Using Space As A Nonlinear Plasma Laboratory

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Invited Tutorial Paper

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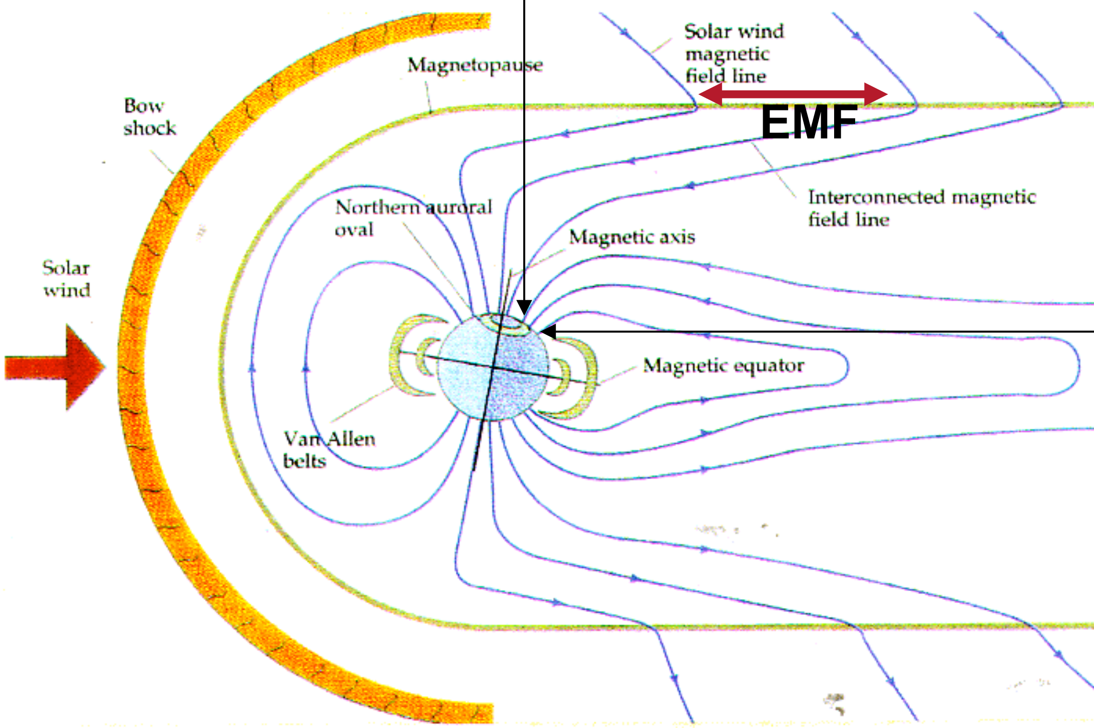
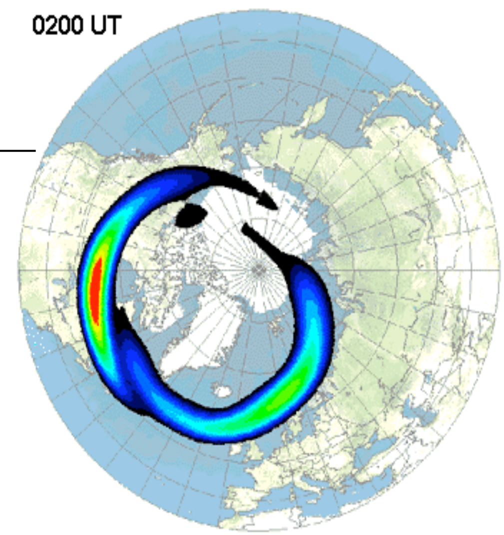
November 18, 2008
Dallas, Tx

Space Plasma Environment

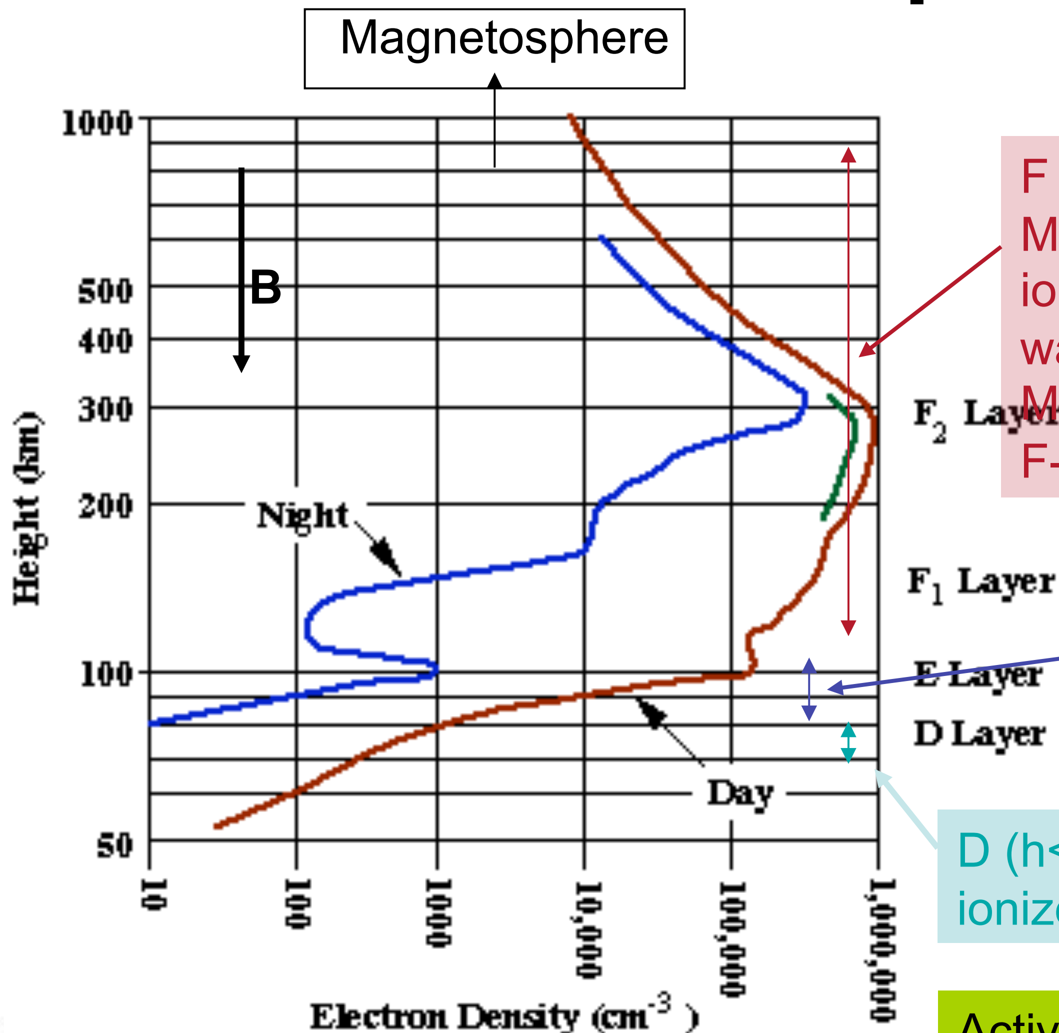
Ionosphere



Electrojet



The Polar Ionosphere as Plasma



F (h> 120 km):Collisionless ($\nu << \Omega$), Magnetized plasma – Electron and ion plasma waves, cyclotron waves, whistlers, MHD (Shear-Msonic) waves. Notice min. of V_A at F-peak.

E(70<h<120 km): $\omega_e, \Omega_e > \nu$, $\Omega_i < \nu$ EMHD plasma – Helicon waves – no Alfven or Ion Cyclotron waves

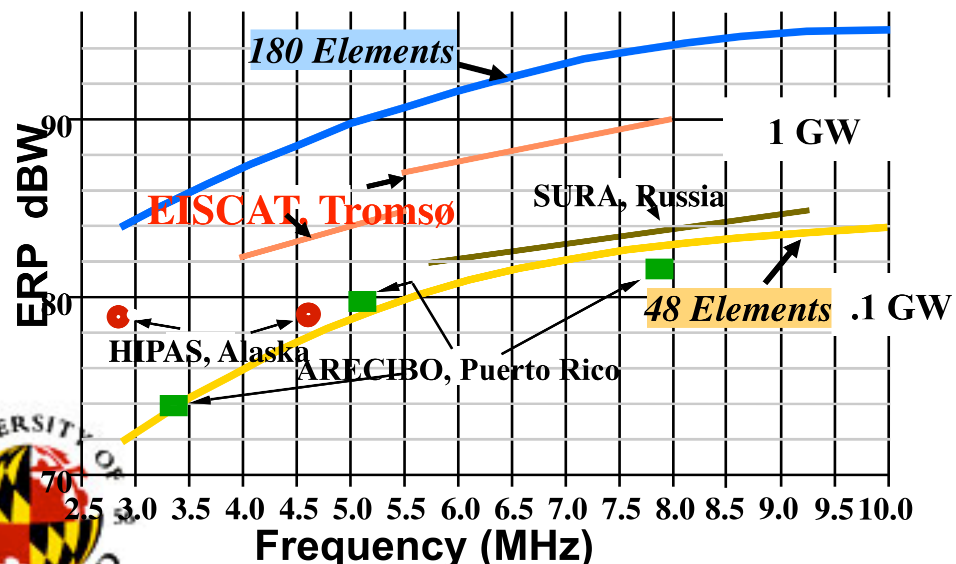
D (h<70 km): $\nu > \Omega_e, \omega_e$ weakly ionized gas – not plasma

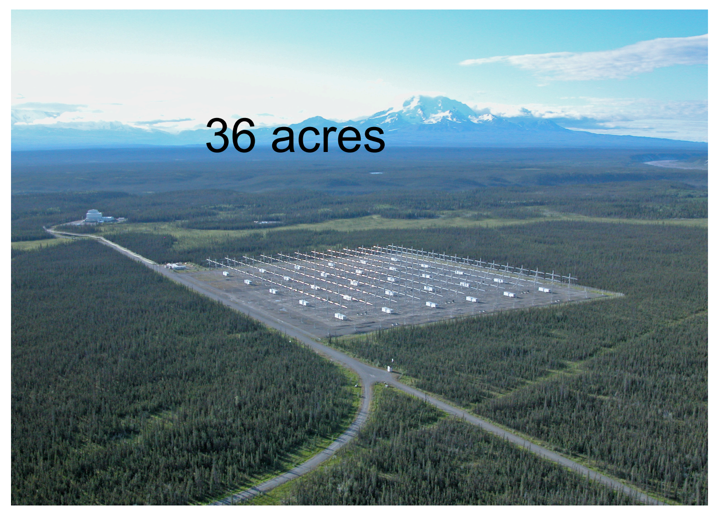
Active Regions (Plasmas with Free Energy): E-Electrojets

Active Experiments
Inject Energy in Space
Ionospheric Heaters – HAARP

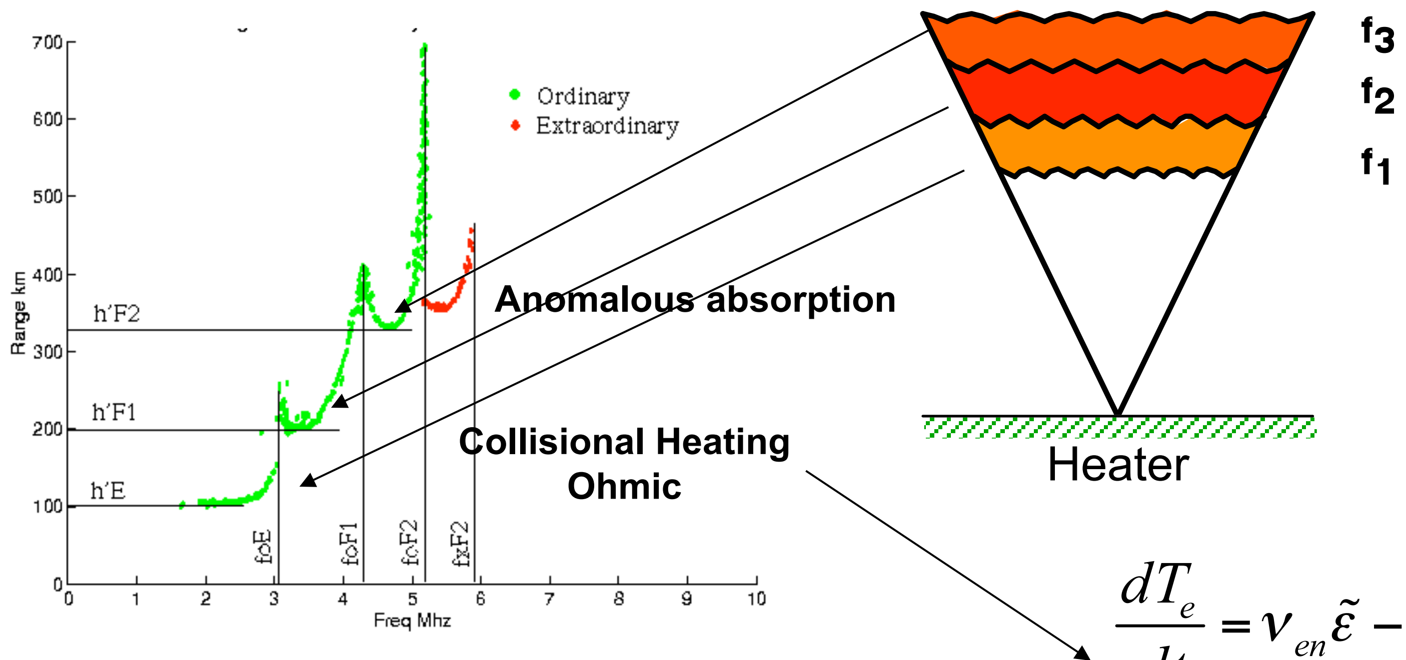
- **Ionospheric heater - Powerful HF transmitter (2.8-10 MHz) that induces controlled temporary modification to the electron temperature at desired altitude.**

- **Use in conjunction with diagnostics to study, in a cause and effect fashion:**
  - **EM propagation, plasma turbulence and instabilities**
  - **Response of magnetospheric plasma and Radiation Belts to controlled perturbations of the ionospheric plasma**





How to control location and profile of electron heating



$$\frac{dT_e}{dt} = \nu_{en}\tilde{\varepsilon} - losses$$

$$\tilde{\varepsilon} = \frac{1}{2} m\left(\frac{eE}{m\omega_{eff}}\right)^2$$

$$\omega_{eff}^2 \approx (\omega \pm \Omega_e)^2 + \nu_{en}^2$$

Ionosonde - Radar

$$\omega_{pr} = \omega_e(h) = 5.6x10^4\sqrt{n(h)} \quad \text{O-mode}$$

$$\omega_{pr} = \omega_e(h) + \Omega_e/2 \quad \text{X-mode}$$

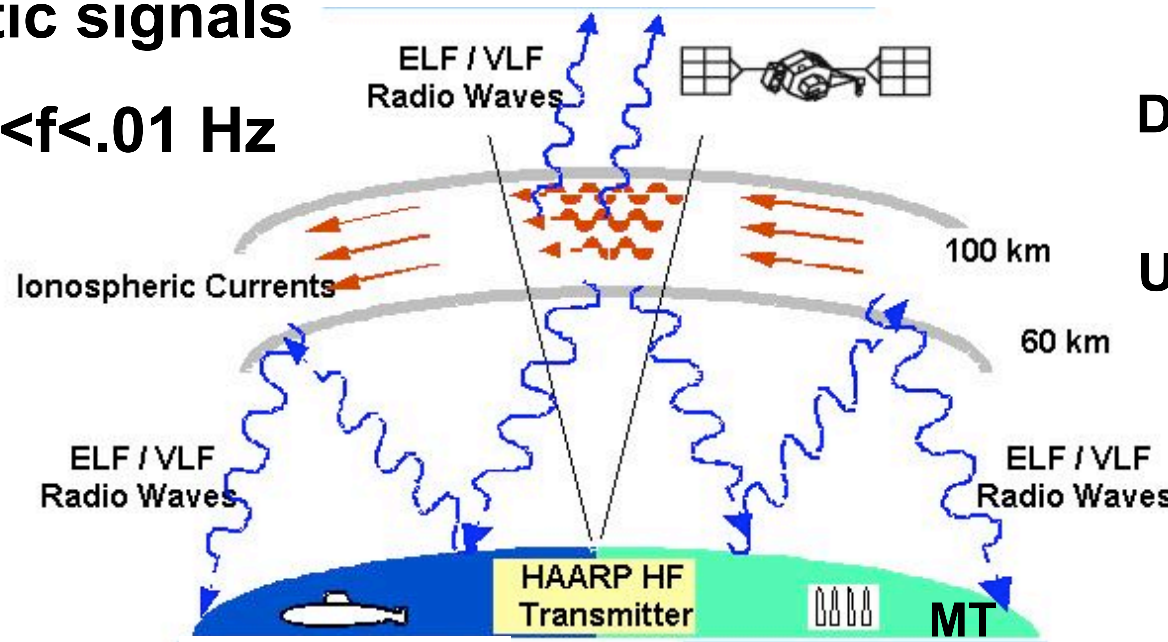
The Polal Electroiet (PEJ) Antenna

Use modulated ionospheric heating to inject controlled magnetic signals

30 kHz<f<.01 Hz

Study wave-particle interactions

Impossible to use conventional low frequency transmitters



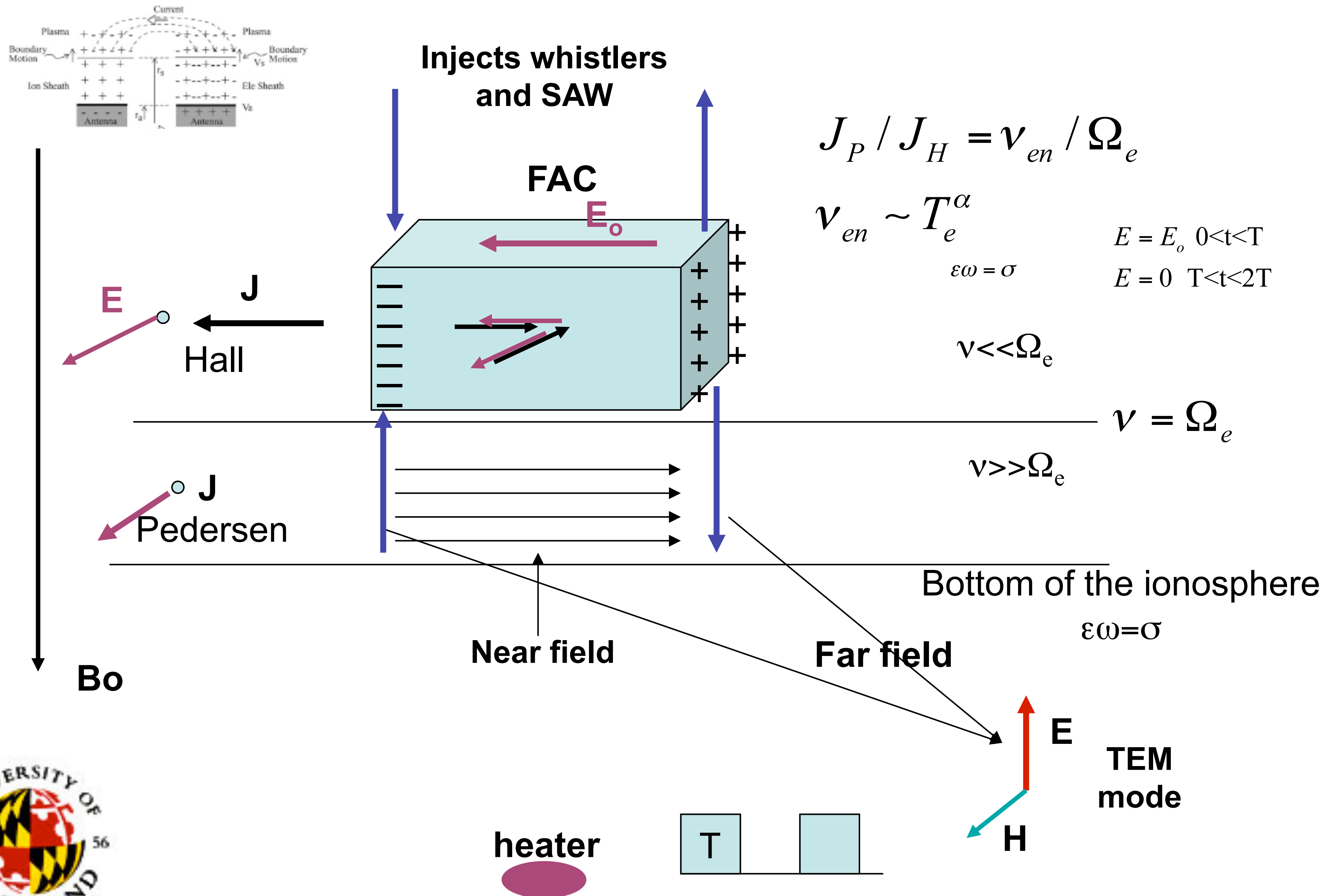
Downconvert HF to

ULF/VLF/ELF

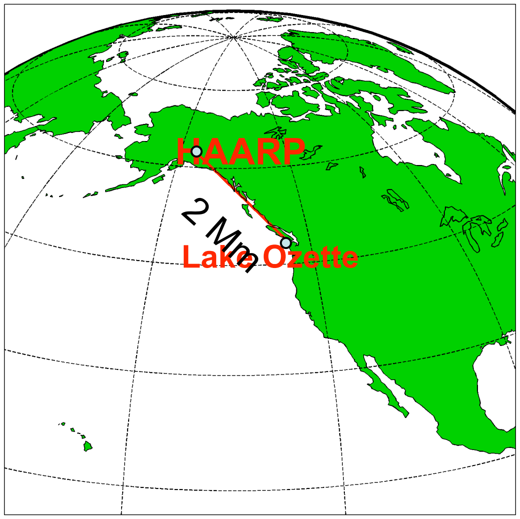
EM Energy

How does the PEJ work ?

