Experimental Studies of RF Generated Ionospheric Turbulence

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Artificial Ionospheric Irregularities
HAARP Experiments
Scientific Objectives

Excite, study and control onset and initial growth of artificial ionospheric irregularities with HAARP

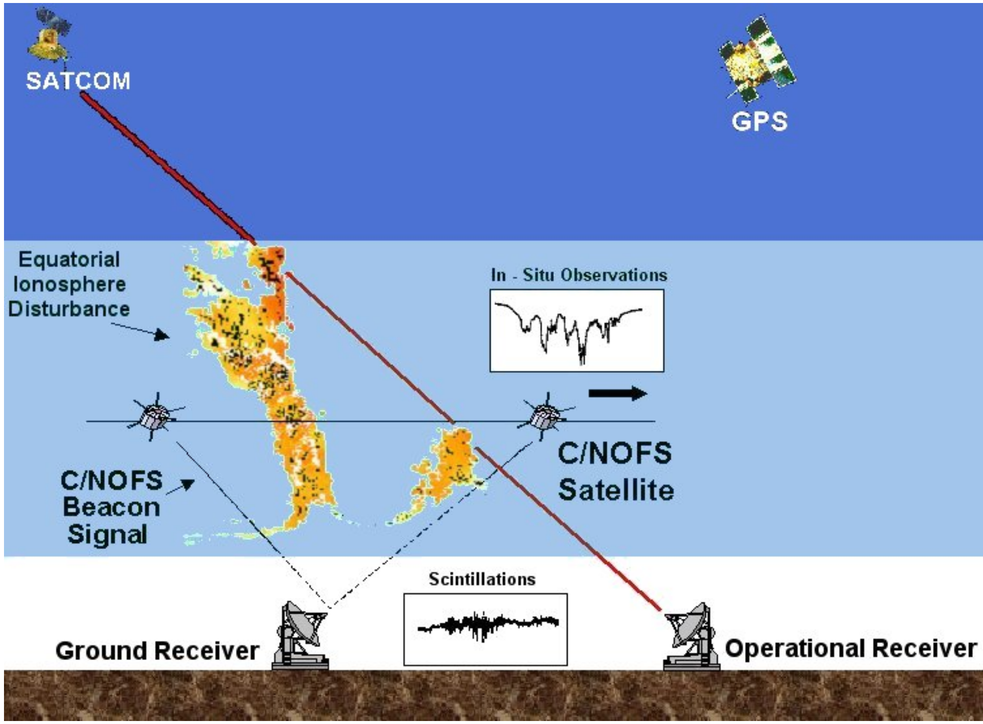
– Monitor and <u>control</u> production of Artificial Field-Aligned Irregularities (AFAI)
  - SuperDARN Kodiak HF radar
– Study diagnostic signature dependence on
  - HAARP HF <u>*pulse length*</u> to the millisecond*
  - HAARP HF <u>*duty cycle*</u>
  - Aspect angle: <u>*vary HAARP HF pointing**</u> and UHF look angles
– High time resolution (3.3ms) MUIR UHF radar data
  - Langmuir wave *intensity*, *spectra*, and *evolution*
  - HFPL Overshoots: 'mini' which *seeds* the 'main' overshoot
  - and <u>*the 'main' overshoot which coincides with GPS scintillation*</u>

- *features <u>unique</u> to HAARP

Communication/ Navigation Outage Forecast System

C/NOFS

C/NOFS satellite launched 16 Apr 08 provides continuous monitor of ambient ionosphere & irregularities



Mission elements

- Satellite: 13 deg inclination, 400 x 850 km alt
- Ground-based instruments
- Data Center
- Models

Mission Goals

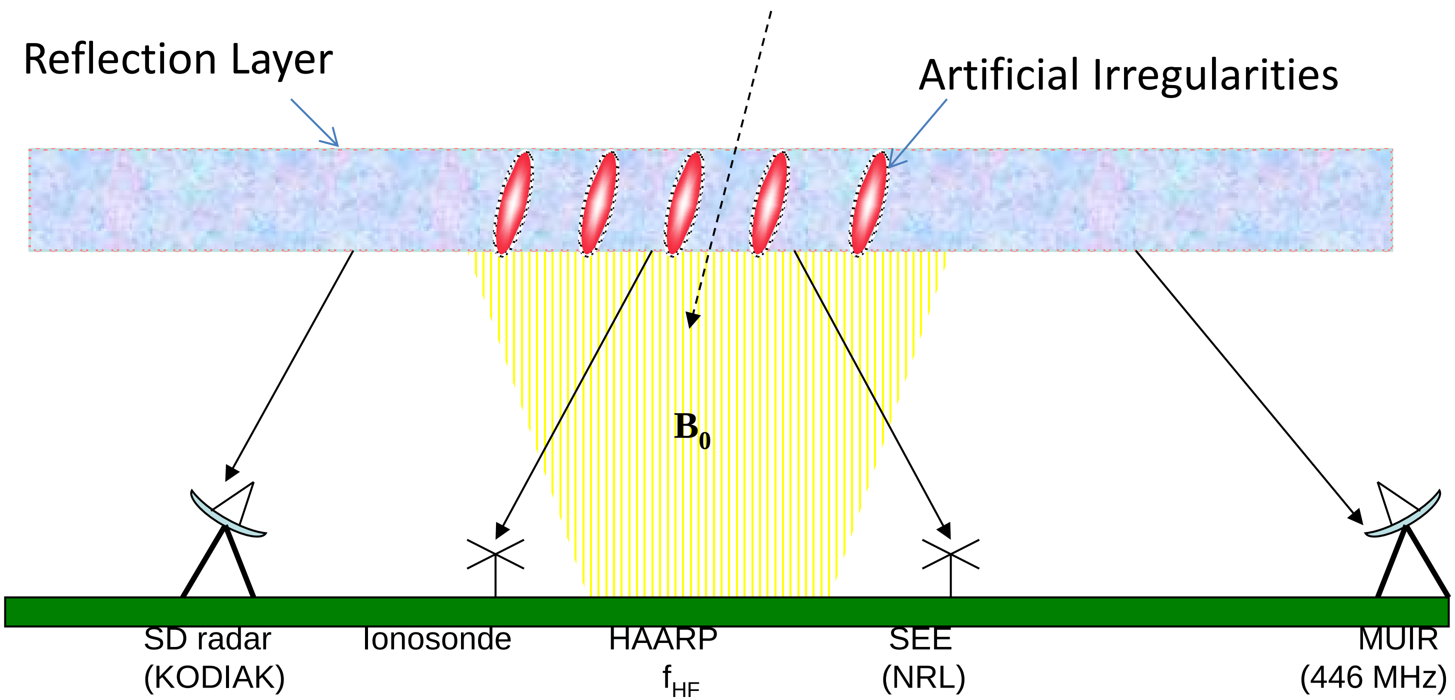
- Nowcast and forecast ionospheric scintillation and electron density
- Develop improved understanding of equatorial ionosphere and processes that trigger / inhibit irregularities
- Develop capability to produce long term outlook (more than 24 hours)

HAARP and diagnostic instruments

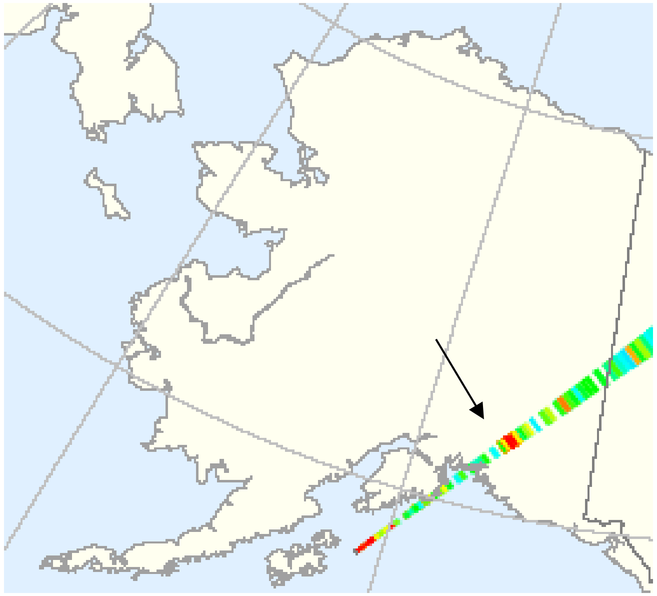
Modular UHF Ionospheric Radar (MUIR)

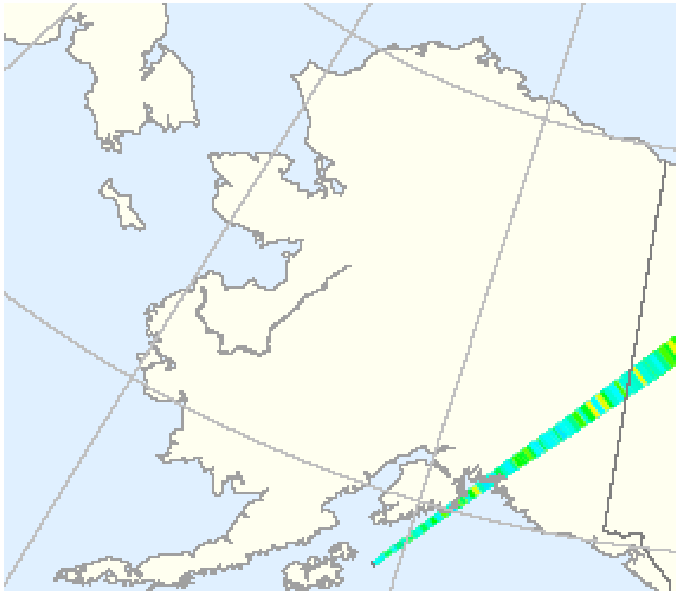
Stimulated Electron Emission (SEE), Ionosonde

