFI)



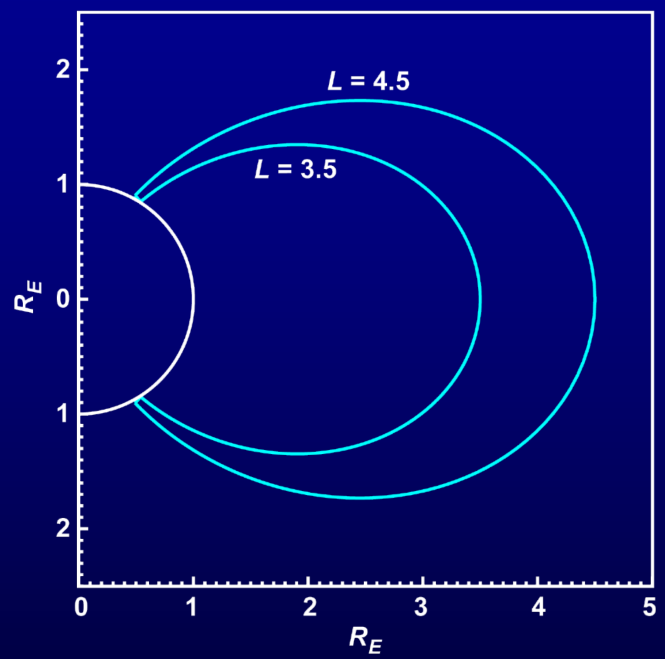
IFI growth rate is large when in the ionosphere

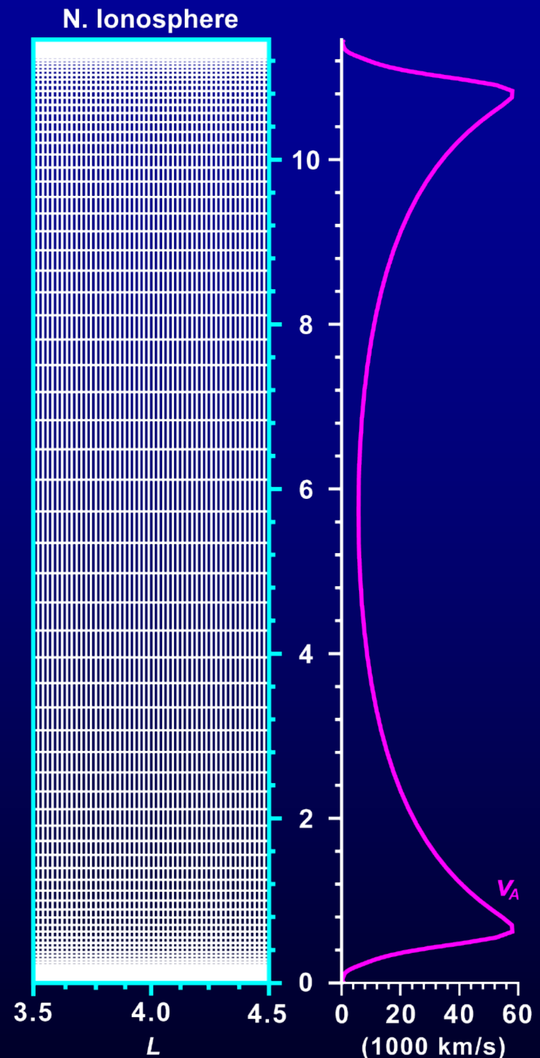
Σ_P is small, $E_\perp$ is large and $k_\perp$ is large

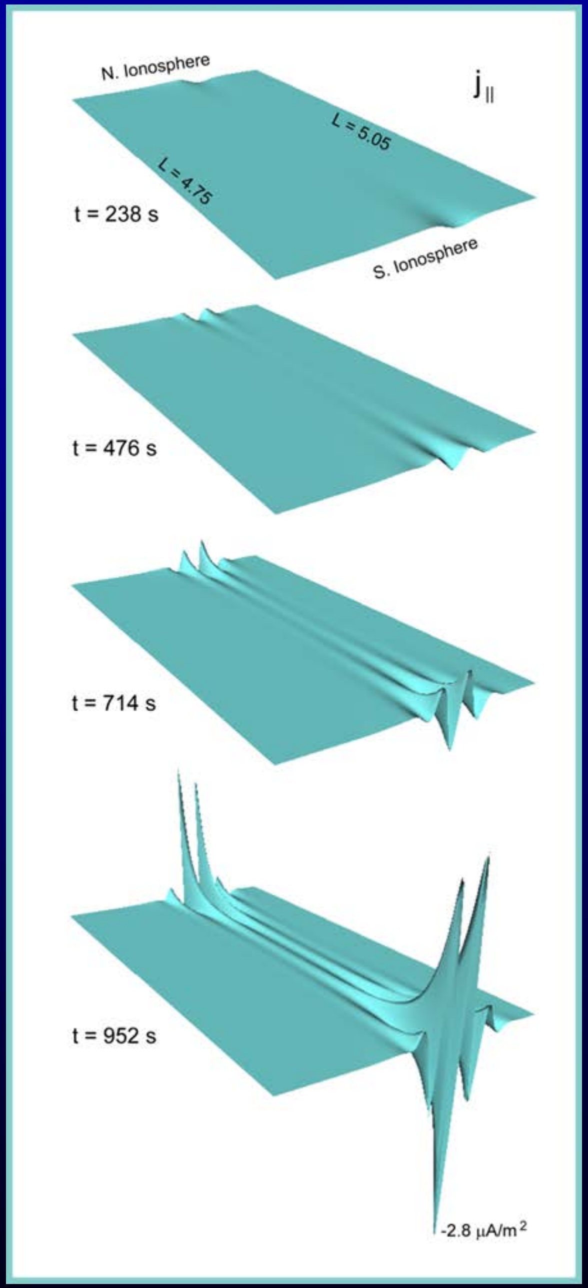
Interaction of ULF FACs with the Ionosphere