The Plasma Physics of the PEJ



Where do we detect the effects

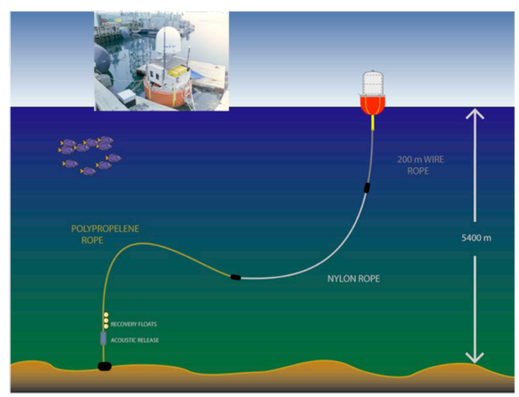


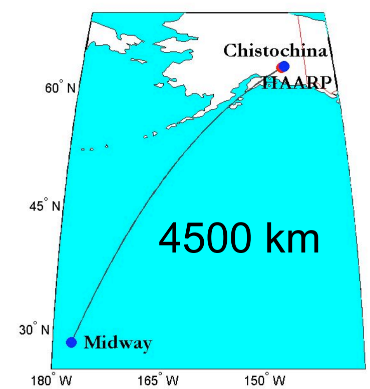
HAARP

DEMETER -DMSP

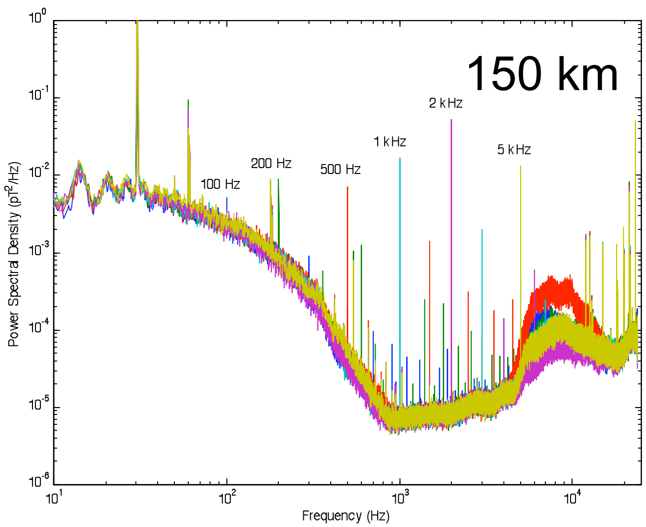
Ground Probes

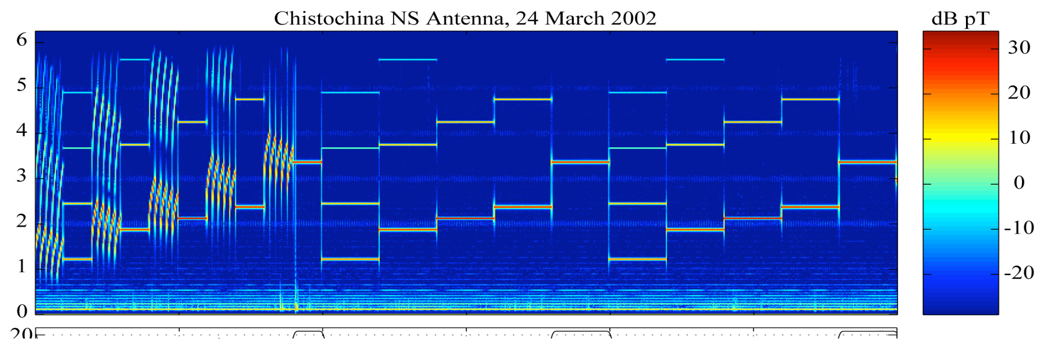
Satellite Probes 650-700 km

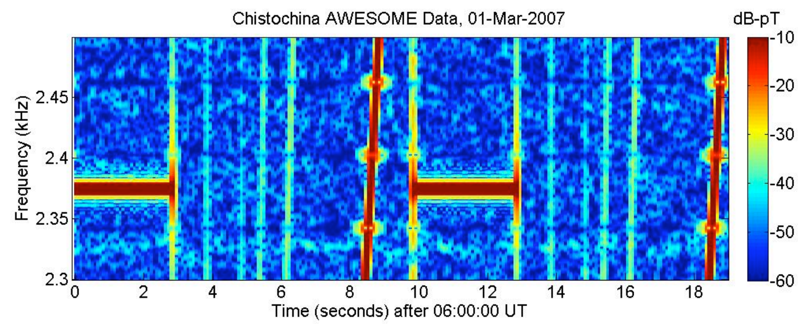


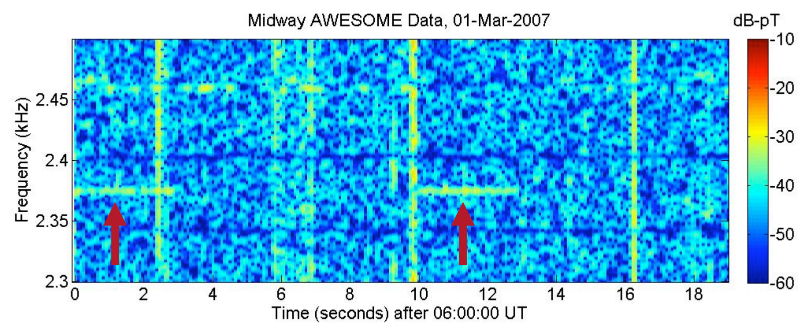


ELF/VLF ground detection and propagation



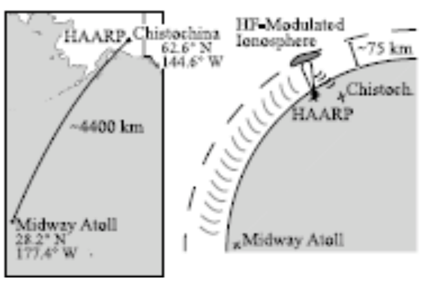






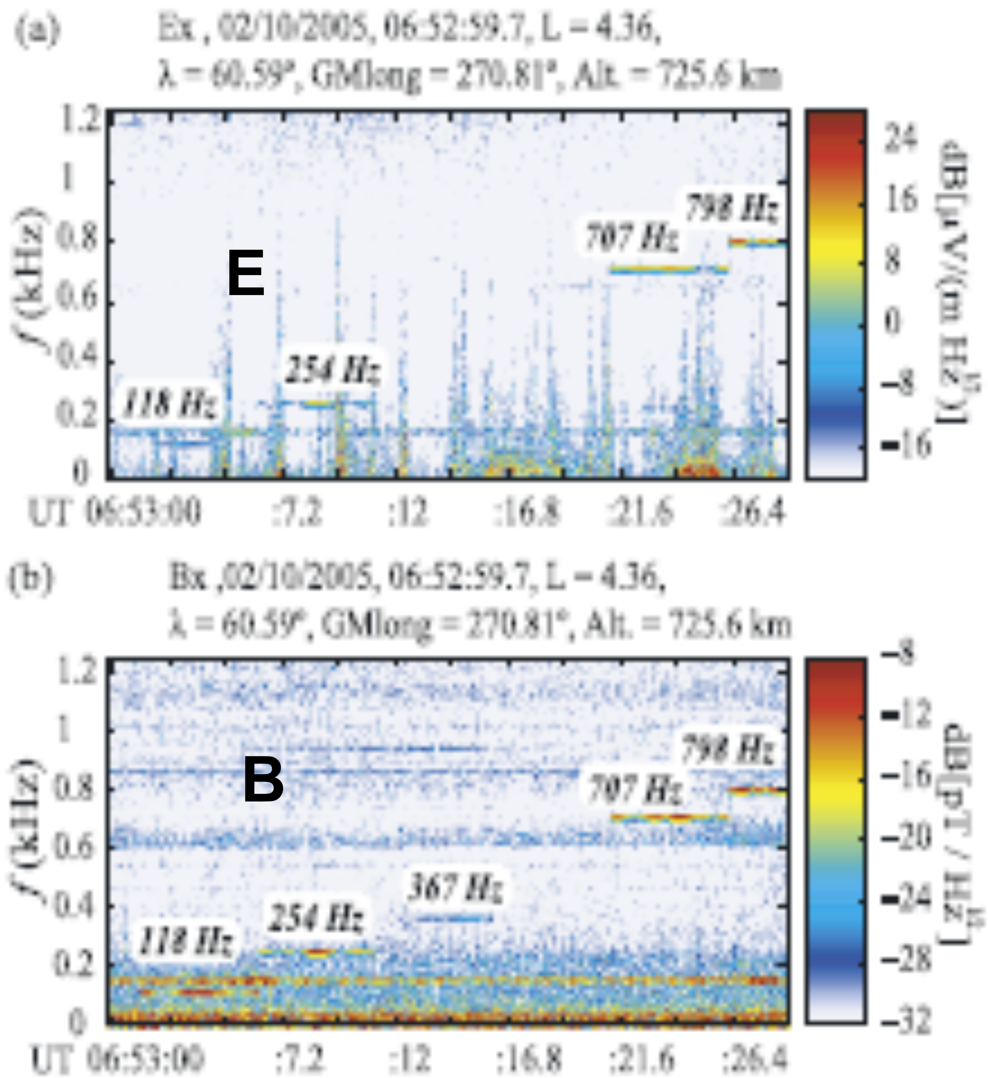
5400 km away

Midway

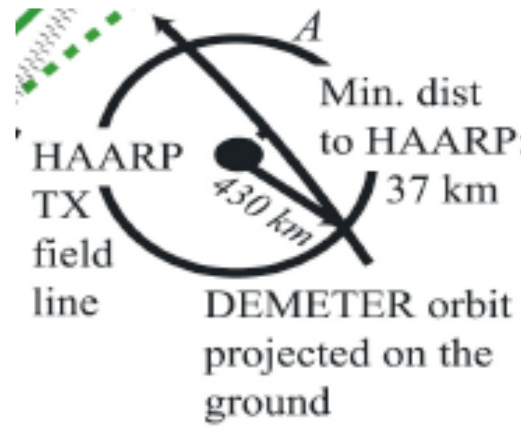


Moore et al. GRL 2008

VLF INJECTION IN SPACE



DEMETER - 700 KM ALTITUDE



Platino et al. GRL 2004

Physics Studies Using the PEJ

- Wave-particle interactions in the Radiation Belts – Whistler range
  - Artificially Stimulated Emissions (ASE)
- ULF (< 8 Hz) – MHD Study
  - E-I Guided propagation
  - SA wave injection in space
  - Excitation of the Ionospheric Alfven Resonator (IAR)
  - SA wave (Pc1) triggering

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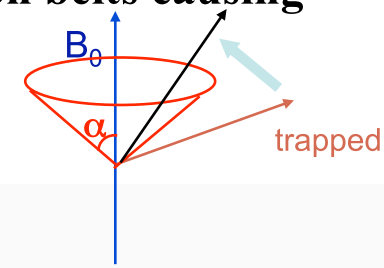
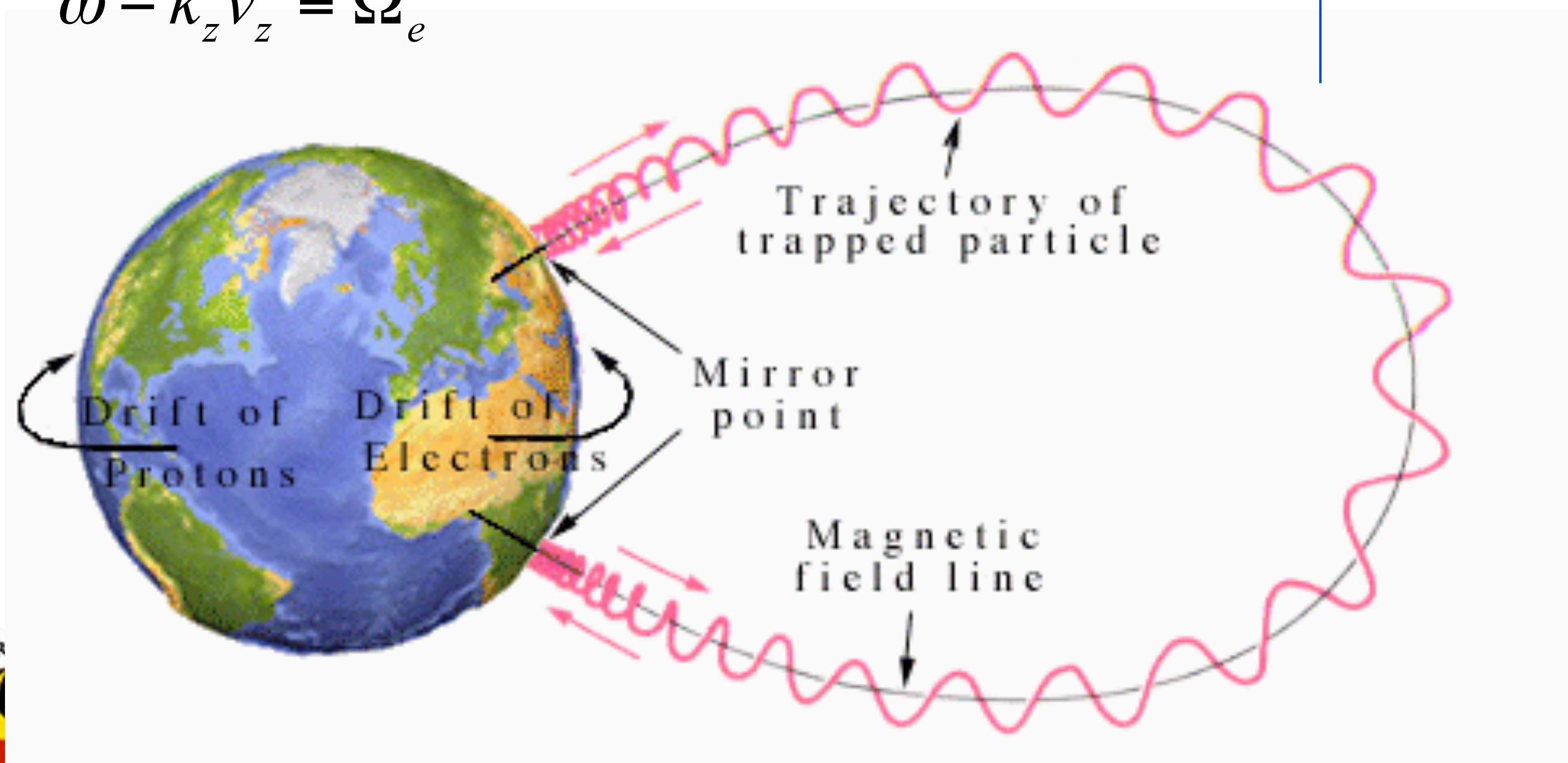
Controlled studies of cyclotron resonant wave-particle interactions

Whistler waves resonate with trapped particles in the radiation belts causing pitch angle scattering and precipitation.

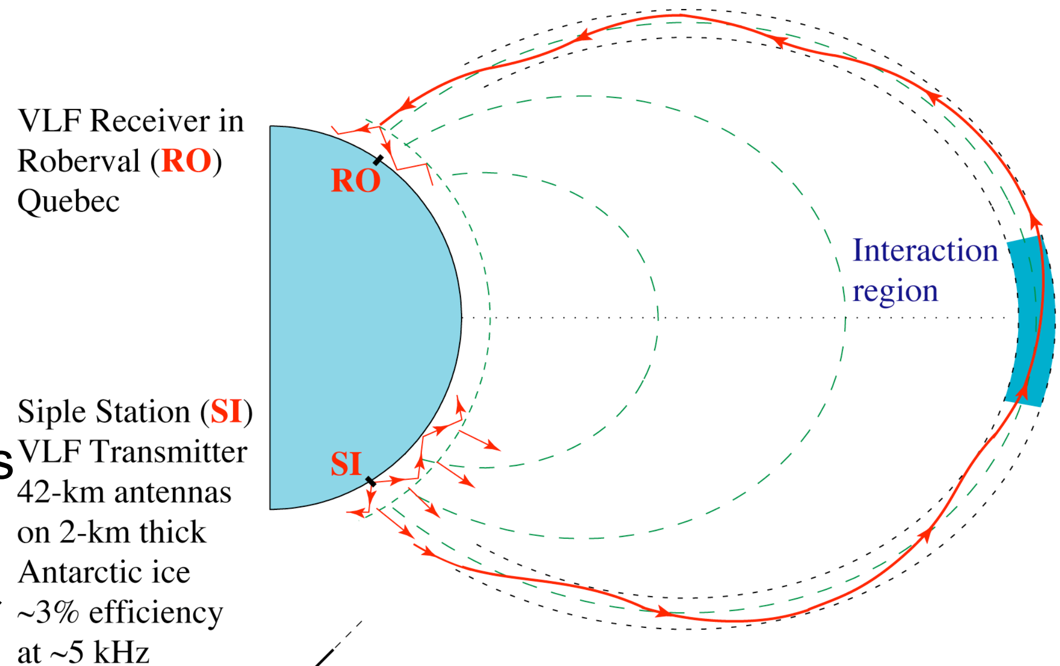


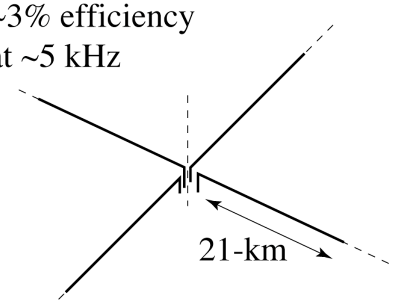
$$\omega - k_z v_z = \Omega_e$$

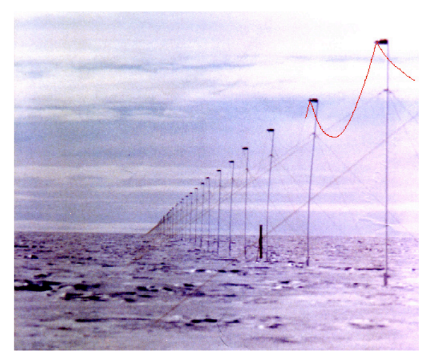


Siple Station, Antarctica VLF Wave-injection Experiment

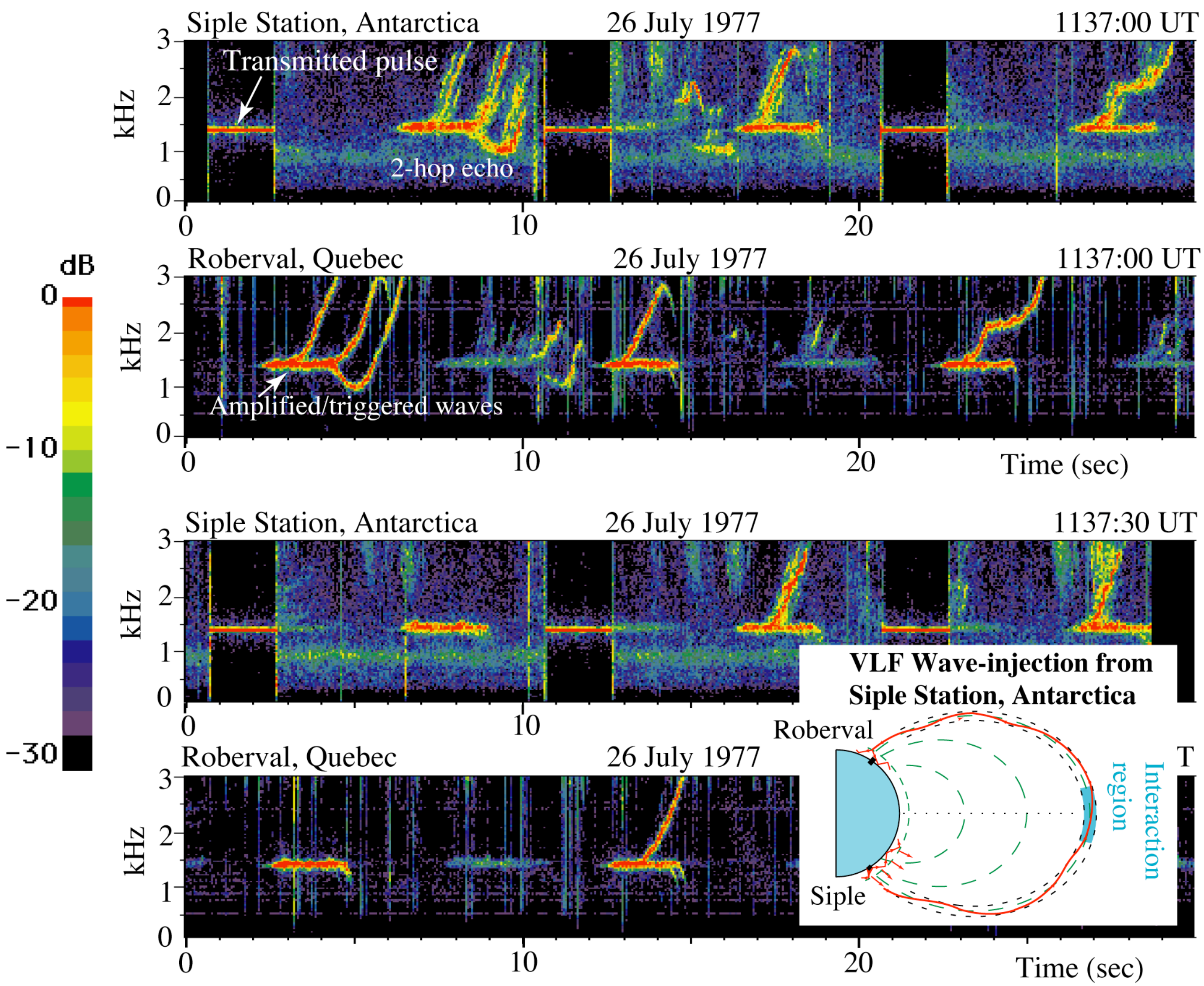
- NSF-funded Stanford experiment (1973-88)
- VLF waves (~1.5-5 kHz) injected from Siple Station, Antarctica
- 150 kW transmitter, 42-km antennas
- Tuned with large capacitors and coils
- VLF receiver at Roberval & Lake Mistissini, Quebec
- Controlled studies of cyclotron resonant wave-particle interactions
- Uncovered many aspects of wave growth & emission triggering



