Current HF Experiments & Capabilities Related to Workshop Task Statement:
" Virtual ULF/ELF/VLF Ionospheric Antennae"
Resolving Critical Radiation Belt & Geospace Issues

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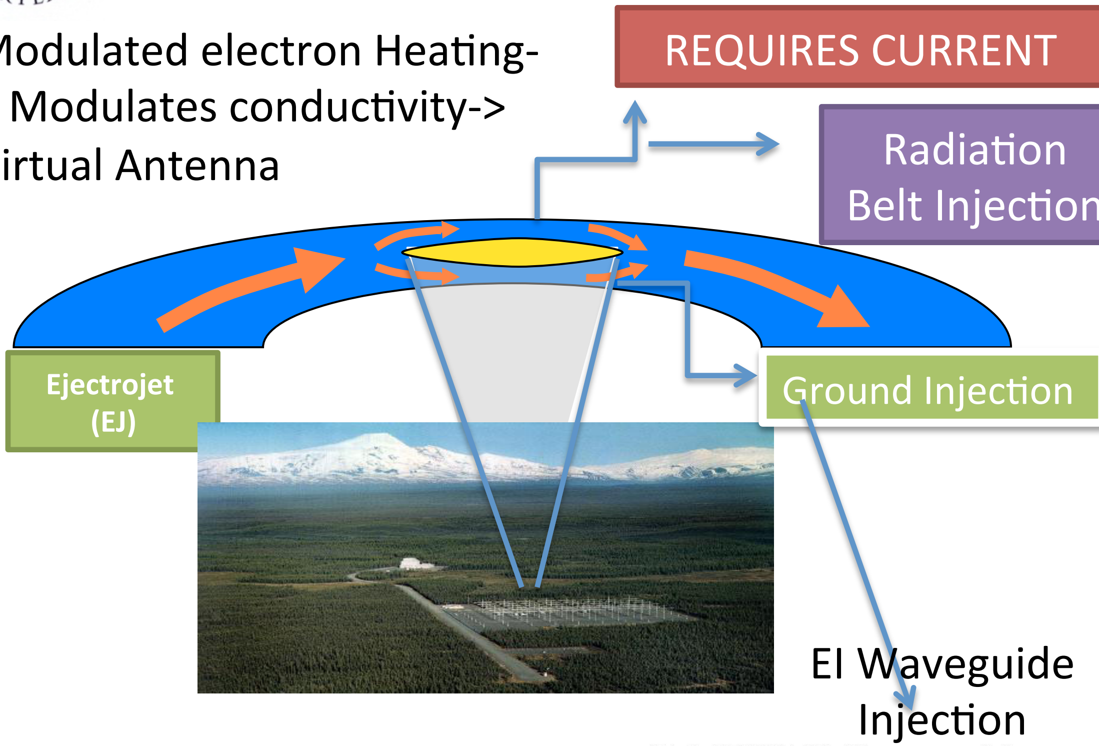
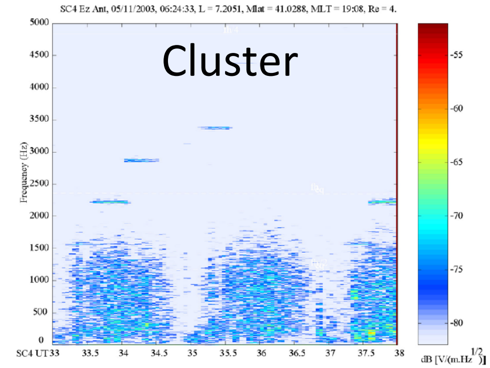
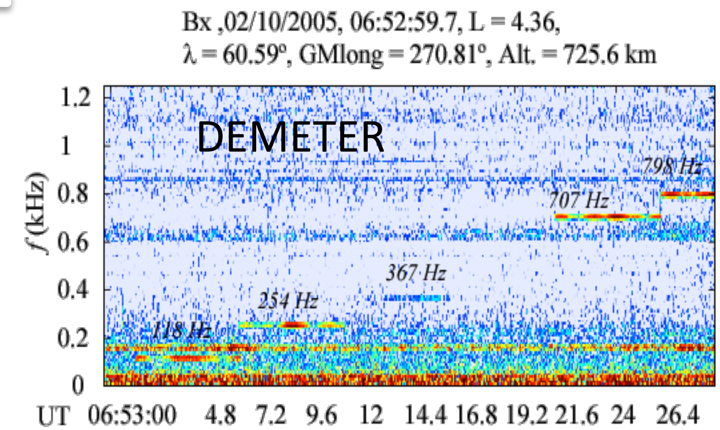
VIRTUAL ANTENNA – CURRENT MODULATION (PEJ)

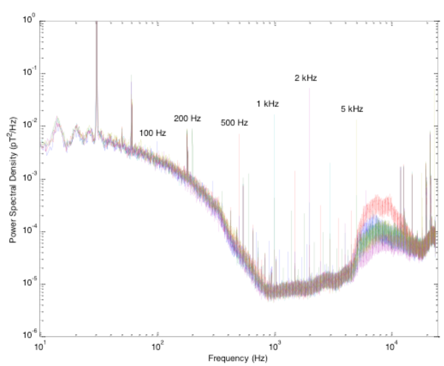
Modulated electron Heating-> Modulates conductivity-> Virtual Antenna



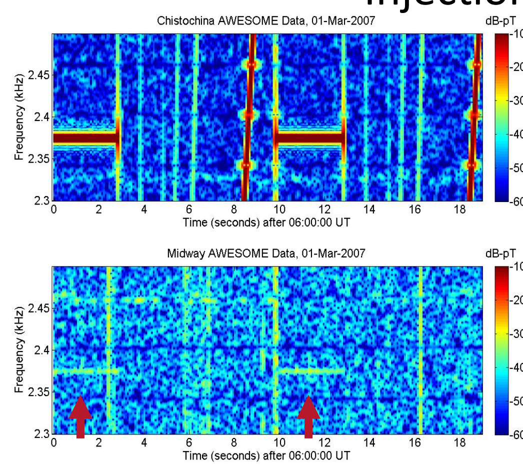


Platino et al., JGR 2004, 2006

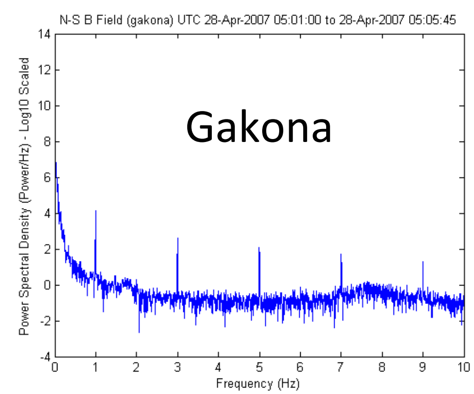




DELTA Mine – Papadopoulos, PARS, 2007



5400 km away Midway, Moore et al., JGR 2007

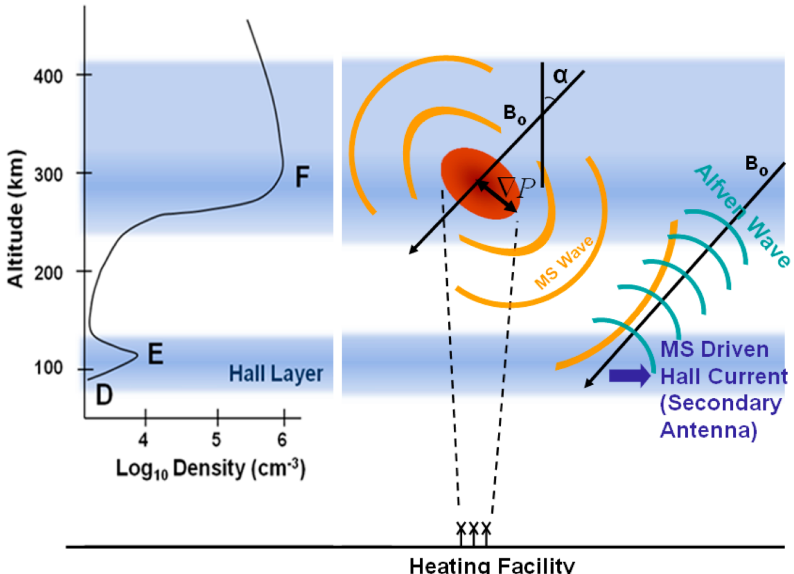


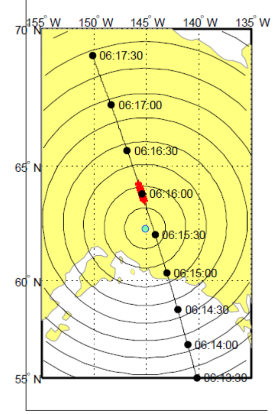
Papadopoulos et al., URSI, 2010; JGR 2005