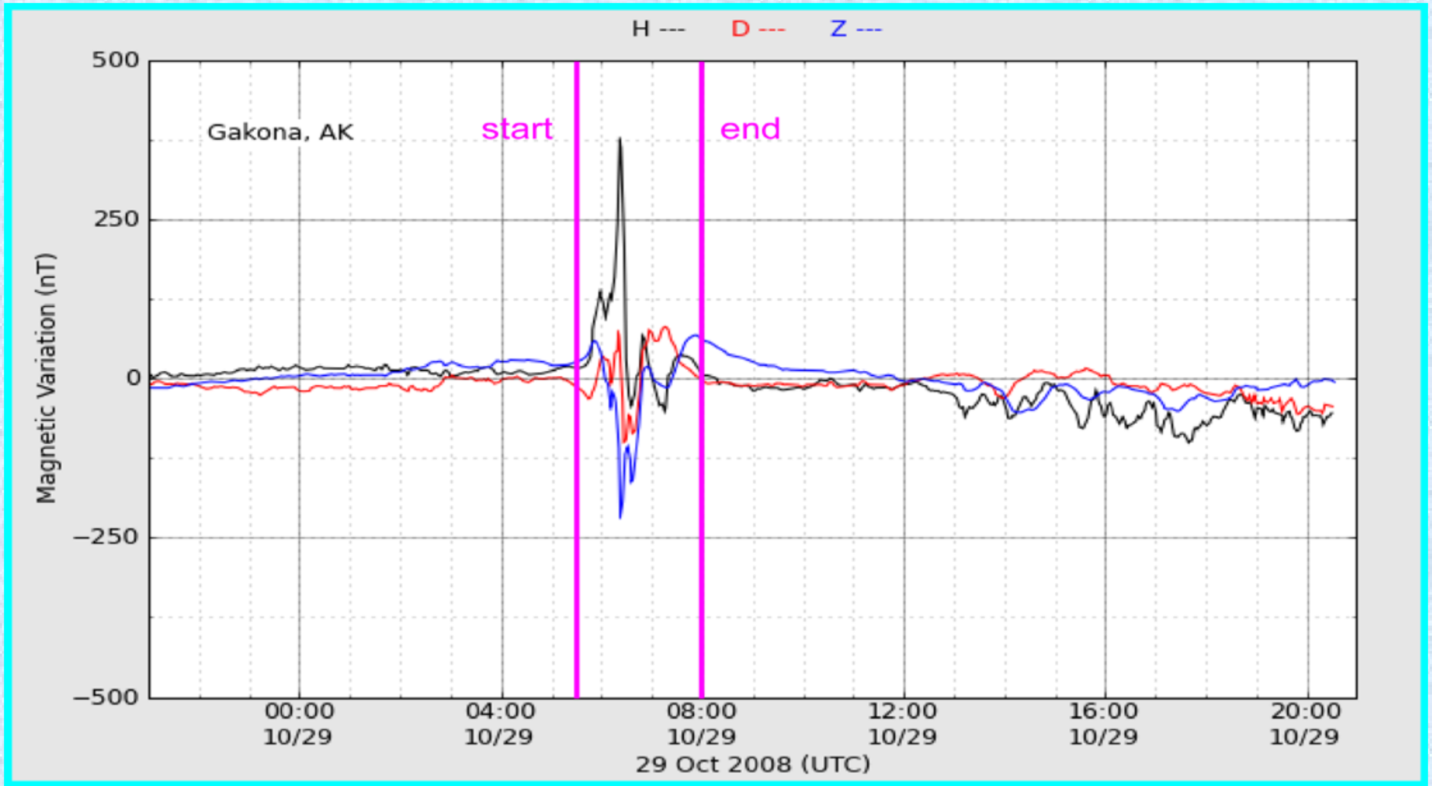
SIMULATIONS

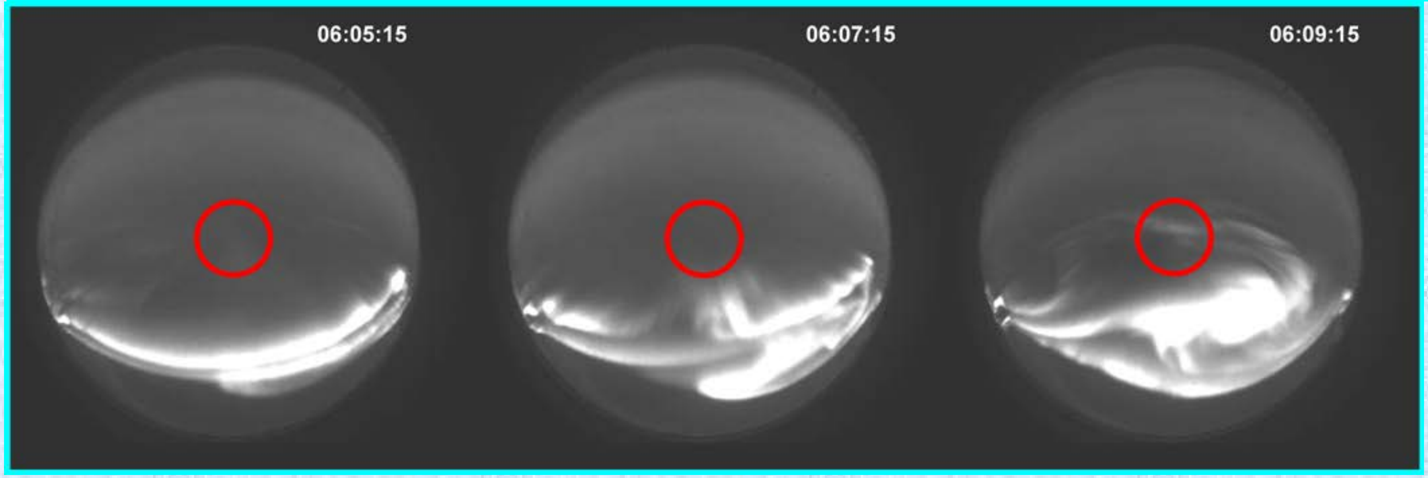




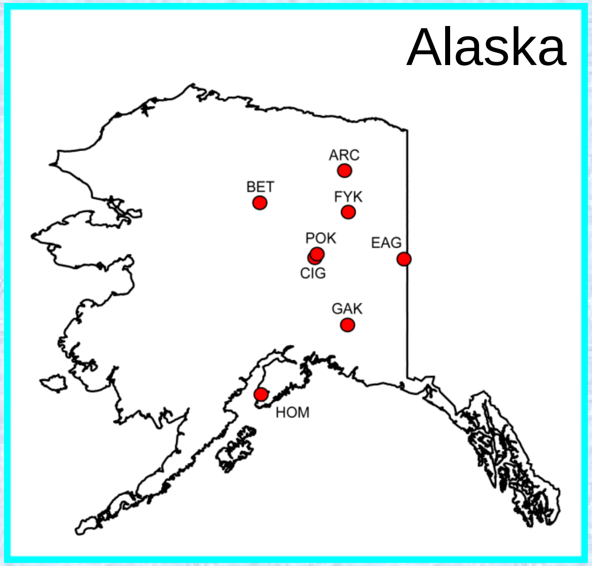


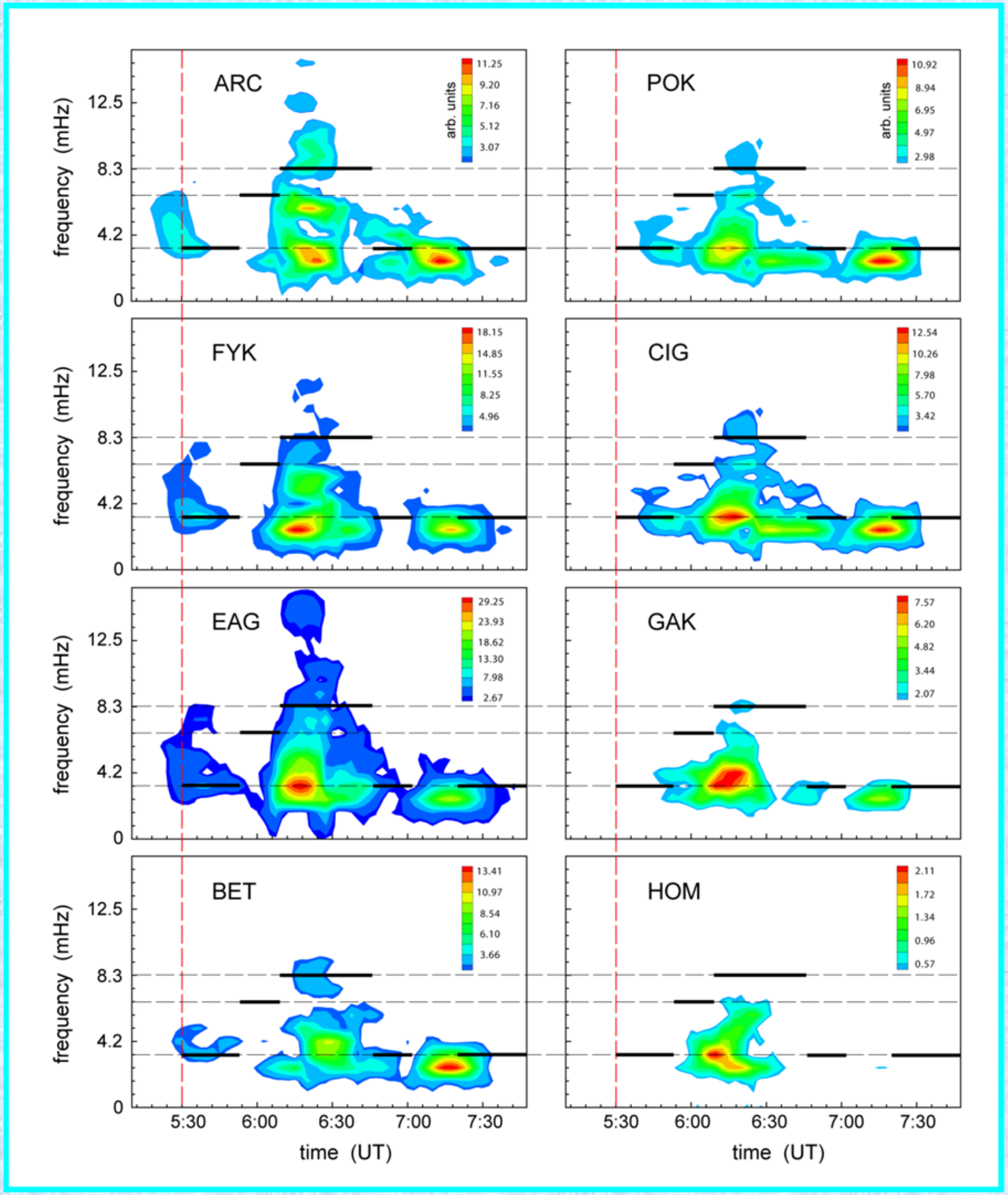
HAARP Experiment on 29 October 2008



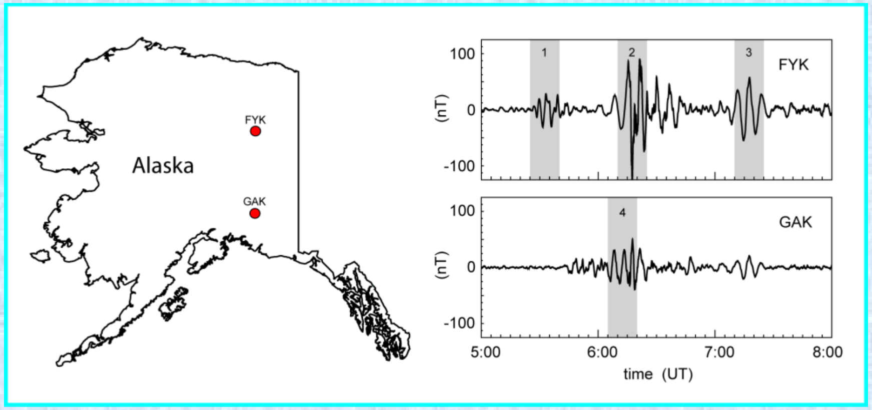


UAF/GI Magnetometer Array (MAGI)