Kodiak Super Dual Auroral Radar Network (SuperDARN) HF radar



Mills, J. and Sheerin, PARS 2000
Wood, M. K. and Sheerin, PARS 2008

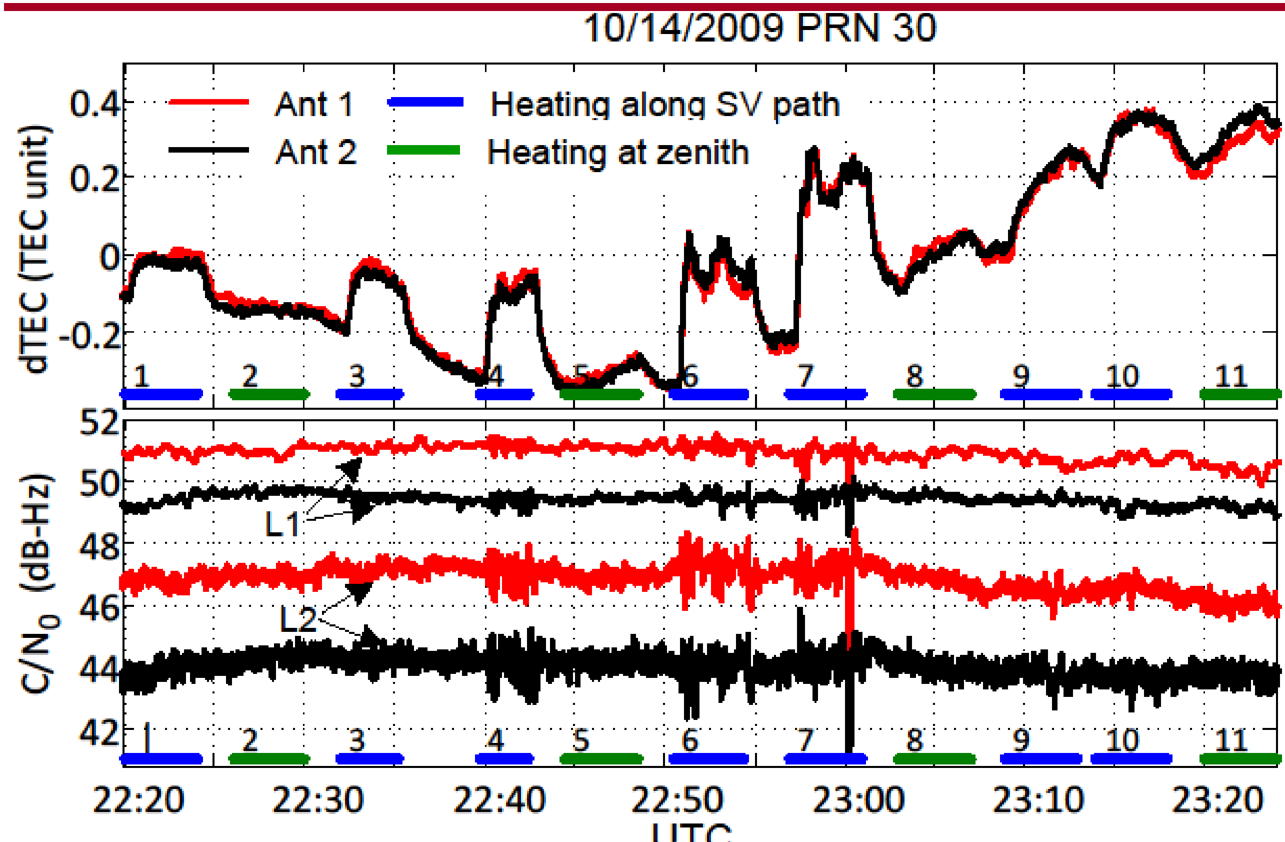




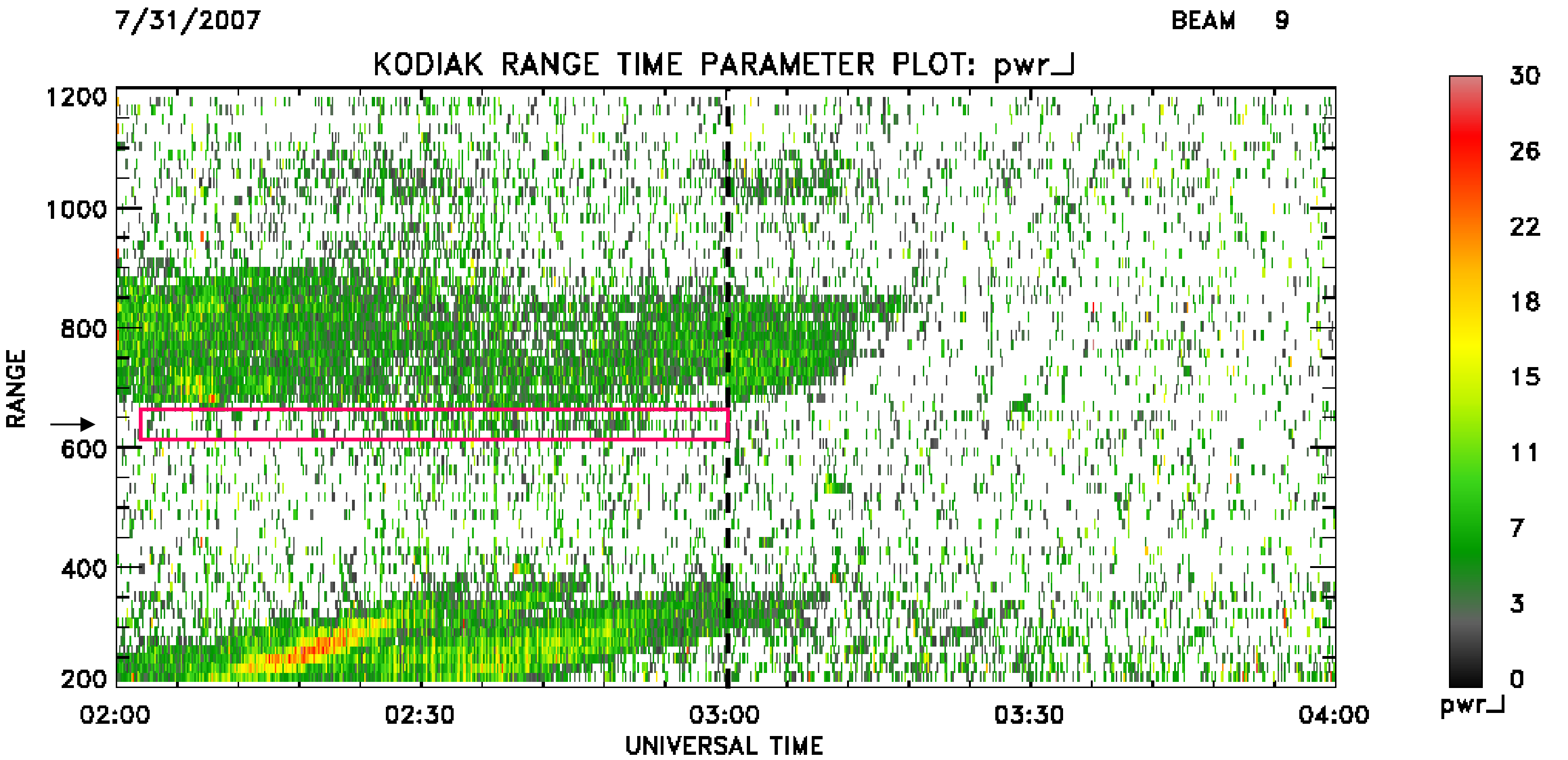
(a) SuperDARN Kodiak beam 9 scatter from AFAI over HAARP (most intense red spot indicated by arrow) only when HAARP pointed 11.5º south of vertical on 1 Aug 2008. Other radar echoes are from natural irregularities. (b) The next 6 min. period is typical showing AFAI suppressed at all other HAARP pointing angles with 0.5% duty cycle.

Using HAARP Morton demonstrated impact of AFAI on GPS

Artificial Heating Effects Studies

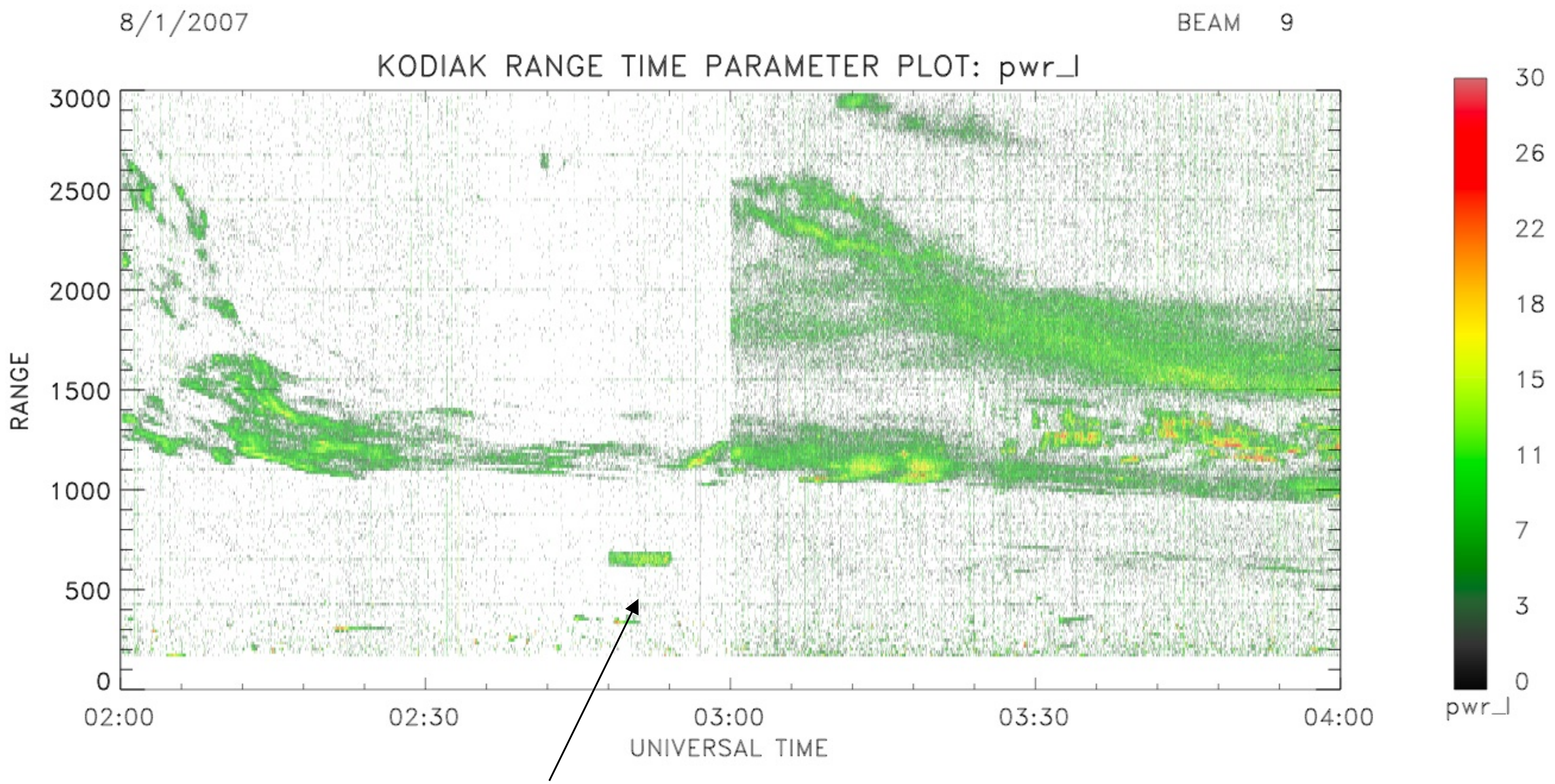


We can control onset of AFAI with shorter HAARP HF pulses / lower duty cycle *



- First hour: HAARP 1% duty cycle and 100 ms pulse
- Second hour: HAARP 0.5% duty cycle and 60 ms pulse