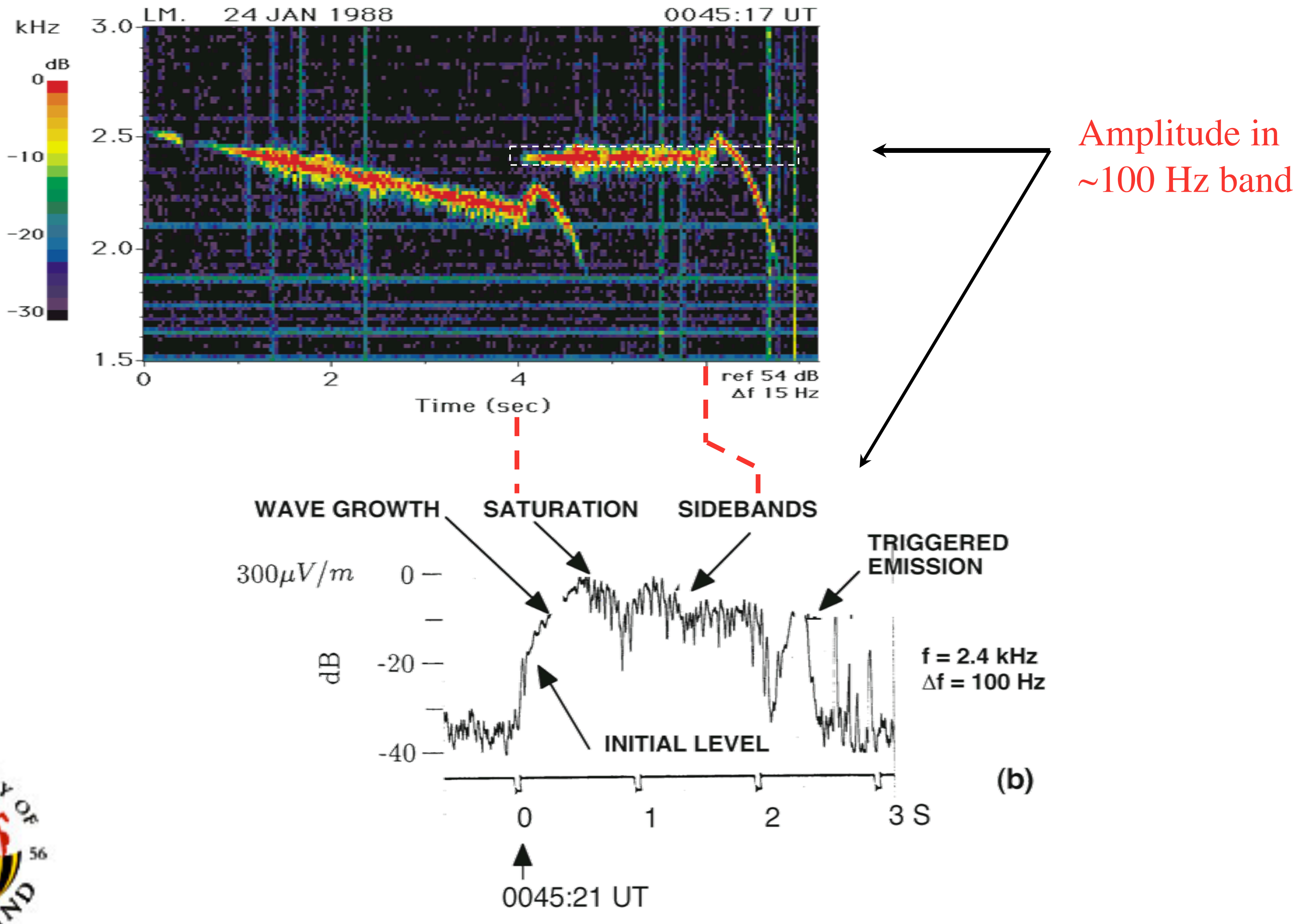




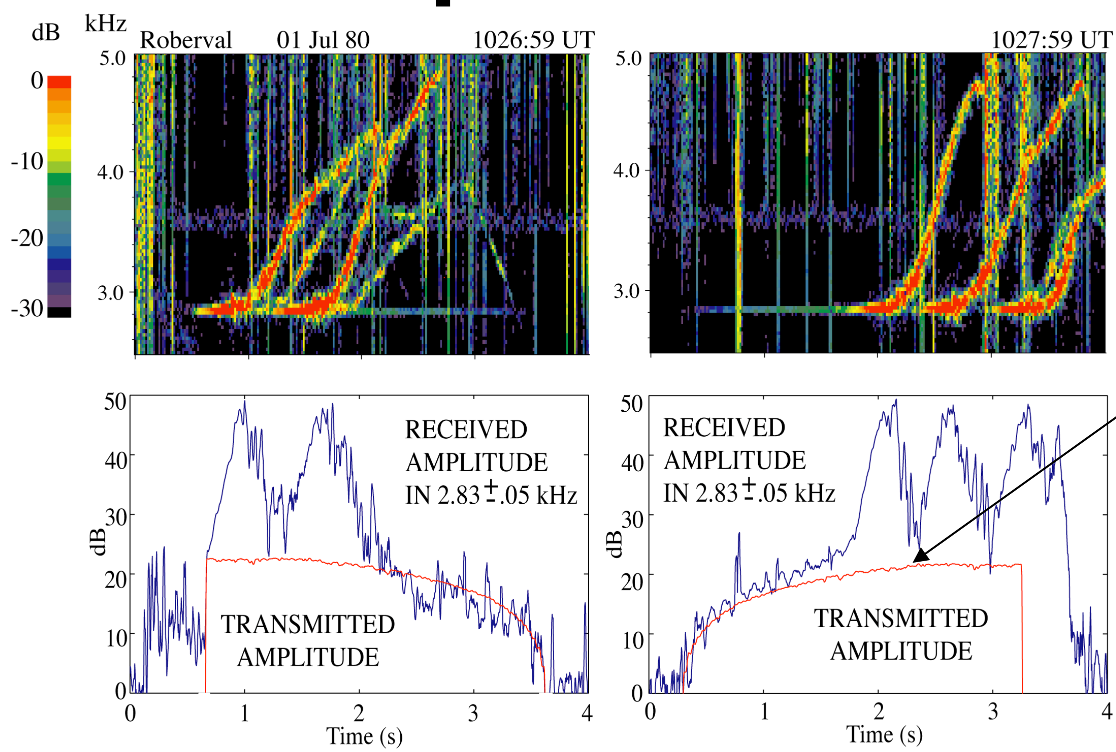
Amplified VLF Signals with Intense Triggered Emissions



Growth & Saturation



Amplitude Effect on Growth



COHERENT GROWTH
20-30 dB

- **THRESHOLD**
- **SIGNAL SATURATION**
- **TRIGGERED EMISSIONS**

– risers, fallers, hooks

- **ENTRAINMENT**

TRANSITION TO OSCILLATOR BEHAVIOR

A serious challenge to our current understanding of nonlinear plasma physics – See Lampe, Ganguli, Joyce, Manheimer YO3.9

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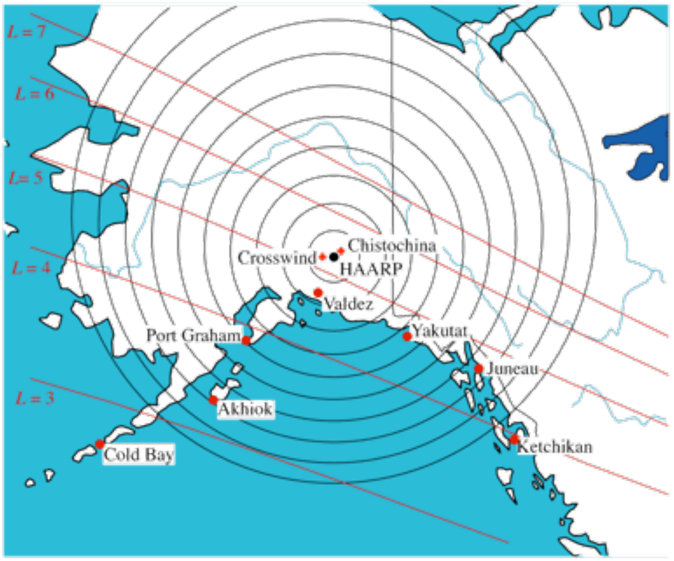
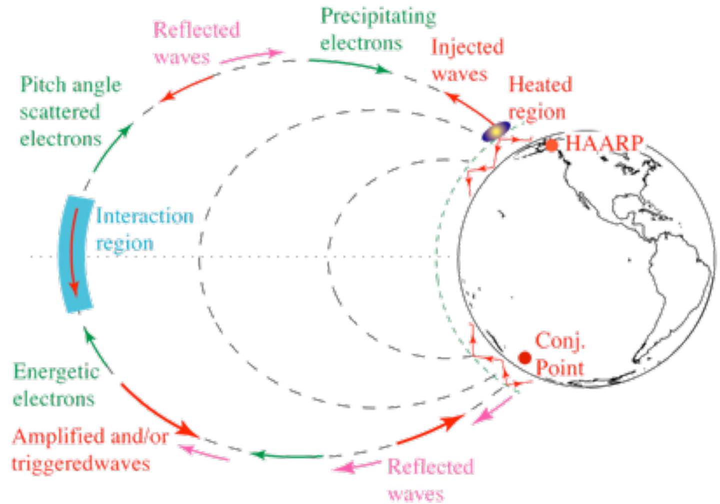
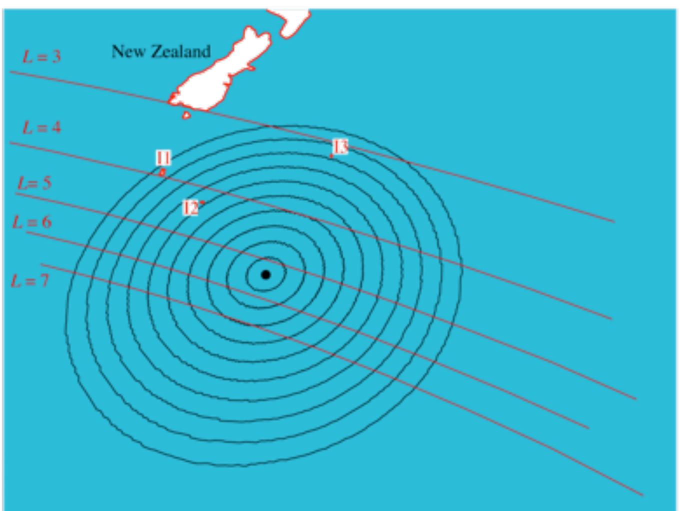
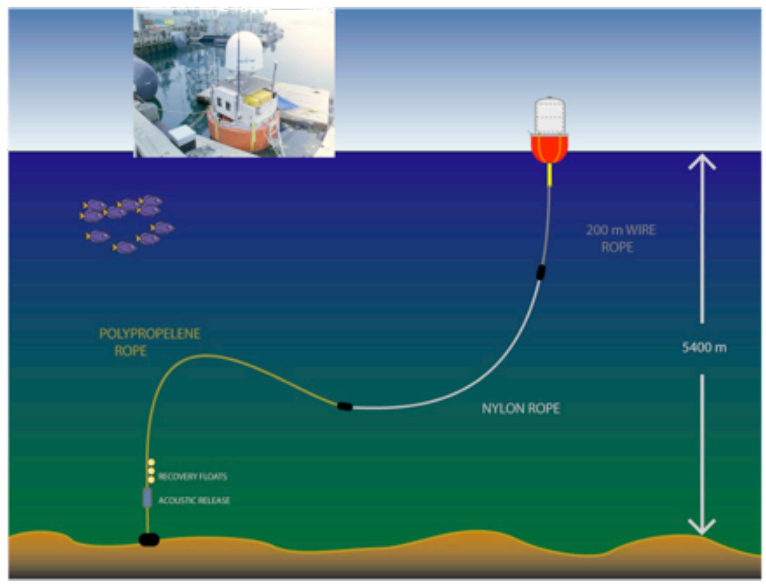
HAARP ELF/VLF INJECTION STUDY



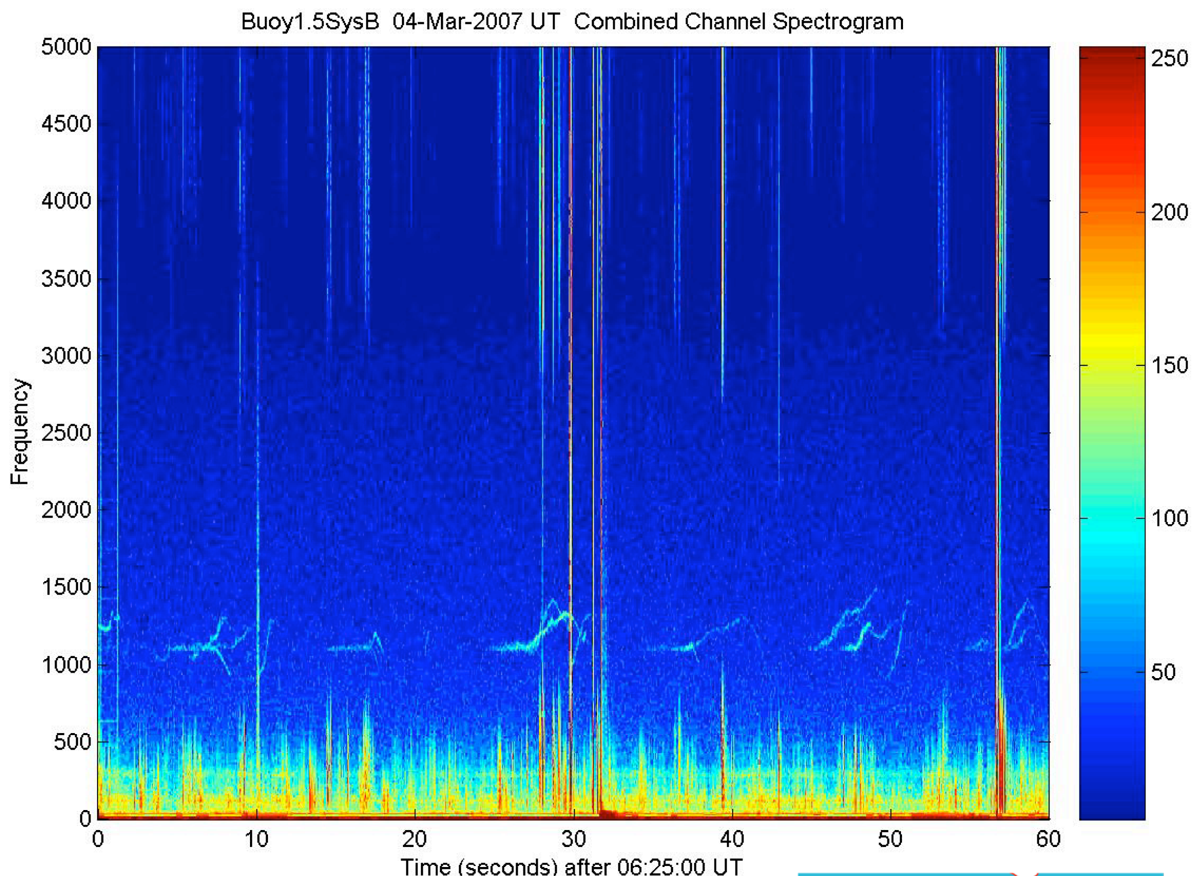


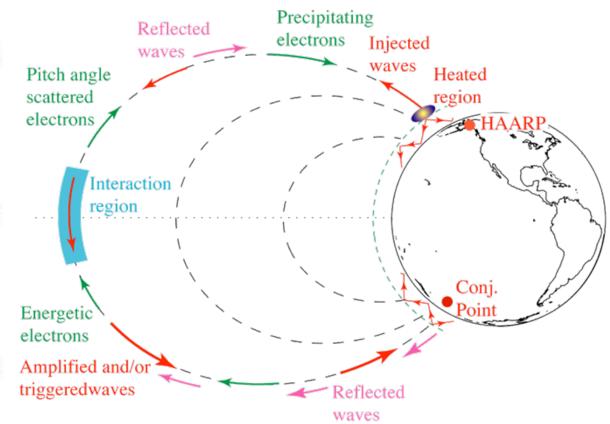


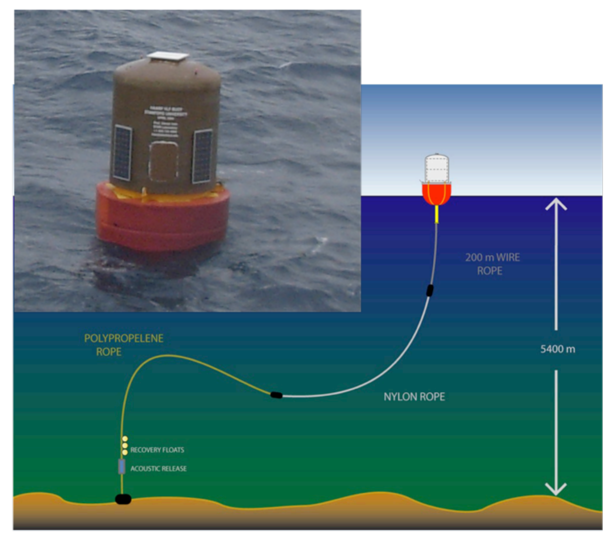


EXPERIMENTS CONDUCTED BY STANFORD UNIVERSITY – U. INAN

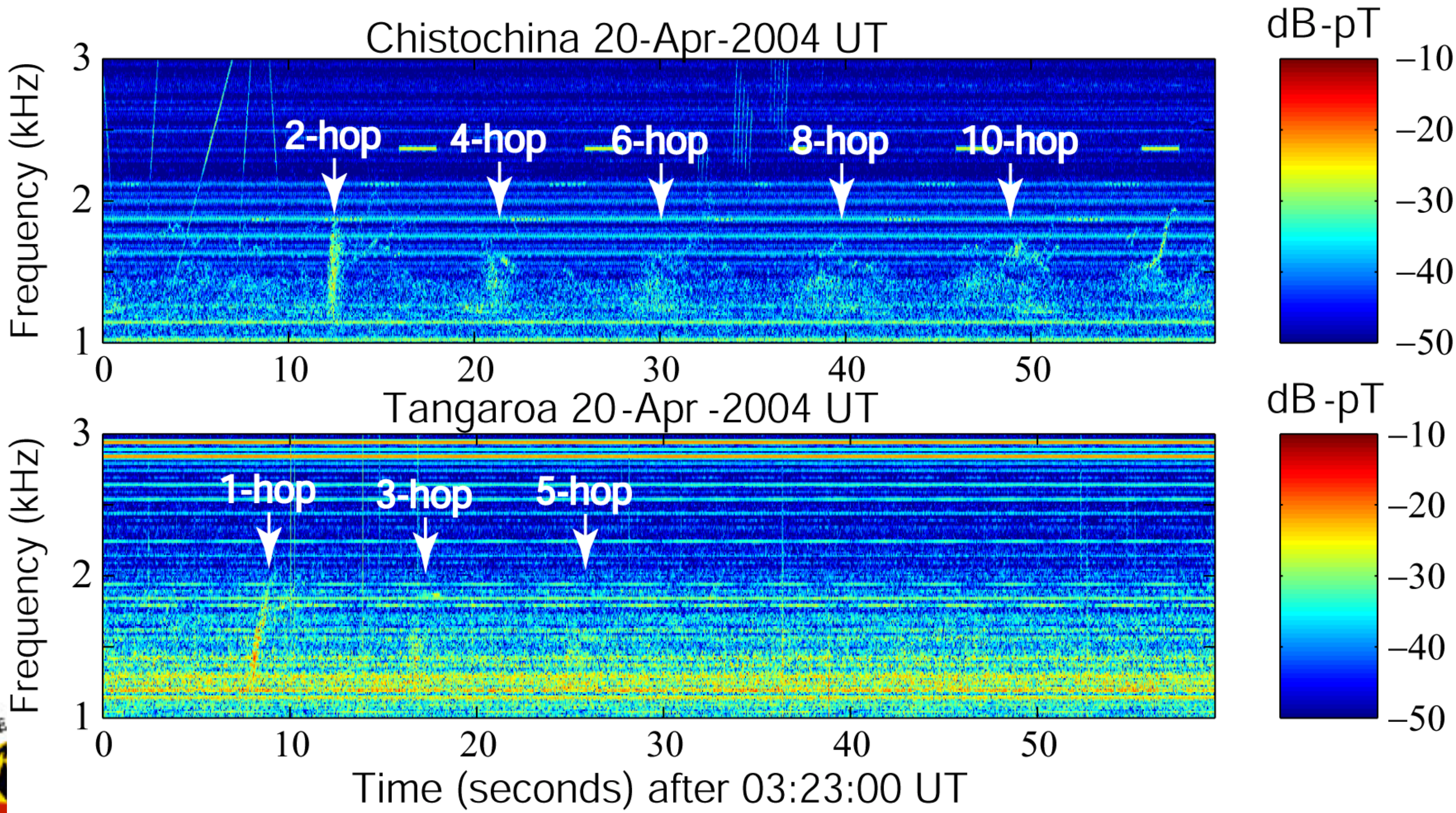
Amplified ELF Signals on the HAARP Stanford Buoy