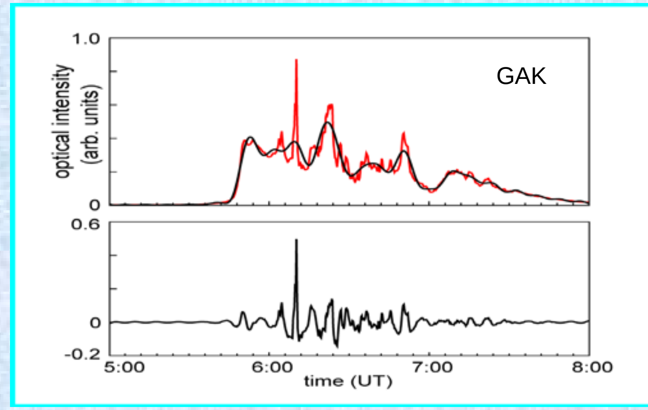


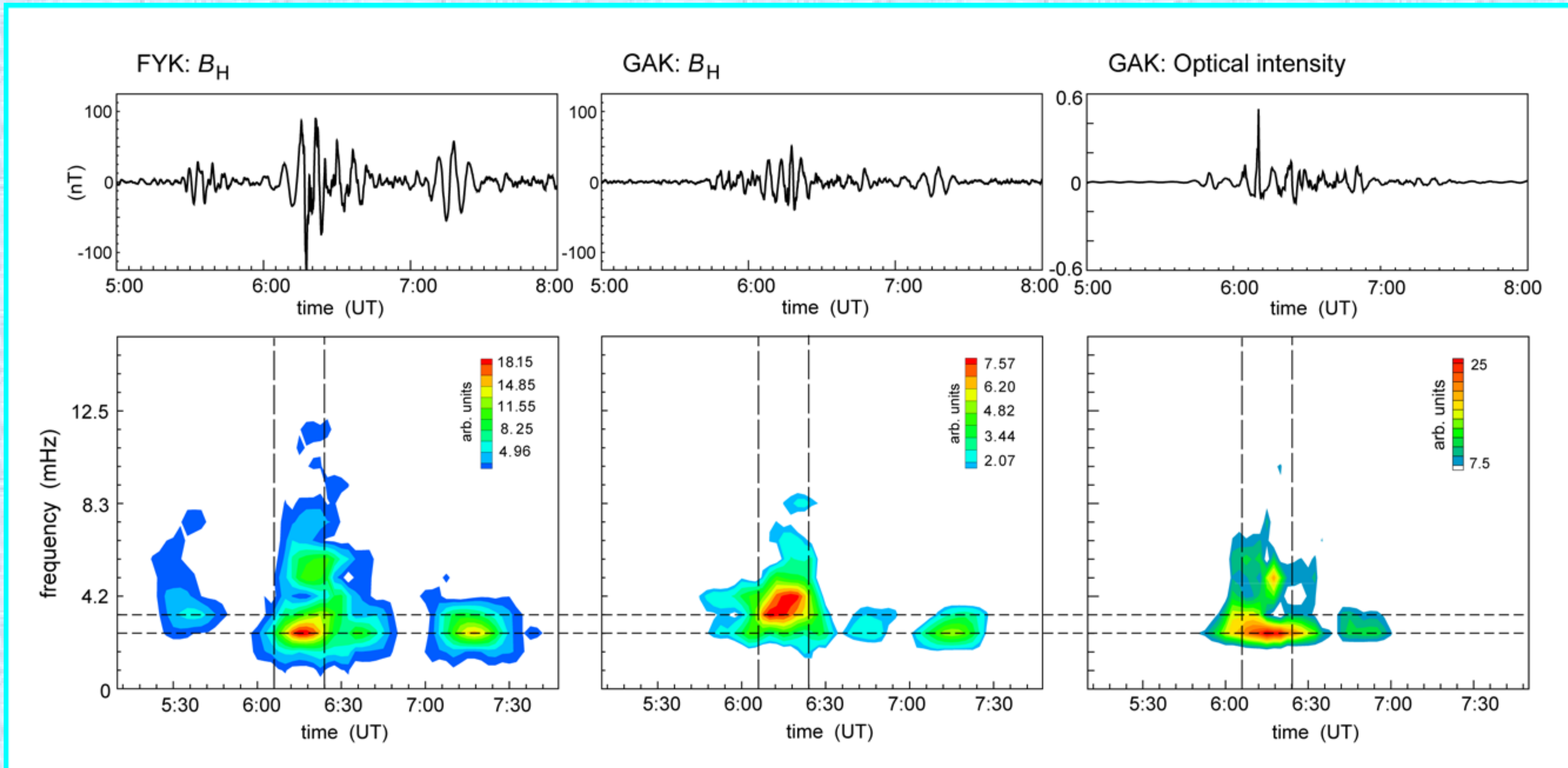


Magnetometers

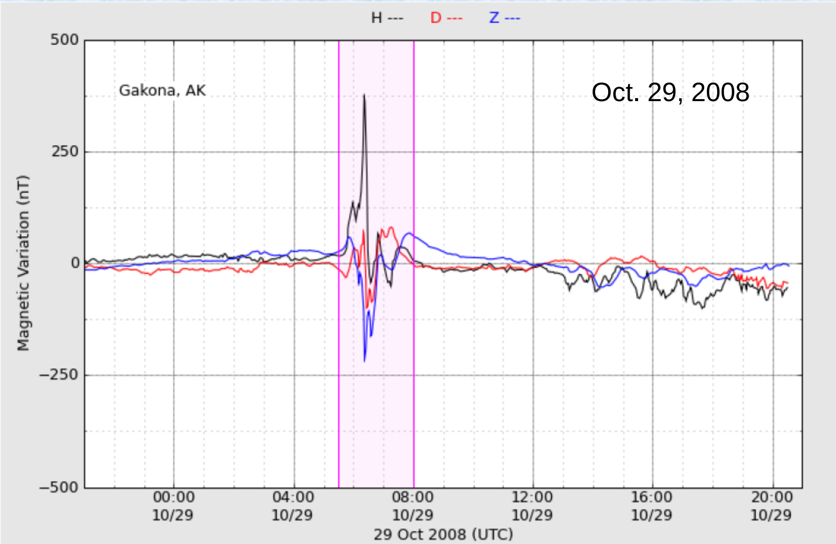


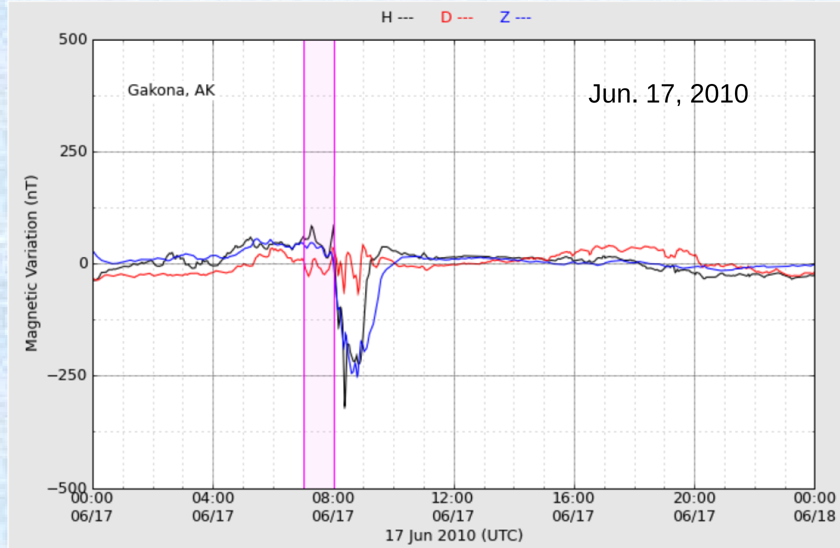
Imager

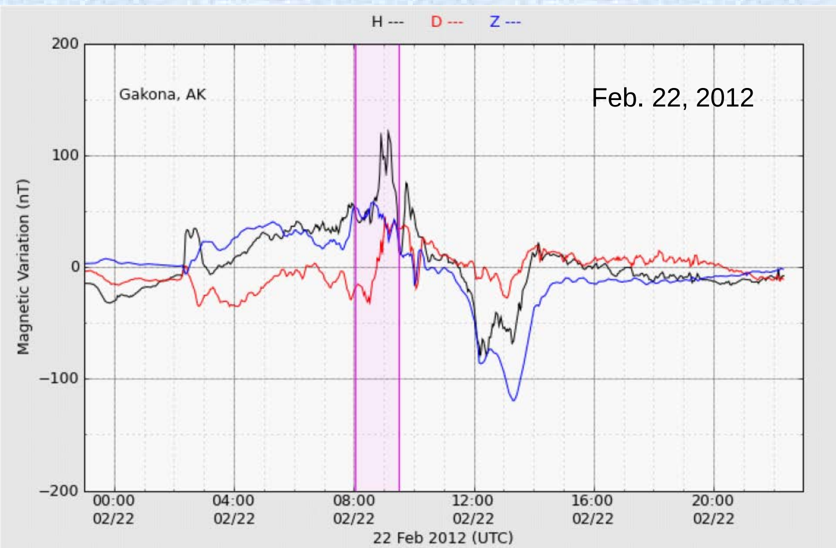


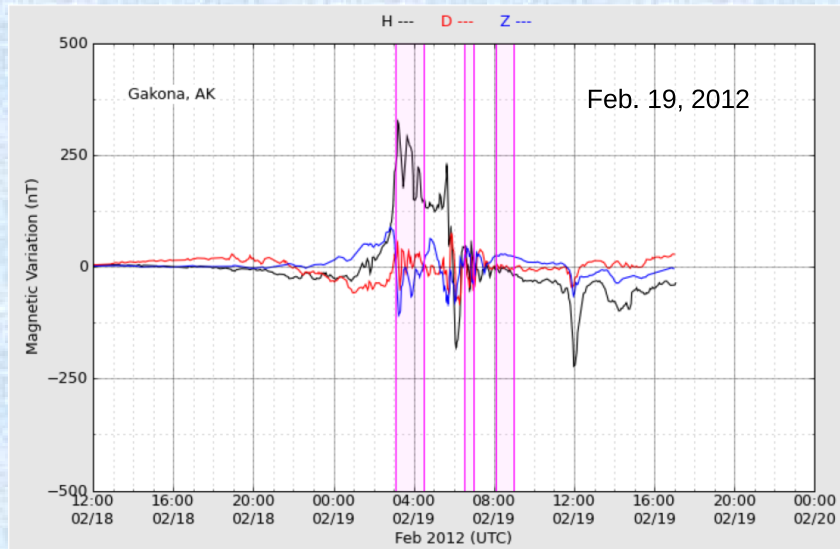


HAARP-triggered large-amplitude waves



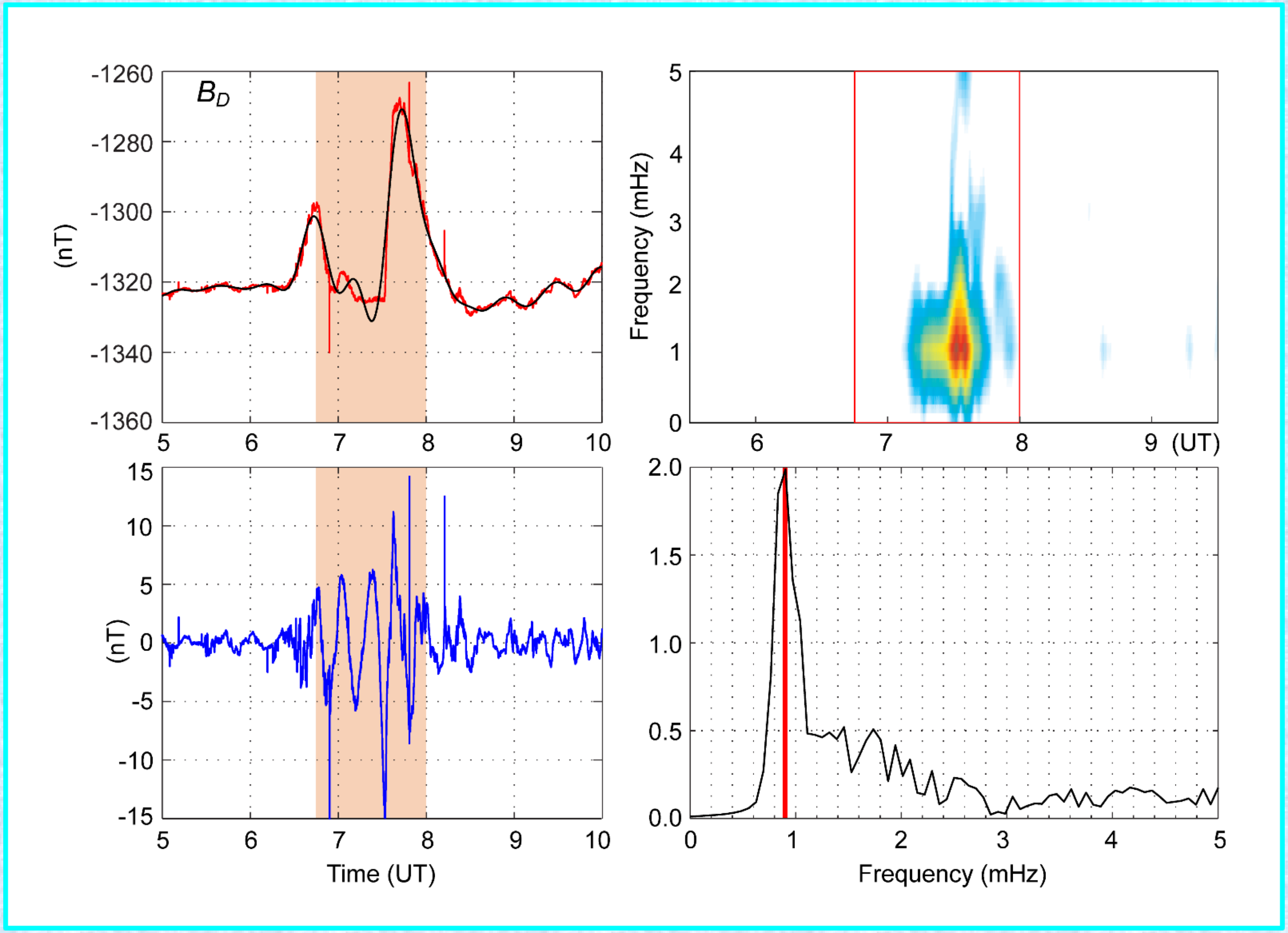




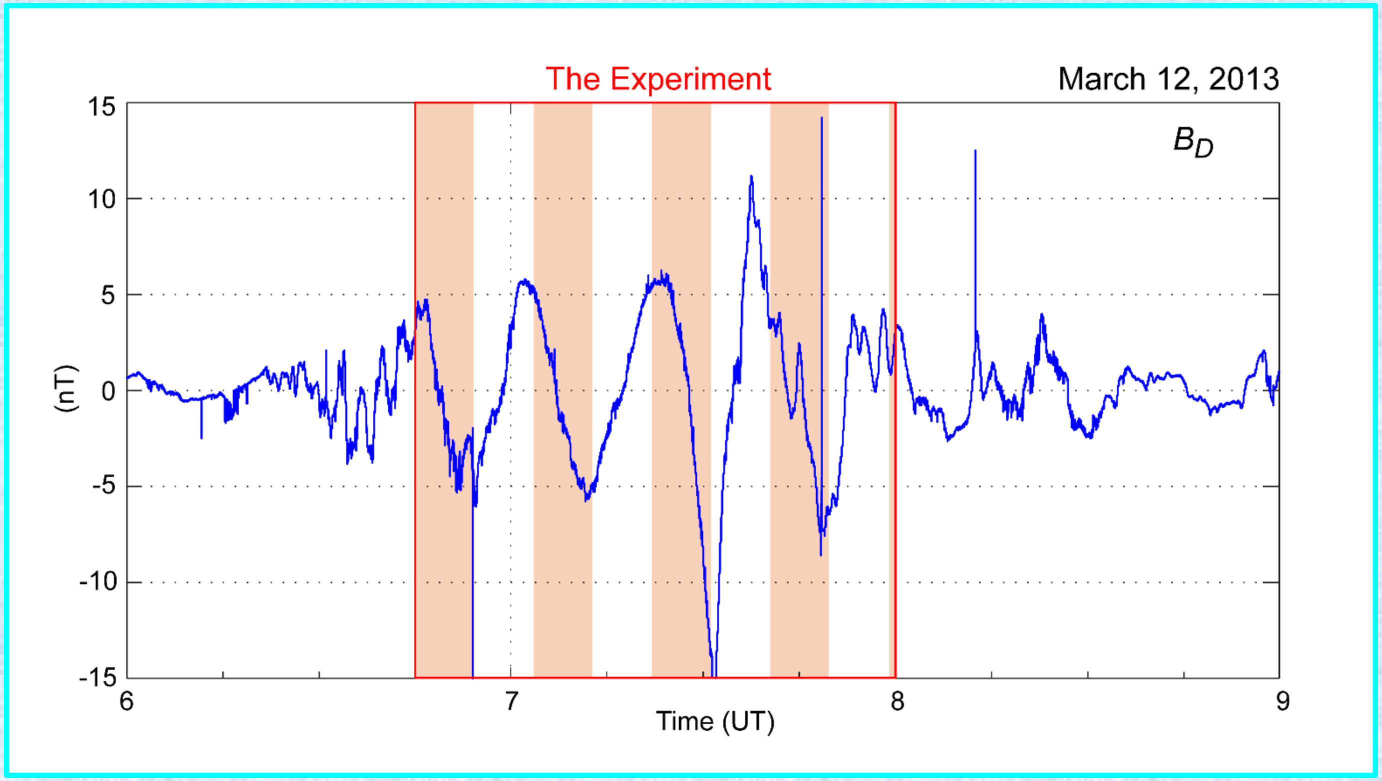


ULF Waves and Artificial Aurora

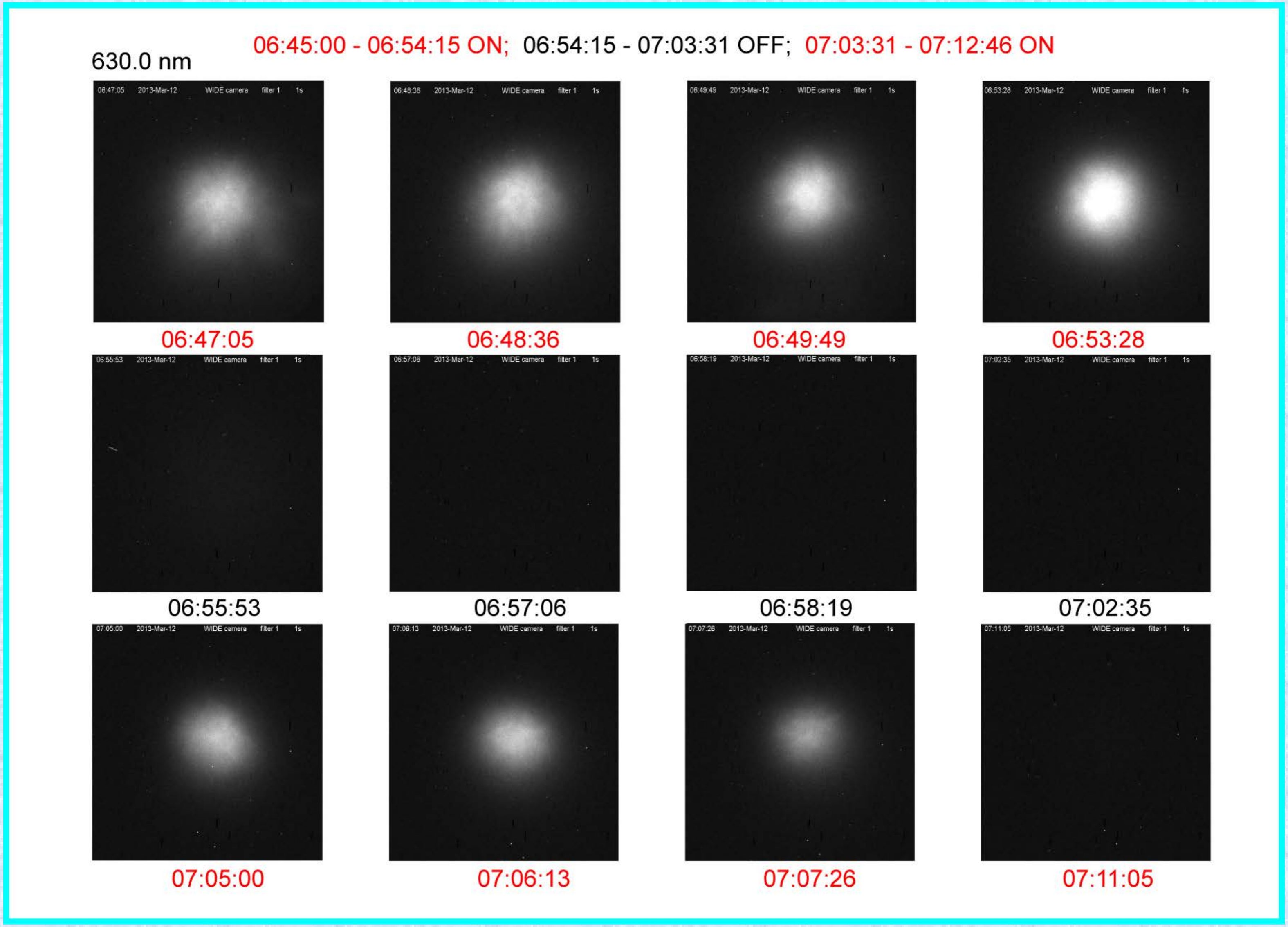
HAARP Experiment on 12 March 2013



HAARP Experiment on 12 March 2013

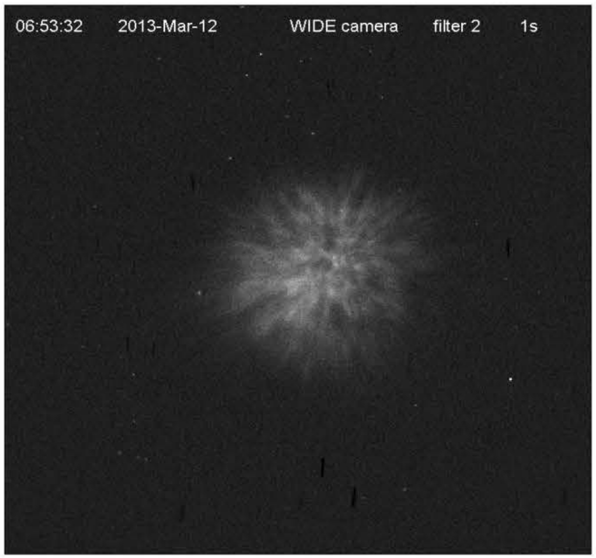


HAARP Experiment on 12 March 2013



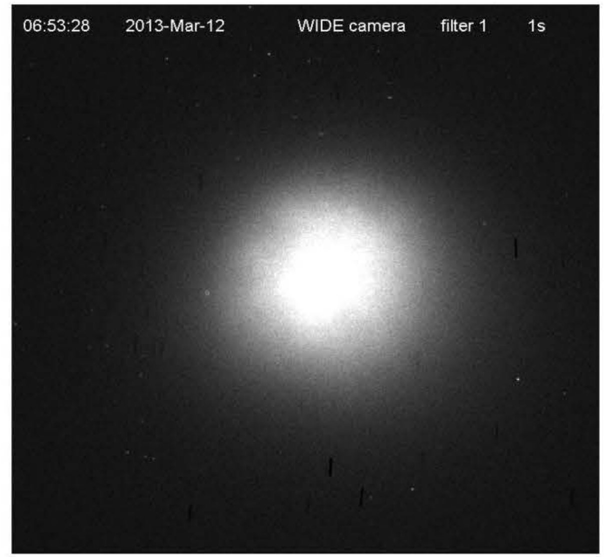
HAARP Experiment on 12 March 2013

555.7 nm



06:53:32

630.0 nm

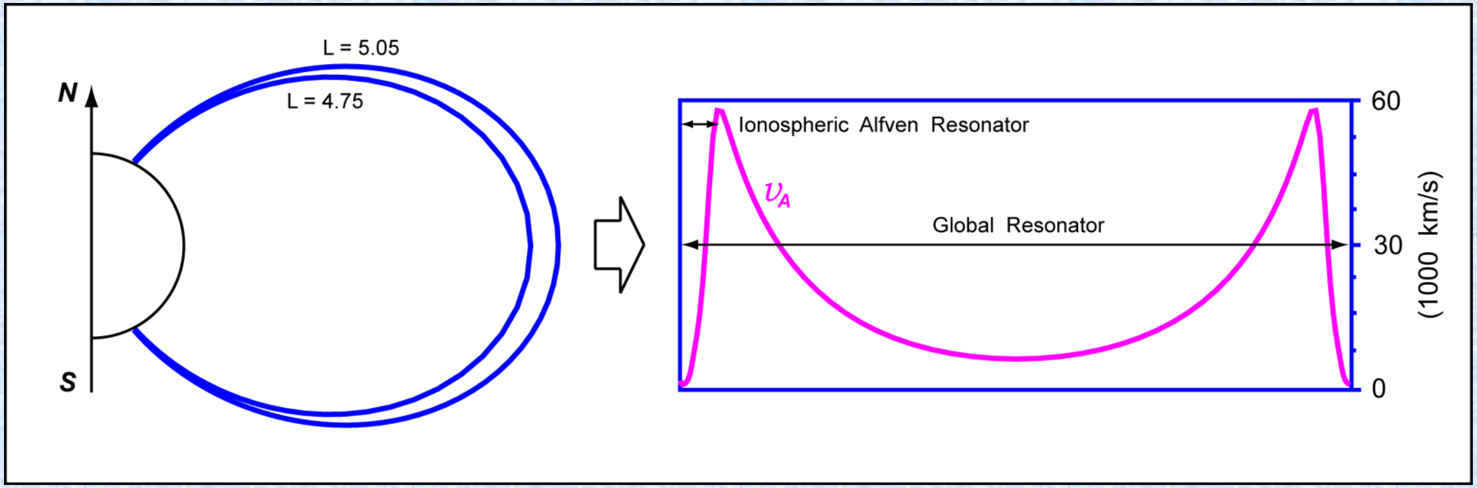


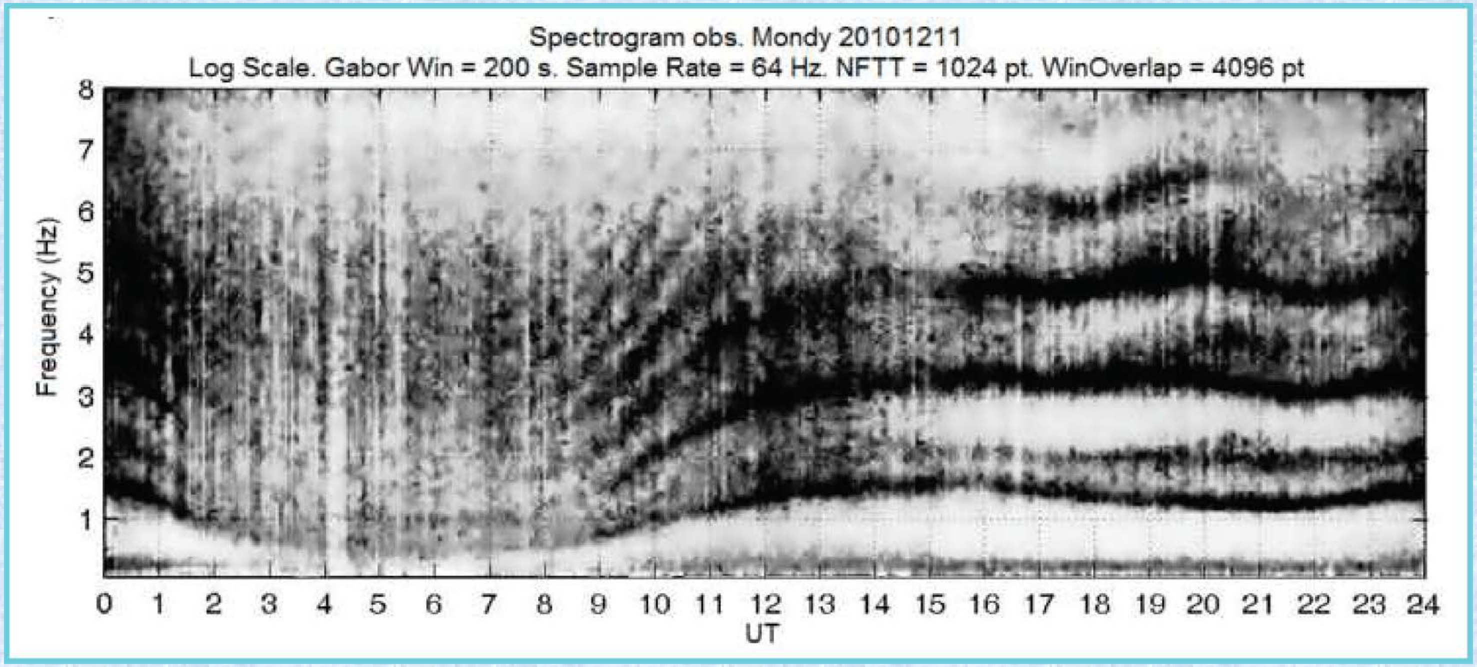
06:53:28

FLR Conclusions:

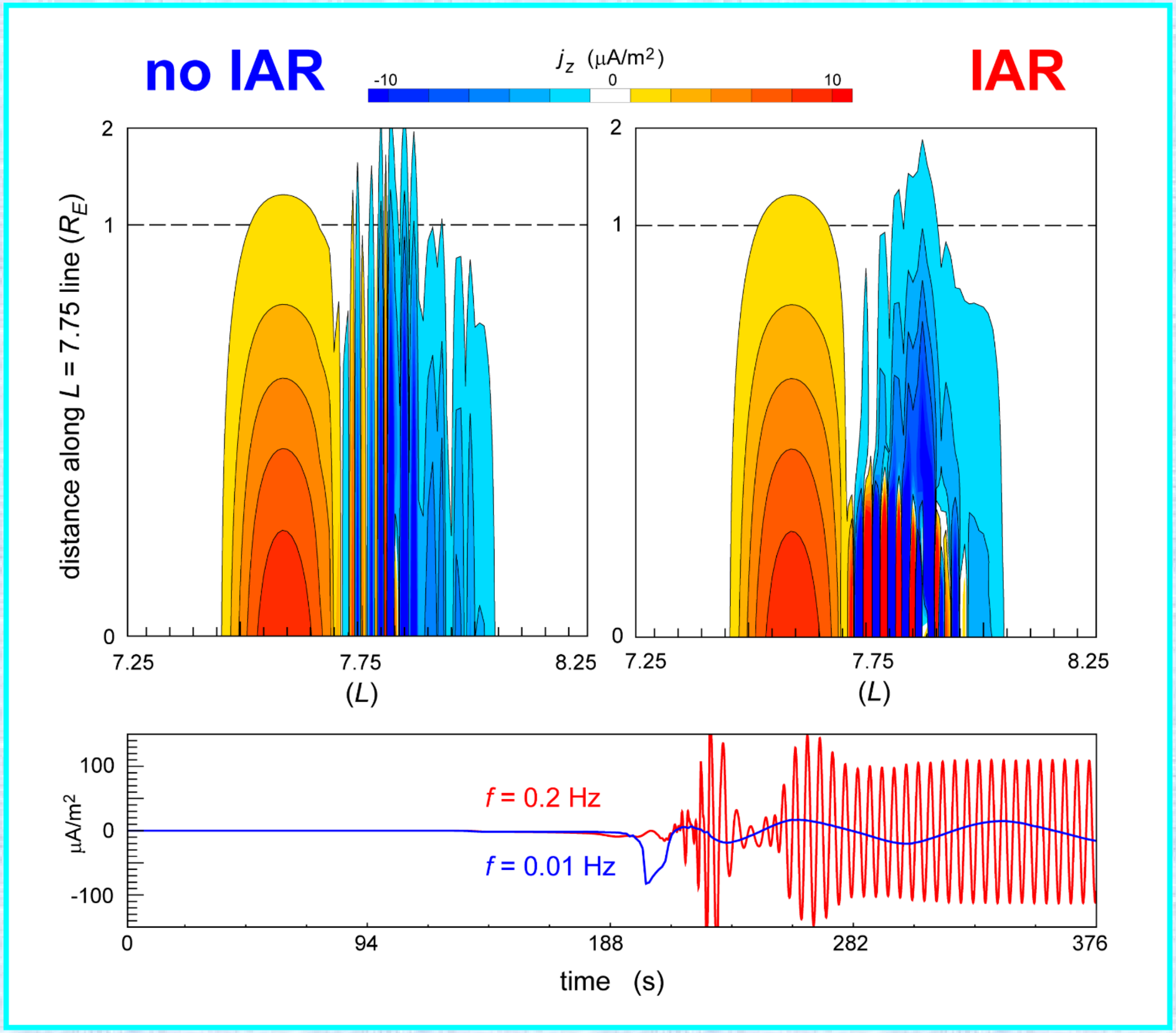