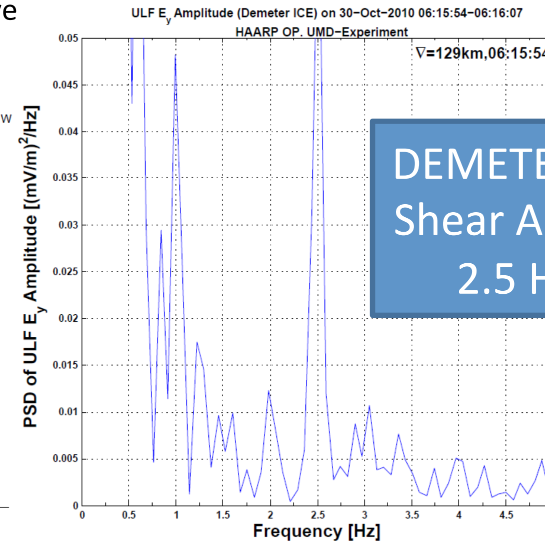
VIRTUAL ANTENNA – IONOSPHERIC CURRENT DRIVE (ICD)

DOES NOT REQUIRE CURRENT- f < 70 Hz

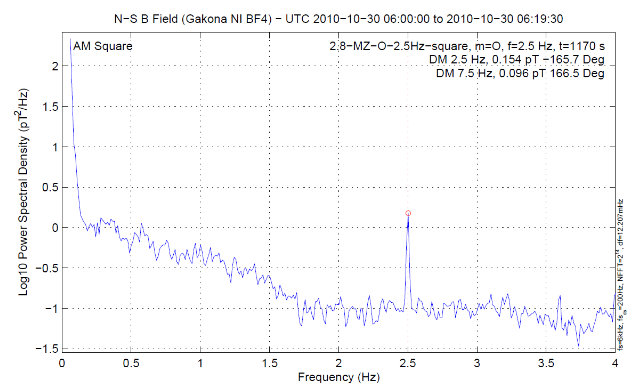
MS-> Magnetosonic
SAW-> Shear Alfven Wave
EJ-> Electrojet

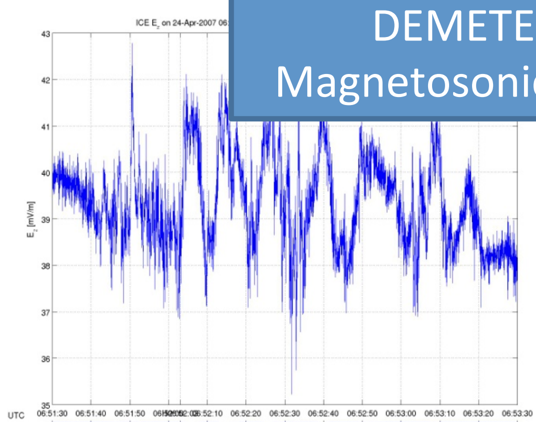




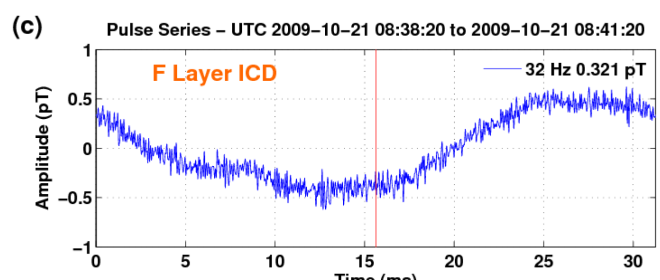


DEMETER
Shear Alfven
2.5 Hz





DEMETER
Magnetosonic .1 Hz



GROUND

Papadopoulos et al. GRL, 2011 a,b; Eliasson et al. JGR, 2012

Cause and Effect Studies of the Physics of Radiation Belts; Priority recommendation of Decadal Survey

- What is the attenuation rate of Shear Alfven (SA) waves propagating towards the conjugates?
- Are there regions of mode conversion of SA waves to Electromagnetic Ion Cyclotron (EMIC) waves and what are the characteristics of the resonant conversion?
- What are the properties of the EMIC waves?
- What are the pitch angle scattering rates of relativistic electrons by EMIC waves?
- What are the pitch angle scattering rates of multi-MeV protons by SA waves?
- What are the properties of Field Line Resonances (FLR) in the inner RB?
- What controls the Ionospheric Alfven Resonator (AIR) structure and amplification?
- What is the non-linear physics of Artificially Stimulated Emissions (ASE) and how it relates to chorus?
- Is there an Alfven maser and what are the operational characteristics?
- Can FLR precipitate electrons?
- What are the properties of Alfvenic waveguide?

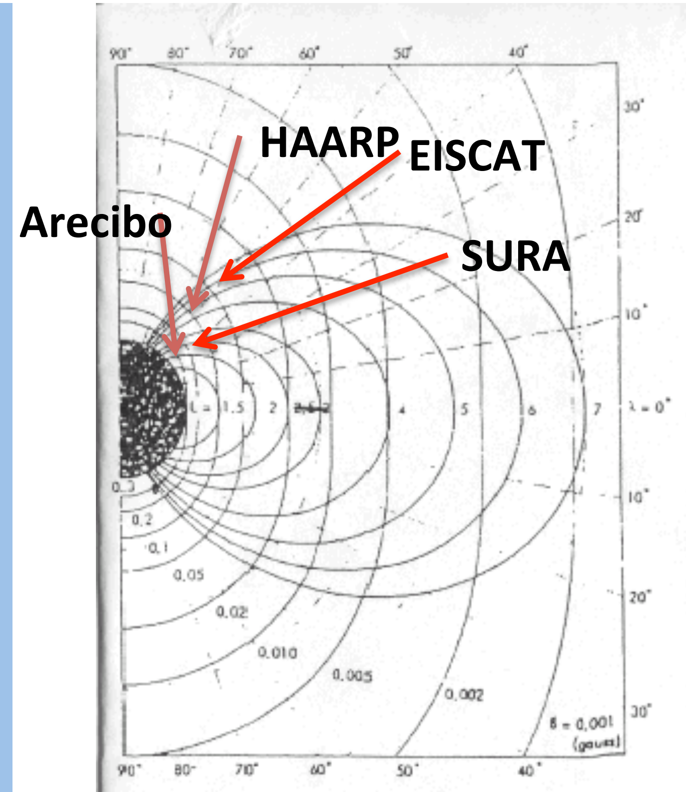


Figure 2-8. Constant-B surfaces in a dipole field.

Use Ionospheric heaters (HF) to inject ULF/ELF/VLF waves in the L-shell that spans the heater.

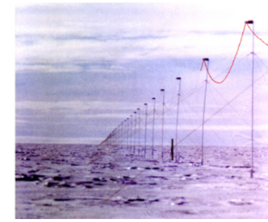
Diagnose by Van Allen,Resonance, DSX, ePOP/Cassiope, ERG, BARREL,Orbitals + microsats and ground instruments (ISR, sensors,…)

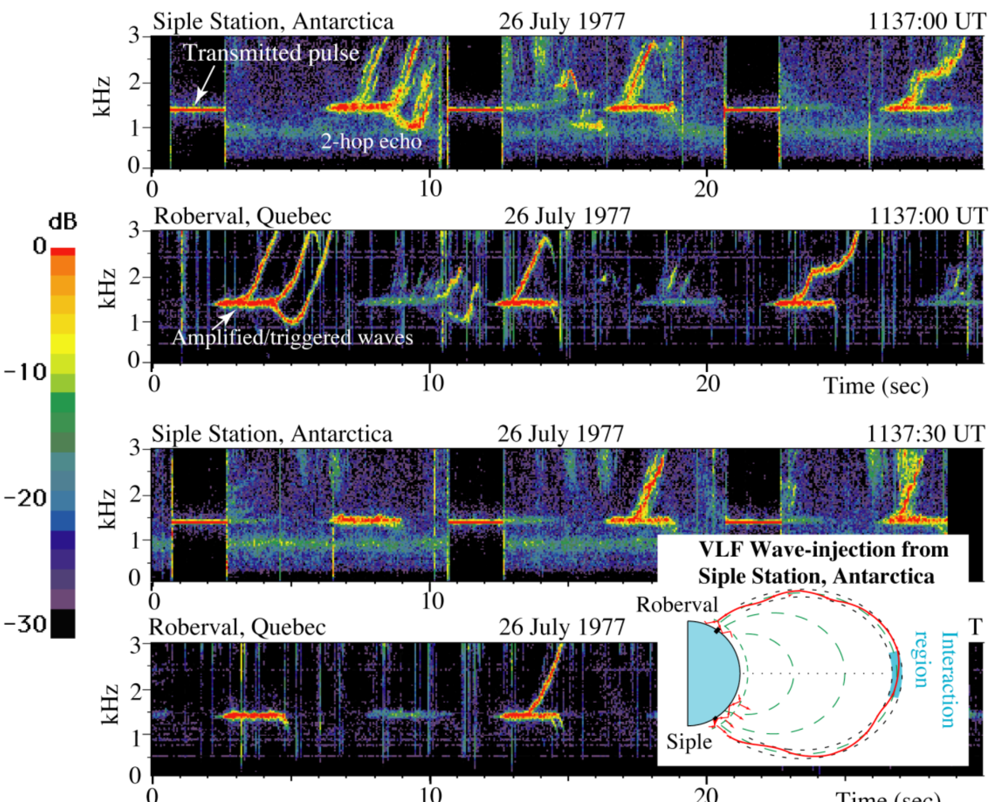
EXAMPLES OF PAST AND CURRENT INVESTIGATIONS