SuperDARN Kodiak Observations:
for 2 hours of continual pulsing transmissions
Low HAARP HF duty cycle <u>suppresses</u> AFAI <u>*except*</u> with HAARP HF pointed at 11.5˚



- <u>No</u> HF-induced AFAI <u>except</u> when HAARP HF pointed 11.5˚ strong artificial aurora has been observed in this range by Kosch providing an <u>*important discovery as to the nature of FAI*</u>

Simulations of AFAI due to thermal self-focusing

--Gondarenko, et al. 2005 JGR 110, A09304

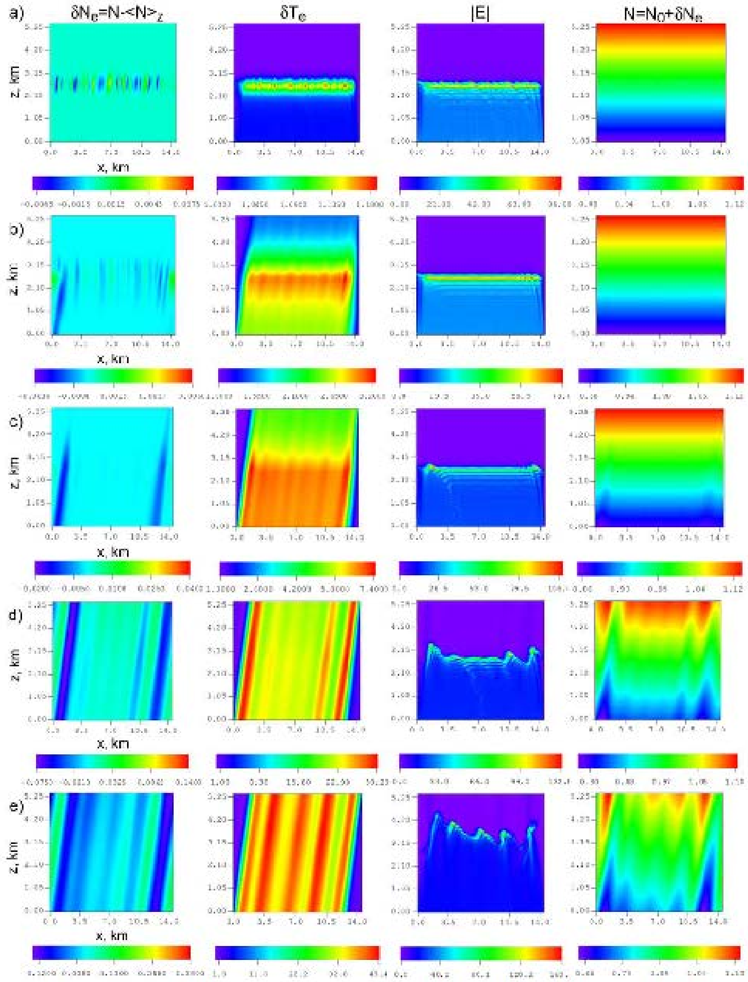
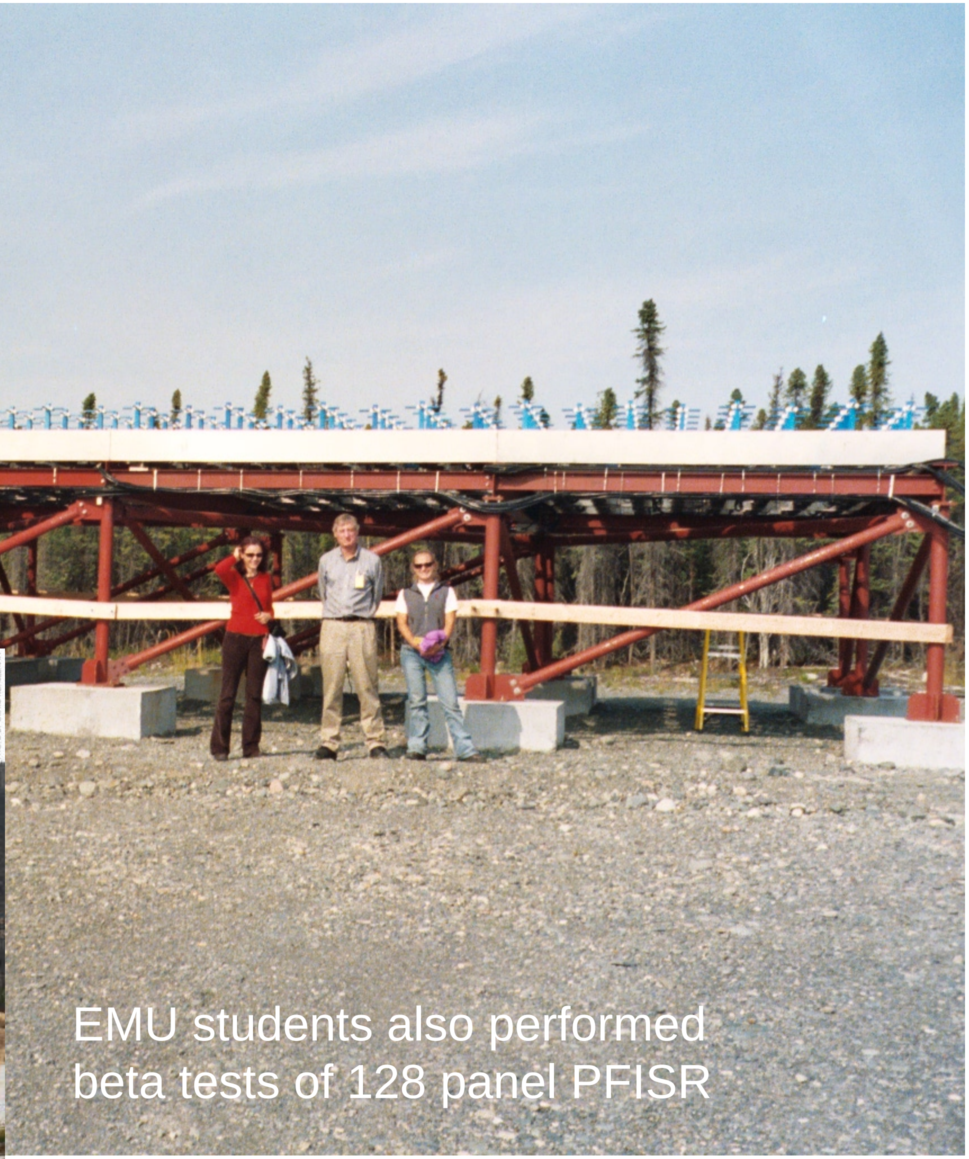


Figure 3. Contours of the electron temperature fluctuation δT_e, density fluctuation δN_e, amplitude of the total electric field $|E|$, and density $N = N_0 + \delta N_e$ for $\gamma = 12°$, $\alpha = 19°$, $\nu_{e0} = 500$ s^{-1} at five times: (a) t = 0.4 ms, (b) t = 11 ms, (c) t = 41 ms, (d) t = 191.28 ms, and (e) t = 347.28 ms.

***Modular* U**HF **I**onospheric **R**adar *MUIR*

Dr. Raluca Ilie, U. Mich., Prof Watkins, UAF, and
Dr. Erika Roesler Harding, SNL



MUIR Radar Data

Generation of HF (ω_0) Pumped Plasma-Lines and Ion-Lines in Backscatter Radar Spectra (ω_R,k_R)

First Order *Ion Line* and *Plasma Line*

Radar Wave

Pump Wave

Plasma Line

$$EM_0(\omega_0) \xrightarrow{PDI} \begin{cases} \left.\begin{matrix} EM(\omega_R) \\ EP_1(\omega_0 - \omega_{IAR}) \end{matrix}\right\} \xrightarrow{Scatter} EM(\omega_R \pm \omega_0 \mp \omega_{IAR}) \\ \left.\begin{matrix} IA_1(\omega_{IAR}) \\ EM(\omega_R) \end{matrix}\right\} \xrightarrow{Scatter} EM(\omega_R \pm \omega_{IAR}) \end{cases}$$