- Large-amplitude shear Alfven waves can be generated in the earth magnetosphere by the natural drivers (e.g., solar wind) and their frequencies will be defined by the frequency of the driver and parameters of the magnetosphere.
- The waves also can be generated by artificial drivers (e.g., ionospheric heating). To reach large amplitude these waves needs to be amplified inside the magnetospheric resonator and utilize energy stored in the ionosphere, using, for example, the ionospheric feedback mechanism. In this case, the ionosphere will influence the frequency of the resonant waves.
- In general, the ionospheric feedback mechanism, or the ionosphere itself, should affect frequencies and amplitude of ULF waves generated by the artificial and natural drivers.

Ionospheric Alfven Resonator

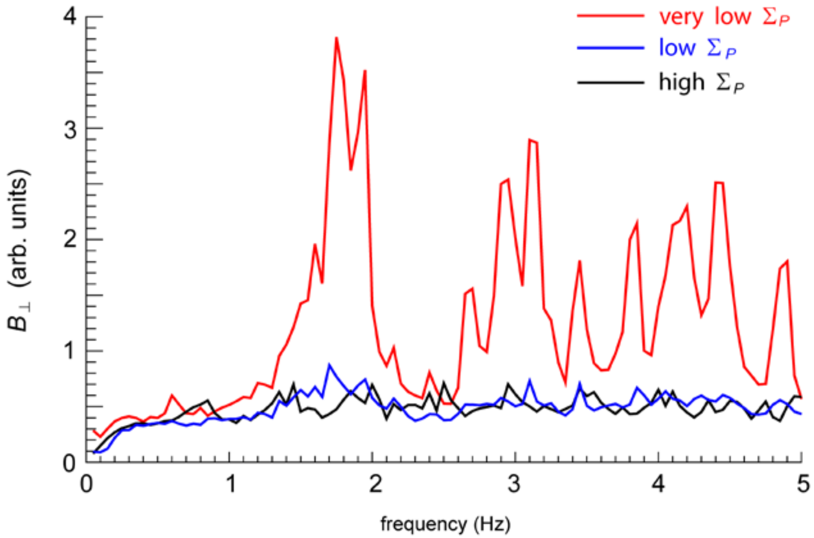


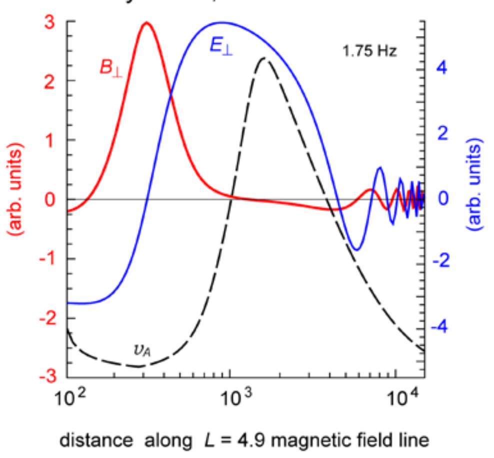


Ionospheric Alfvén Resonator



IAR without IFI





Wave reflection from the ionosphere:

$$E_{\perp r} = R\, E_{\perp i}$$

$$R = \frac{\Sigma_A - \Sigma_P}{\Sigma_A + \Sigma_P}$$

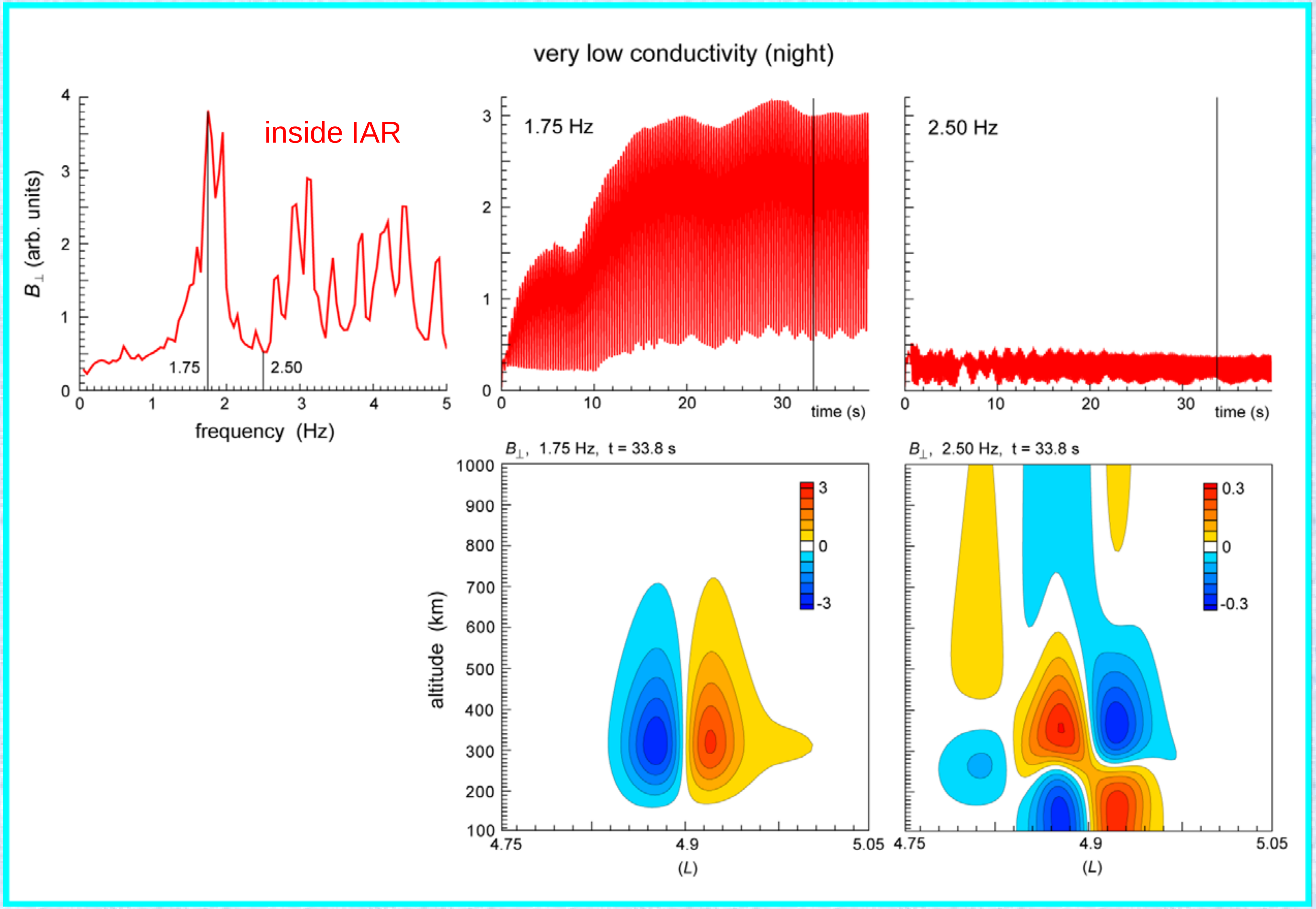
$$\Sigma_A = 1/\mu_0 v_A$$

high Σ_P: **R = -0.310**

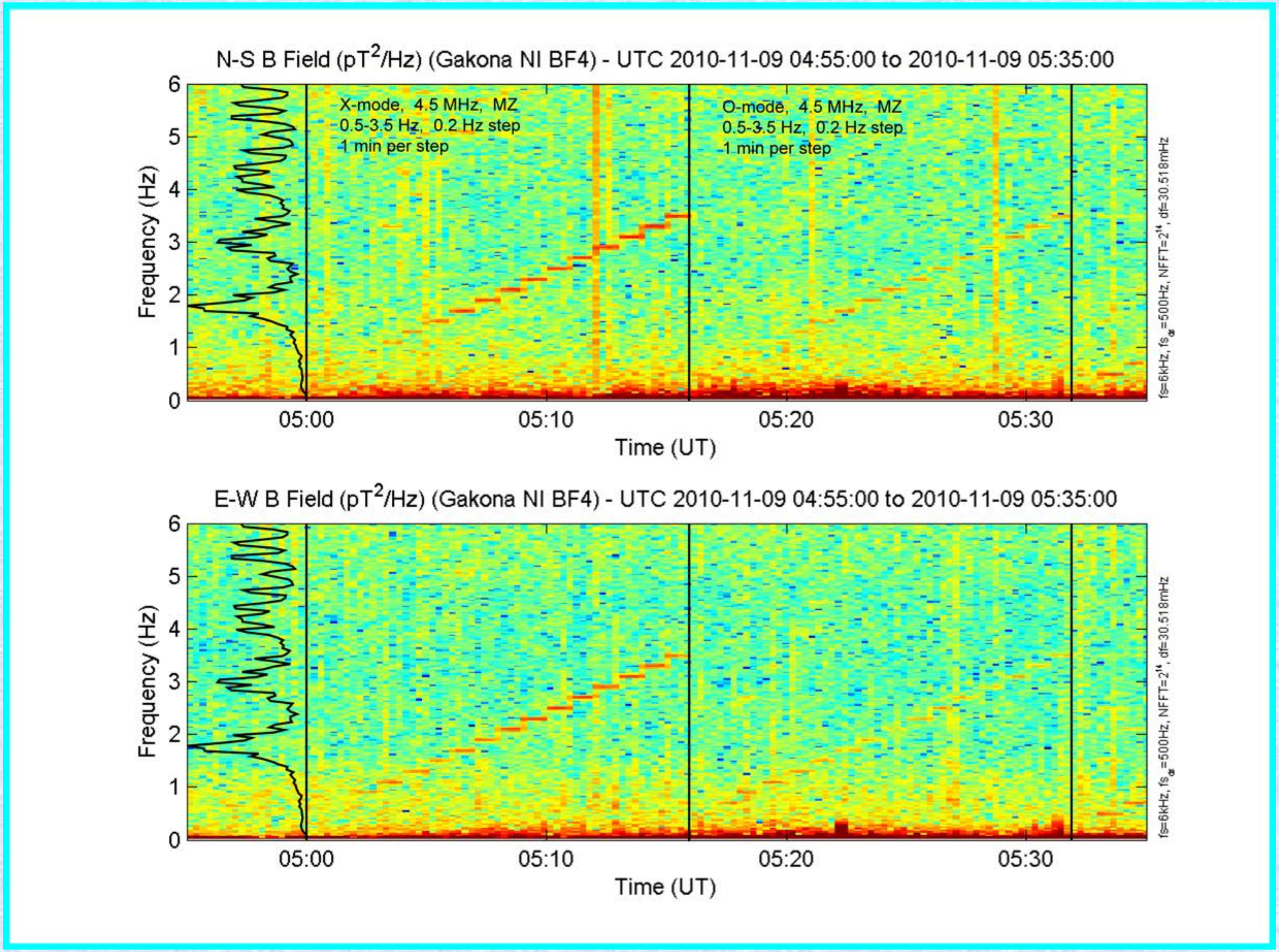
low Σ_P: **R = 0.032**

very low Σ_P: **R = 0.510**

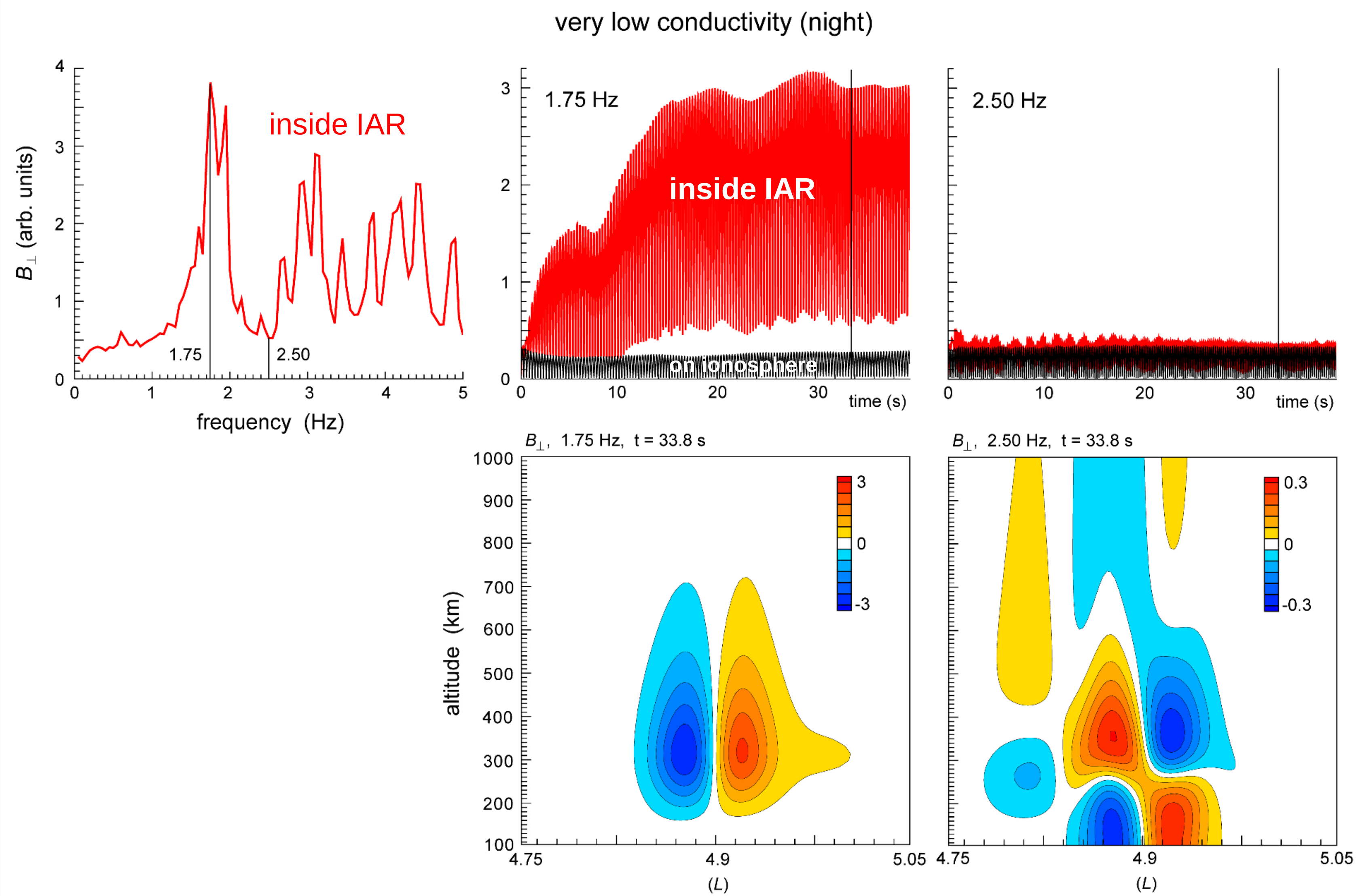
IAR without IFI



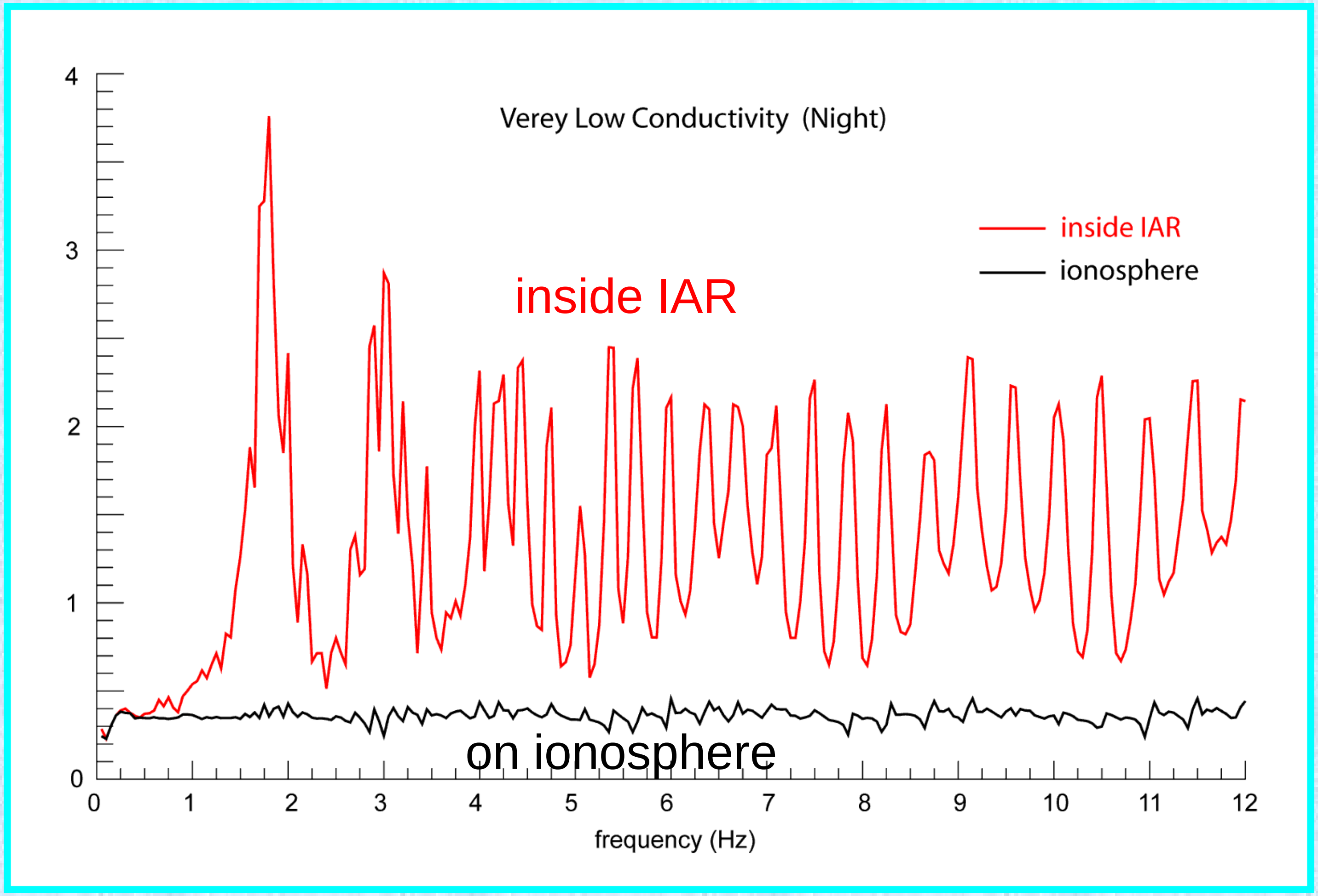
Night (very low conductivity)