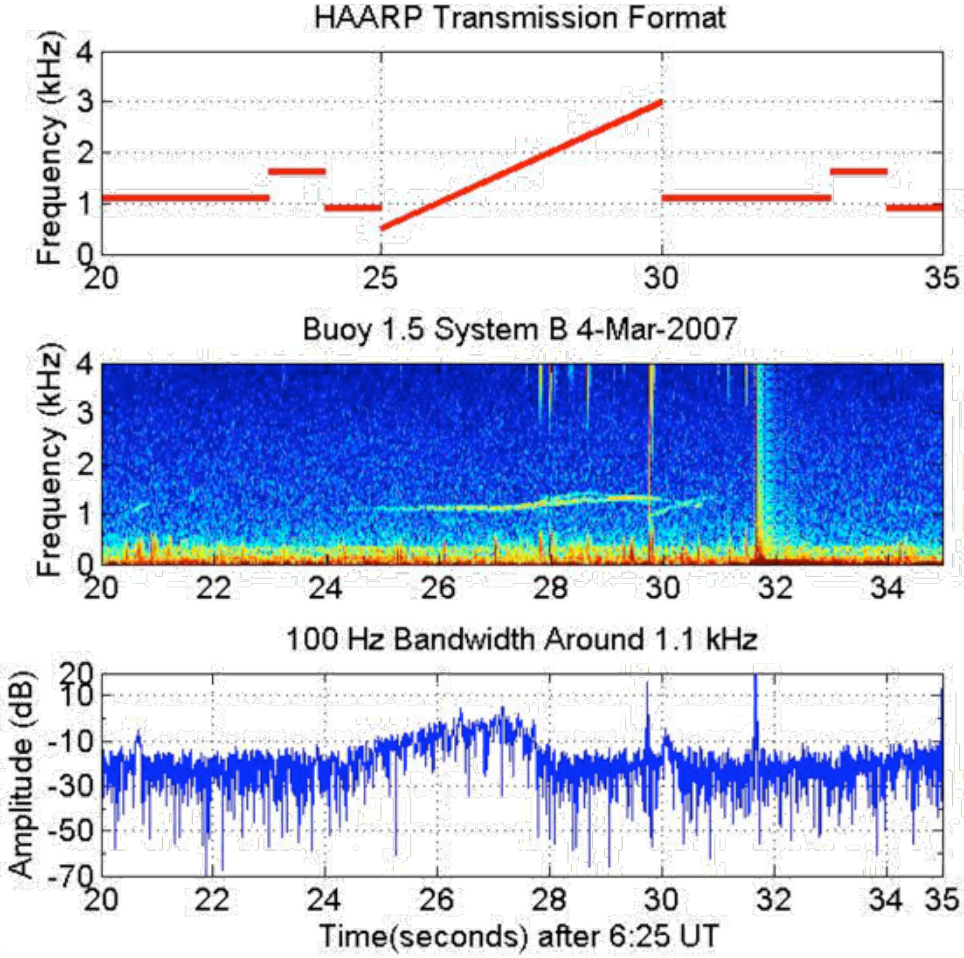


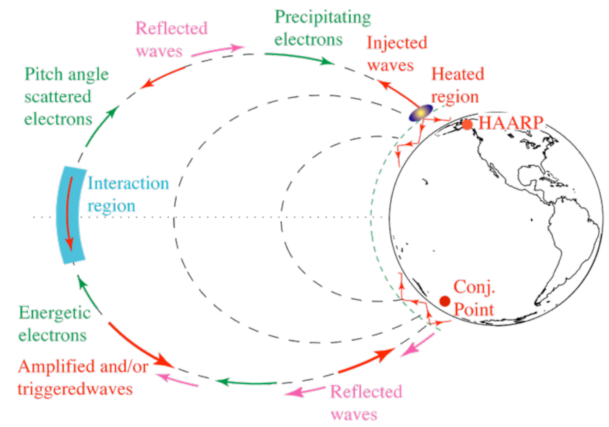


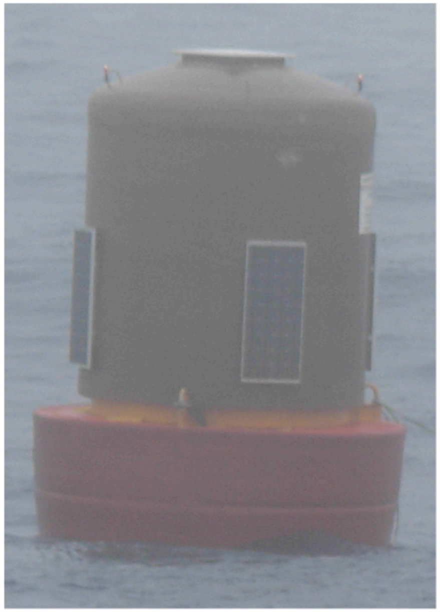
Multiple Traverses Between Hemispheres



15 dB/s Amplification & Triggered Emissions

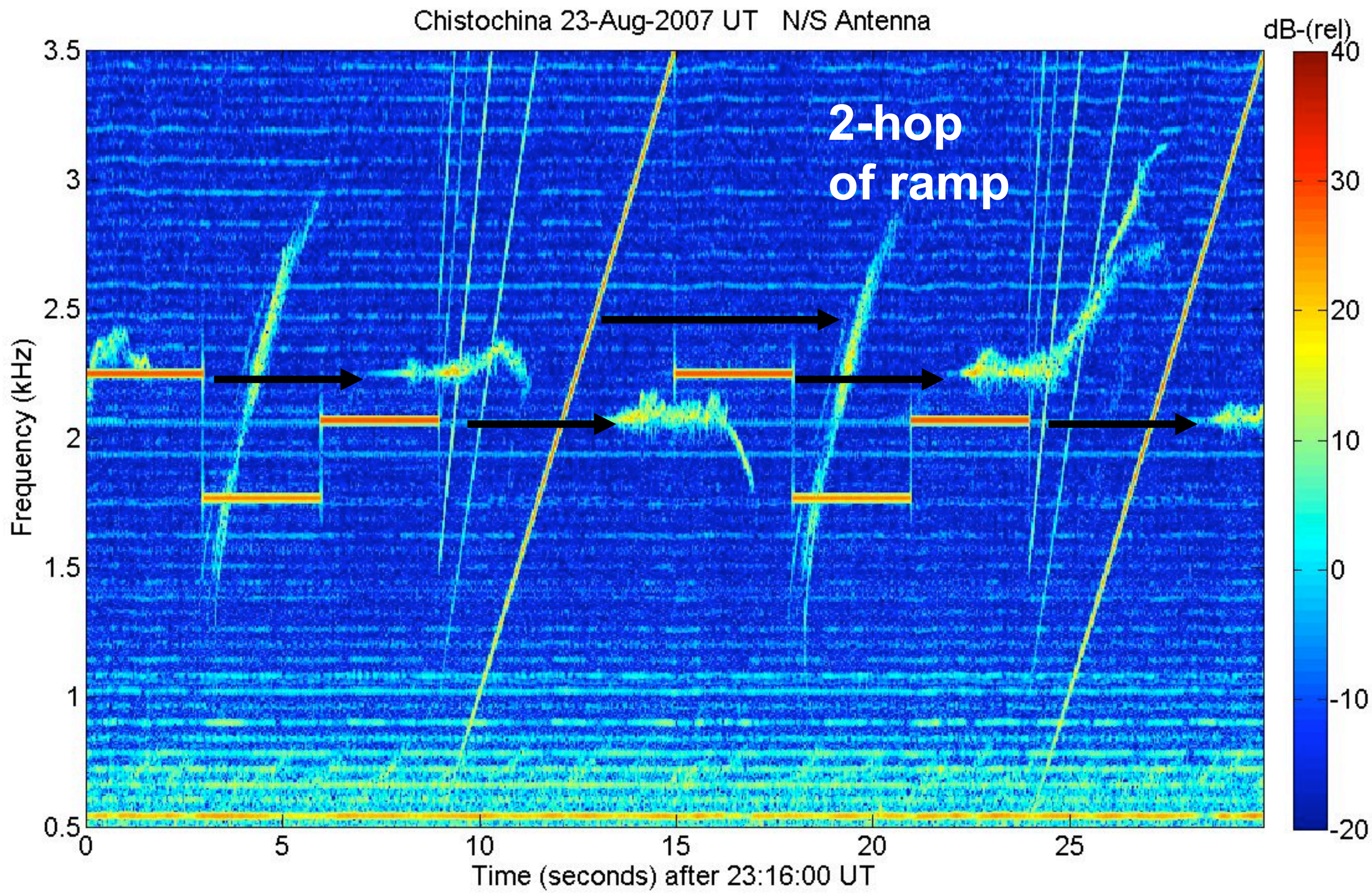






Only the pulse at 1100 Hz is amplified

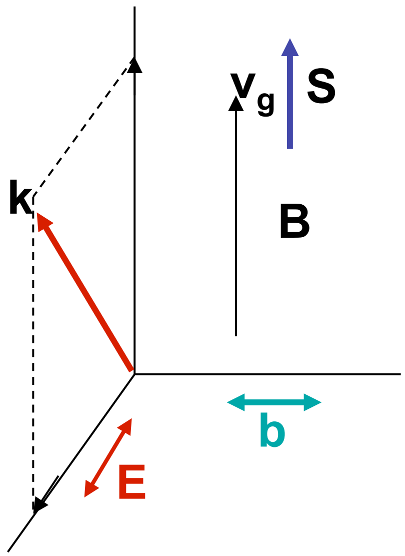
Two-Hop Echoes of HAARP ELF/VLF Pulses and Ramps



Pulses above 2 kHz have 1-hop echoes with triggered emissions

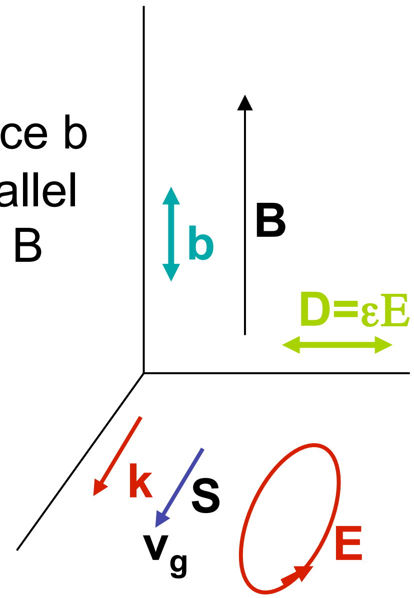
Pulse near 1.7 kHz does not; ramps have echoes with no emissions

MHD Wave Generation

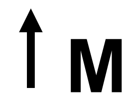


Shear Alfven (SA) guided by the magnetic field

Notice b parallel to B

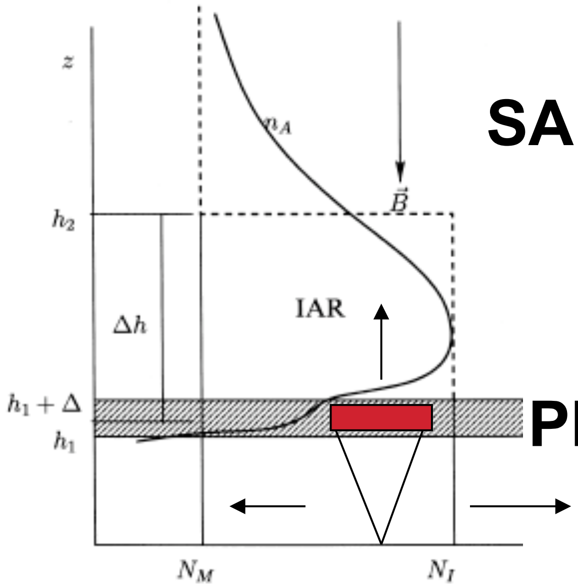


Magnetosonic (MS) Isotropic



PEJ injects oscillatory field aligned currents excites only SA modes

MHD Wave Generation by the PEJ



PEJ

SA will be guided by the magnetic field to the conjugates – No lateral propagation through the plasma

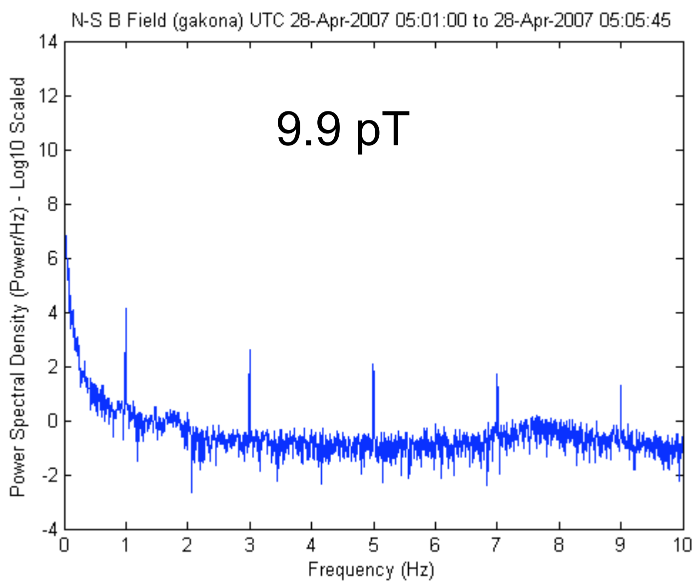
$$f \approx c / 2\pi R_E \approx 8 Hz$$ **Schumann**

Evanescent in EI Waveguide if f<8Hz

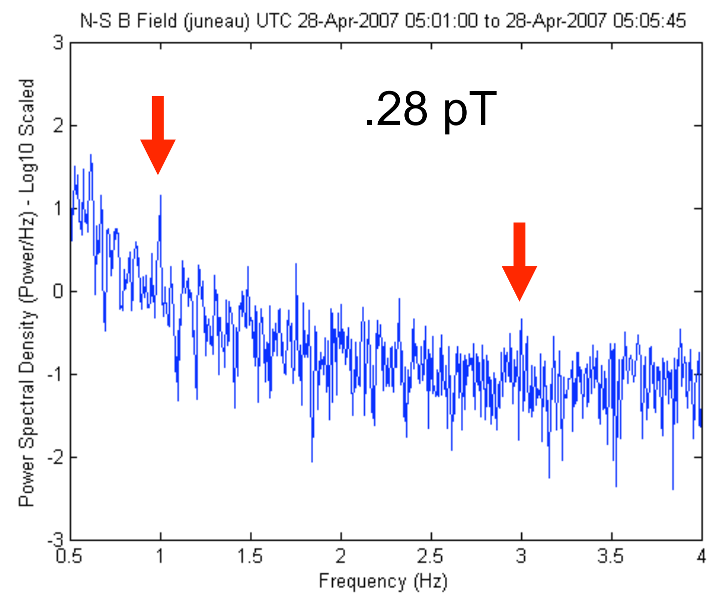
- **SA waves can be detected: (a) In the near zone below the heated spot and (b) By satellites over-flying the heated spot but confined to the magnetic flux tube that spans the heated spot (c) Through the EI waveguide for f>8 Hz (Schumann Resonance)**

ULF Signal Propagation Evanescent Mode (1 Hz)

Gakona

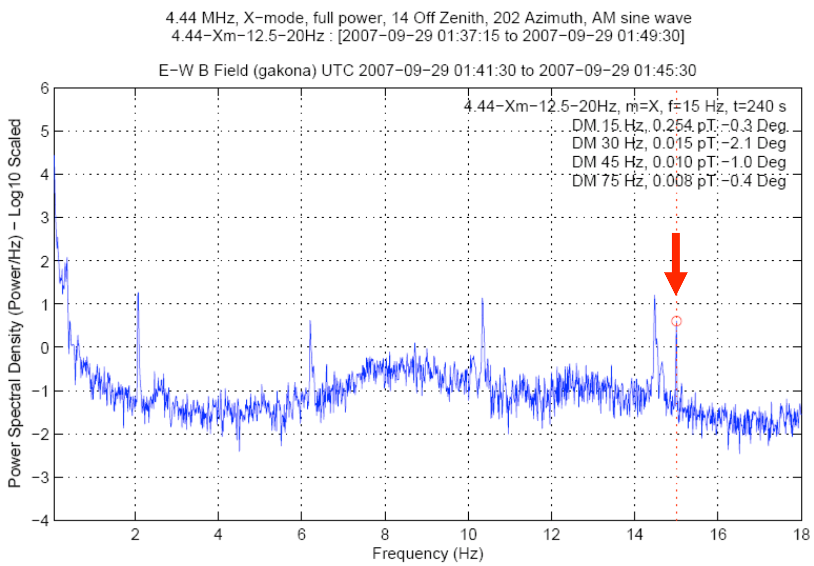


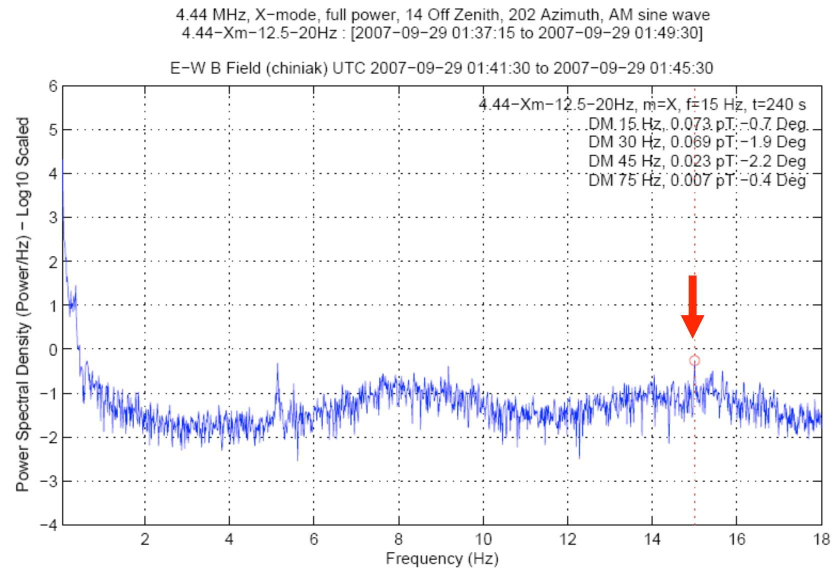
Juneau – 800 km



- 28 April, 2007 UTC 05:01:00 – 05:05:45
- HAARP at 2.88 MW and 3.3 MHz
- Detected 1 Hz & 3 Hz peaks
- $B \sim 1/R^2$ wave evanescent (Frequencies below Schumann Resonance)

ULF Signal Propagation
Propagating Mode (15 Hz)





Gakona **Chiniak – 670 km**

Clear 15 Hz peak can be seen at both sites

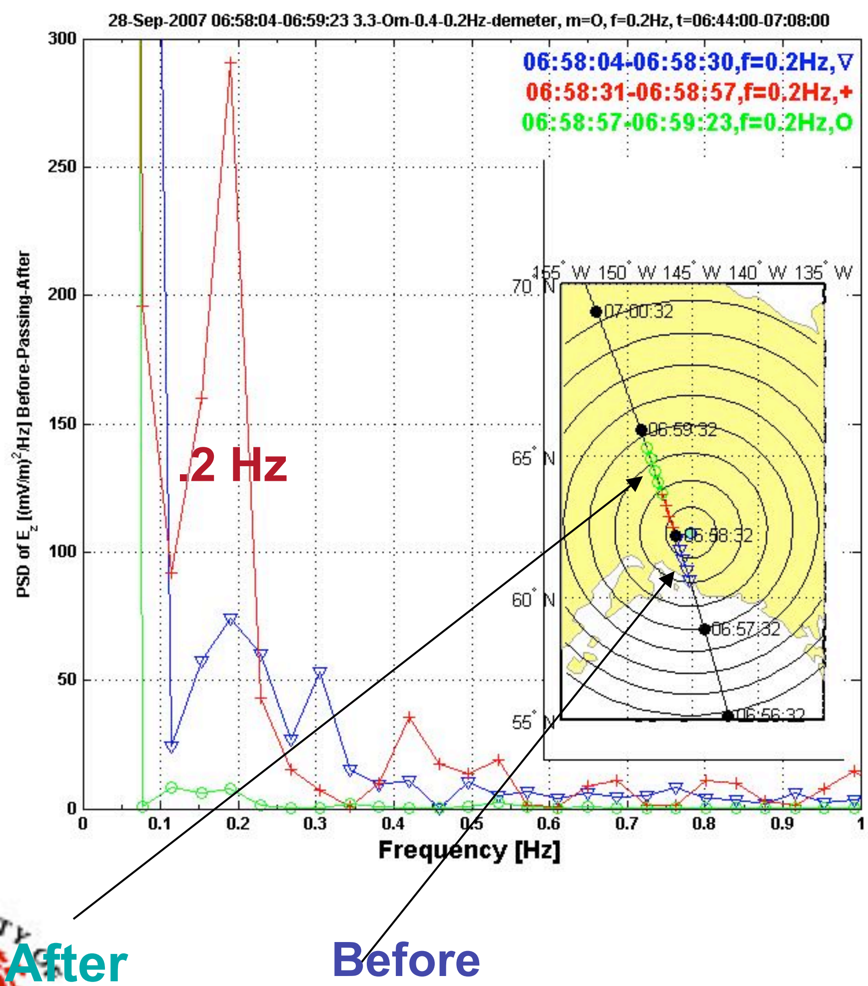
EW Amplitudes:

Gakona: 0.25 pT

Chiniak: 0.07 pT

Propagating mode
3 dB attenuation

SAW DEMETER Detection



Frequency .2 Hz

Closest distance 80 km

Detection time 25 sec

Detection distance 150 km

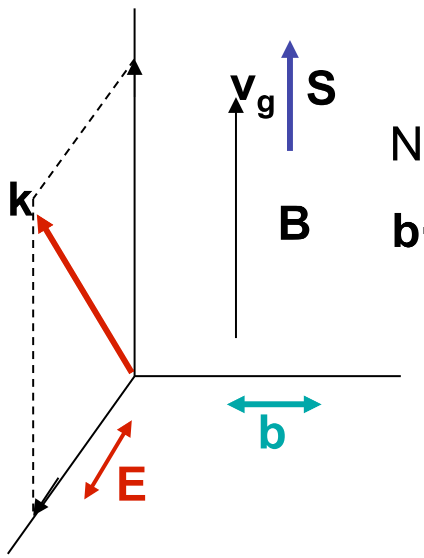
Maximum E ~ 10 mV/m

Estimated power ~ kW

1.5 pT on the ground

SEPTEMBER 28, 2008

SA Waves – Ionospheric Alfven Resonator (IAR)