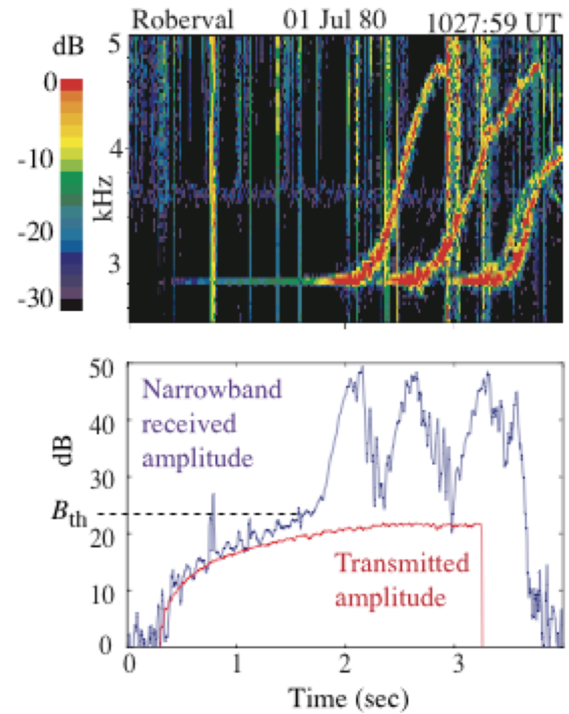
Artificially Stimulated Emissions (ASE) Key RB Physics Issue – Physics of Chorus

Siple Station Antartica – (Stanford – NSF) Helliwell (1973-1987):

L=4.2, 1.5 MW, 42 km length antenna on 2 km thick ice sheet, Inject 3-6 kHz – limited bandwidth
Very difficult and inefficient to inject ELF/VLF with ground facilities

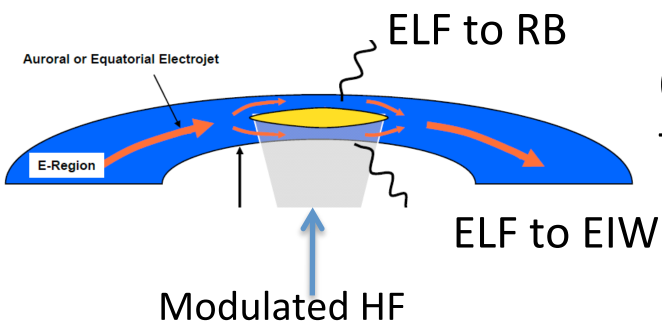






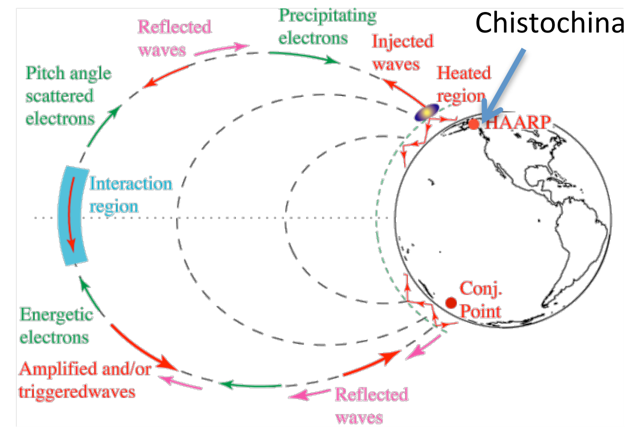
Triggered Emissions

HAARP Artificially Stimulated Emissions



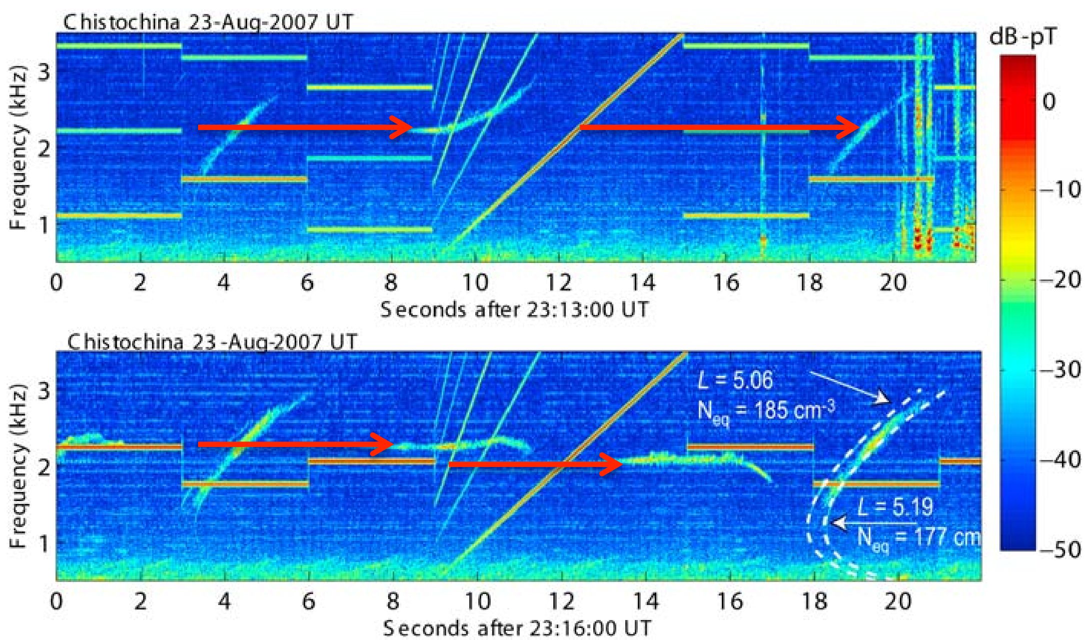
Key non-linear issue in understanding physics of RB (chorus, precipitation, wave-particle amplification, triggered EMIC, etc.)

Diagnostics ?