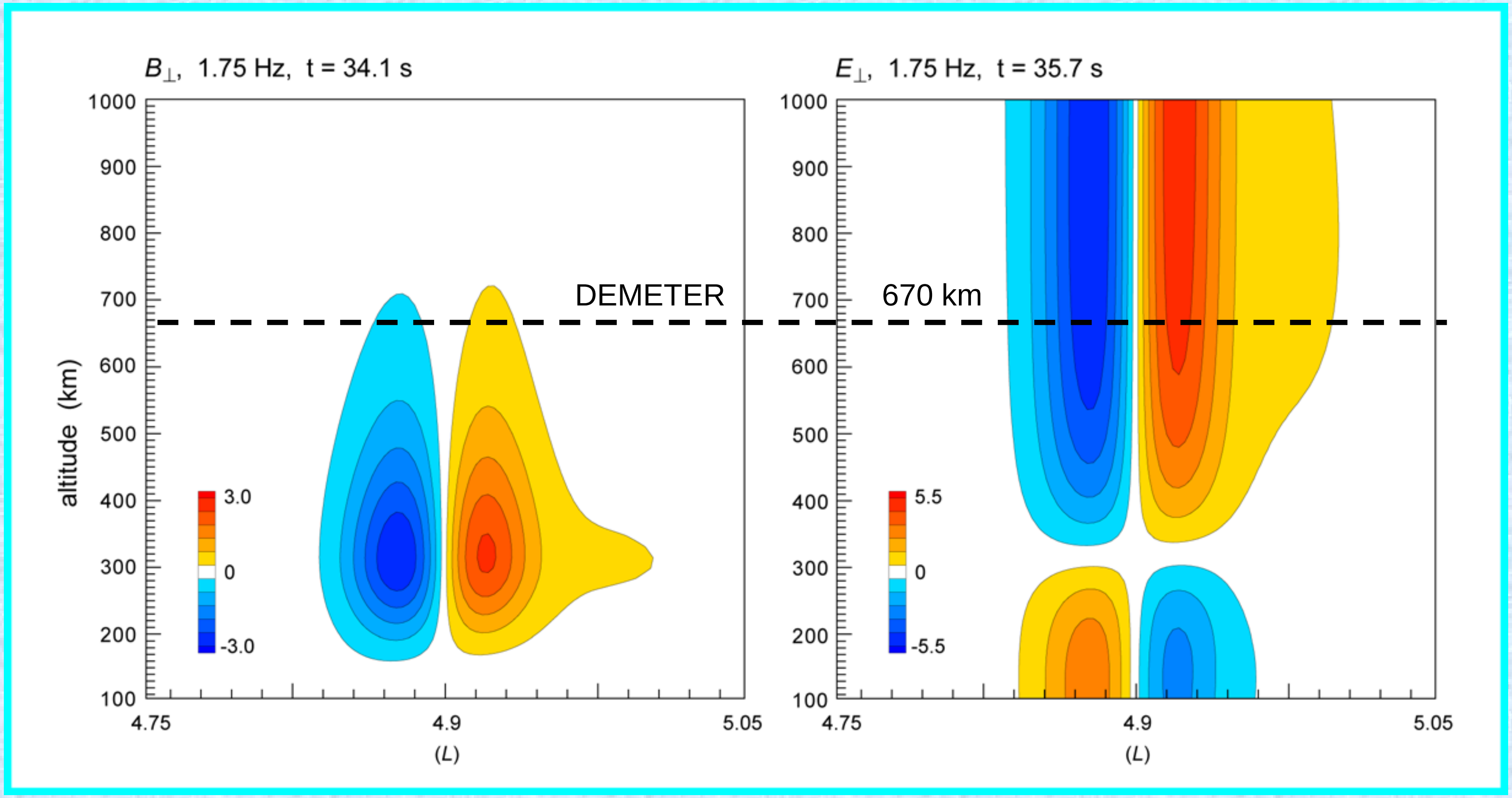
IAR without IFI



IAR without IFI



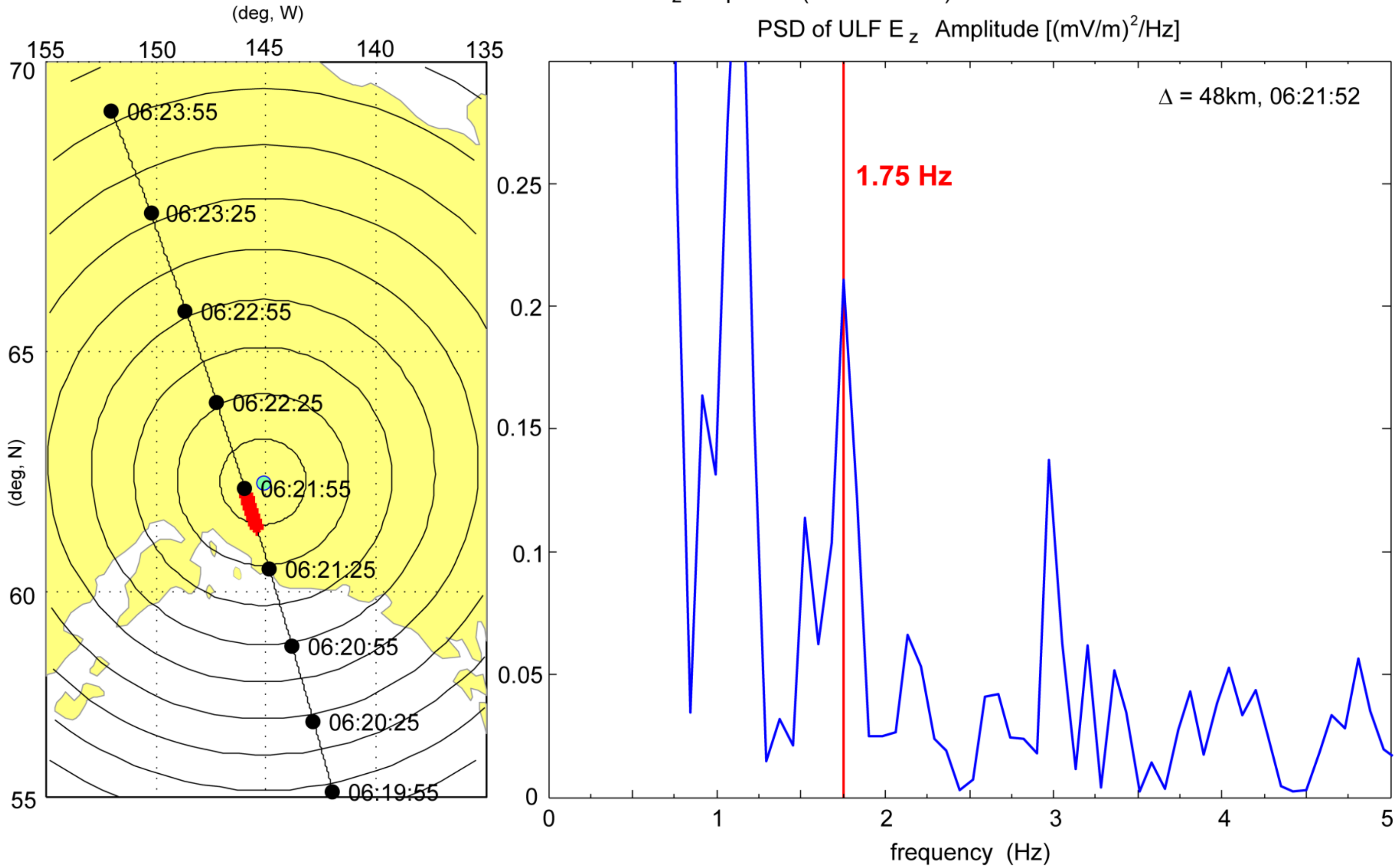
IAR, very low conductivity, 1.75 Hz

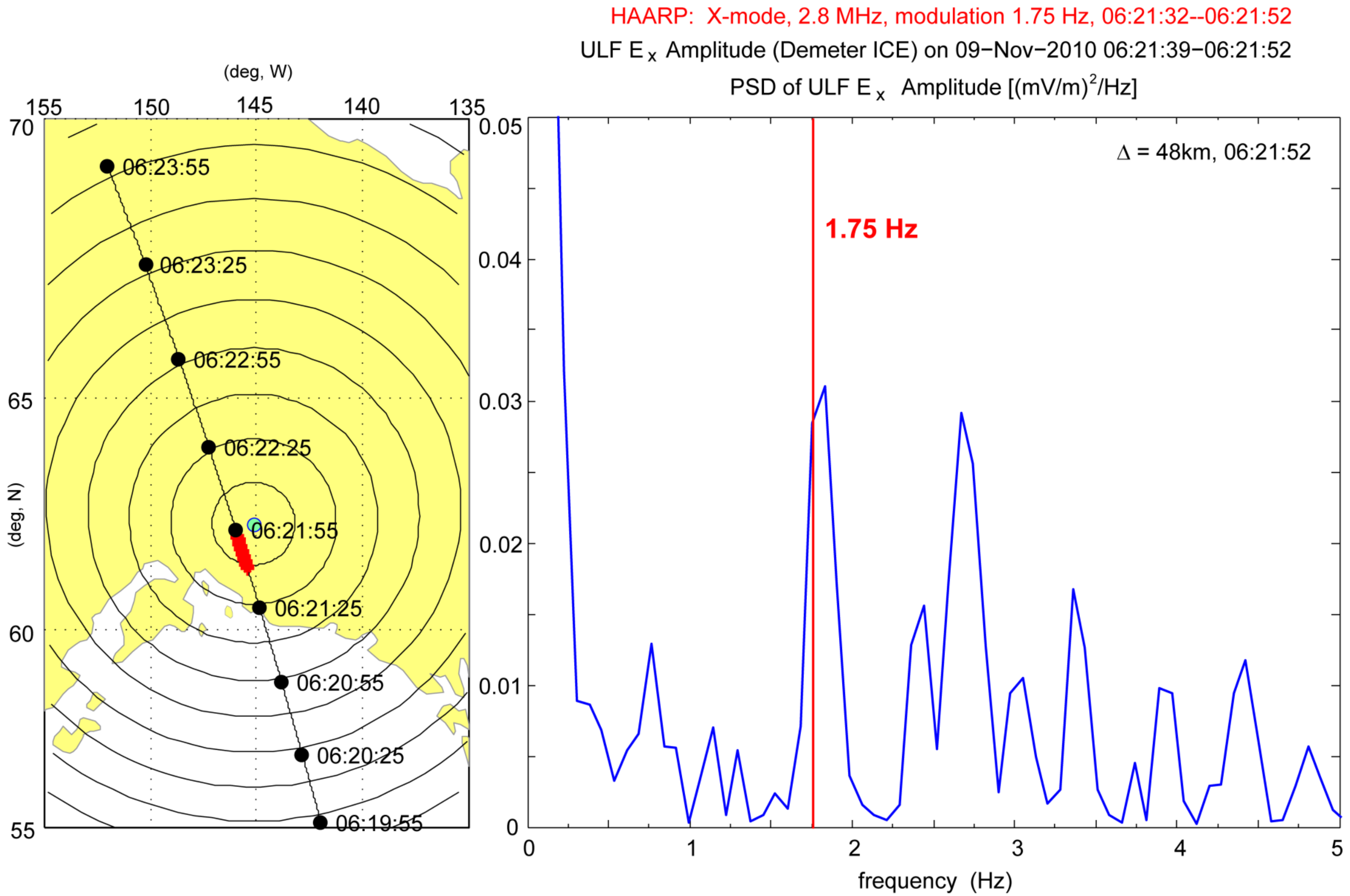


HAARP: X-mode, 2.8 MHz, modulation 1.75 Hz, 06:21:32--06:21:52

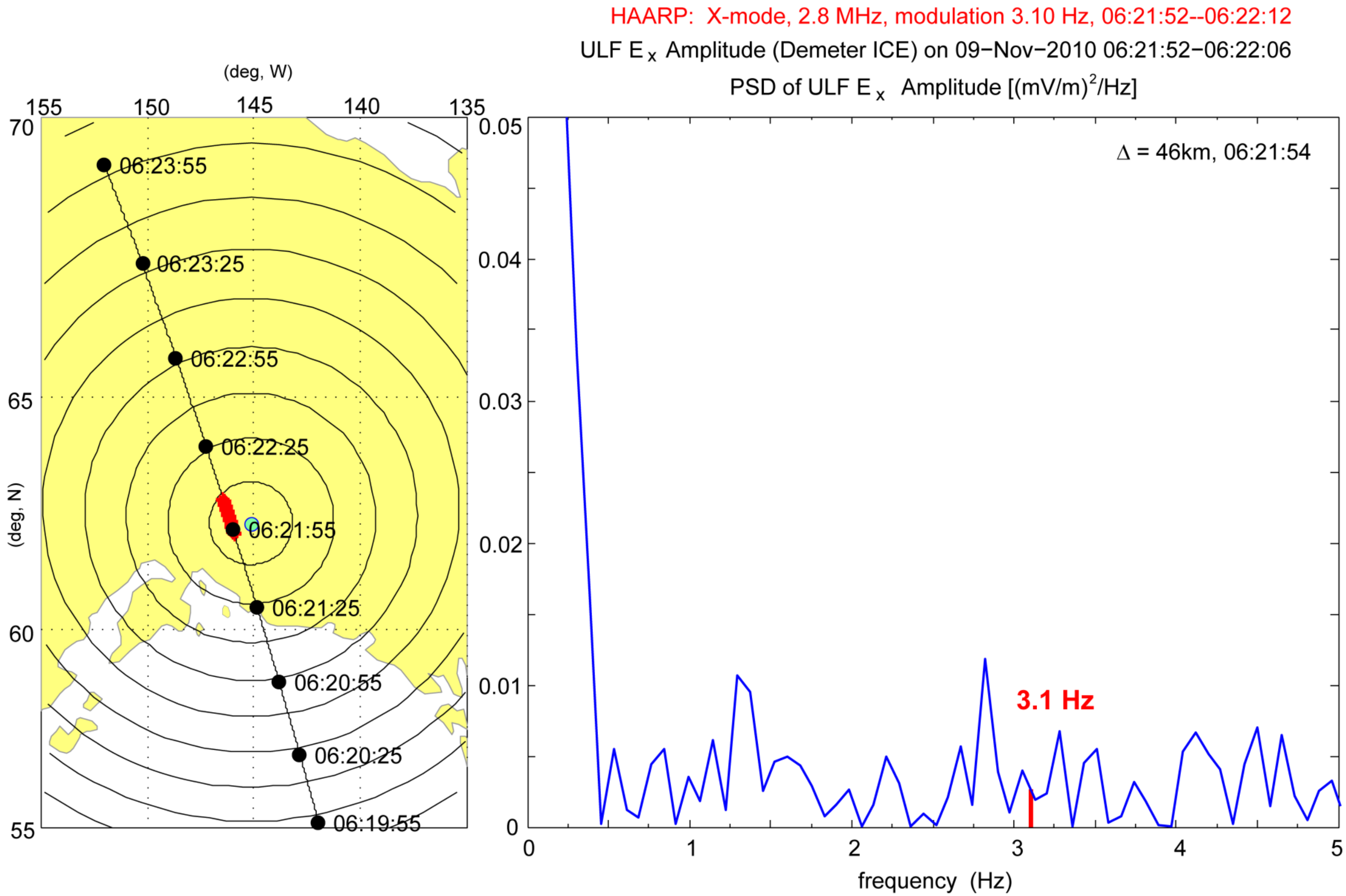
ULF E_z Amplitude (Demeter ICE) on 09−Nov−2010 06:21:39−06:21:52