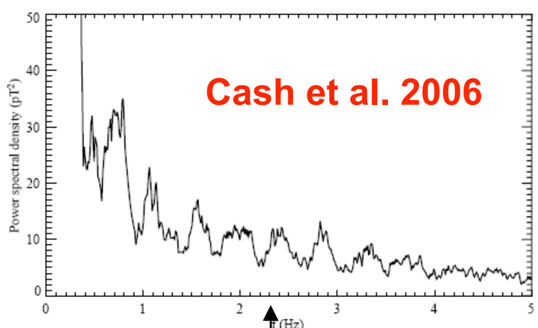


Notice

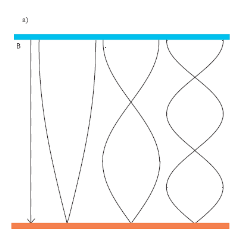
b·B=0

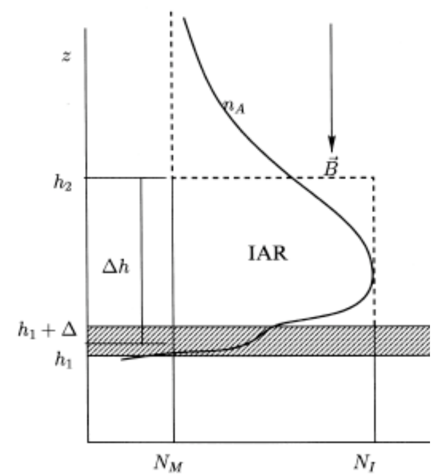
SA wave is guided along the B field

Reflections create standing wave structure



$$\omega_R \approx n \frac{\pi V_A}{(\Delta h)}$$



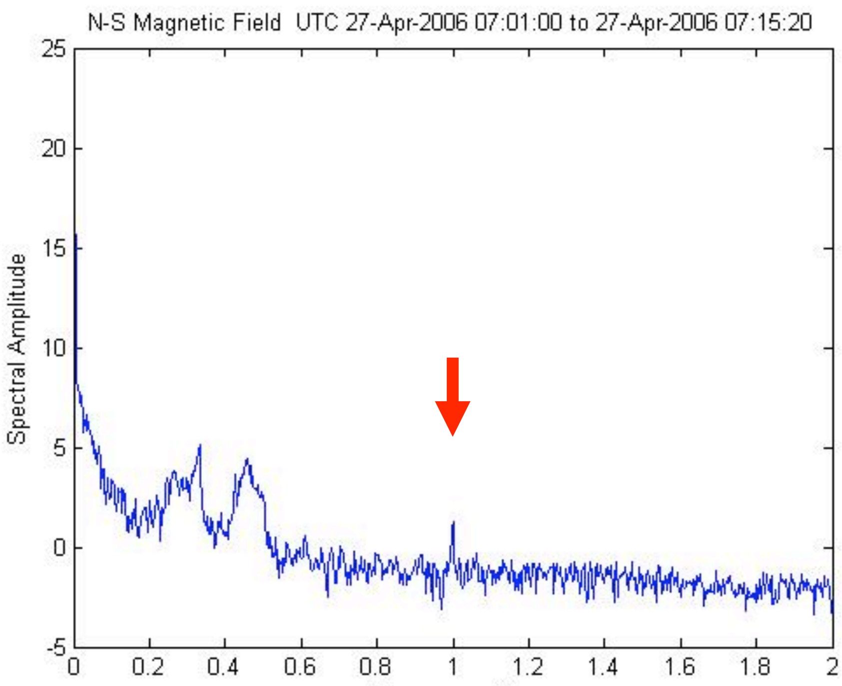


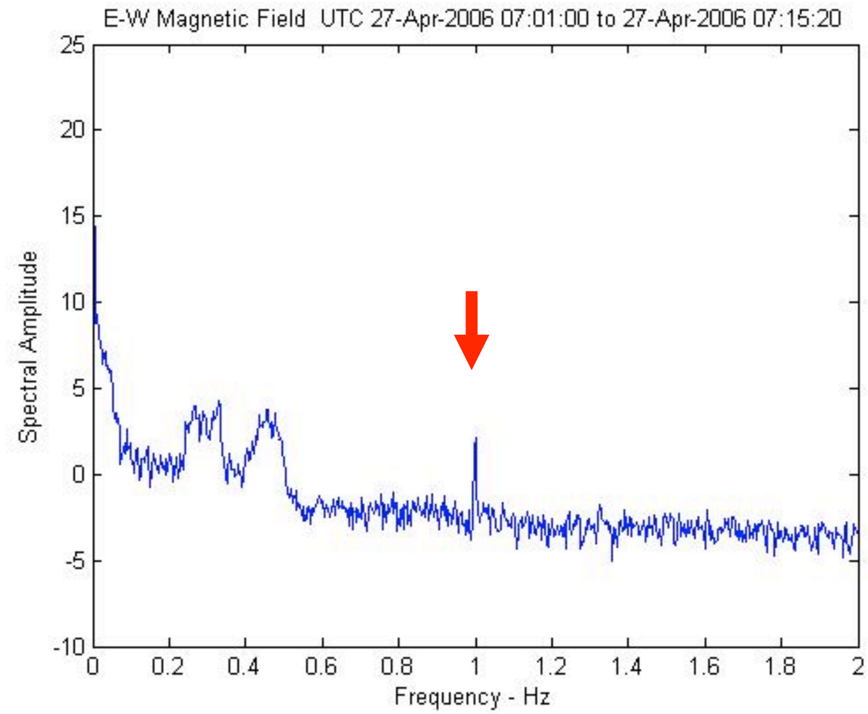
$\eta = c/V_A$

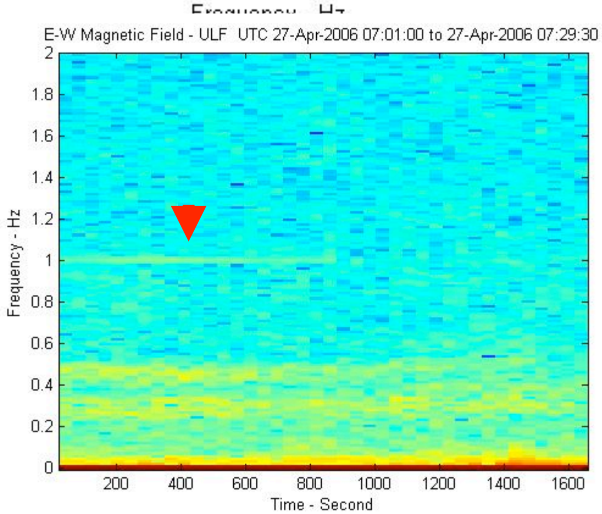
***Fabry-Perot* like Resonator**

Natural SA waves

IAR Excitation by the PEJ

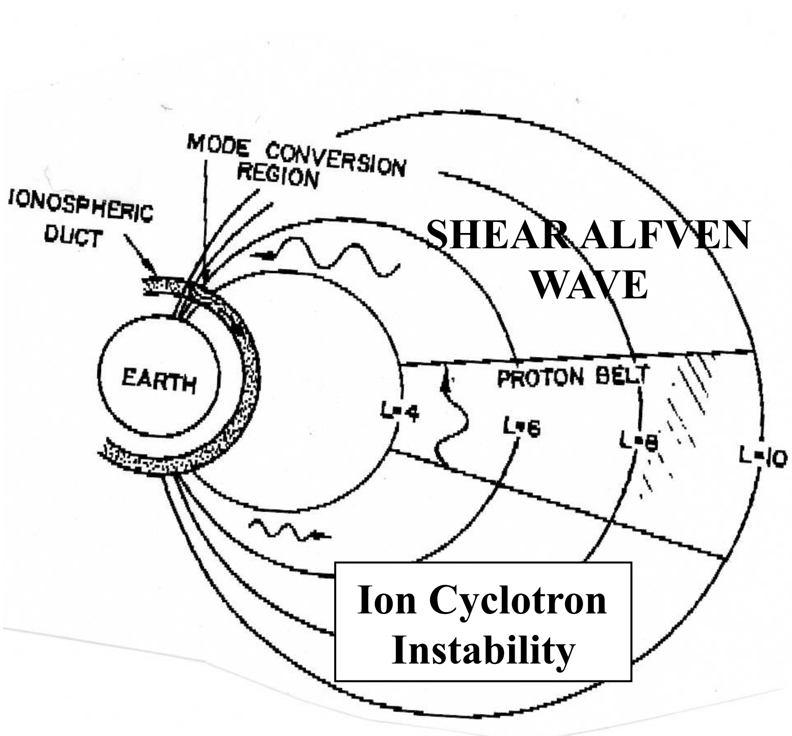


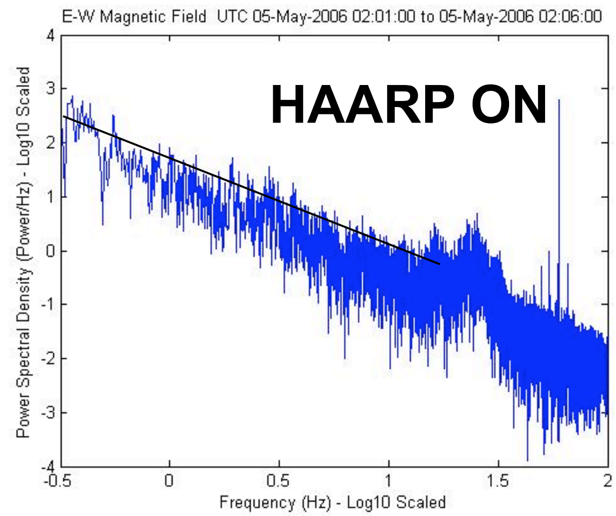


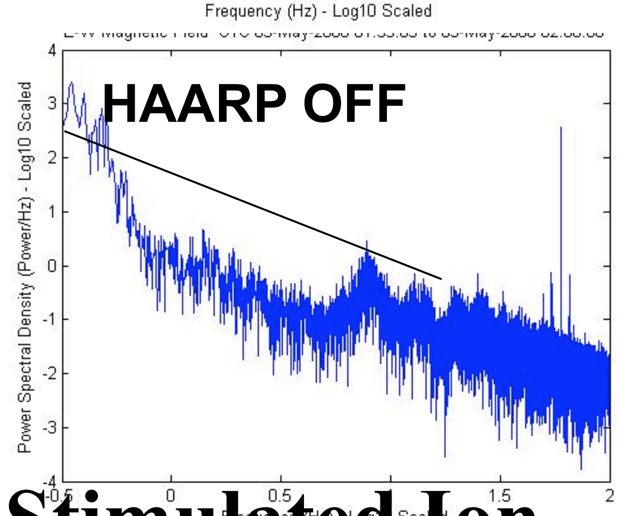


Excitation of the IAR due naturally excited waves at .25 Hz and .5 Hz and by HAARP generated SA at 1.0 Hz.

STIMULATED SA EMISSION ?



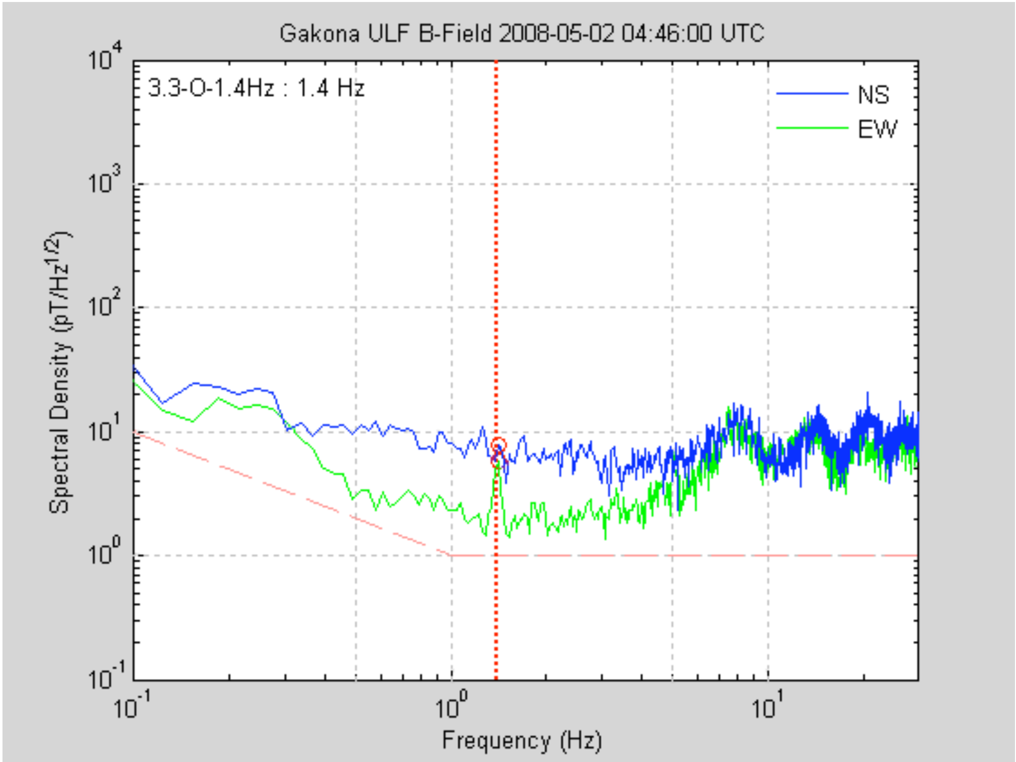




Triggered Pc1 and Stimulated Ion Precipitation ?

ULF at Gakona – Power Spectral Density (PSD)

- Frequency spectrum in a moving time window
- Clear Schumann resonances at 8, 14, .. Hz
- Signals emerge as freq. peaks in sync with HAARP ULF operation
- Greatly varying background below 1 Hz



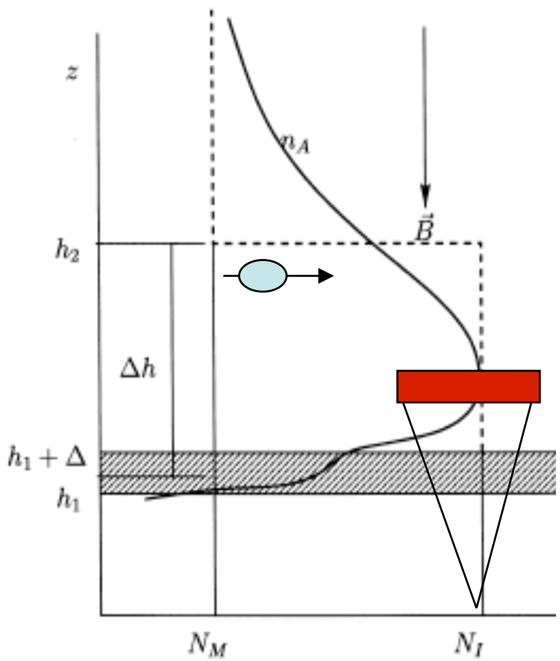
Triggered Pc1 broadband

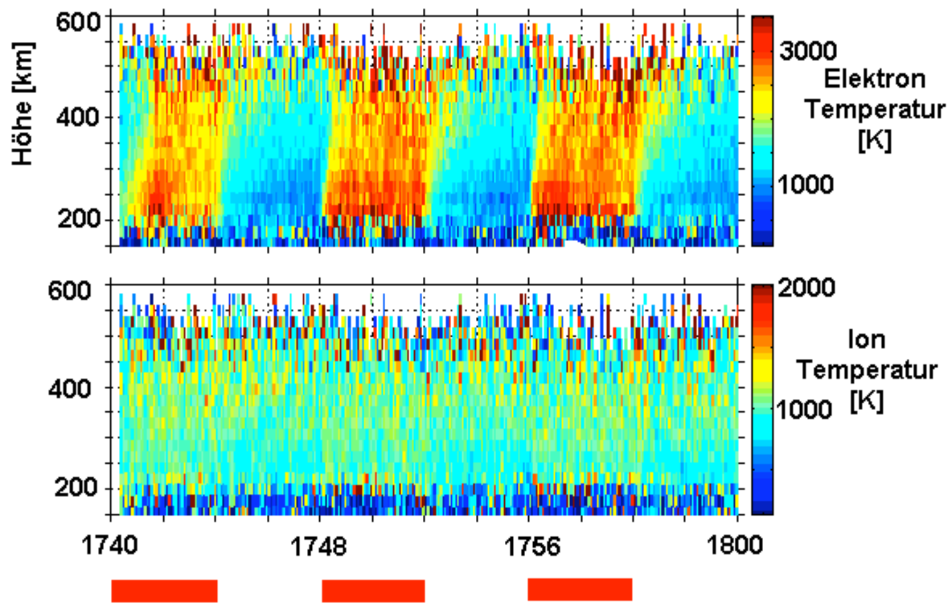
10'

F-Region Heating Physics Studies

- F-Region current drive
  – Msonic wave generation and propagation
- F-region plasma turbulence
  – Field aligned striation spectra
  – Electron acceleration optical emissions
  – Ion heating and outflow- Ducts
  – Stimulated EM emissions (SEE)
    - Gyro-harmonic studies
    - Stimulated Brillouin Scattering (SBS)

F-Region Heating-Current Drive





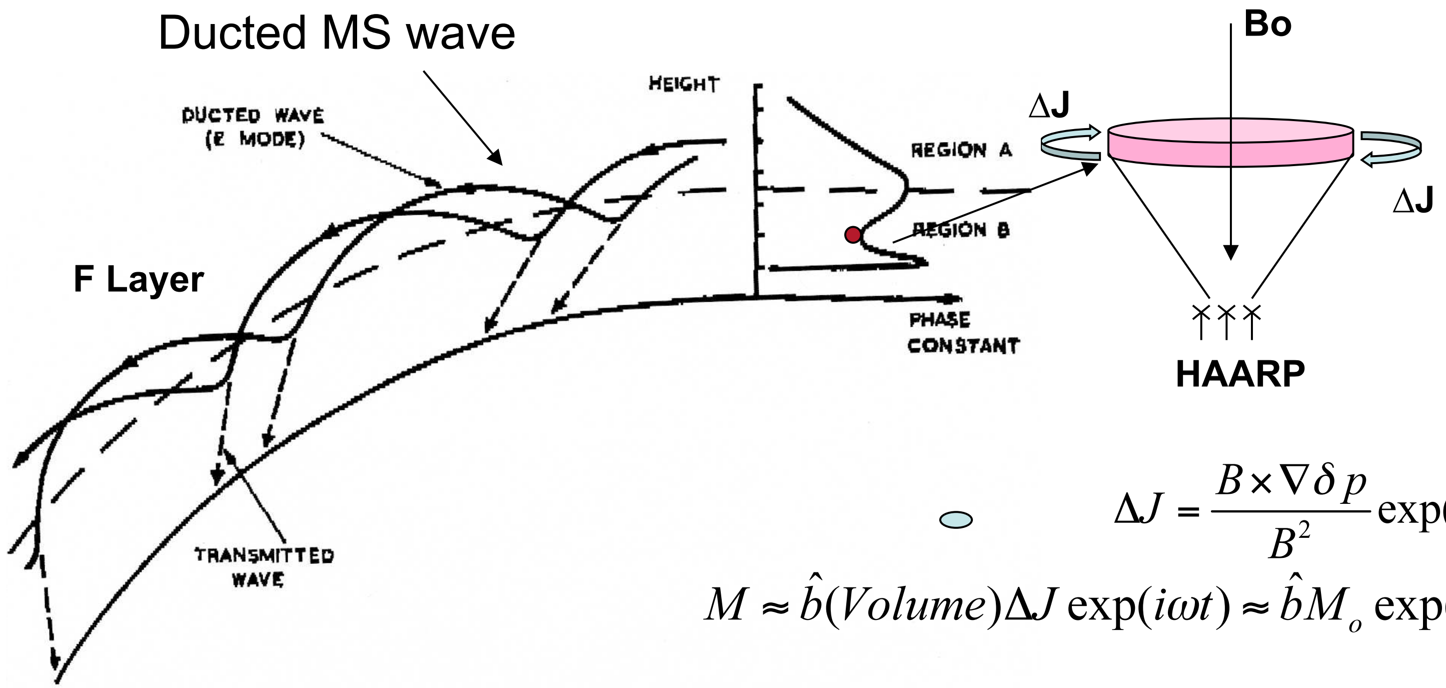
Response time .5-1 sec

Drive AC
Diamagnetic Current
Loop

$$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$

F-Region Msonic Wave Generation

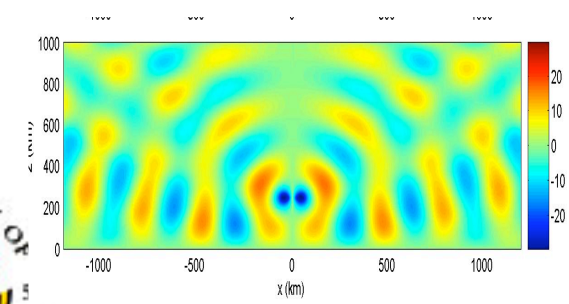
Ejet not needed



$$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$

$$M \approx \hat{b}(Volume)\Delta J \exp(i\omega t) \approx \hat{b} M_o \exp(i\omega t)$$

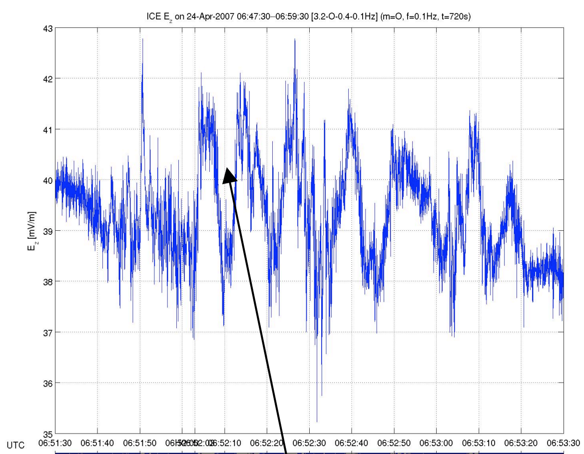
M parallel to B



The wave propagates isotropically but is reflected at the D/E region and is much weaker on the ground under the heated region. It can be measured by satellites or at large lateral distances (skip zone)