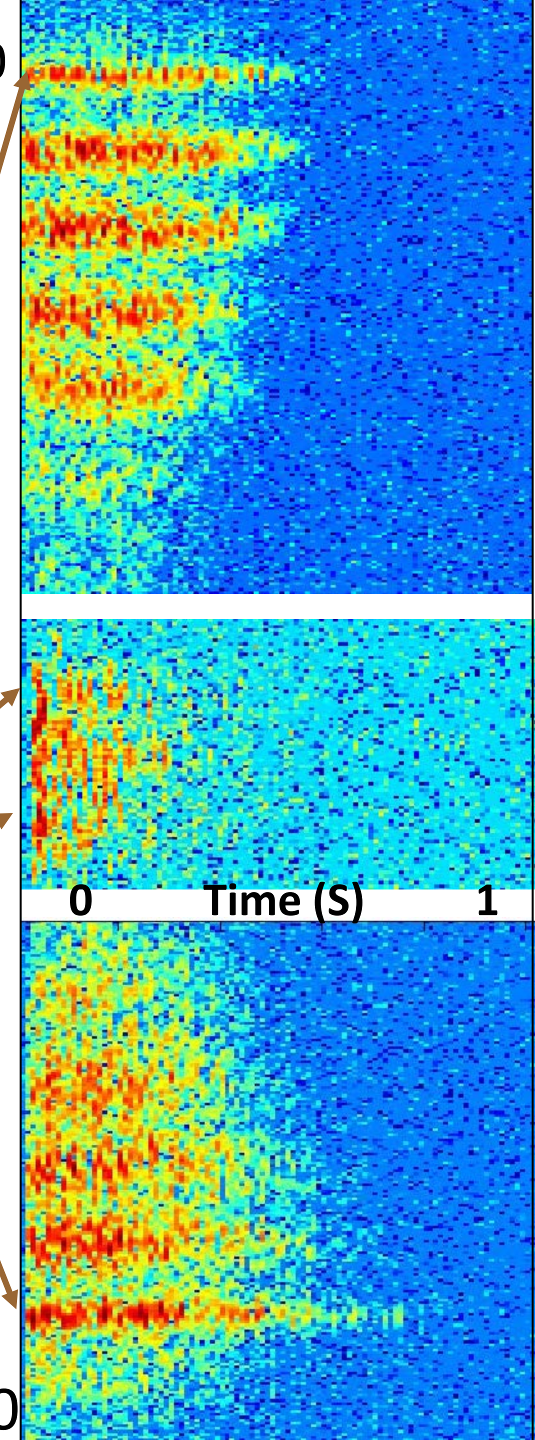
Electrostatic

Radar Wave

Ion Line

$\omega_R + \omega_0$

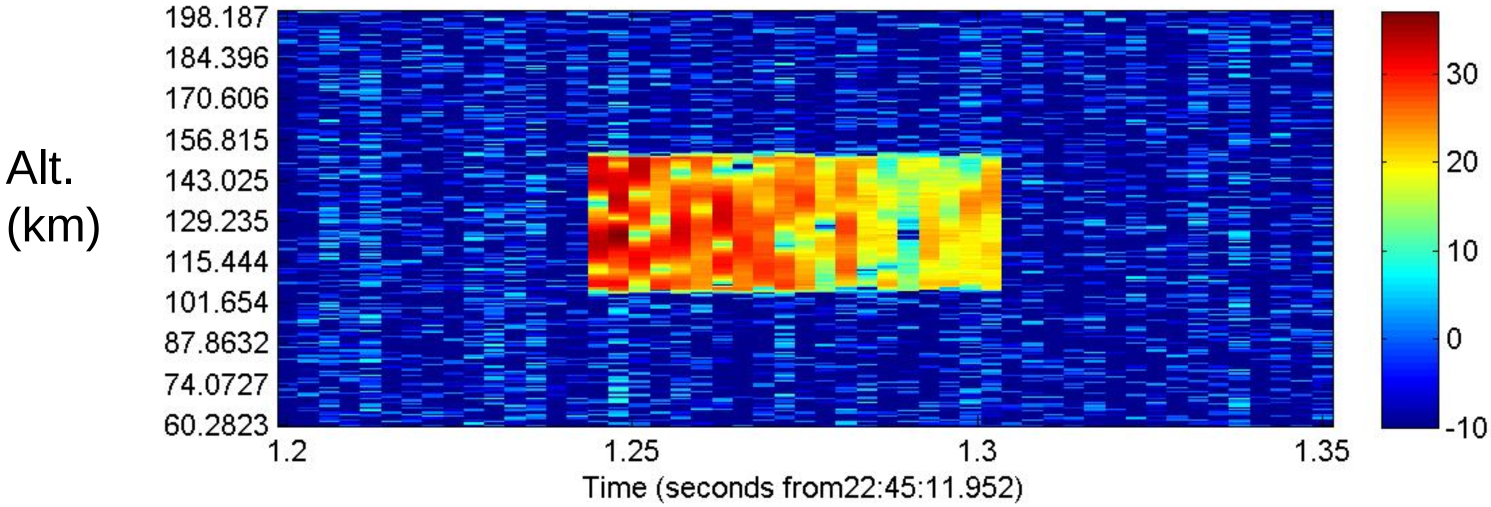
ω_R

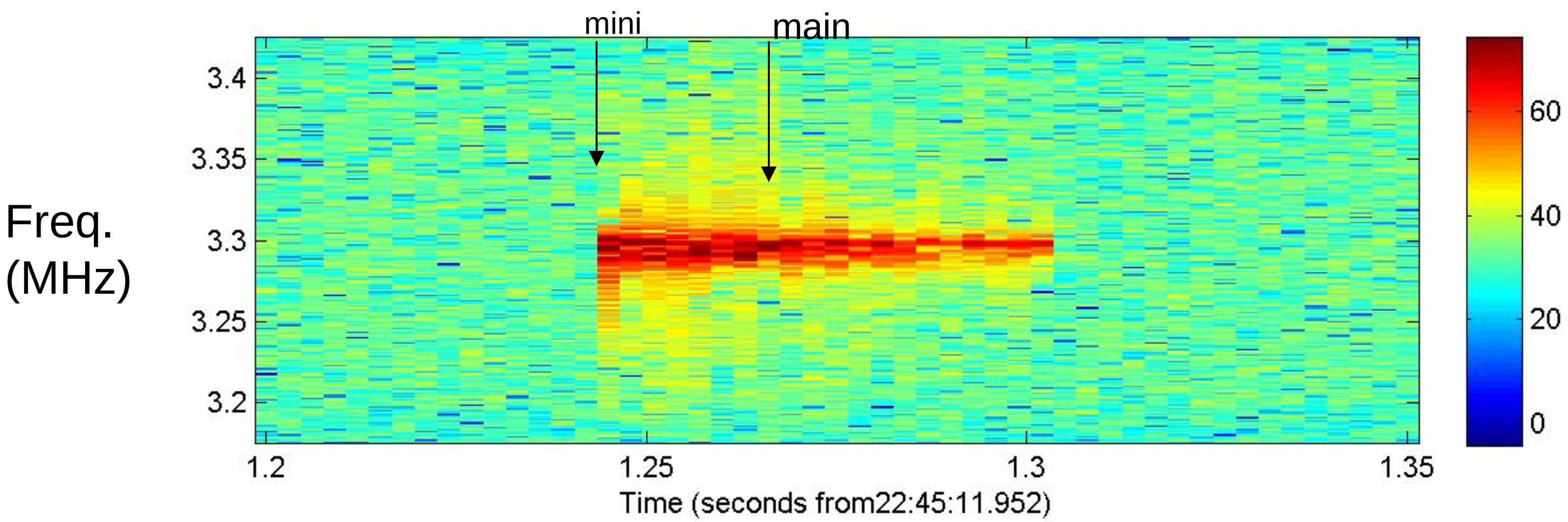


$\omega_R - \omega_0$

Watkins and Bernhardt

The MUIR radar at HAARP shows the *onset* and *growth* of AFAI over 30 ms to levels deleterious to GPS signals <u>with 3 millisecond resolution</u>



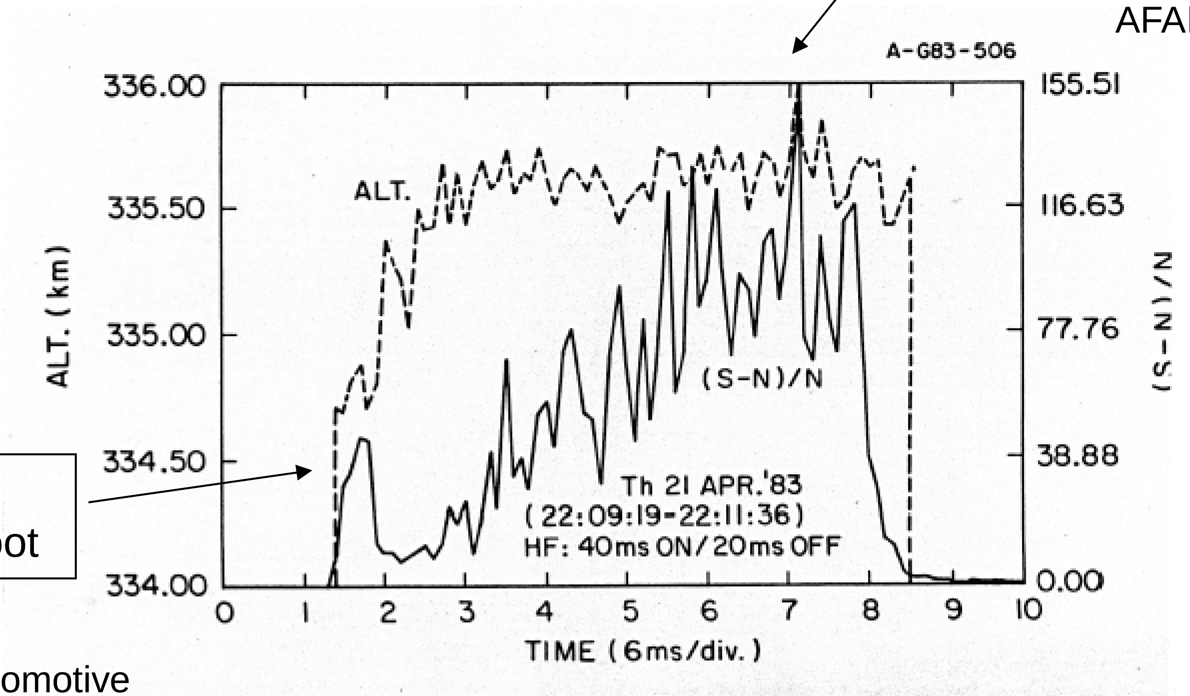


‘Mini’ and ‘Main’ plasma line overshoots observed at AO

Duncan and Sheerin, JGR 90 8371(1985)