Golkowski et al. JGR 2008, 2010

2-hop echoes

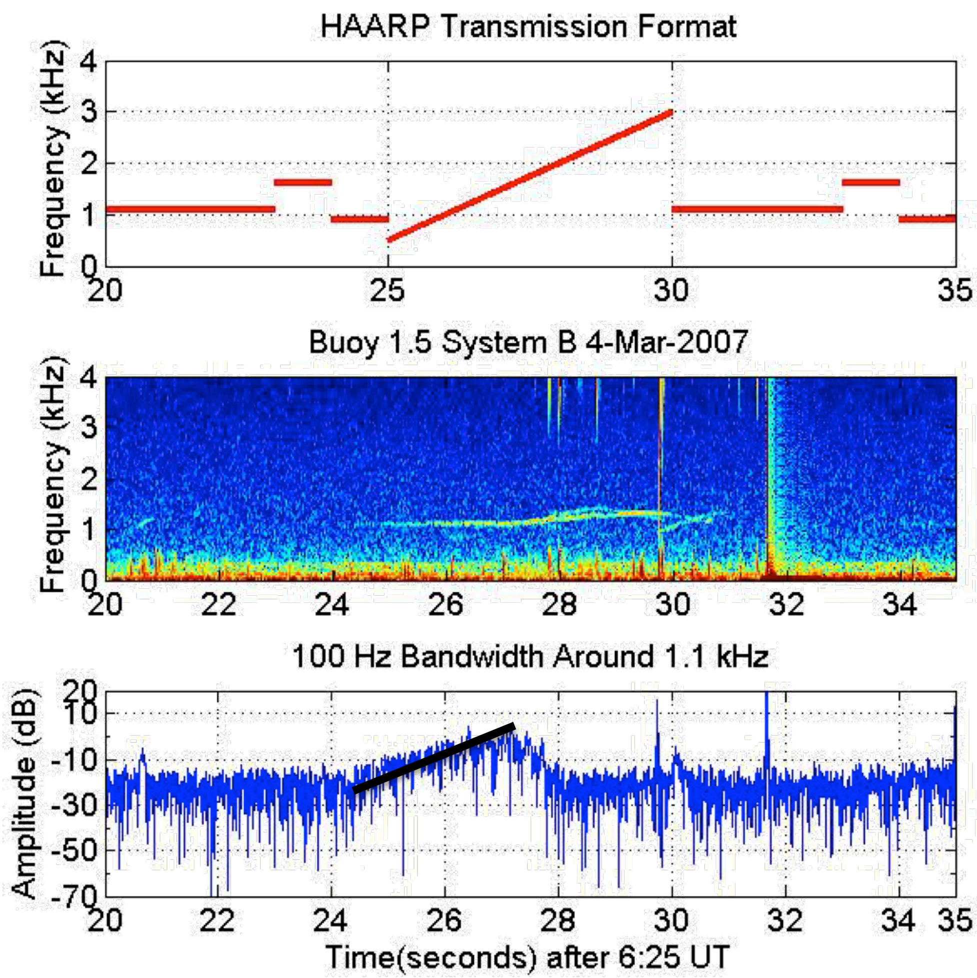


Conjugate

Buoy System

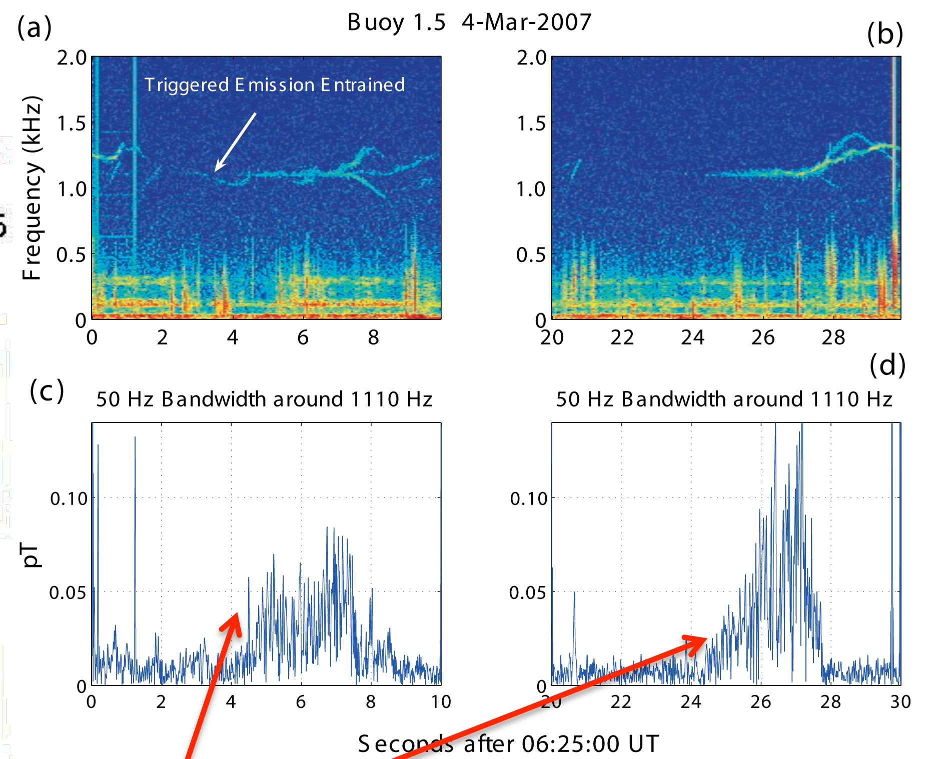
Pulses above 2 kHz have 2-hop echoes with triggered emissions
Pulses below 2 kHz and above 2.8 do not; ramps most often have echoes

15 dB/s Amplification & Triggered Emissions



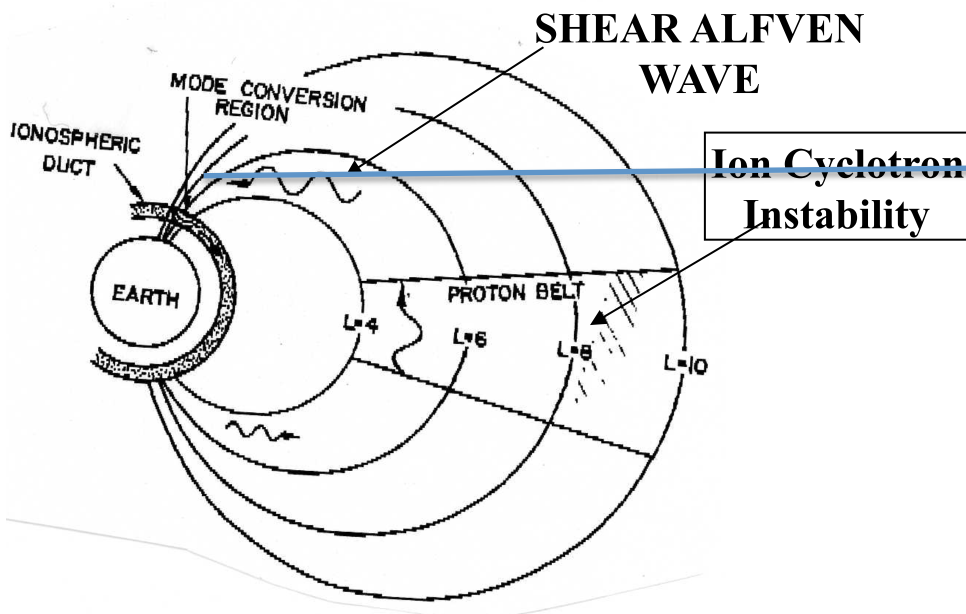
Only the pulse at 1100 Hz is amplified

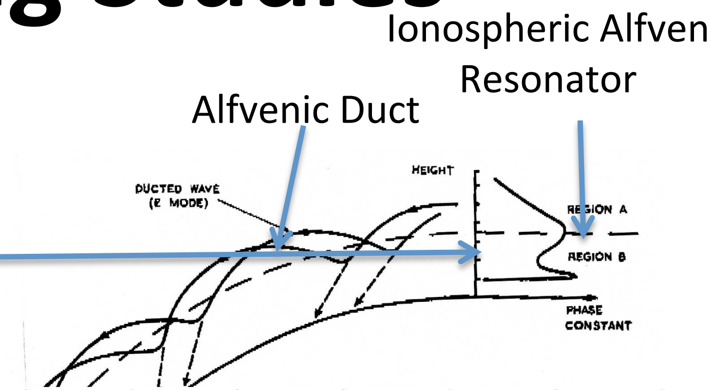
Golkowski et al., JGR 2008, 2010

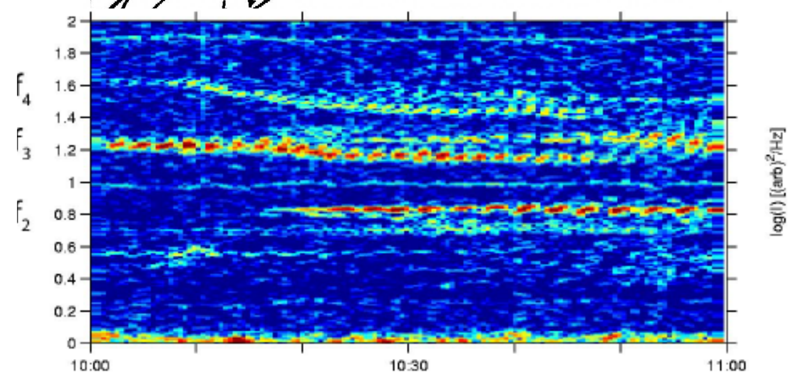


Amplification with and without entrainment. RHS amplification steady below noise floor. LHS initial amplitude above noise due to previous echo (mode locking of coupled oscillators)