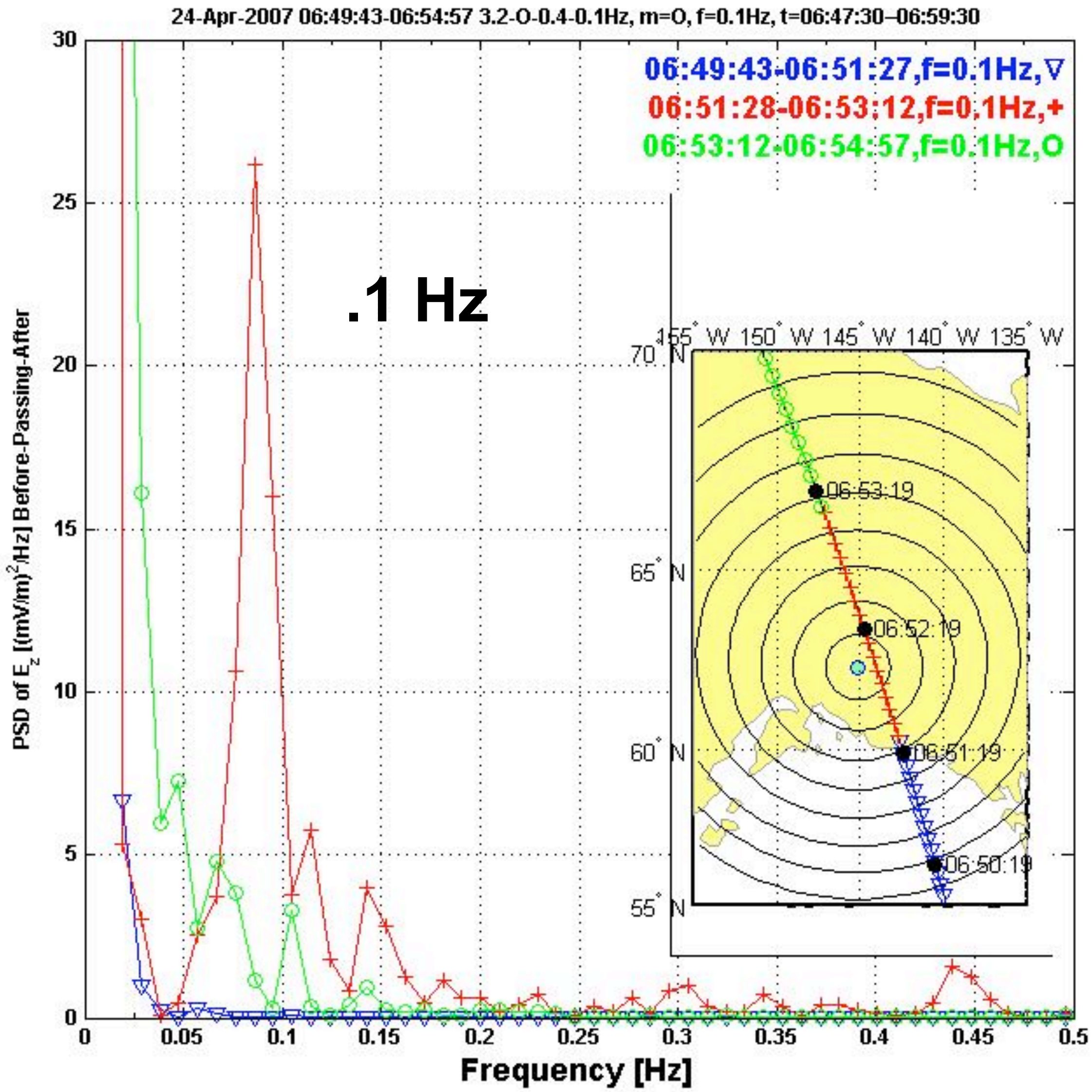
Msonic Wave Injection

DEMETER



10 sec oscillations

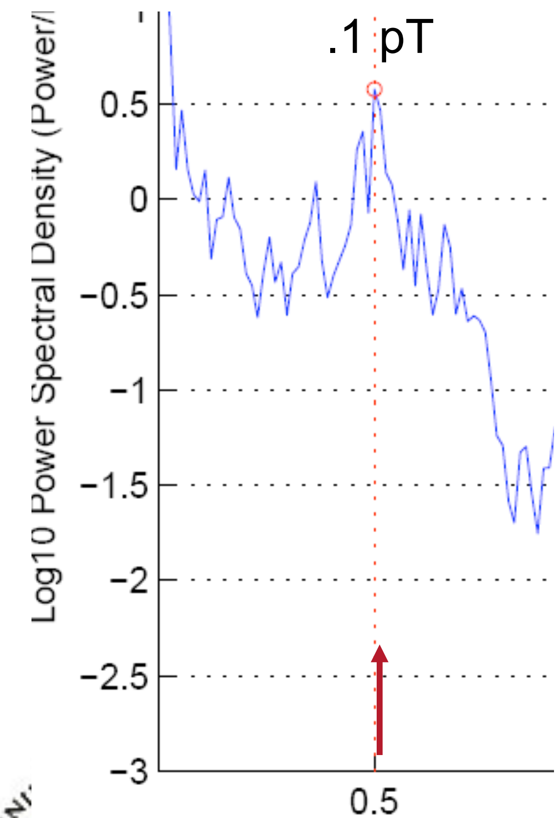
kW power



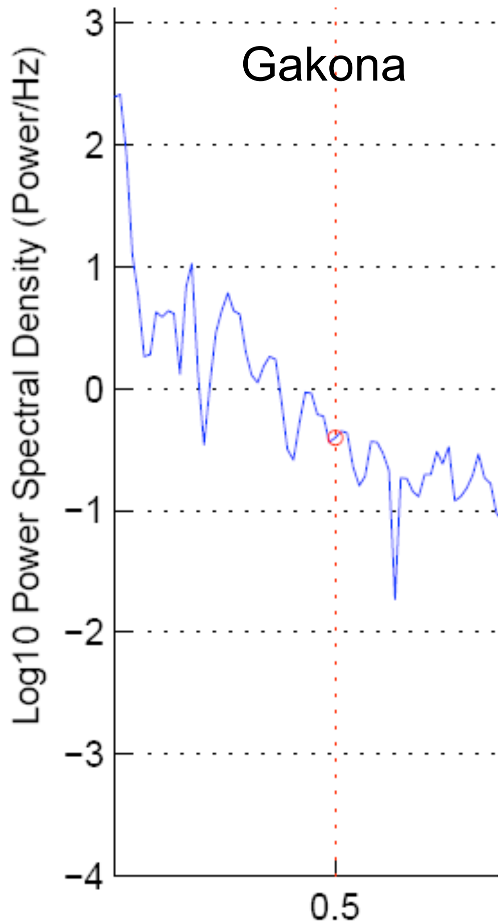
Lake Ozette vs. Gakona Detections

Example .5 Hz

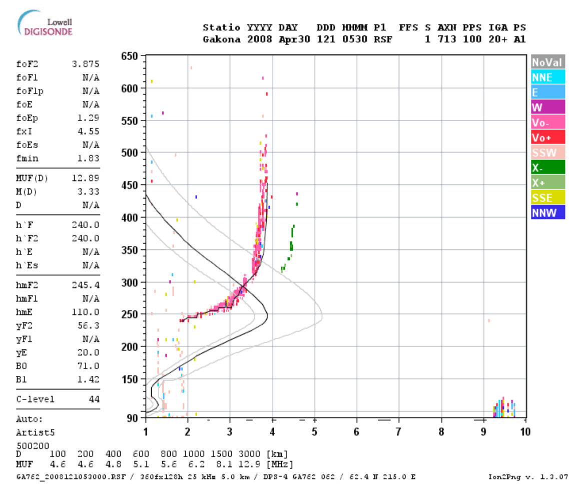
Ozette

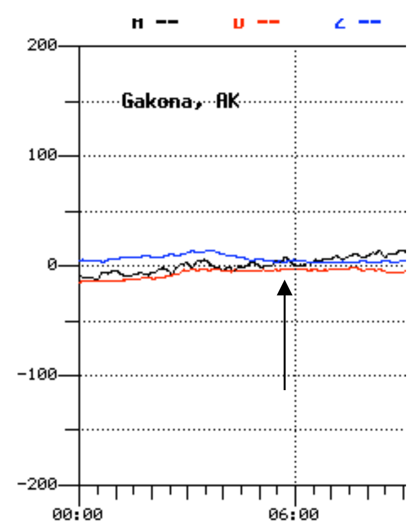


f Hz



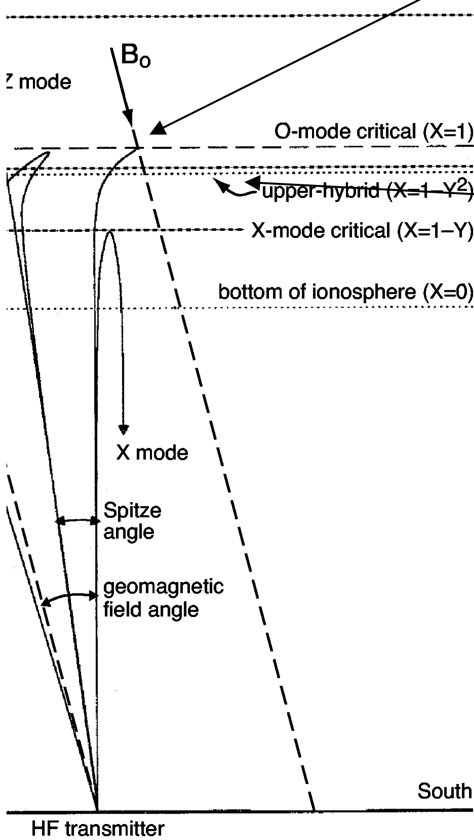
f Hz



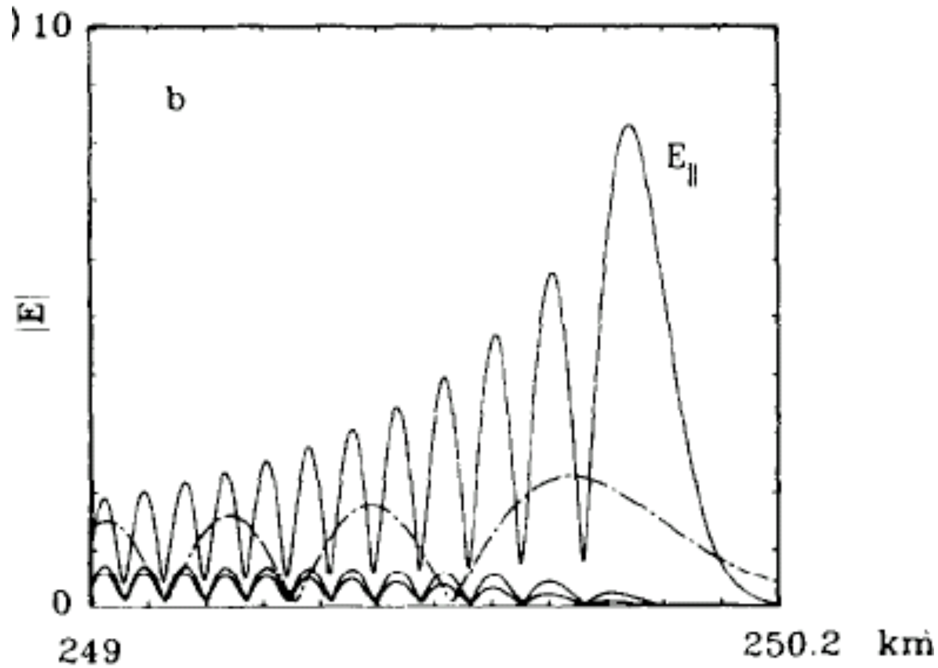


F Region Heating

Langmuir+Ion Acoustic Instability -PDI -OTSI
Soliton+caviton pairs – Suprathermal tails

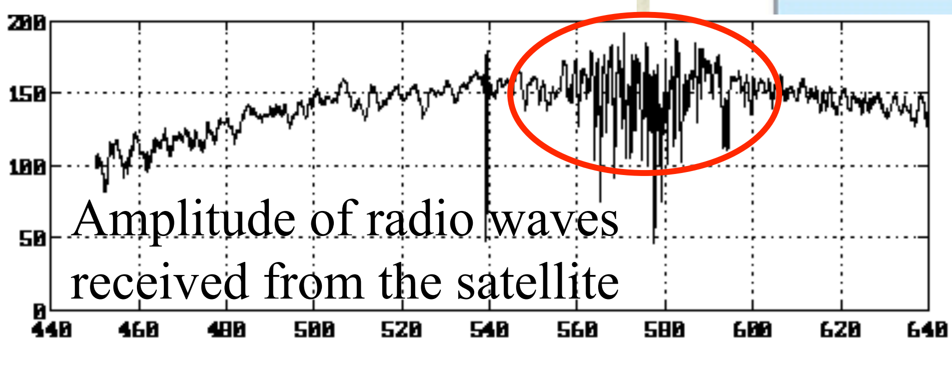


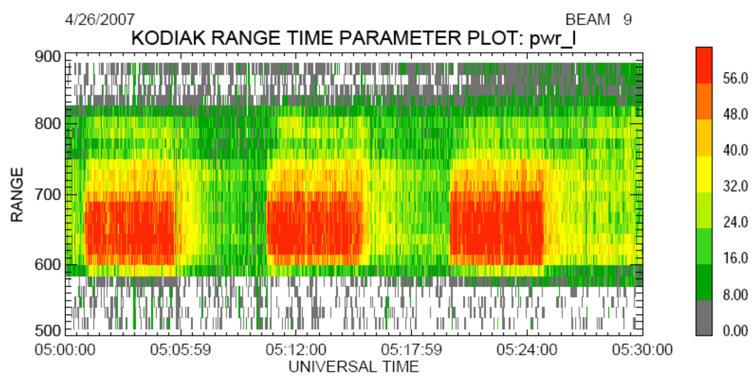
Upper hybrid turbulence – Striations – Electron Heating

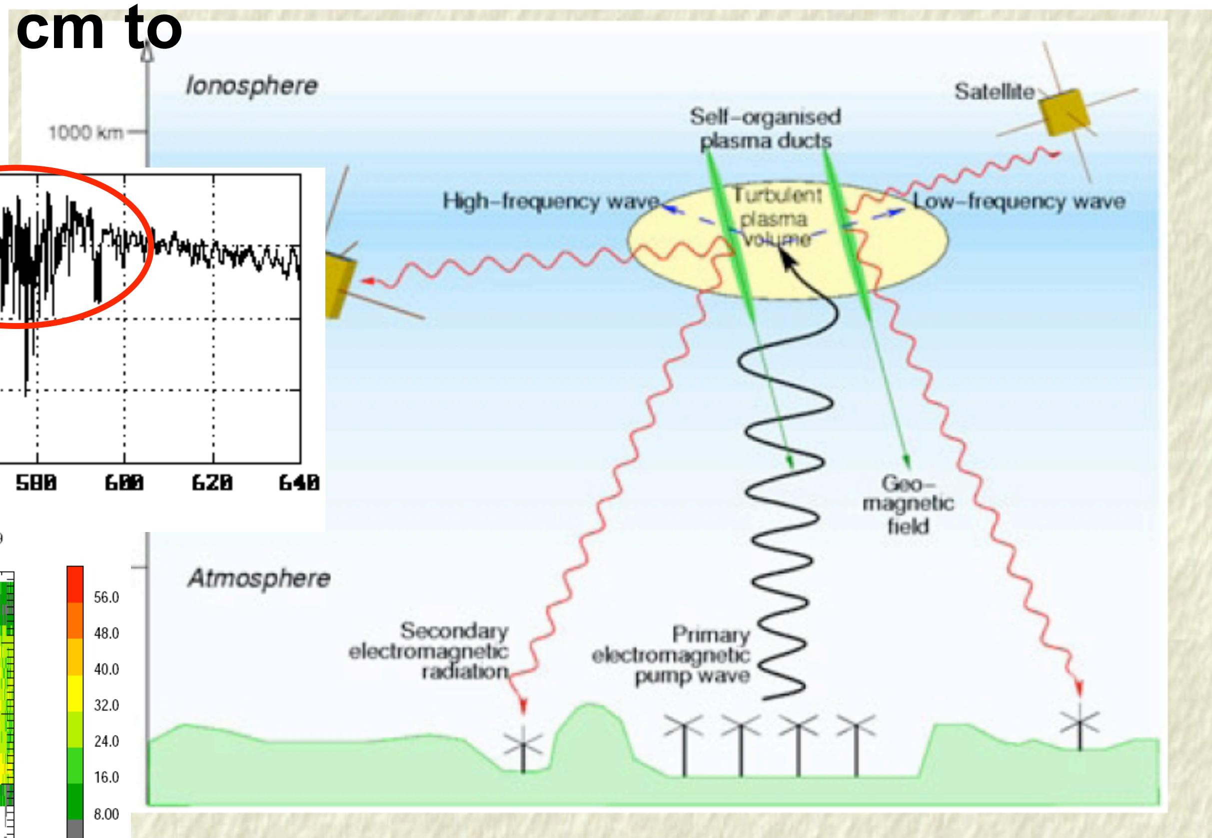


F-Region Turbulence

Field aligned irregularity structure from 10's cm to tens of km

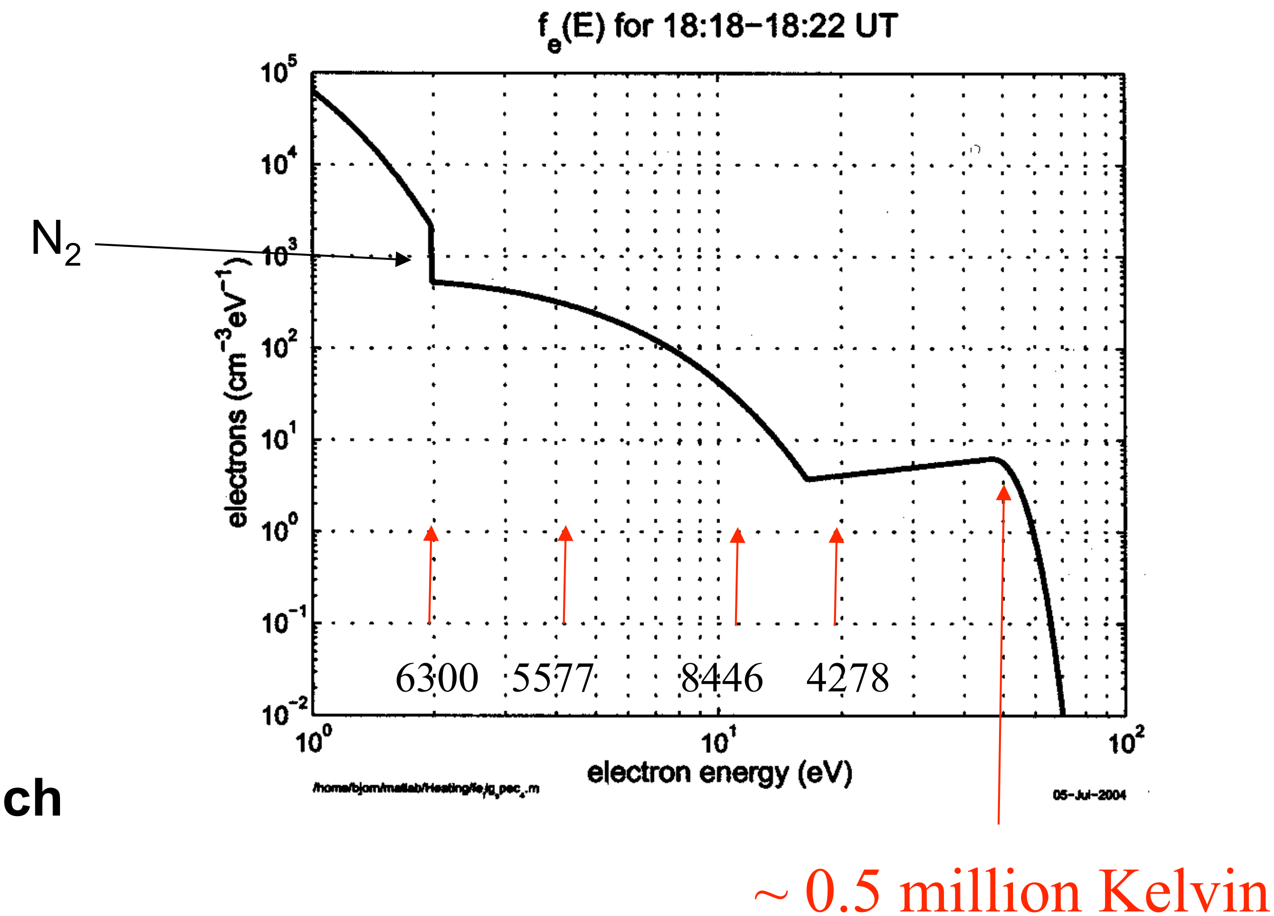






Artificial Aurora – The Zenith Effect
Electron Acceleration

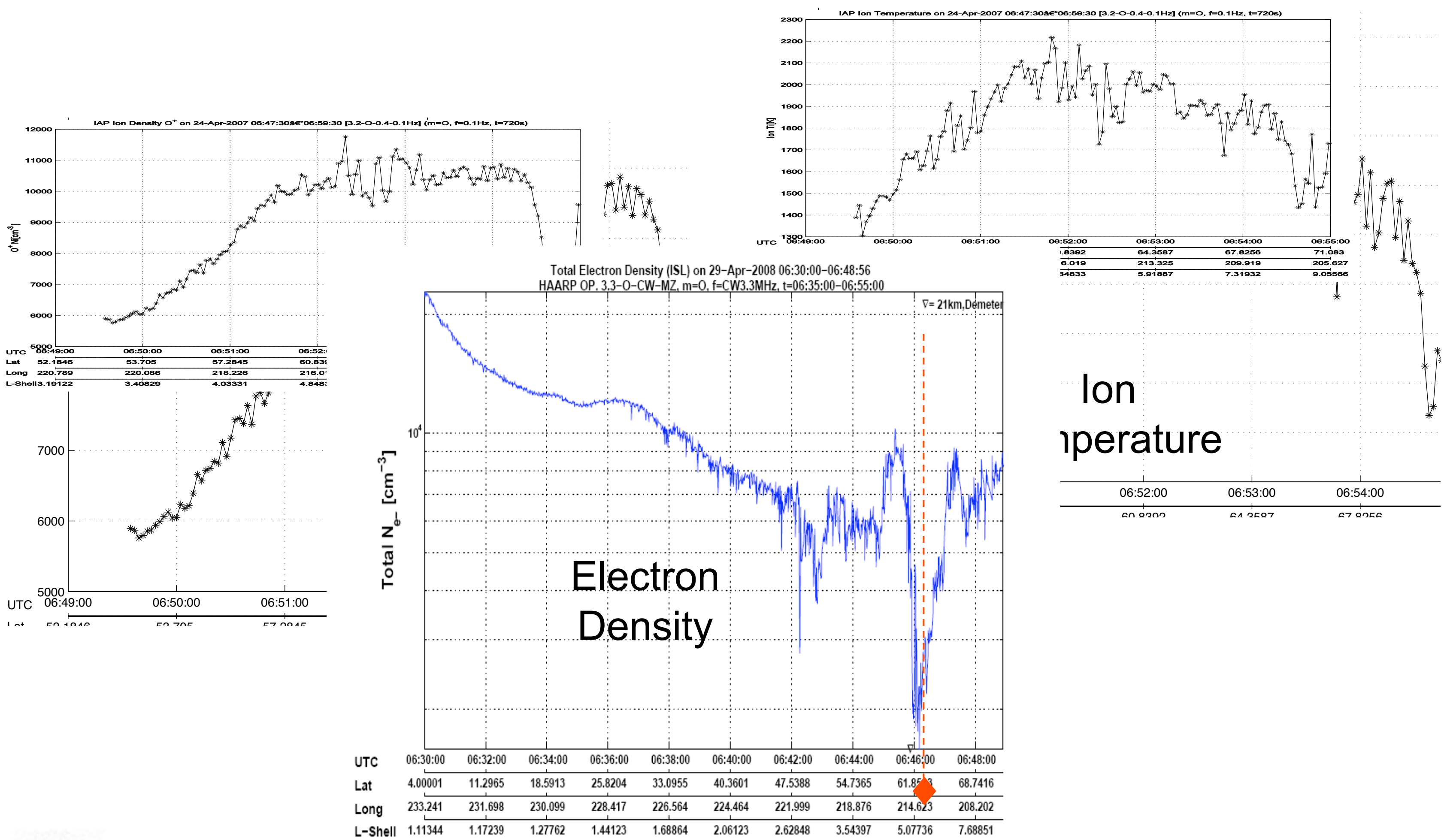
Reconstruction of the EDF



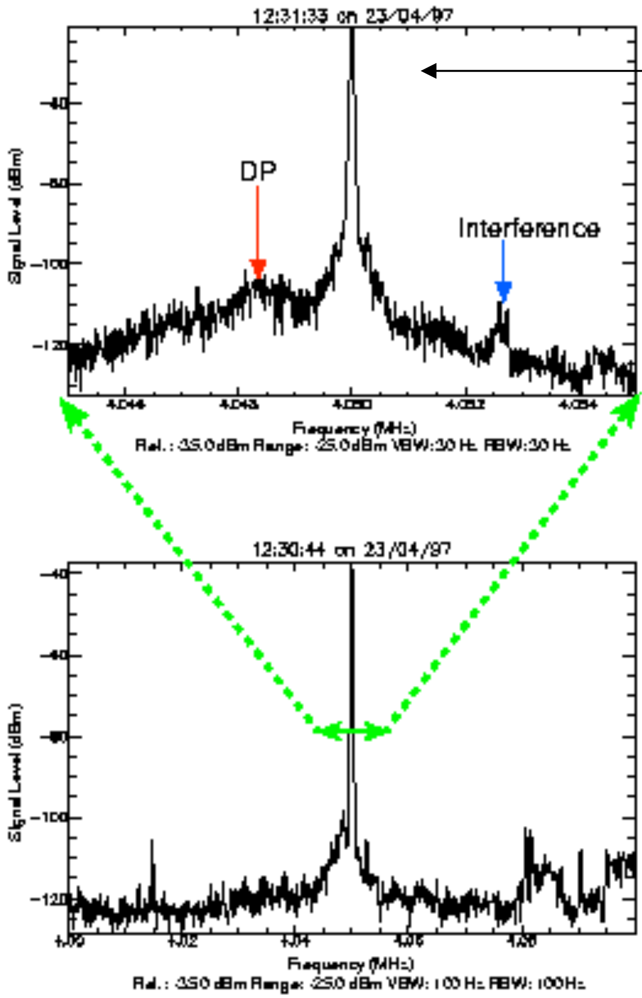
M. Kosch

Electron temperature <3500 K ➔ Bulk electron energy <0.3 eV

Ion Heating – Outllows - Ducts

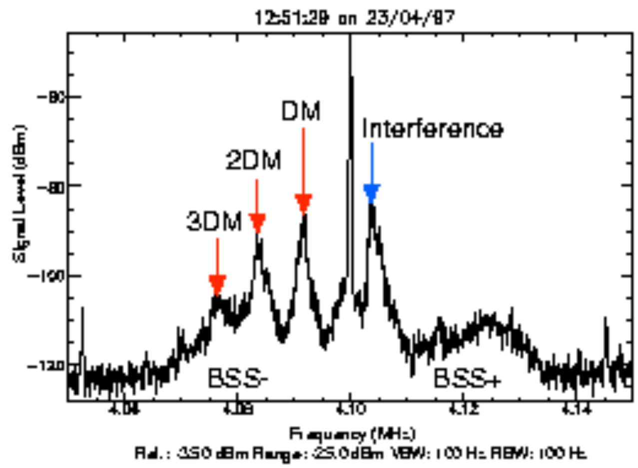


Stimulated Electromagnetic Emissions (SEE)



HF transmit frequency

3rd Electron Gyroharmonic



Above Gyroharmonic

are weak radio waves produced in the ionosphere by HF pumping.