Main overshoot

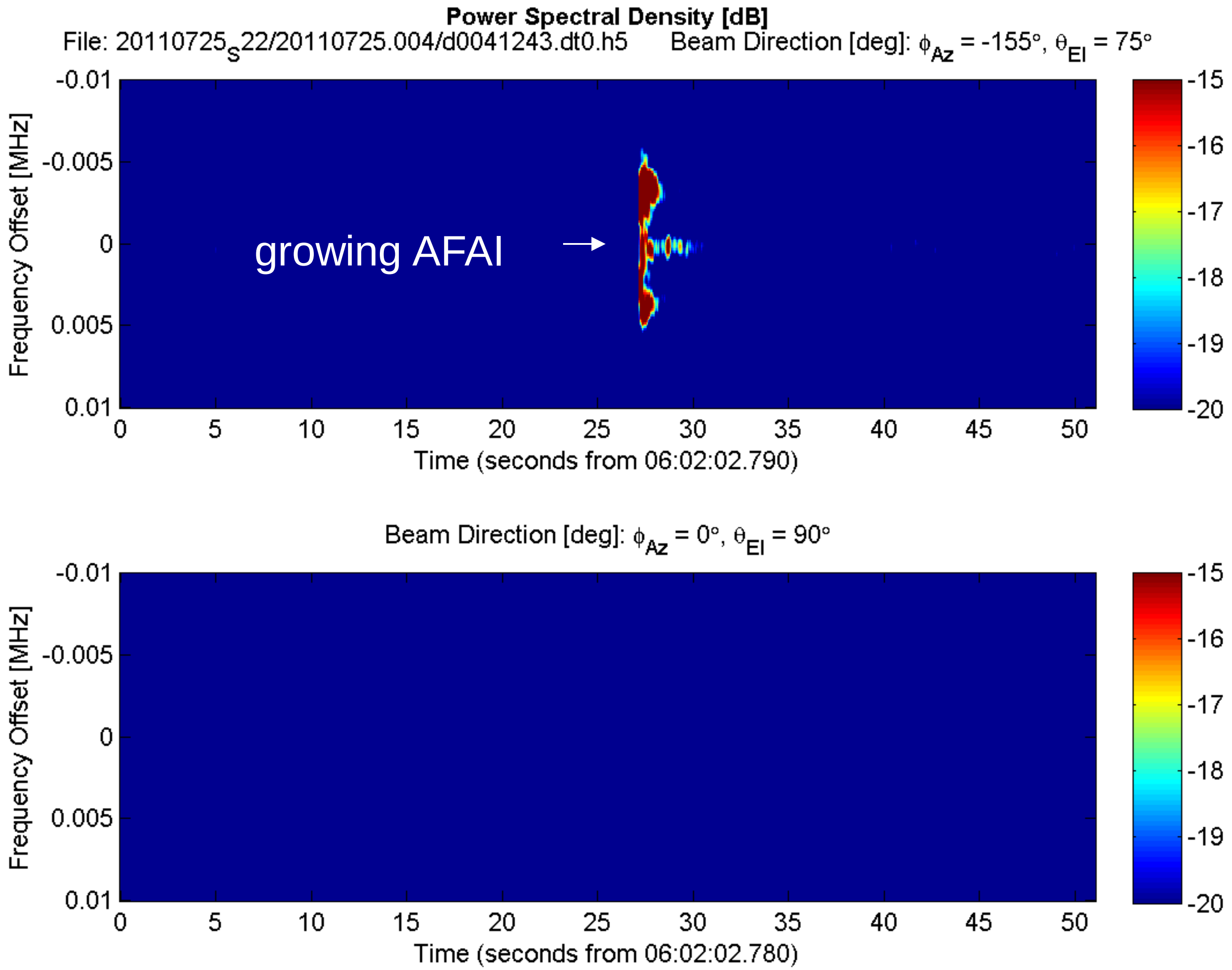
thermal timescales
AFAI ~ 0.03 secs



Mini-overshoot

ponderomotive
timescales ~ few ms

July 2011 Discovery
Ion Line spectra for longer pulses show overshoot then development of thermal filaments Artificial FA Irreg.



Aspect angle dependence: HF refraction and UHF radar pointing determine HFPL spectra observed

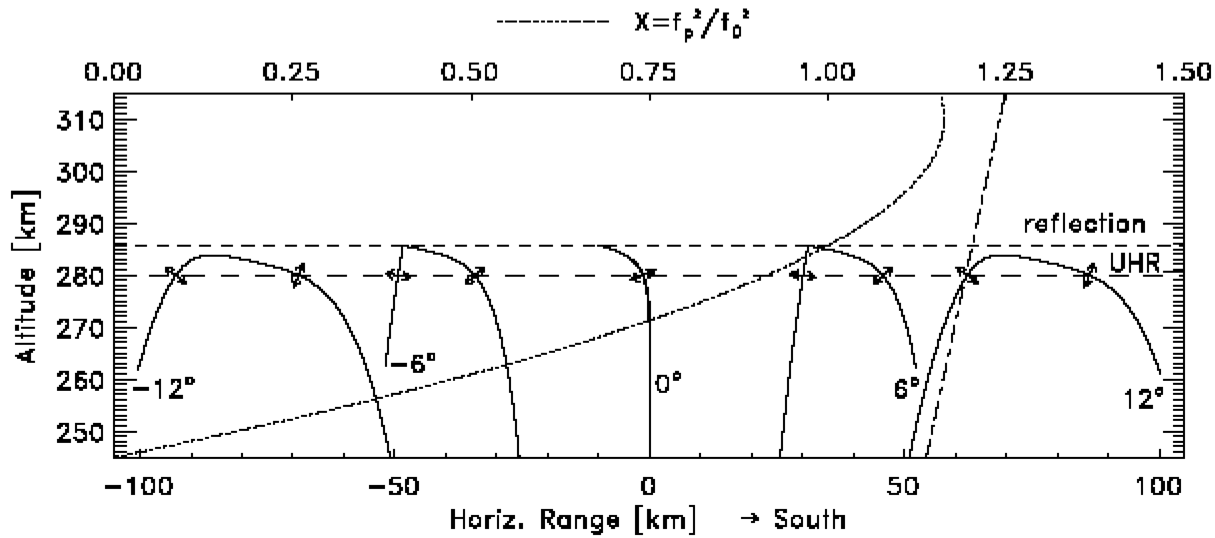
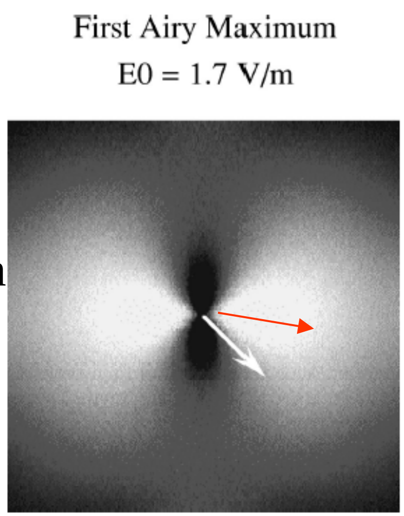


Figure 11. Schematic diagram of ray tracing HF waves of varying angles of incidence into a horizontally uniform ionosphere. The ionospheric electron density profile is shown by the curved dotted line and relates to the upper X-axis, which is normalised to the pump frequency of 4.544 MHz. The reflection height and upper-hybrid resonance (UHR) heights are shown labeled and the wave electric field direction of the upward and downward going waves at the UHR height are shown by arrows. The magnetic field direction is shown as a dash-dotted line. Efficient HF-induced heating is expected where the wave electric field is perpendicular to the magnetic field such that coupling to upper-hybrid waves is most efficient.

Rietveld, et al JGR 108 (2003)

DuBois, D. F. et al., Phys Plasmas <u>8</u>, 791 (2001)
Mjolhus, E. et al. Nonlin. Proc Geophys. <u>10</u>, 151 (2003)

796 Phys. Plasmas, Vol. 8, No. 3, March 2001



Cavitation regime

FIG. 3. Modal energy spectra, $k^2|\mathbf{E}(\mathbf{k}_x,\mathbf{k}_y)|^2$, near altitude of the first pump interference maximum with $n/nc=0.996$, for the heater intensity of 1.7 V/m. The **k** vector observed by the Arecibo radar is indicated (approximately) by an arrow.

Tromsφ Radar angle

Arecibo Radar angle

$\longleftarrow \langle|\mathbf{E}(\mathbf{k}_x,\mathbf{k}_y)|^2\rangle \longrightarrow$

PDI-LDI Cascade regime

Phys. Plasmas, Vol. 8, No. 3, March 2001

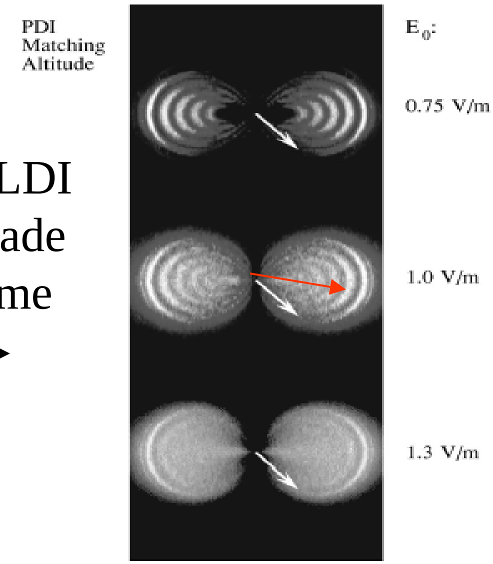


FIG. 1. Modal energy spectra, $k^2|\mathbf{E}(\mathbf{k}_x,\mathbf{k}_y)|^2$, for the PDI matching altitude with $n/n_c=0.962$ for the Arecibo radar for three heater intensities. The **k** vector observed by the Arecibo radar is indicated (approximately) by an arrow.