PSD of ULF E_z Amplitude [(mV/m)^2/Hz]





HAARP: X-mode, 2.8 MHz, modulation 1.75 Hz, 06:21:32--06:21:52
ULF E x Amplitude (Demeter ICE) on 09−Nov−2010 06:21:39−06:21:52
PSD of ULF E x Amplitude [(mV/m)2/Hz]
(deg, W)
155
150
145
140
135
70
65
60
55
(deg, N)
06:23:55
06:23:25
06:22:55
06:22:25
06:21:55
06:21:25
06:20:55
06:20:25
06:19:55
Δ = 48km, 06:21:52
1.75 Hz
0.05
0.04
0.03
0.02
0.01
0
0
1
2
3
4
5
frequency (Hz)

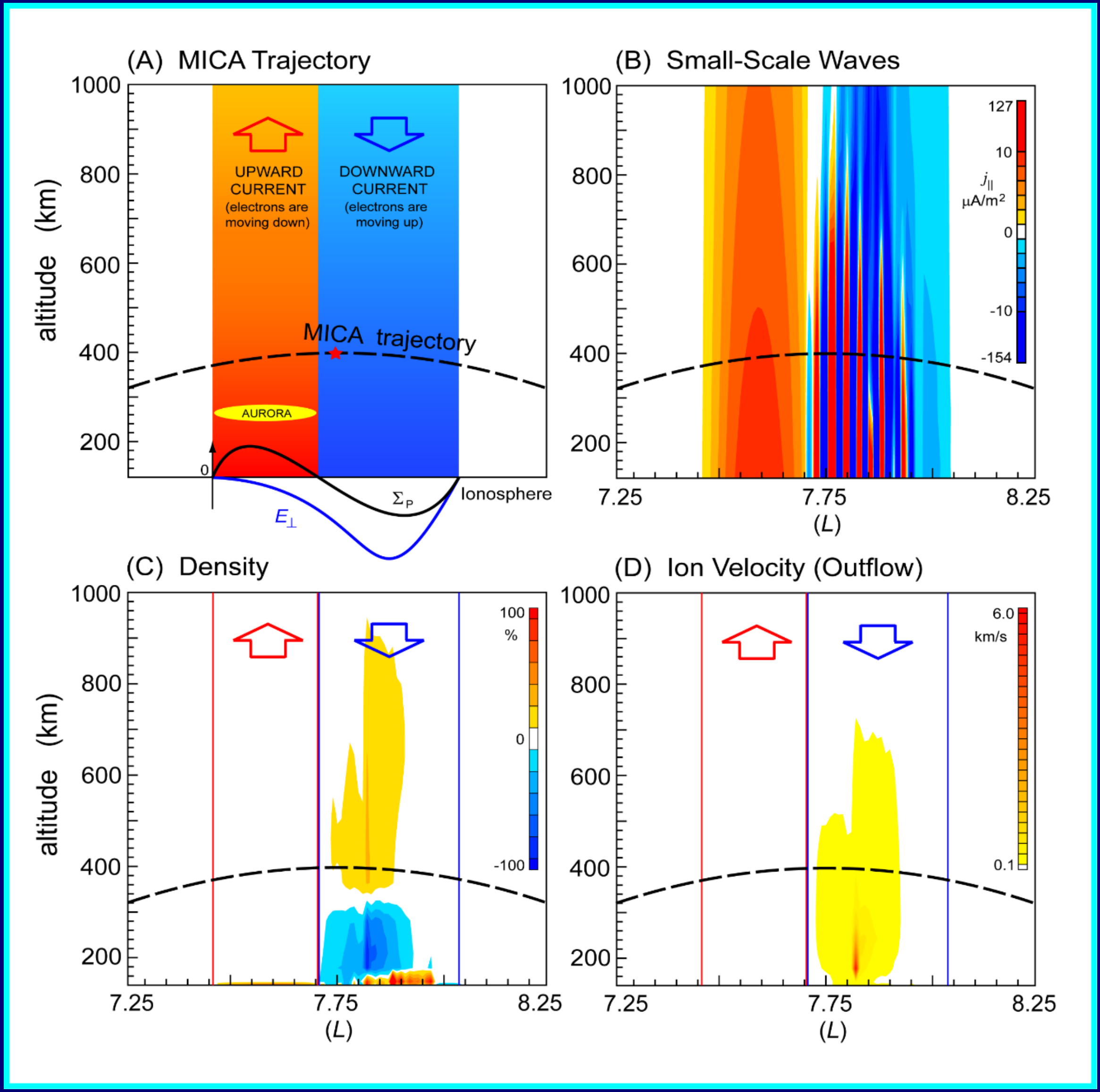

HAARP: X-mode, 2.8 MHz, modulation 3.10 Hz, 06:21:52--06:22:12
ULF E x Amplitude (Demeter ICE) on 09−Nov−2010 06:21:52−06:22:06
PSD of ULF E x Amplitude [(mV/m)2/Hz]
(deg, W)
155
150
145
140
135
70
65
60
55
(deg, N)
06:23:55
06:23:25
06:22:55
06:22:25
06:21:55
06:21:25
06:20:55
06:20:25
06:19:55
Δ = 46km, 06:21:54
3.1 Hz
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
frequency (Hz)

IAR Conclusions:

- The most probable mechanism for generation large-amplitude Alfven waves in IAR under natural conditions is IFI driven by the electric field penetrating into the ionosphere when the ionospheric conductivity is low (night time). In this case the ionosphere defines frequencies of the waves and the waves can be detected by variations of the magnetic field on the ground.

- ULF waves inside the IAR also can be generated by artificial drivers (e.g., ionospheric heating) without involvement of the IAR. In this case their frequencies will be mostly defined by the parameters in the low magnetosphere, and they can be detected by measuring electric or magnetic field inside the IAR on low-orbiting satellites and sounding rockets.

Magnetosphere-Ionosphere Coupling in the Alfvén Resonator (MICA) sounding rocket



MICA

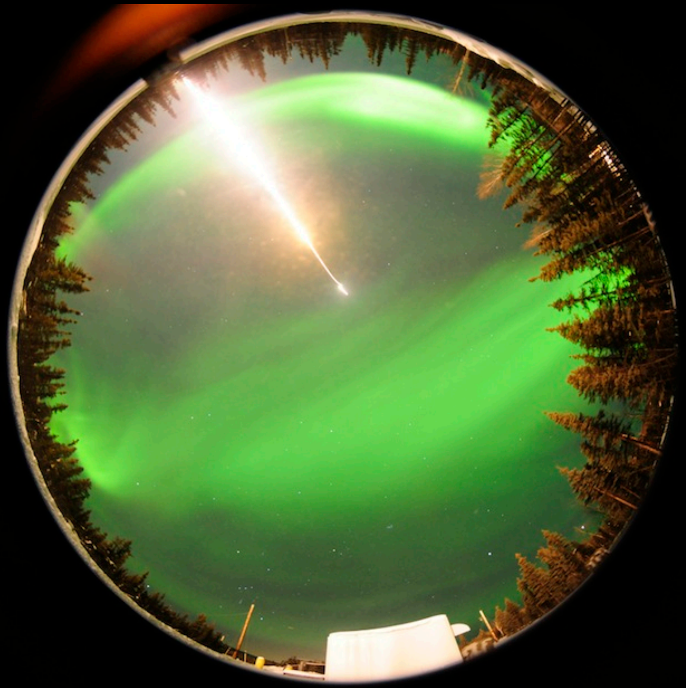
- Launched on February 19, 2012 at 05:41:06 UT.
- Launch site – Poker Flat Research Range.
- Scientific mission: the role of ionosphere in actively determining the origin and evolution of Alfvenic processes in the downward current region of discreet aurora.

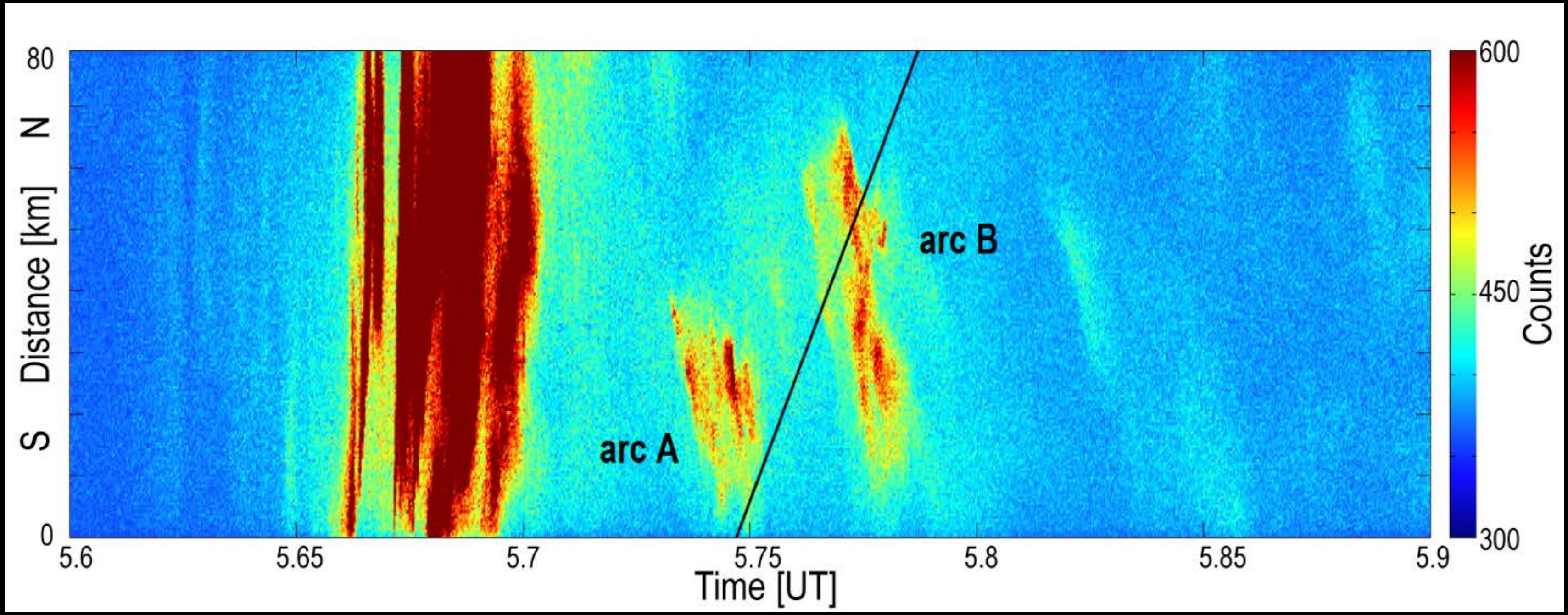
* Not to scale

MICA

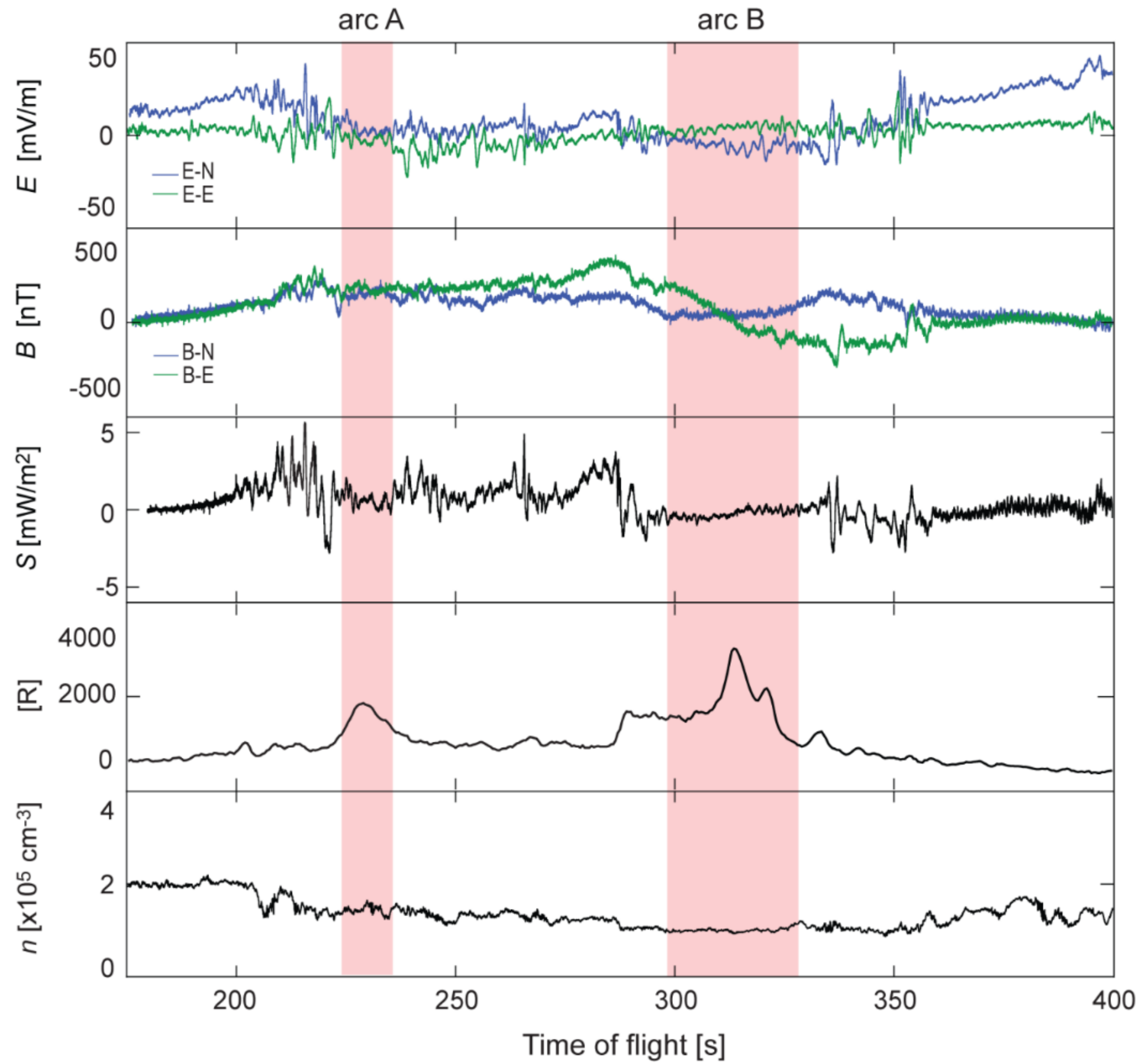
- Apogee – 325.4 km
- Flight duration – 552 s.