Gyroharmonic ≈ 1.38 MHz in F-layer

(Honary et al., Ann. Geophysicae, 1999)

SEE Spectra

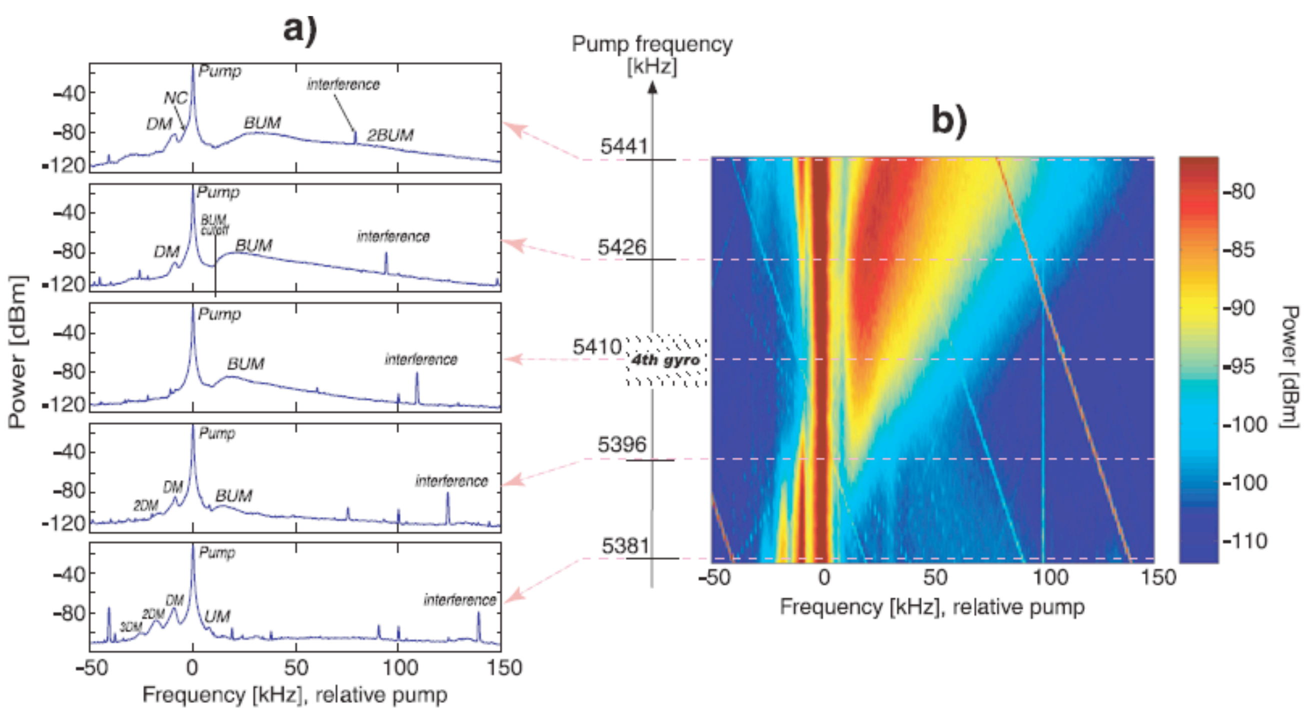
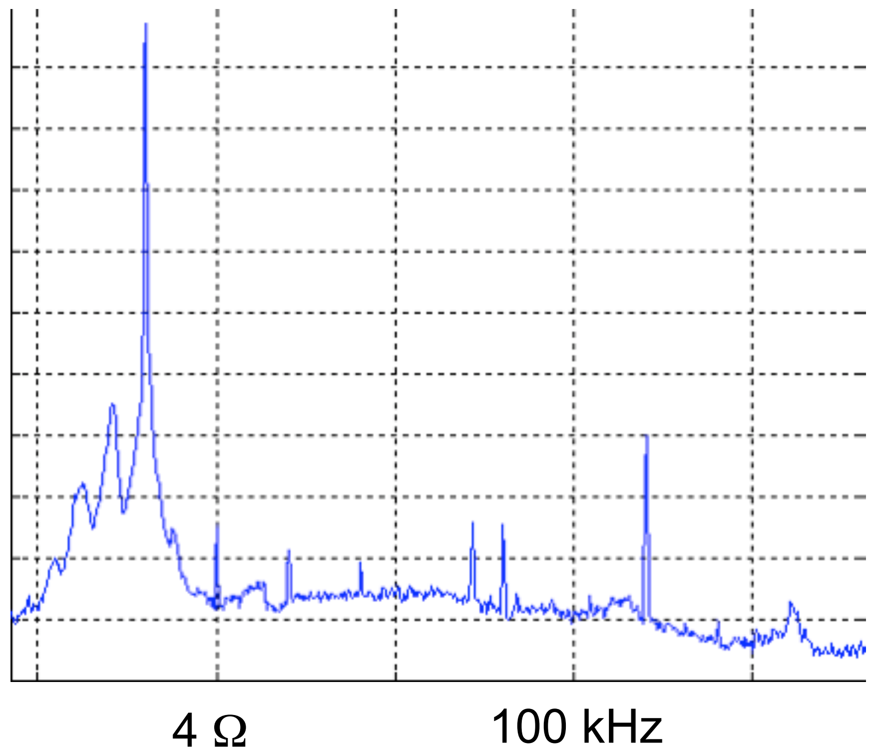


Figure 3. (a) The stack of five plots showing SEE spectra for the five different pump frequencies marked on the vertical axis in the middle of the figure. The standard SEE spectral features and the pump are labeled. These spectra are cross sections of the pump relative spectra versus pump frequency two-dimensional plot in Figure 3b. (b) The position of the cross sections are marked with dashed, magenta lines. The estimated range of the local fourth gyroharmonic is shown as a hatched region on the pump frequency axis.

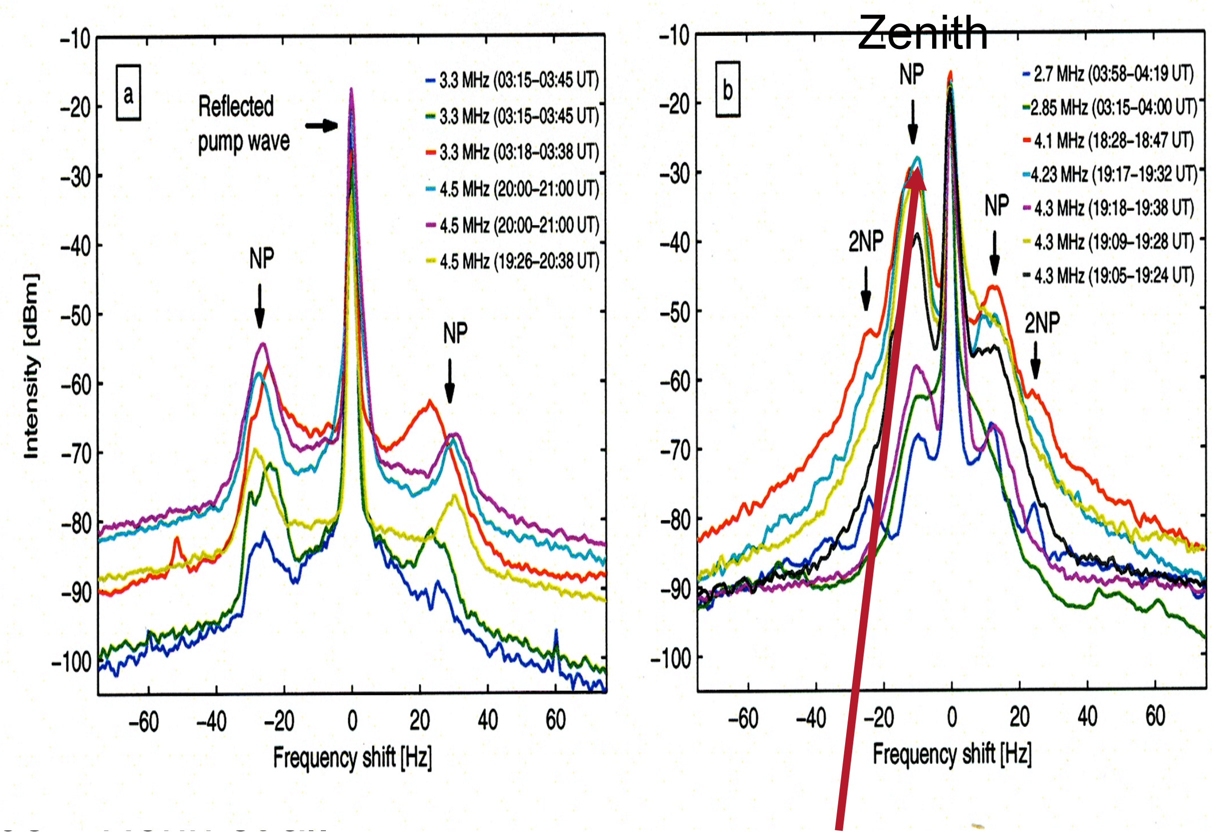
Carozzi et al., JGR 2002

SEE Gyro-Harmonics



SURA Facility SEE Carozzi et al.JGR 2002

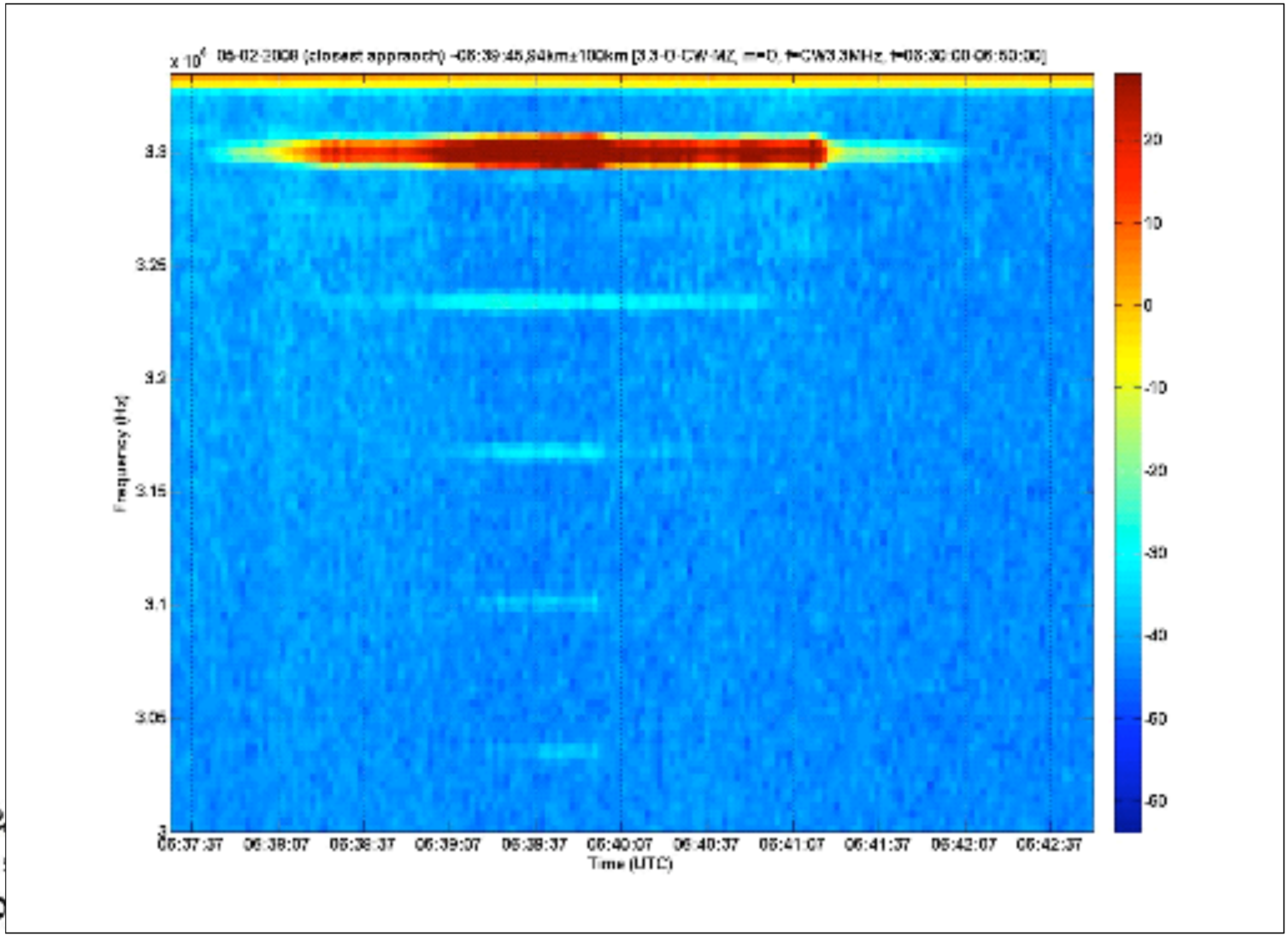
Stimulated Brillouin Scattering HAARP



HAARP

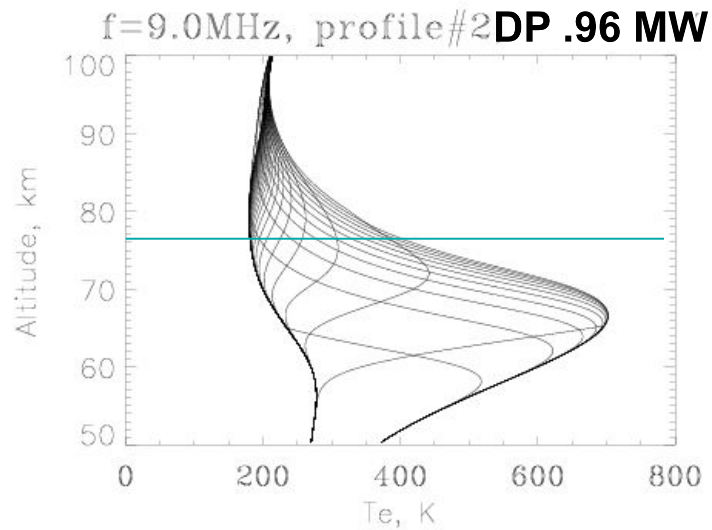
40 dB stronger than any other SES

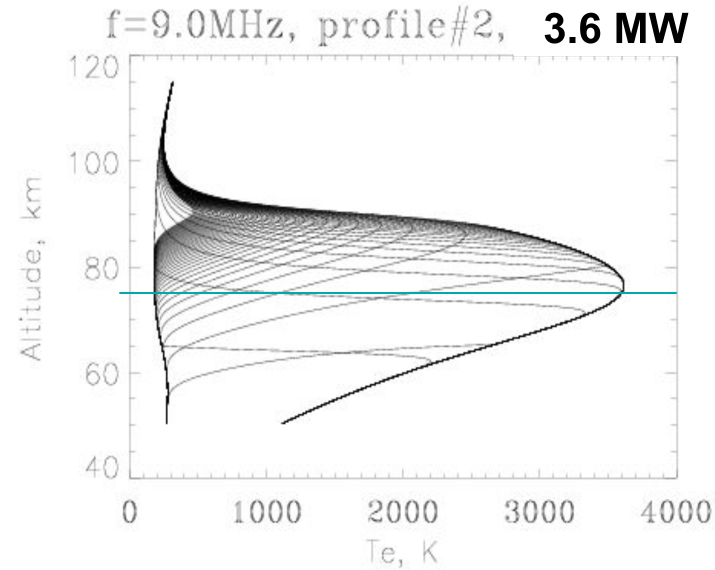
HAARP HF DEMETER Detection
First SEE Satellite Detection?

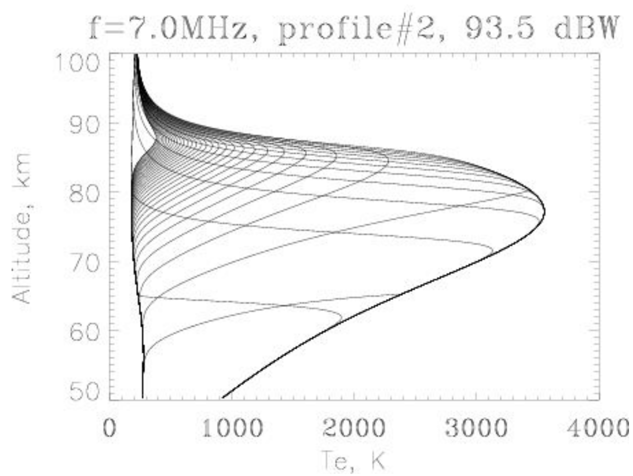


Supplementary Slides

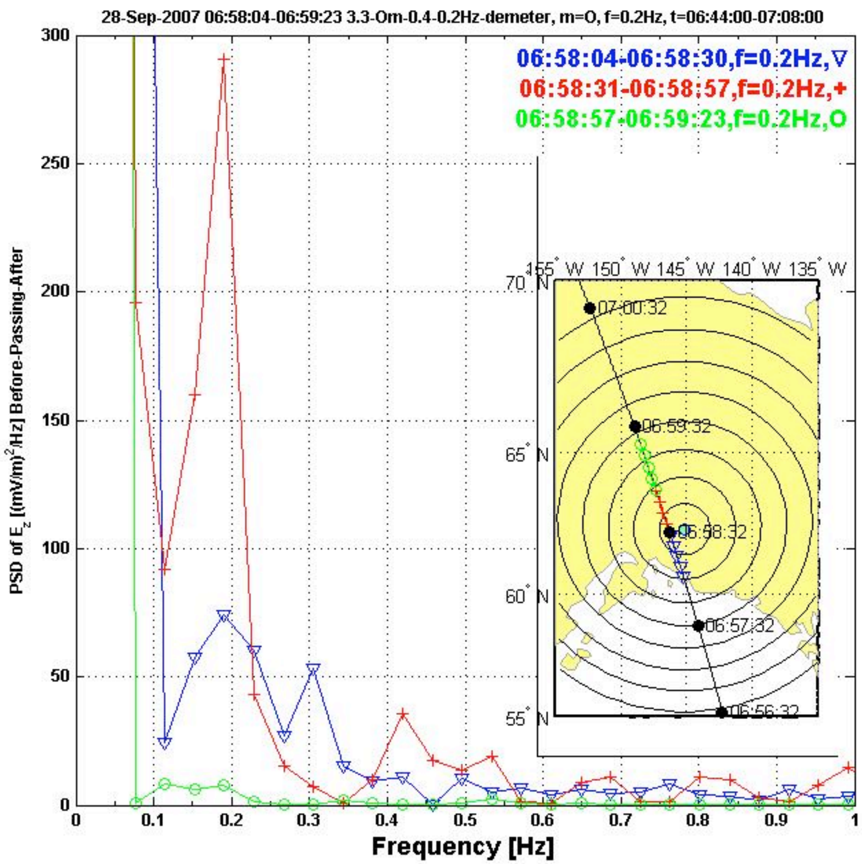
Temperature profile control - Saturation