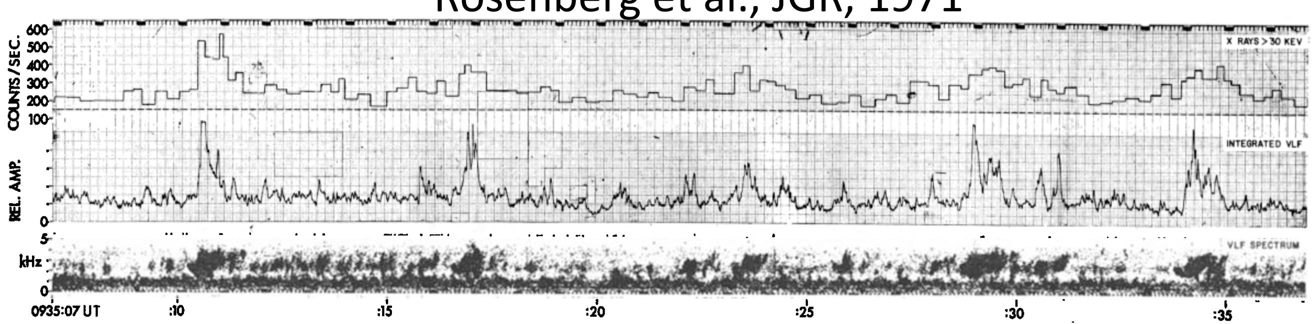
M-I SAW Coupling Studies







Rosenberg et al., JGR, 1971



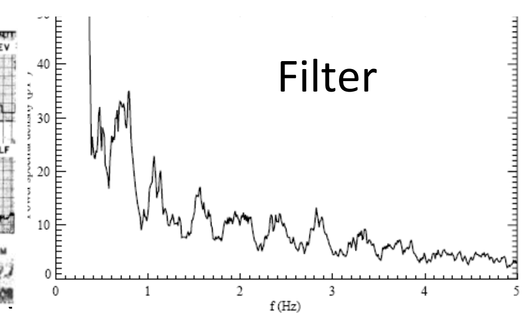
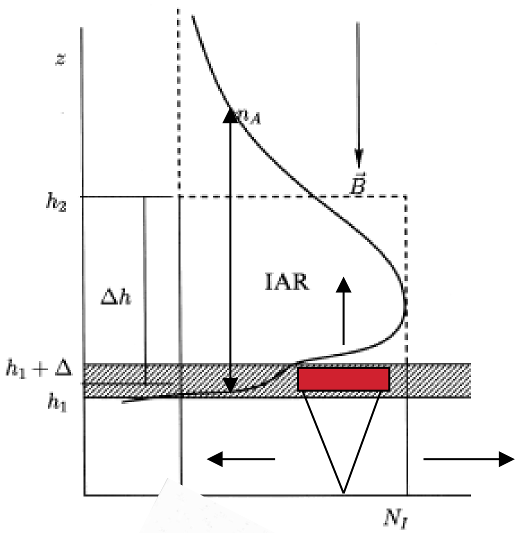
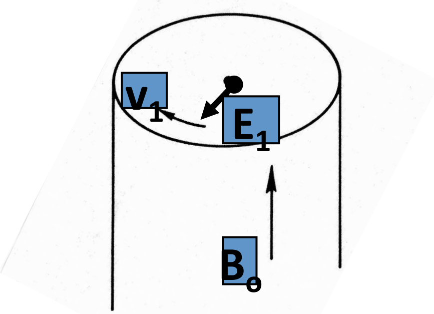


Fig. 1. A 30-sec segment of simultaneous recordings of X-ray count rate for $E > 30$ kev (top), integrated VLF amplitude from 0.6 to 5 kHz (middle), and VLF spectrum from 0 to 5 kHz (bottom), at Siple station, Antarctica, on January 2, 1971. The dashed line in the top portion of the figure refers to the cosmic-ray background level of $\sim$175 c/sec. (Because of a plotting error the X-ray record must be shifted 0.15 sec to the right relative to the VLF records; no correction is required in Figure 2.)

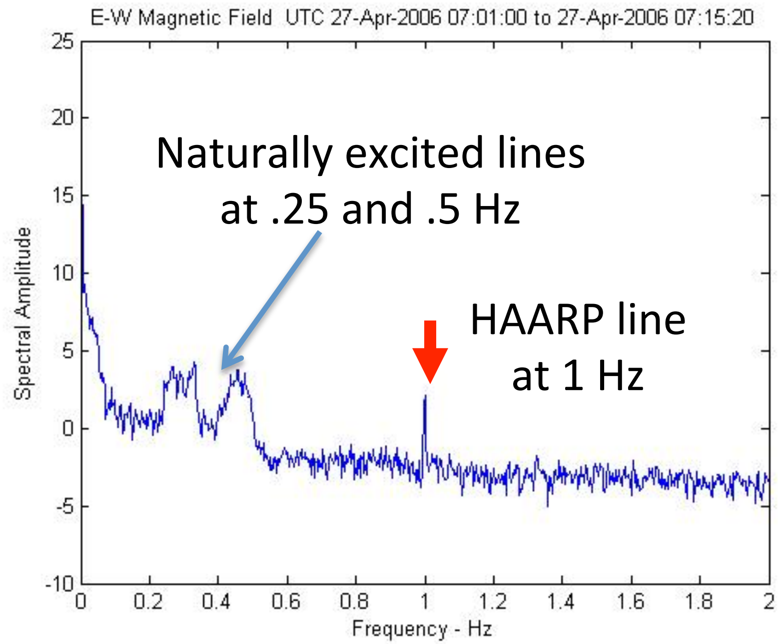
Quasi-periodic ULF/VLF and electron precipitation

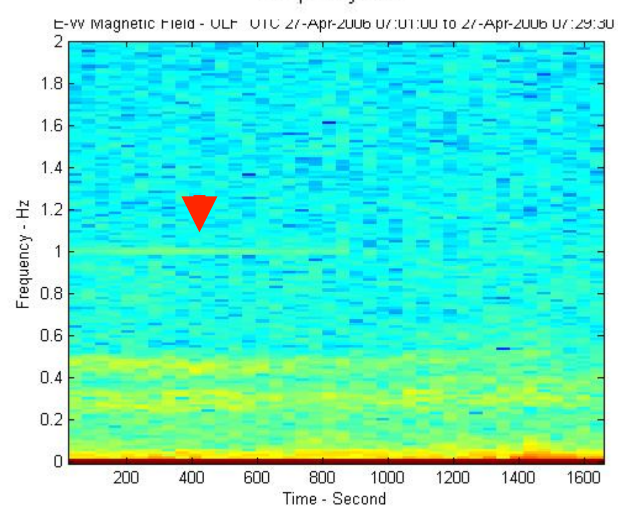
Physics of Pc-1 MHD Waves
Ionospheric Alfven Resonator (IAR)