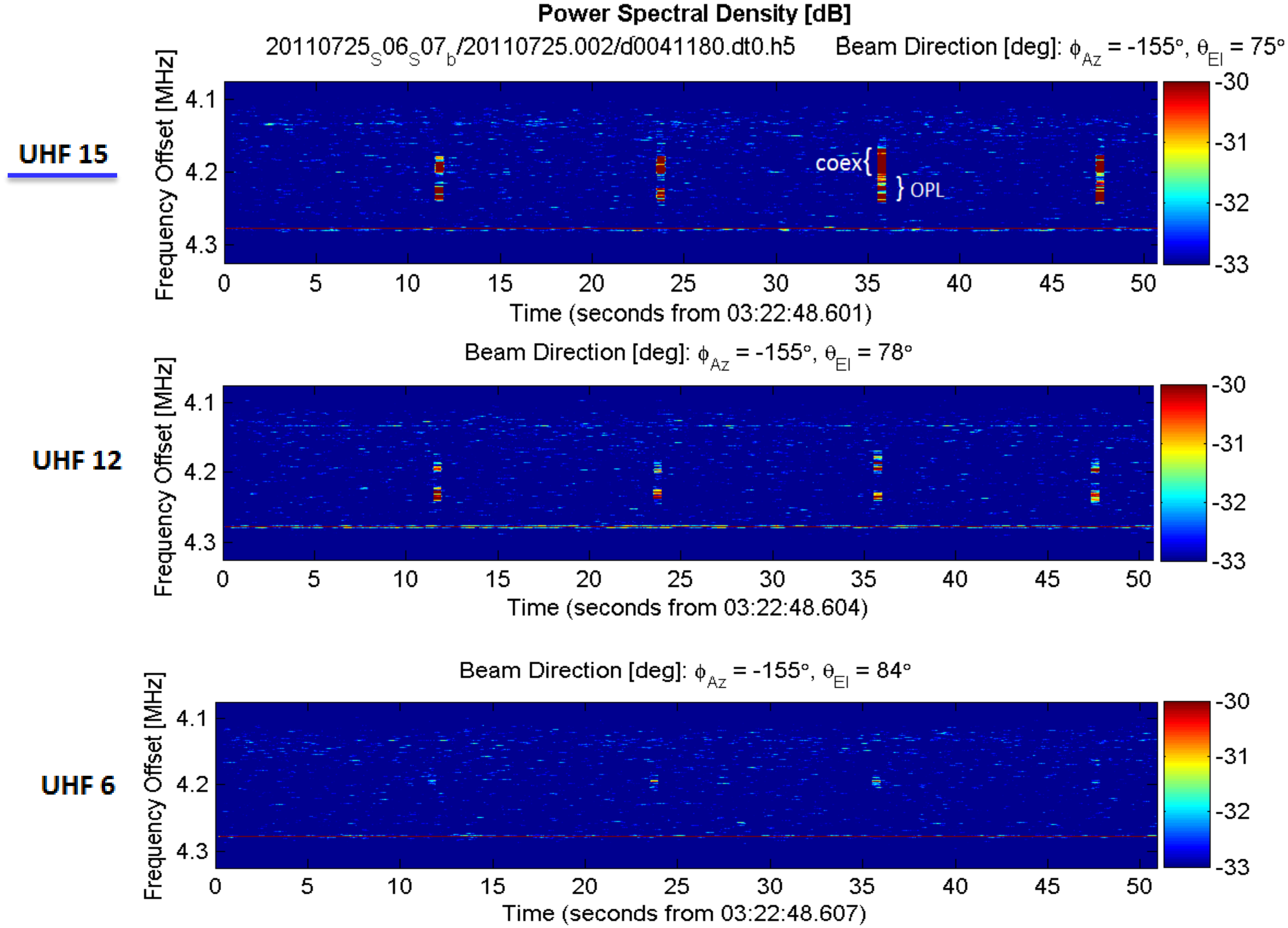
There is a continuous range of altitudes where the PDI-LDI cascade is excited but the radar observes a fixed k and cannot see all of these.

For example the primary PDI line can be seen by the radar only at the altitude z_r where the frequency matching condition is satisfied

$$\omega_0 = \sqrt{\omega_{pe}(z_r)^2 + 3k_r^2 v_e^2 + \Omega_{ce}^2 \sin^2\theta_r} + k_r c_s$$

HF pointed at 7° and *simultaneous* MUIR observations at 6, 12 and 15° enabled by *phased array* radar show collapse and cascade strongest at Mag Zen. 15°

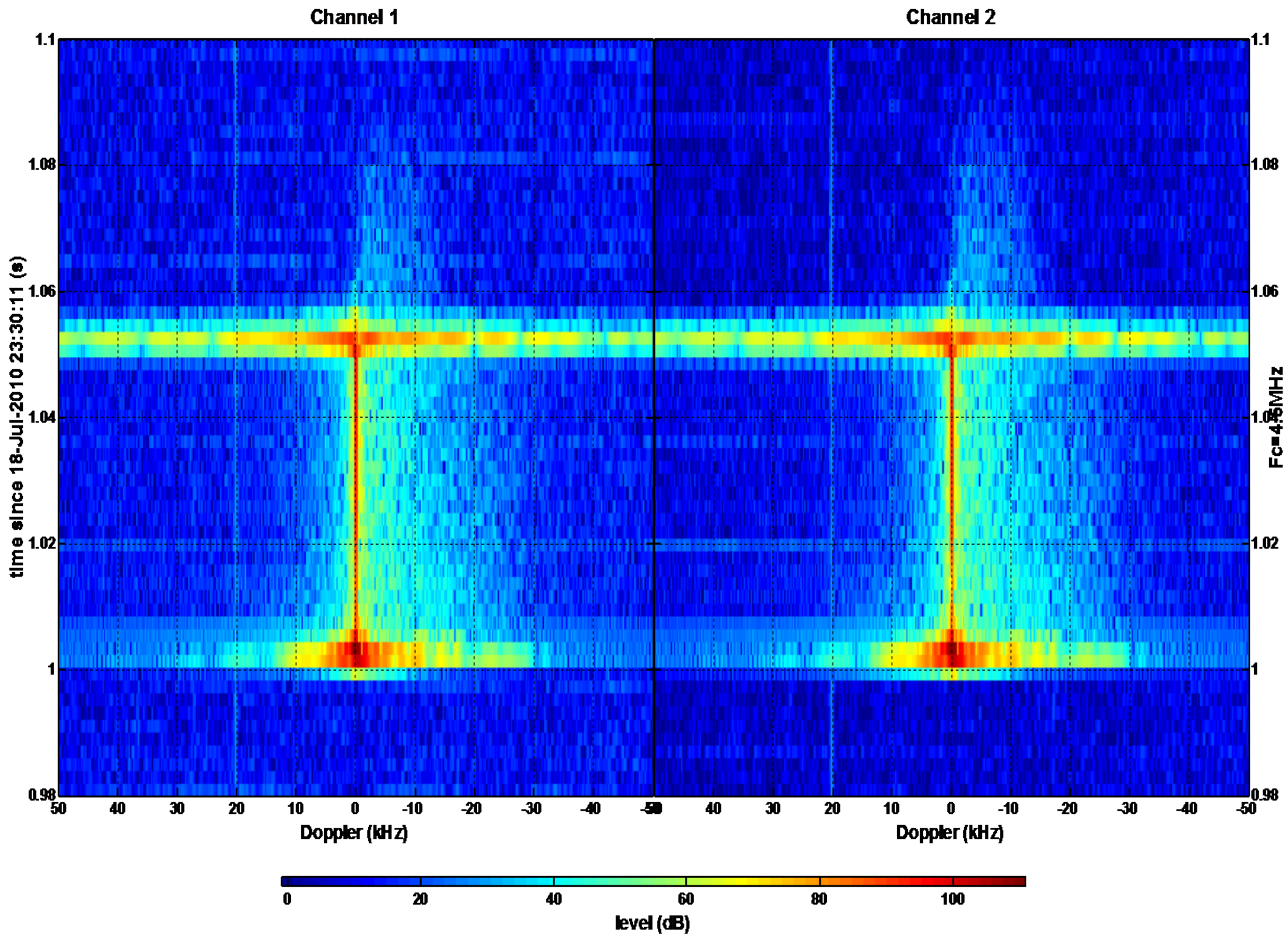
HF 7° has strong echo at UHF 15°



SEE Receiver

to compare with ES plasma waves in MUIR data

narrow continuum NC_p in the spectrum



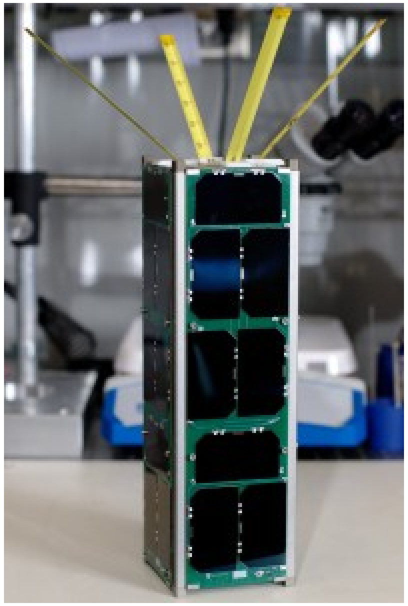
Time (UT)

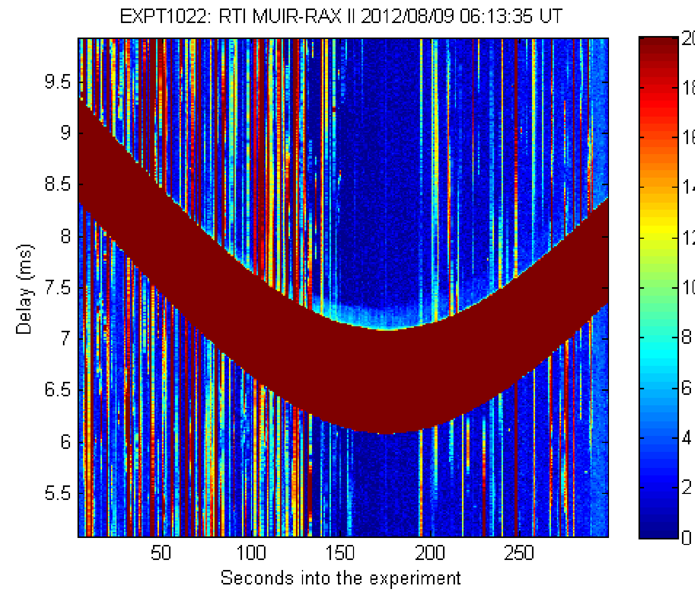
Positive ⟵ 0 ⟶ Negative Positive ⟵ 0 ⟶ Negative

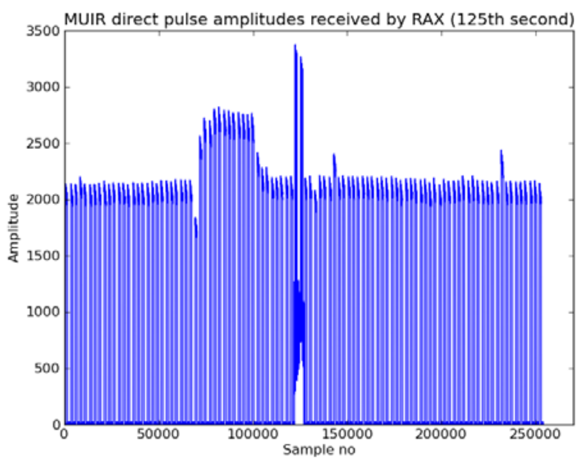
East – West Dipole

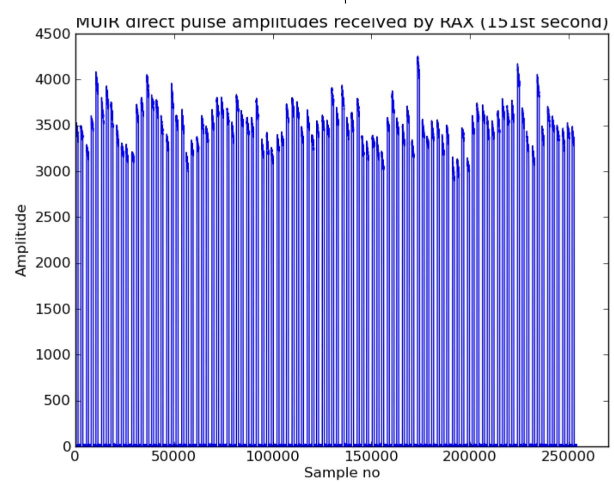
North- South Dipole

Bahcivan records AFAI from MUIR xtr on U.Michigan-built Cubesat RAX2 during HAARP experiment: first such expts