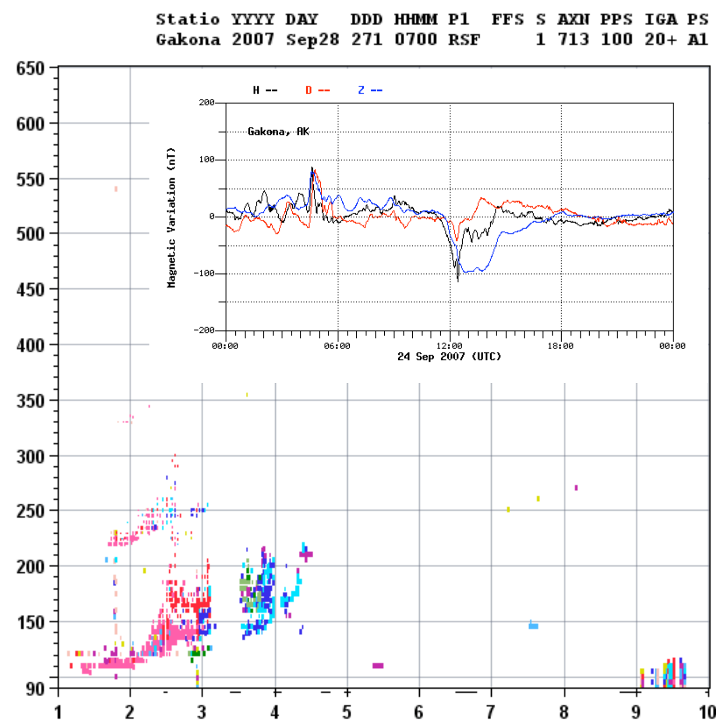




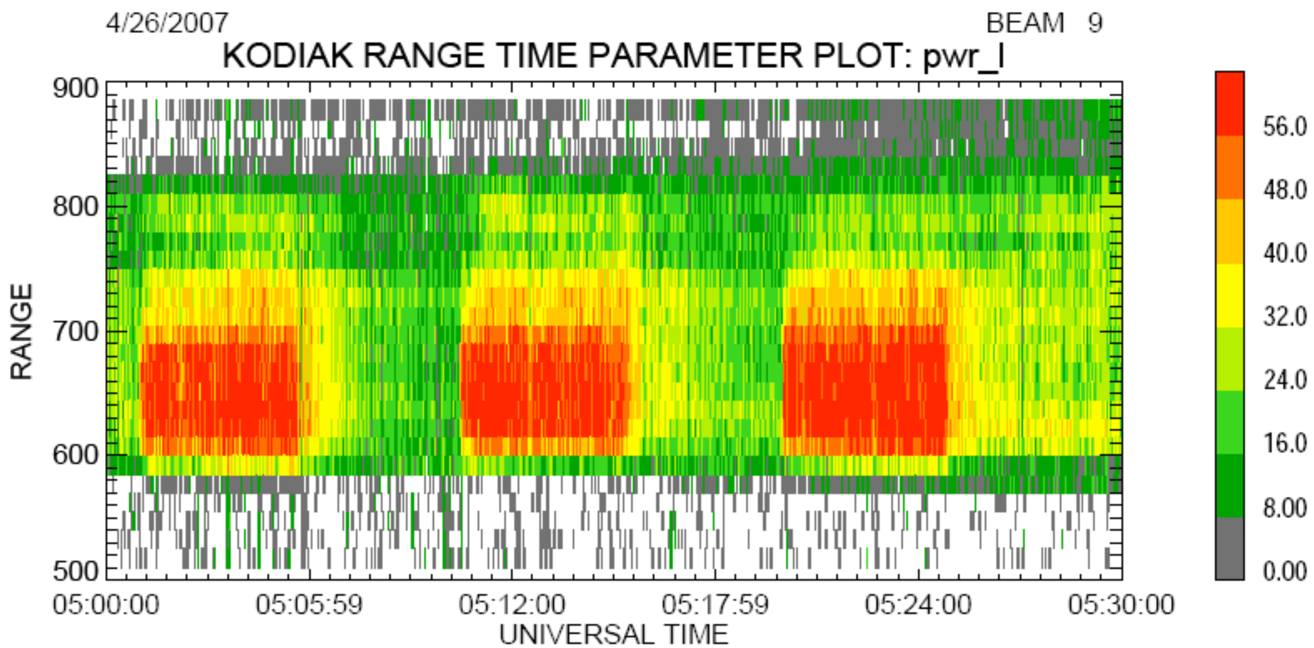


SAW Injection

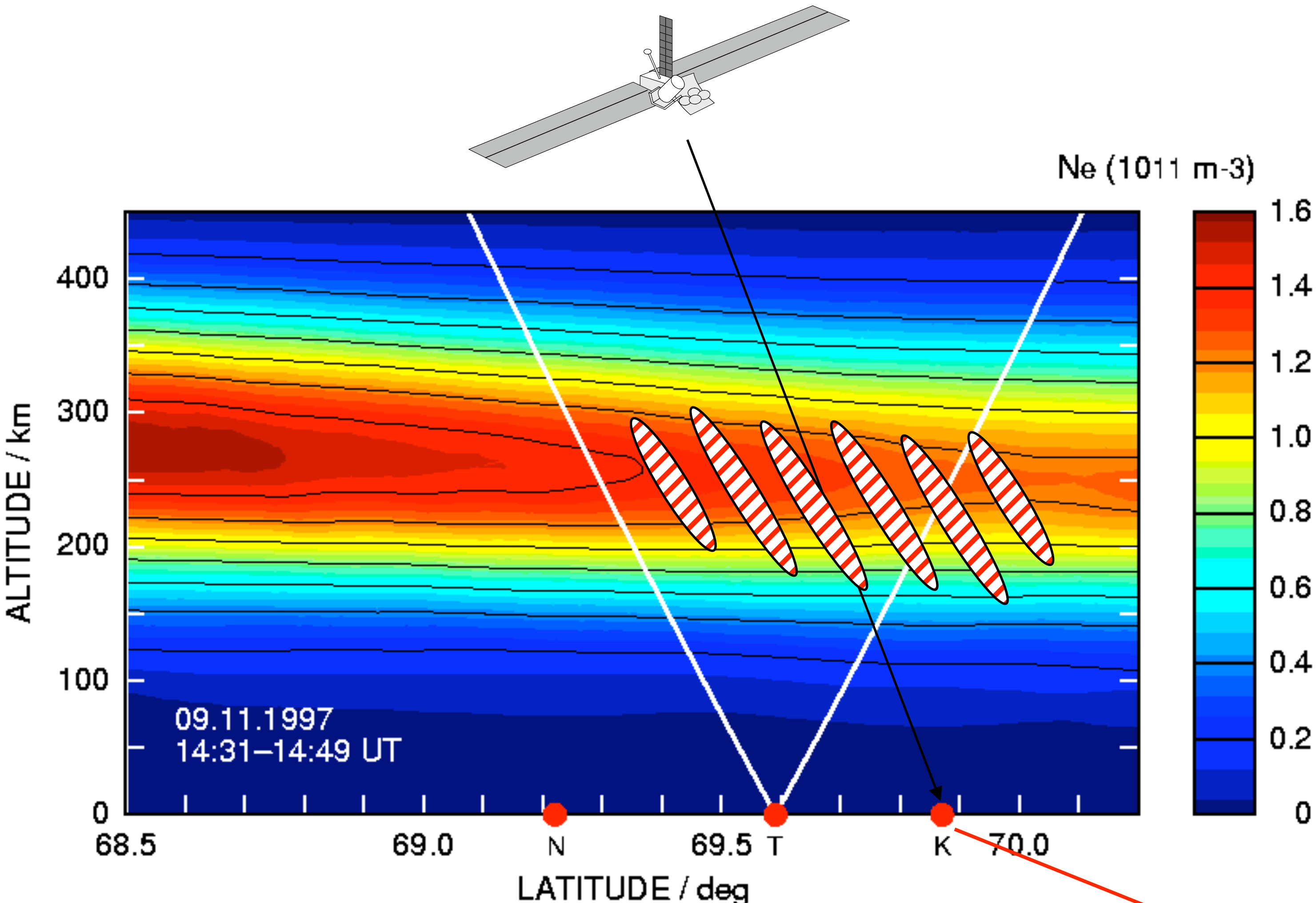


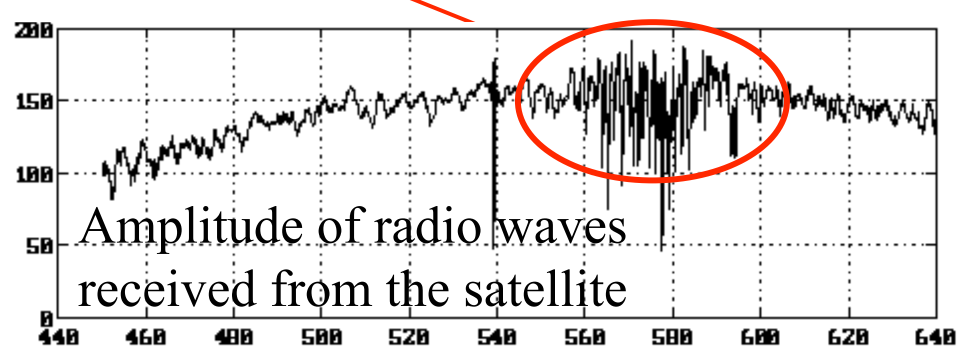


F-Region Structure and Turbulence



UNIVERSITY OF MARYLAND 1856

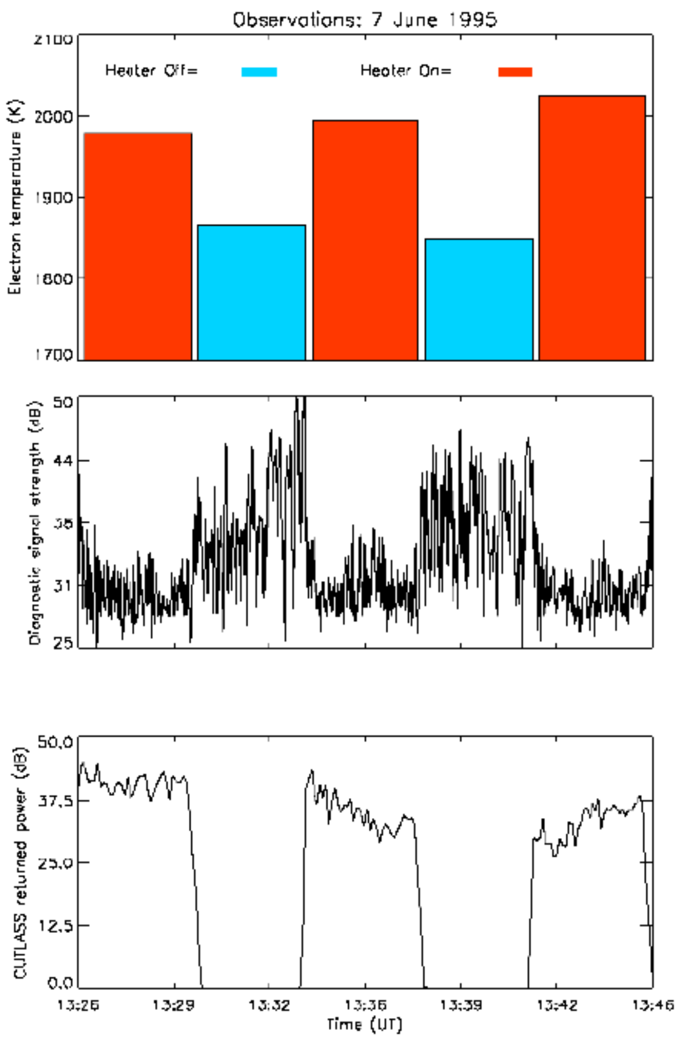


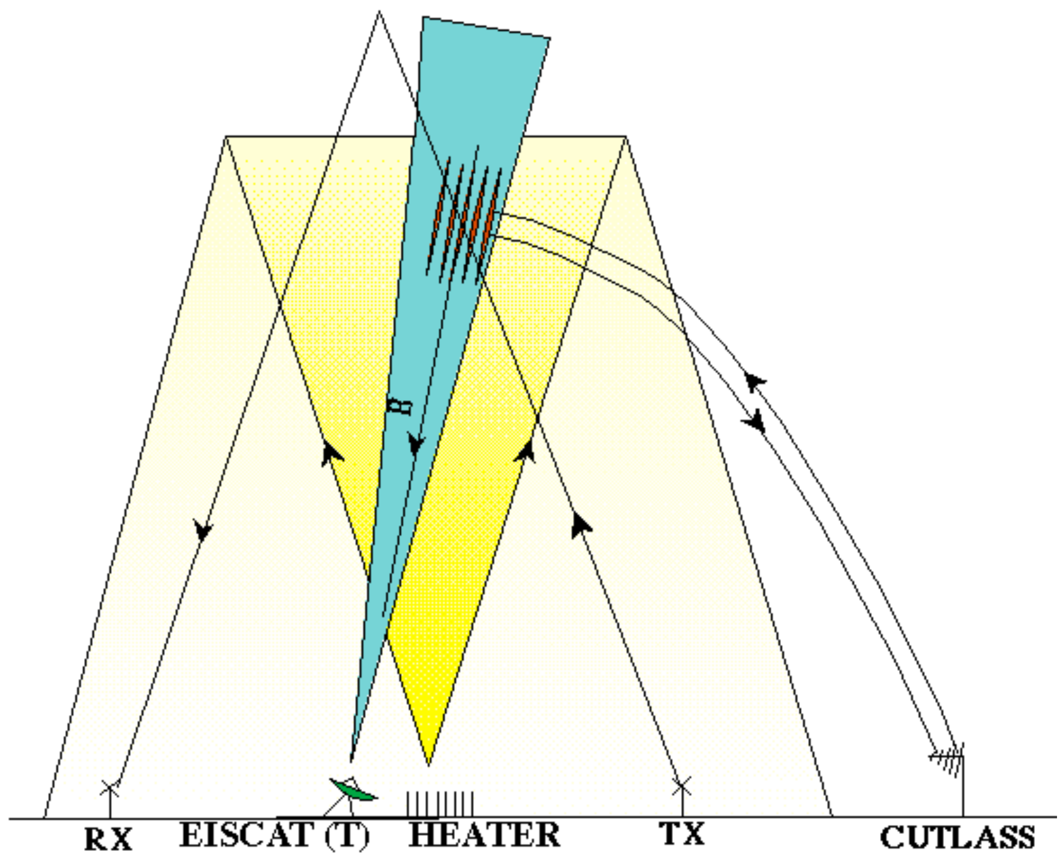


Scintillations
EISCAT
Rietveld

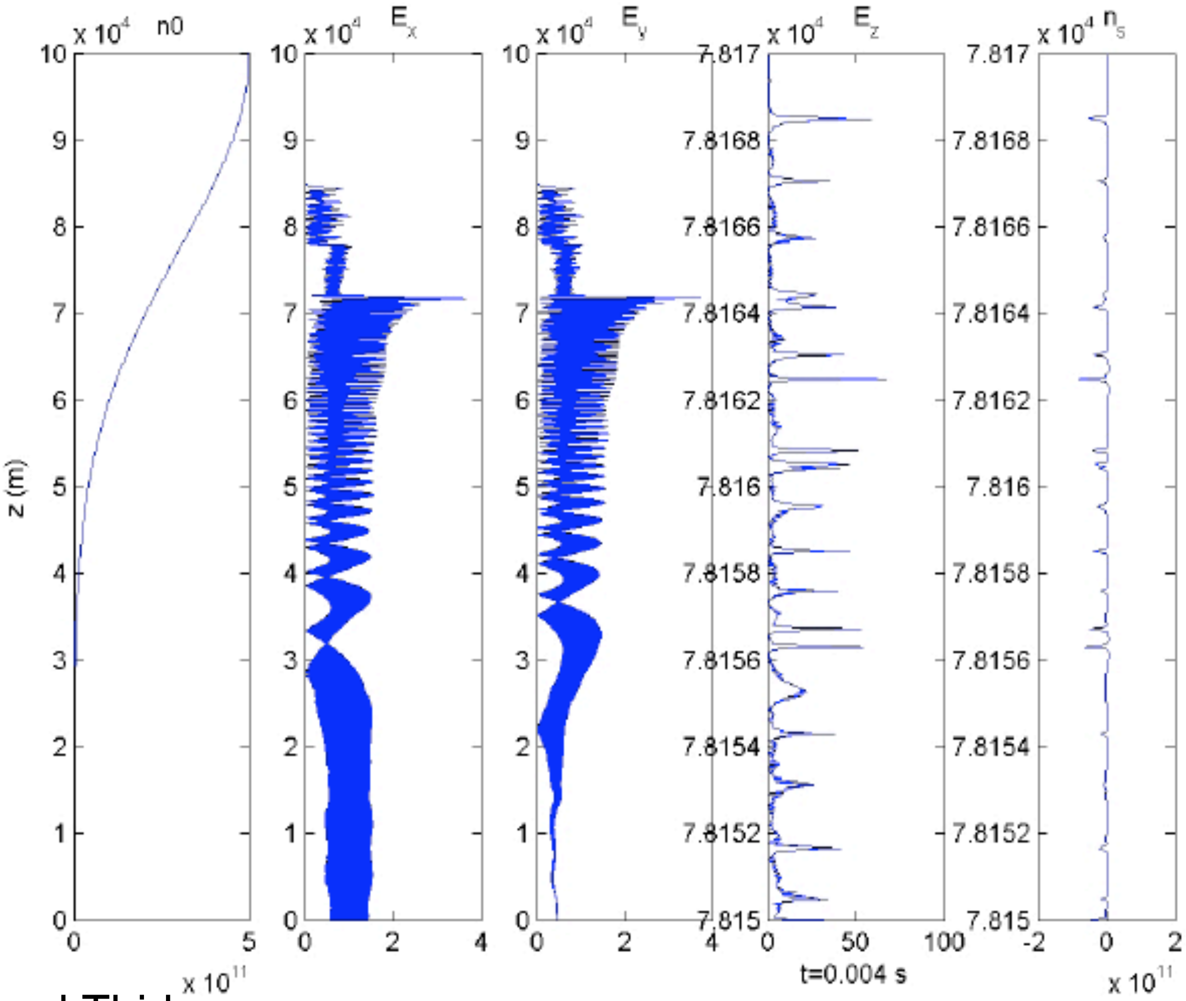
HF pump-induced magnetic field-aligned electron density irregularities (up to ~5%) **causes coherent radar reflections and anomalous absorption** (by scattering) **of probing signals.**

Striations



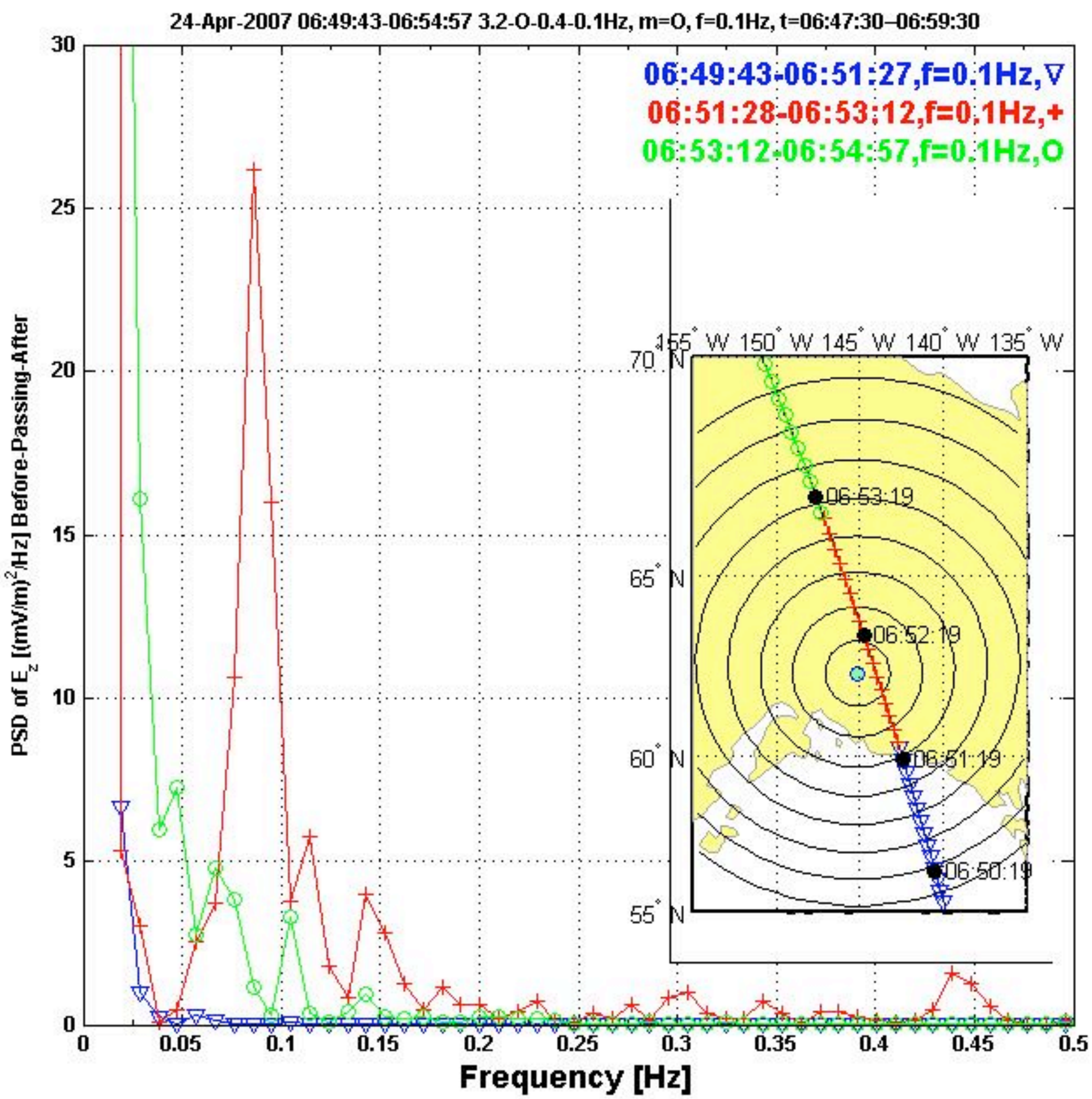


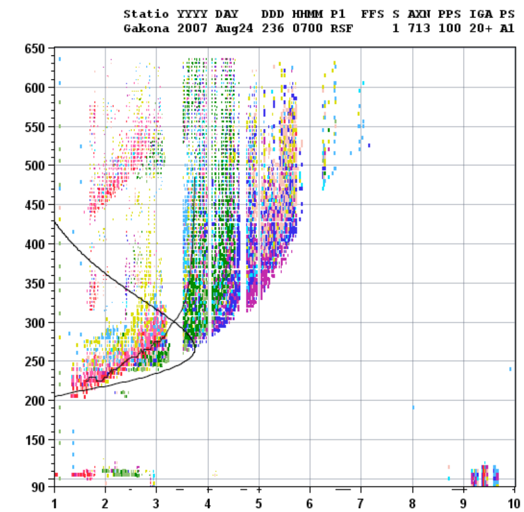
Electron acceleration

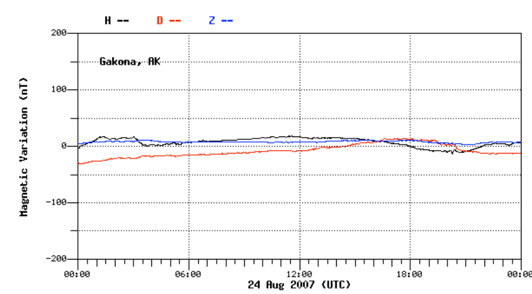


Eliasson and Thide

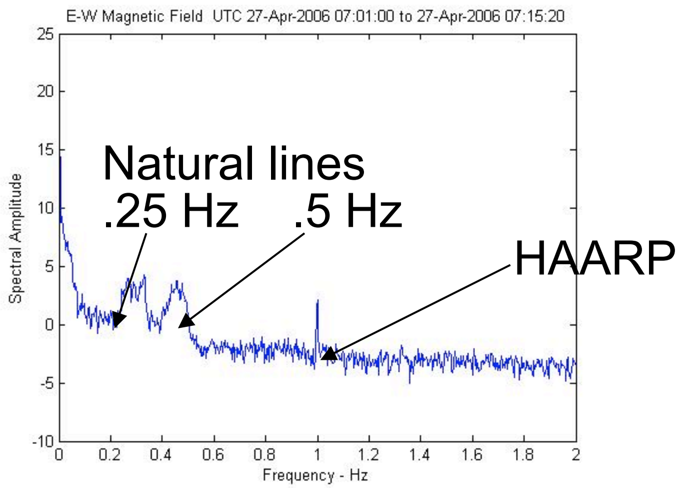
Msonic Wave Injection

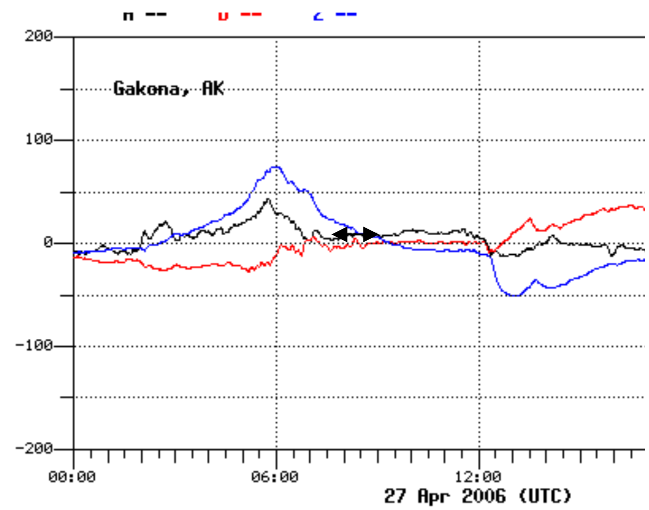


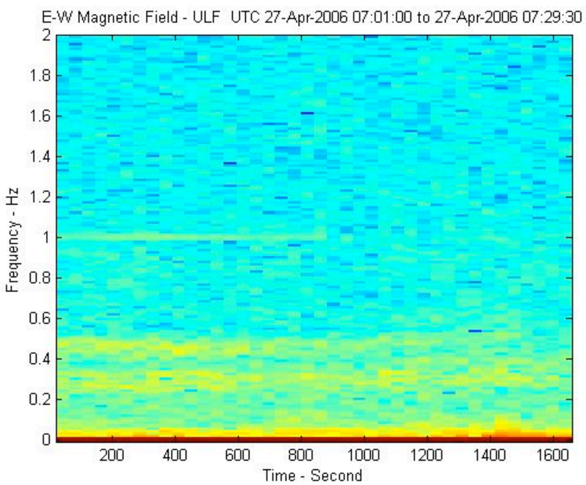


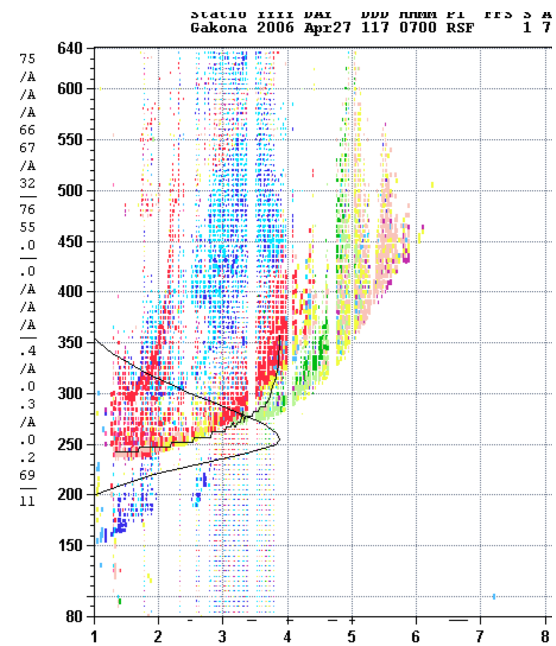


Paradox ?


E-W Magnetic Field UTC 27-Apr-2006 07:01:00 to 27-Apr-2006 07:15:20
Spectral Amplitude
Frequency - Hz
Natural lines
.25 Hz
.5 Hz
HAARP


Gakona, AK
27 Apr 2006 (UTC)
00:00
06:00
12:00


E-W Magnetic Field - ULF UTC 27-Apr-2006 07:01:00 to 27-Apr-2006 07:29:30
Frequency - Hz
Time - Second


Gakona 2006 Apr27 117 0700 RSF