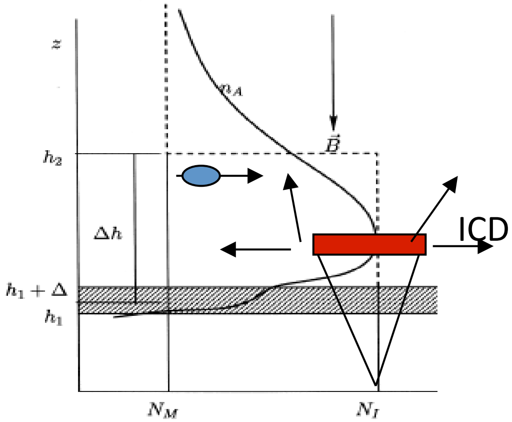


Shear Alfven Wave –Field Guided

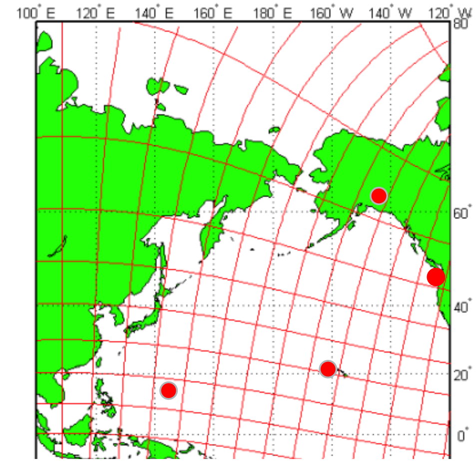


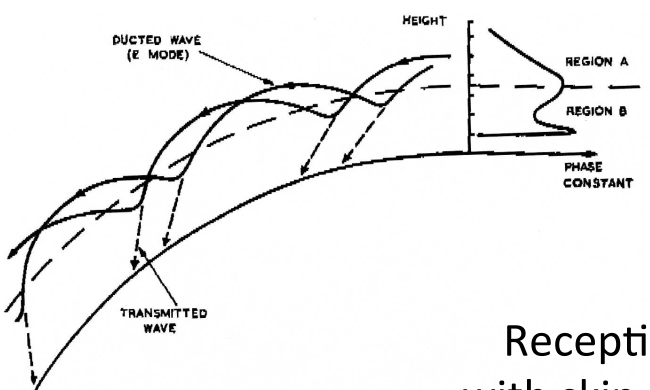


Physics of Pc-1 MHD Waves
Alfvenic Duct

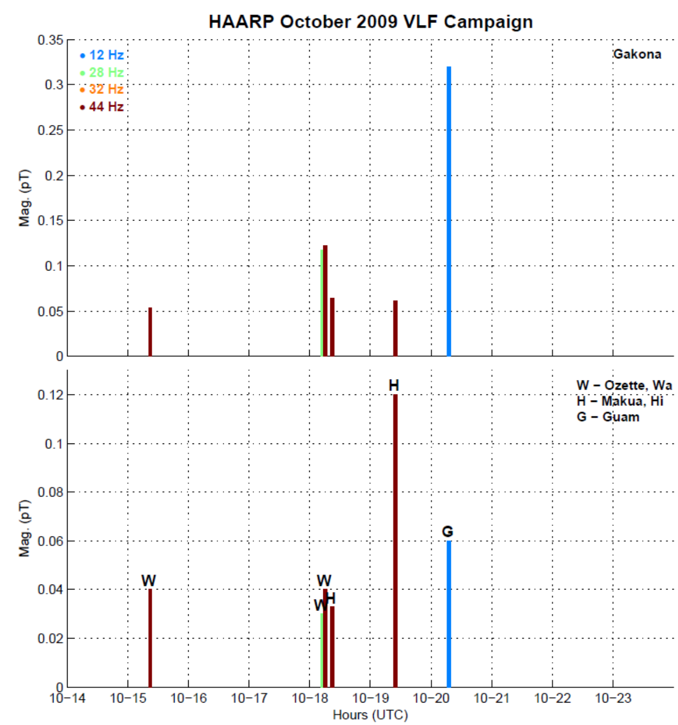


- Distance from Gakona
  - Lake Ozette, WA (W)
    - 1300 mi
  - Hawaii (H)
    - 2900 mi
  - Guam (G)
    - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23

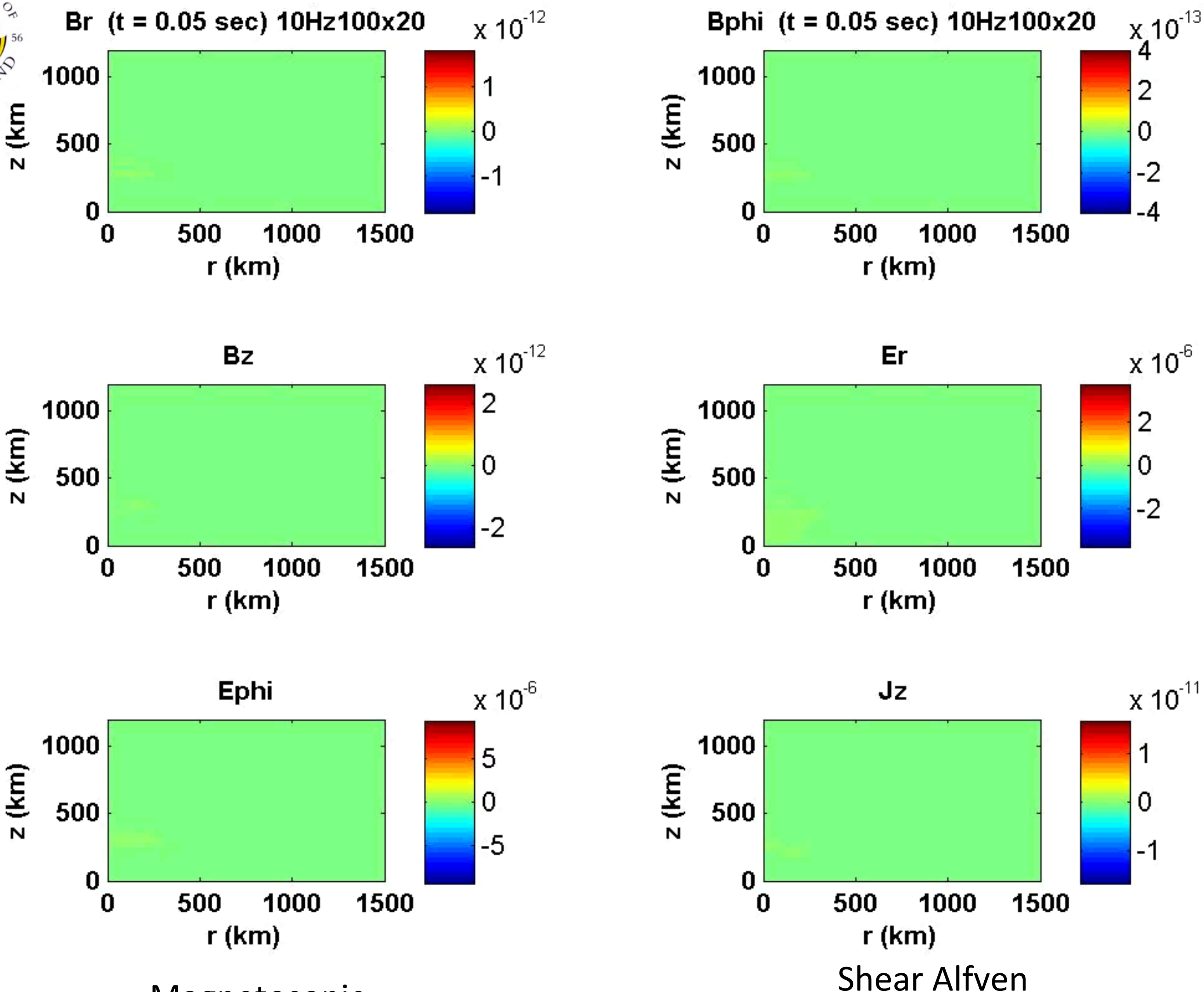




Reception consistent with skip distance effects

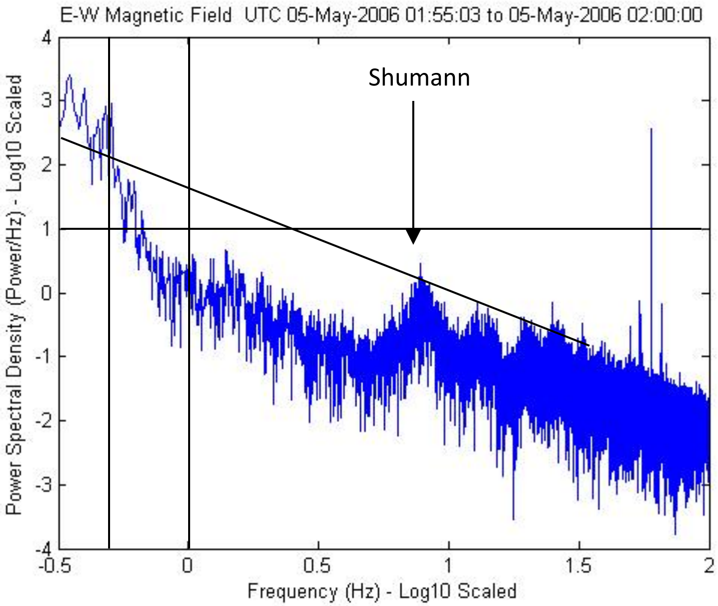


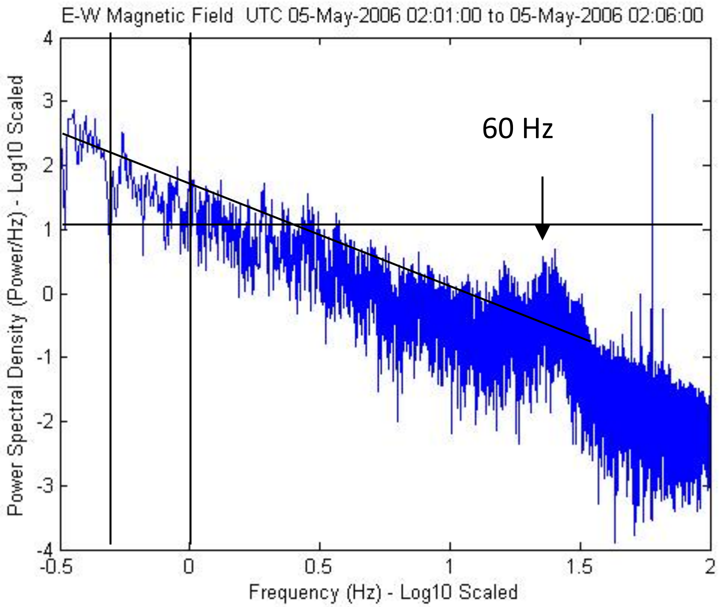
Eliasson, Chang, Papadopoulos, JGR 2012



ICD Simulation

Pc1 Triggered Emissions ?