Summary and Conclusions

- Demonstrated suppression of HAARP-induced AFAI for HF ON < 60 ms *and* < 0.5% duty cycle

  Discovery: for HF at 11.5° (only) a lower threshold for AFAI; which is suppressed at all other aspect angles

Temporal evolution of plasma line:

- Mini-overshoot in collapse line observed ~ 3 - 6 ms
- Main overshoot after 30 ms / corresponds to onset of AFAI
- similar to observations at Arecibo, [Duncan and Sheerin, 1985]
- Bursty behavior in collapse and decay lines which *seed* AFAI

Spectra

- Observed cascade, collapse, and coexistence
- and outshifted PL (‘free mode’)

Summary and Conclusions cont'd.

- **<u>HAARP is *uniquely* suited</u>**
  - to study ionospheric irregularities
  - that cause scintillations impacting GPS/GNSS

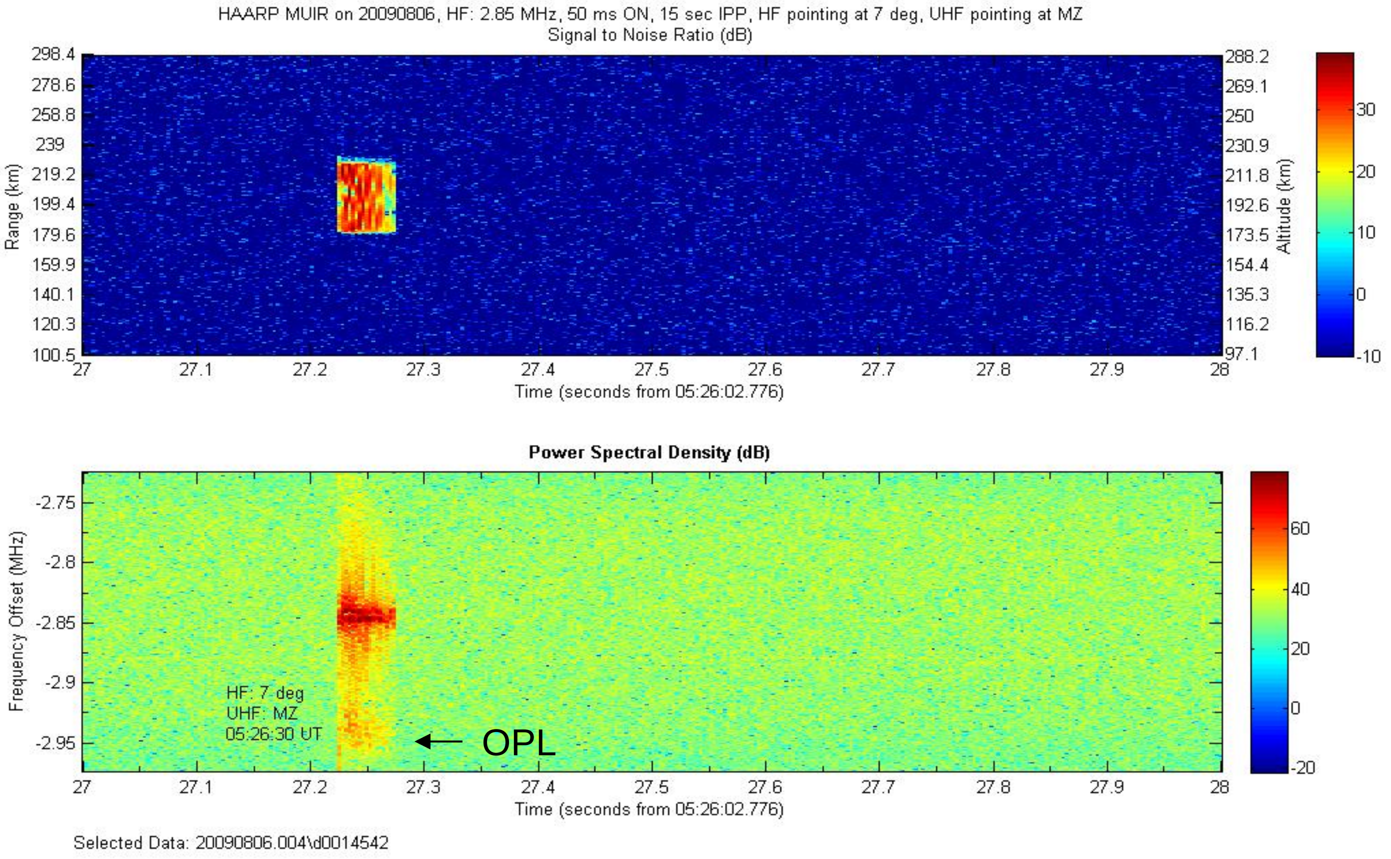
HAARP's <u>unique capabilities</u> that enable <u>this study</u>:

- *<u>phased-array</u>* allows millisecond <u>re-pointing</u>
- *<u>Modulation</u>* of HAARP power in < millisecond to control
- *<u>ERP</u>* dynamic range to highest intensities anywhere

HAARP's location uniquely enables ground to US S/C experiments

including CubeSats

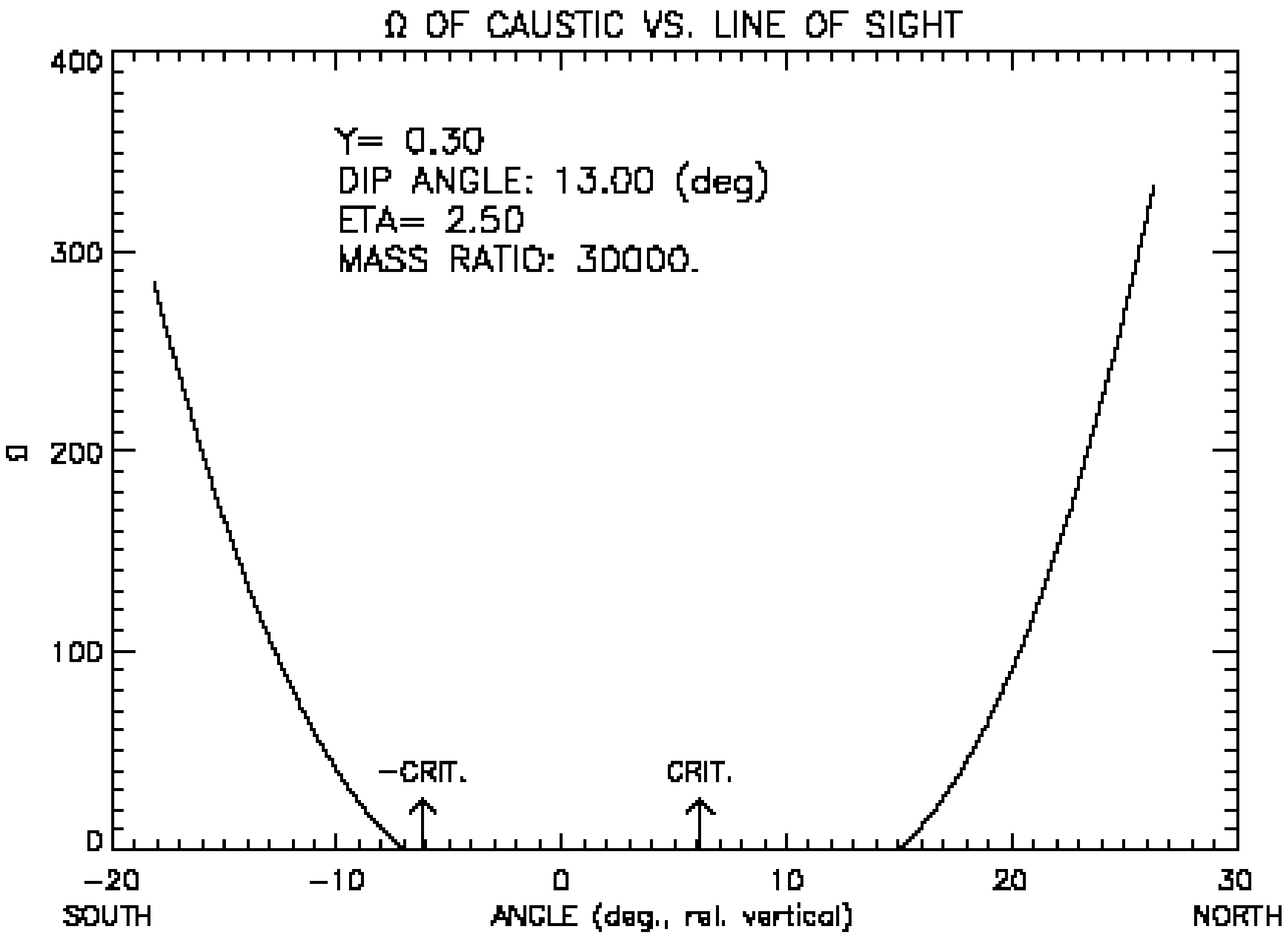
Coex - Single shot plot for 05:26:30 UT
2.85 MHz, HF pointed at 7˚, UHF pointed at MZ
50 ms ON, 15 sec IPP