MICA's trajectory near discrete arcs



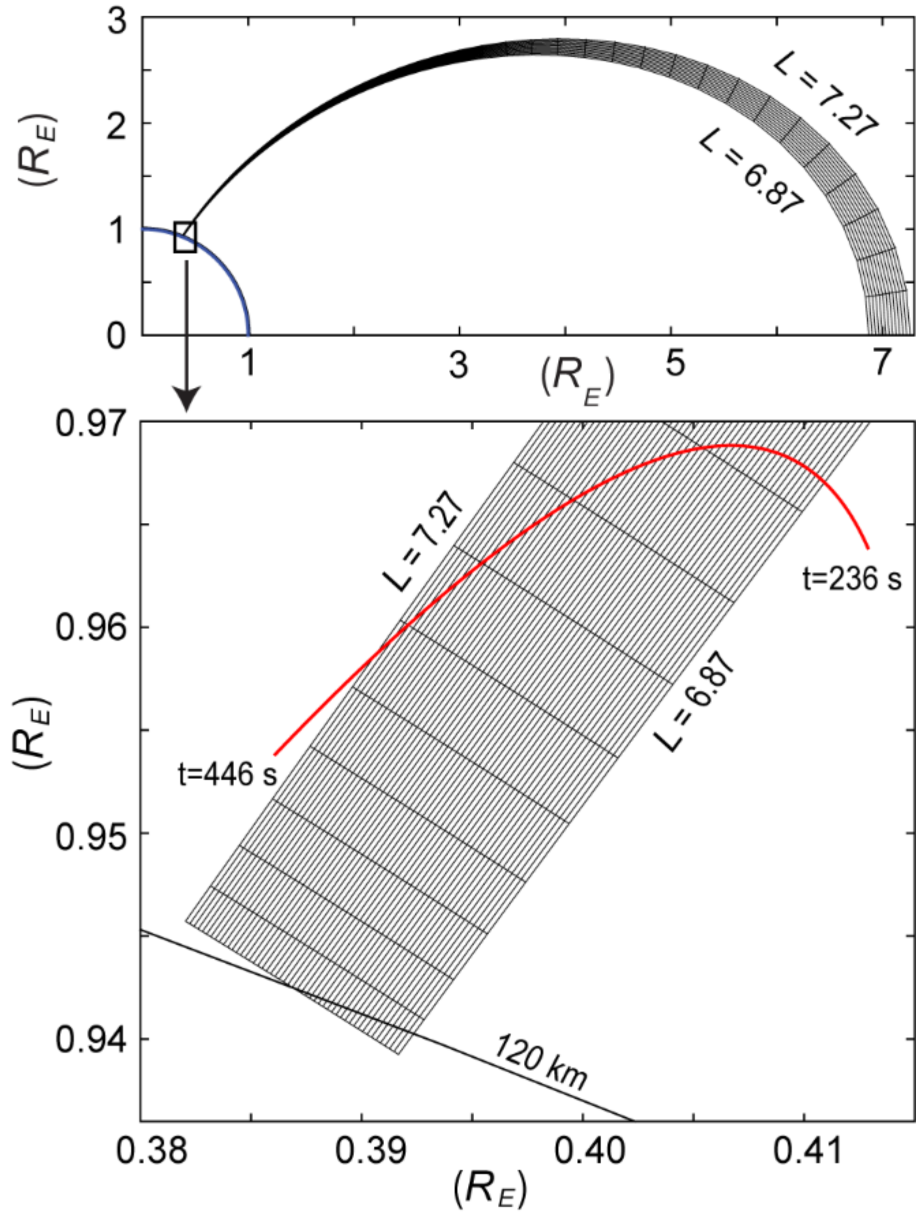


MICA data



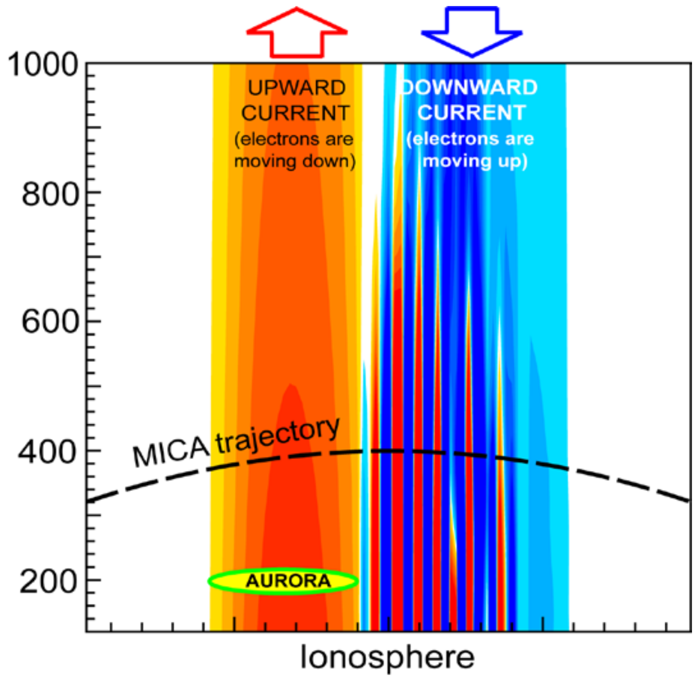
arc A
arc B
E [mV/m]
50
0
-50
E-N
E-E
B [nT]
500
0
-500
B-N
B-E
S [mW/m2]
5
0
-5
[R]
4000
2000
0
n [x105 cm-3]
4
2
0
200
250
300
350
400
Time of flight [s]

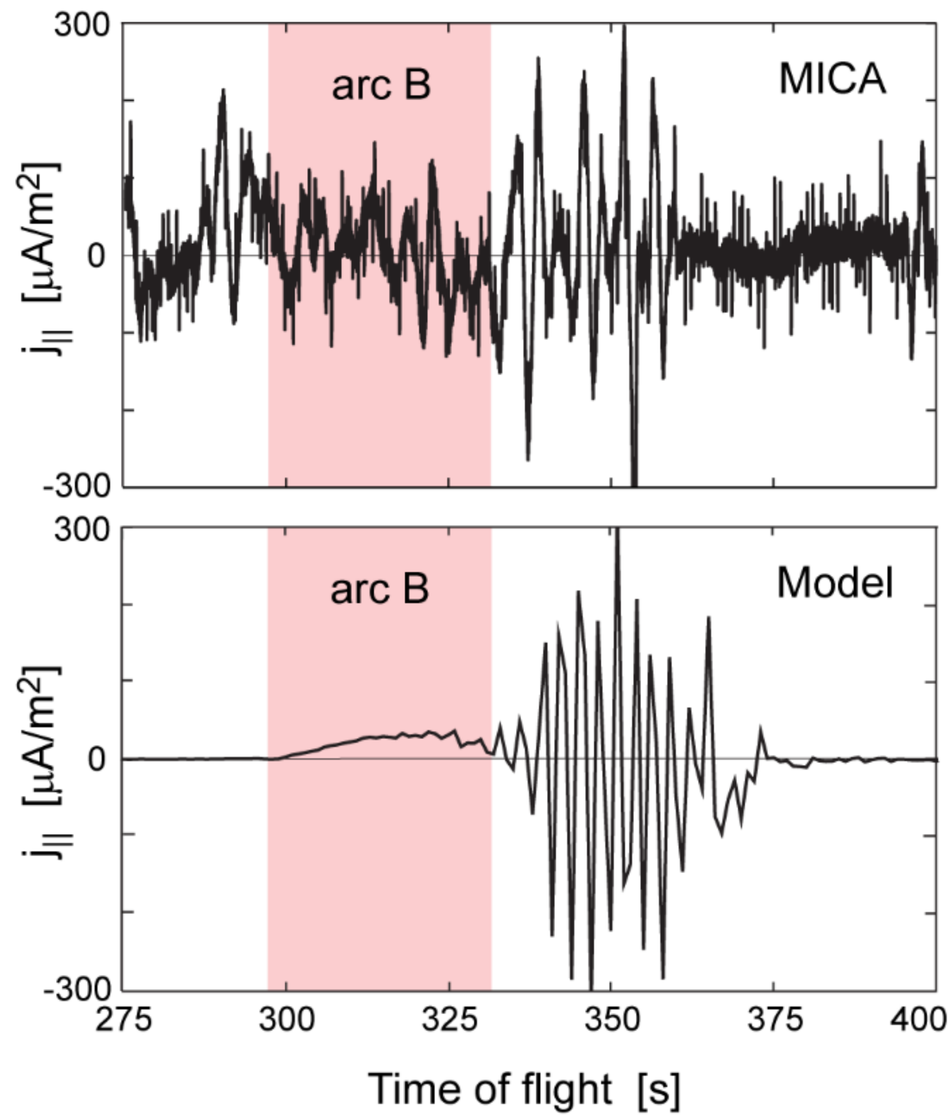
Model



[*Tulegenov and Streltsov*, 2017]

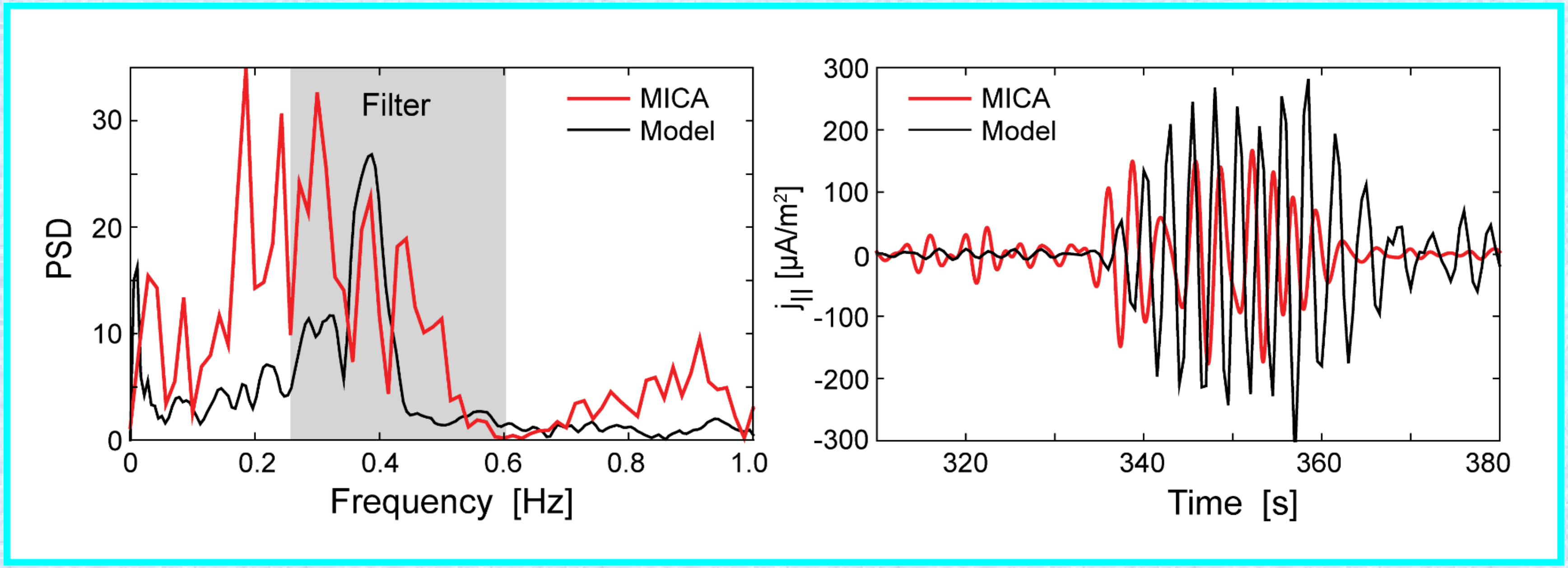
Model Results and Observations





[*Tulegenov and Streltsov*, 2017]

Model Results and Observations



[*Tulegenov and Streltsov*, 2017]

MICA Conclusions:

- MICA sounding rocket experiment confirms the hypothesis by *Streltsov and Lotko* [2004; 2008] that the small-scale, large-amplitude shear Alfévn waves (and the corresponding magnetic field-aligned currents (FACs)) can be generated by IFI driven by the interactions between large-scale FACs and the ionosphere.
- In particular, the MICA experiment confirms predictions that:
  1. the small-scale waves should be observed inside the downward current channel associated with the return current in the vicinity of the discrete auroral arc;
  2. in order to reach the observed amplitudes, frequencies and spatial sizes the waves should be trapped inside the IAR.

Conclusions:

- Large-amplitude ULF waves in the near-Earth’s space environment can be produced by the magnetospheric drivers (solar wind, storms, substorms) and their frequencies will be defined by the frequency of the driver and parameters of the magnetosphere.
- The waves also can be generated by the ionospheric drivers (ionospheric feedback instability), and their frequencies will be defined by the electric field and conductivity of the ionosphere.
- The waves also can be generated by the artificial drivers including heating of the ionosphere with powerful HF waves. Heating produces the strongest effect when it is used to “trigger” natural instability.
- Amplitude of ULF waves generated by all these mechanisms reaches large magnitude when frequency of the driver matches one of the eigenfrequencies of the magnetosphere-ionosphere or ionosphere-ground resonators.