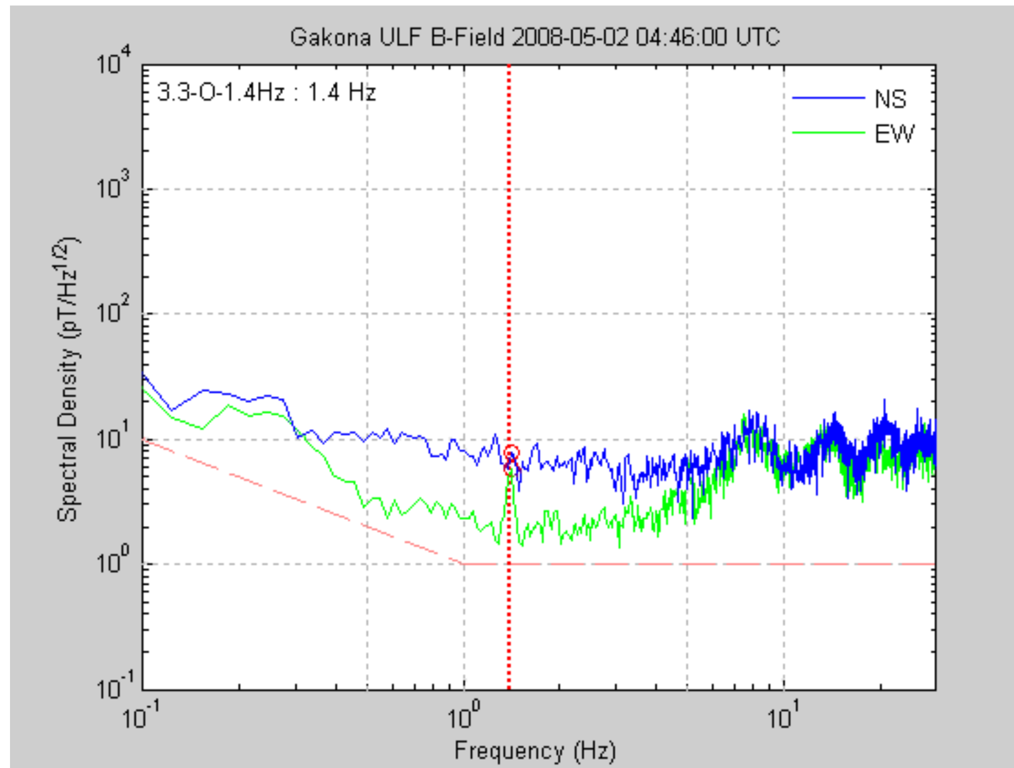


Spectrum before HAARP ULF Start Experiment – Ambient Noise

Spectrum after HAARP ULF Start Noise Increase by more than 10-20 dB between .7-10 Hz

ULF at Gakona – Power Spectral Density (PSD)

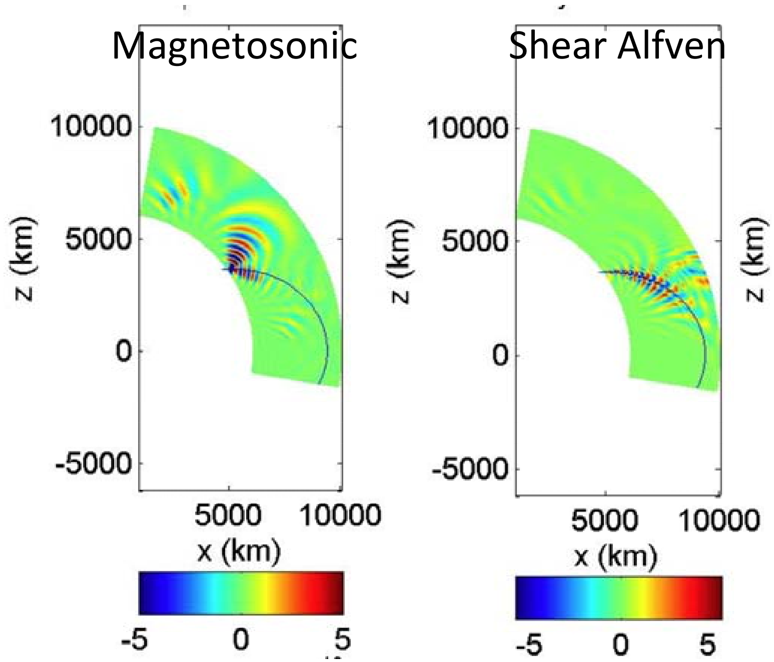
- Frequency spectrum in a moving time window
- Clear Schumann resonances at 8, 14, .. Hz
- Signals emerge as freq. peaks in sync with HAARP ULF operation
- Greatly varying background below 1 Hz



Triggered Pc1 broadband

10’

Example of MHD Wave Propagation Studies in the Inner Belt Using Arecibo and Van Allen Probes



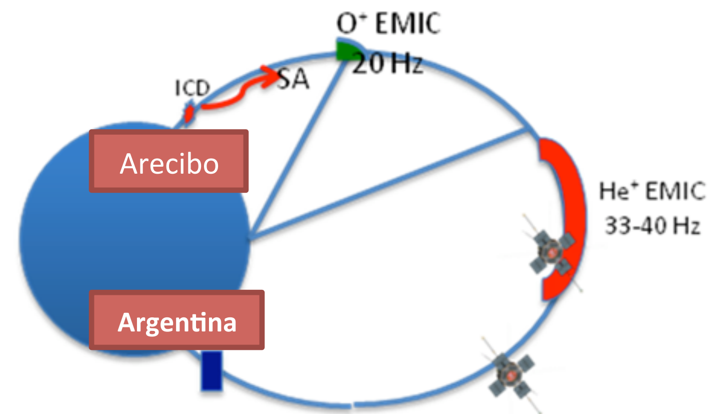
Simulation of MHD Wave injection using the Arecibo Heater

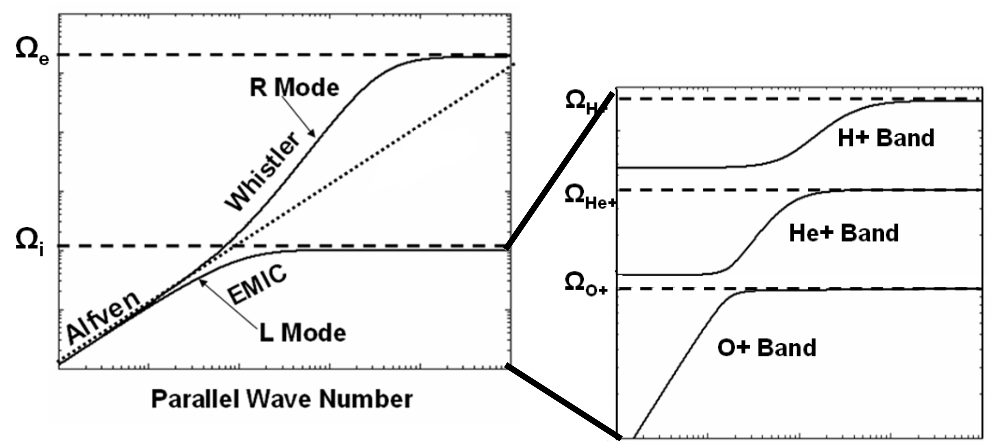
$$-k_z v_z = |\Omega_e| / \gamma$$

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3} \frac{\omega\omega_{pj}^2}{(\omega - \Omega_j)}$$

$$\frac{k^2c^2}{\omega^2} \to \infty \quad \text{for } \omega \to \Omega_j$$

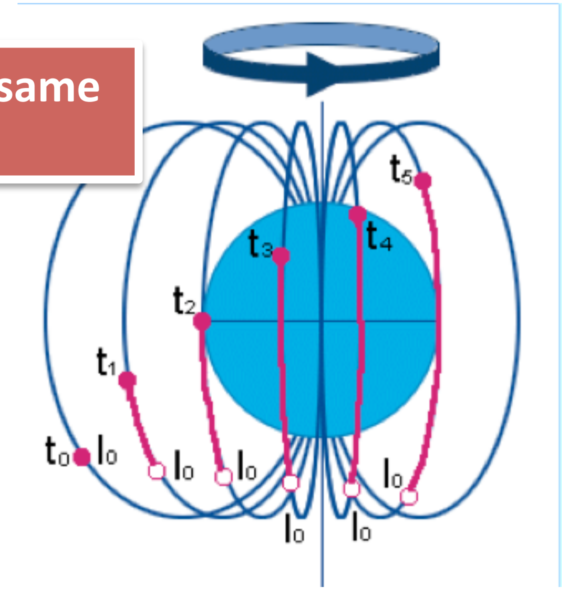
As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance $(1/k_z \to 0)$