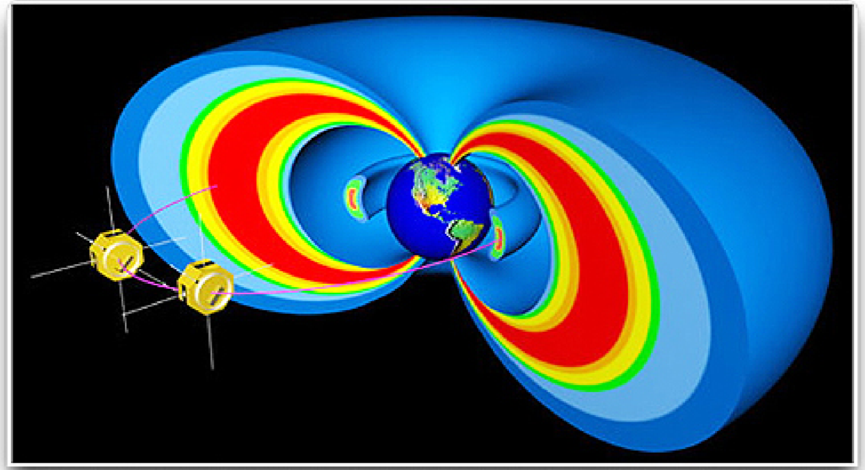
The collapse is present right at the pump frequency of 2.85 MHz.
It has two daughter lines below the pump frequency of 2.85 MHz
OPL are observed with coex

Threshold for OTSI (collapse) increases sharply with HF pointing angle beyond Spitze angle

Mjolhus, et al. NPG 10, 151 (2003)



HAARP can leverage many more multi-agency investments



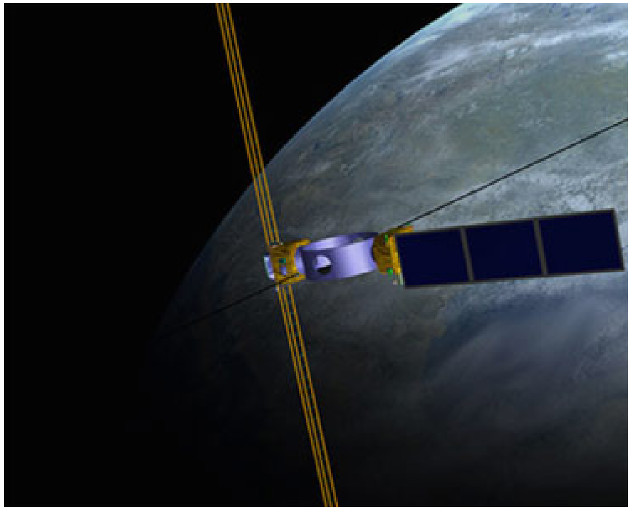
clockwise from below

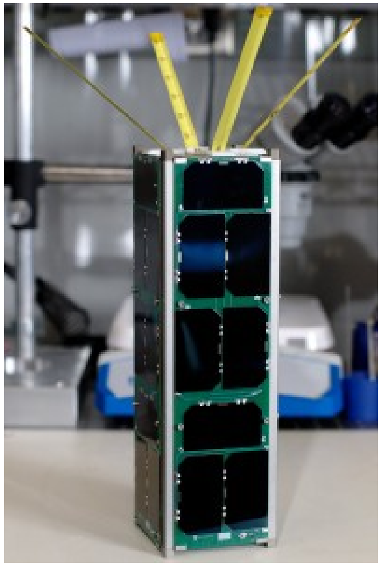
A NSF Arecibo HF facility 2014

U. Mich. **R**adio **A**urora e**X**periment

AFRL *DSX* - NASA *SETs*

NASA *Van Allen Probes*



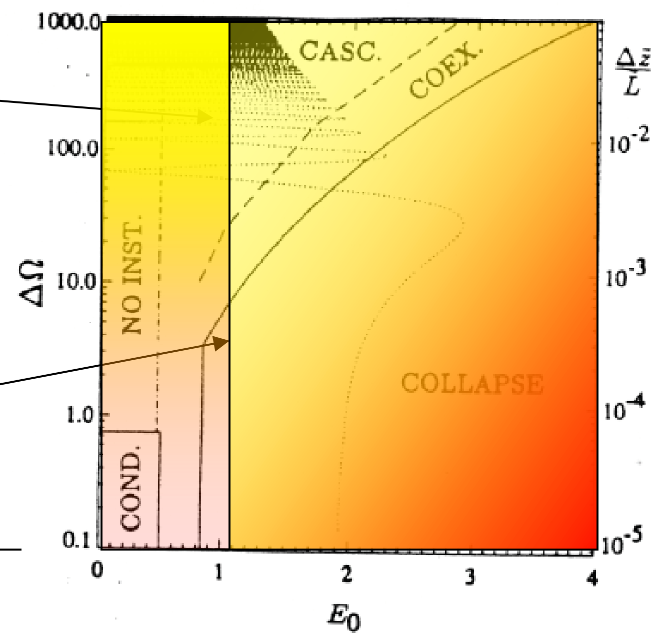


Cascade dominates below the critical reflection layer and lower powers
Collapse dominates close to reflection layer and/or higher powers
HAARP can enter collapse (or coex) regime over a greater range of alt.

Old HAARP expt along B and Tromso expt

Old HAARP expt near critical and AO expt

$f_{HF} = f_p$



Alt.

Our experiments show using

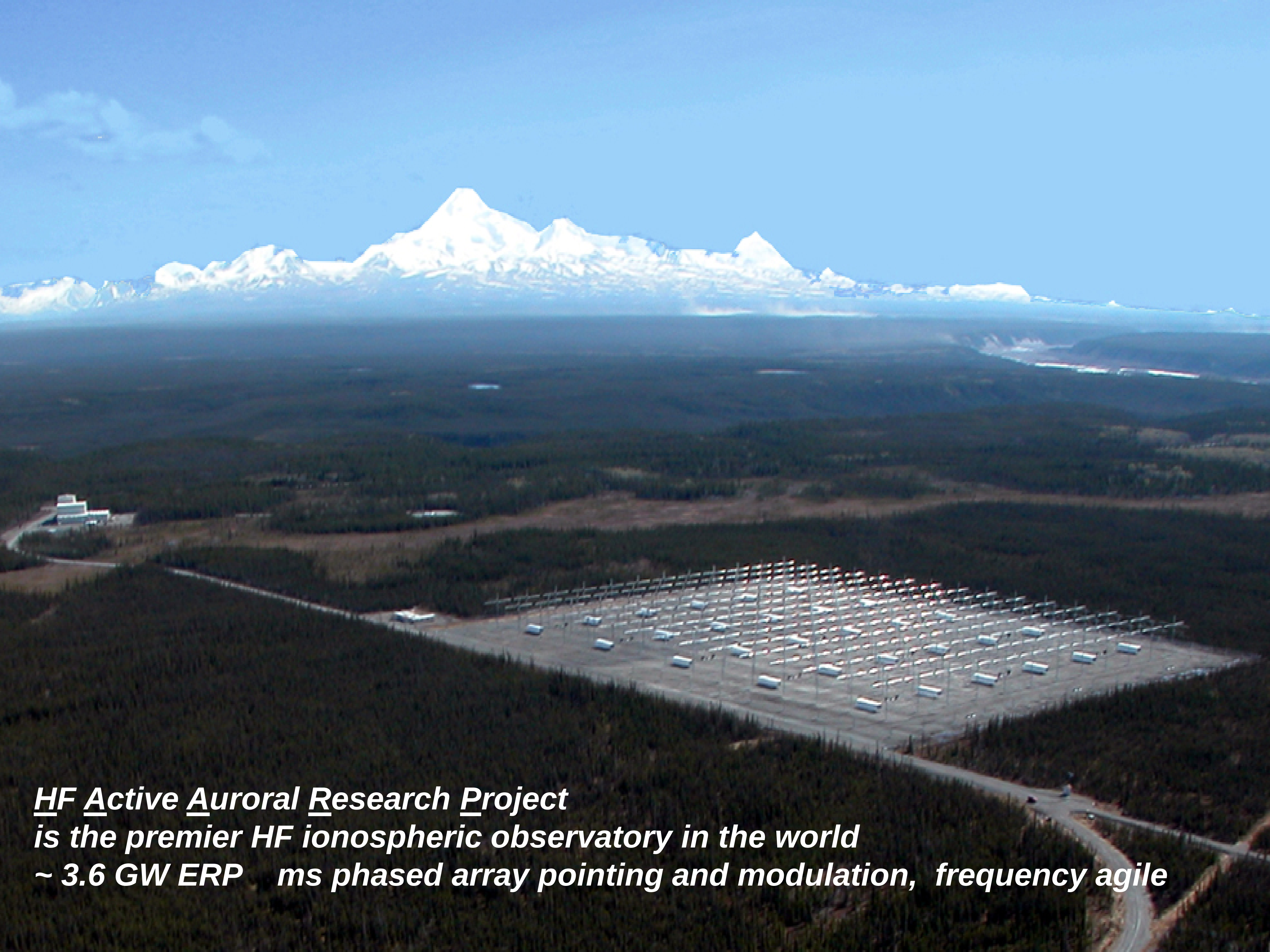
Full HAARP

we can produce either/both

by selecting HF pointing, power and MUIR pointing

Figure 1

Demarcation of the locations of collapse-dominated turbulence (marked *collapse*), cascade-dominated turbulence (marked *casc.*), and coexisting collapse and cascade turbulence (marked *coex.*), in the two-dimensional parameter space of pump strength, E_o, and altitude below the reflection altitude (right vert. axis). From Hanssen et al (Ref. 10).


HF Active Auroral Research Project
is the premier HF ionospheric observatory in the world
~ 3.6 GW ERP   ms phased array pointing and modulation, frequency agile

Ionospheric Diagnostic Instruments at HAARP

- **All sky Riometer**
- **Imaging riometer 8 X 8 Array**
- **Fluxgate Magnetometer**
- **Induction Magnetometer**
- **Digisonde**
- **Optics**
  - **All-sky imager**
  - **Telescopic imager**
  - **Photometers**
  - **14 ft Optical Dome**
- **Tomography Chain (Cordova -> Kaktovik)**
- **VHF Radar (139 MHz)**
- **Modular UHF Ionospheric Radar (MUIR)**
- **Ionospheric Scintillation Receivers**
  - **SATSIN (offsite)**
  - **GPS-NOVATEL**
  - **Total Electron Content**
- **Radio Background Receivers**
  - **Broadband ELF / VLF Receiver network.**
  - **SEE Receiver string.**
  - **HF to UHF Spectrum Monitor**
- **HF 2-30 MHz High Angle Receiving Antenna**
- **Scanning Doppler Interferometer (SDI)**