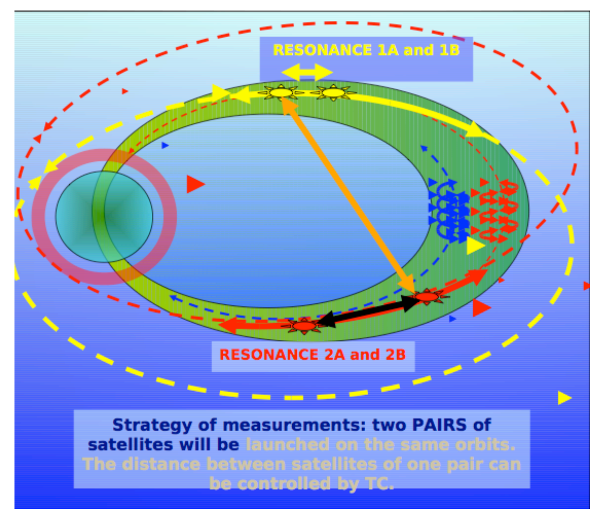


Resonance – The ideal Partner of HAARP

Pair of microsatellites in Magneto-synchronous orbit – Stay on same field line for 45-60 minutes

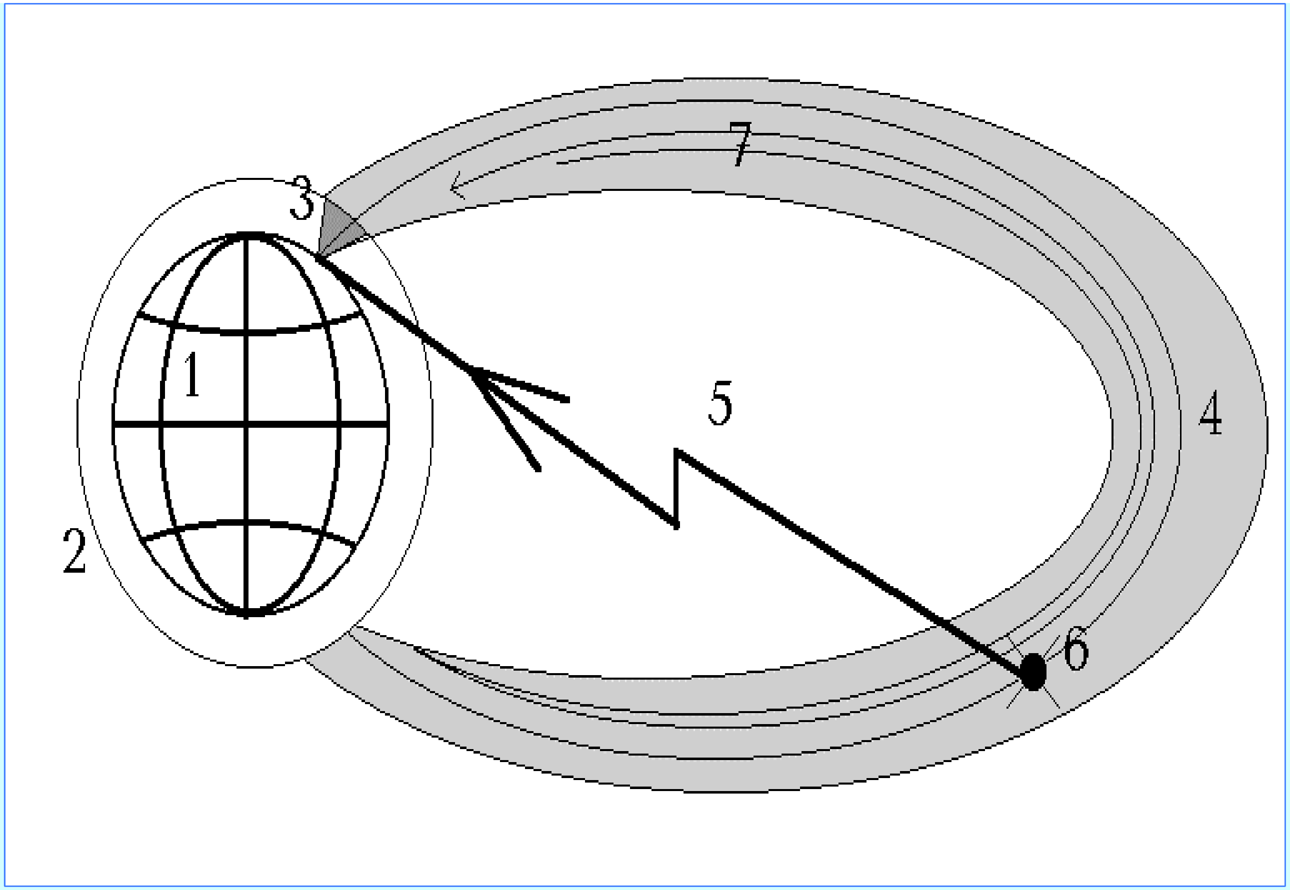


- Wave-particle interactions in the Radiation Belts – Whistler range
  - Artificially Stimulated Emissions (ASE)
- ULF - MHD Study
  - Shear Alfven Waves ,EMIC and Magnetosonic wave injection in space. Interactions with trapped electron and ions
  - Excitation of the Ionospheric Alfven Resonator (IAR)
  - Shear Alfven Wave (Pc1) triggering



Mission to be launched by IKI/Russia Summer 2014

FROM RESONANCE PLAN DOCUMENT

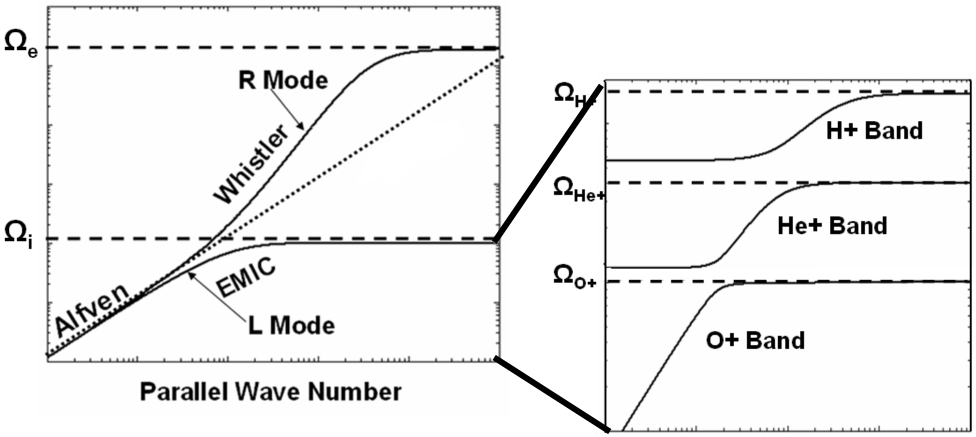


Scheme of a joint experiment with a ground-based heater

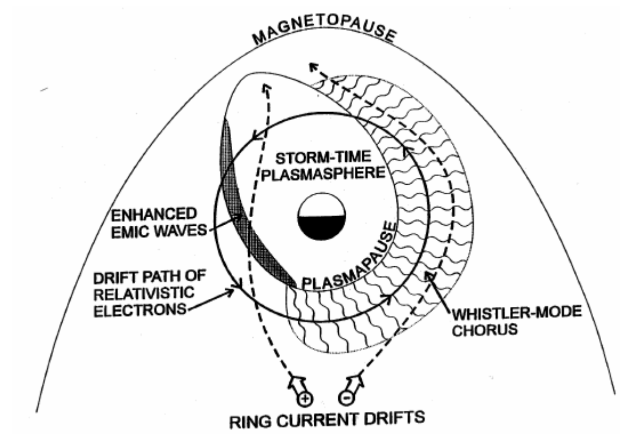
1 – Earth, 2 – ionosphere, 3 – heated ionosphere region, 4 – magnetic flux tube, 5 – TM line, 6 – satellite, 7 – trajectories of particles and guided waves

Supplementary Slides

ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



Outer Belts



Summers et al., 1998, 2000, 2003

$$-k_z v_z = |\Omega_e| / \gamma$$

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3} \frac{\omega\omega_{pj}^2}{(\omega - \Omega_j)}$$

$$\frac{k^2c^2}{\omega^2} \to \infty \quad \text{for } \omega \to \Omega_j$$

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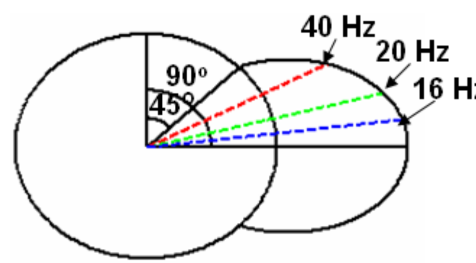
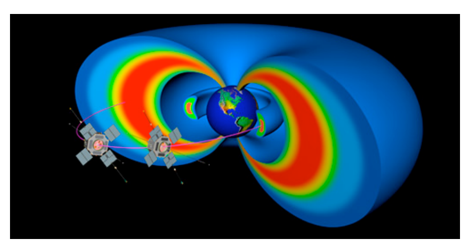
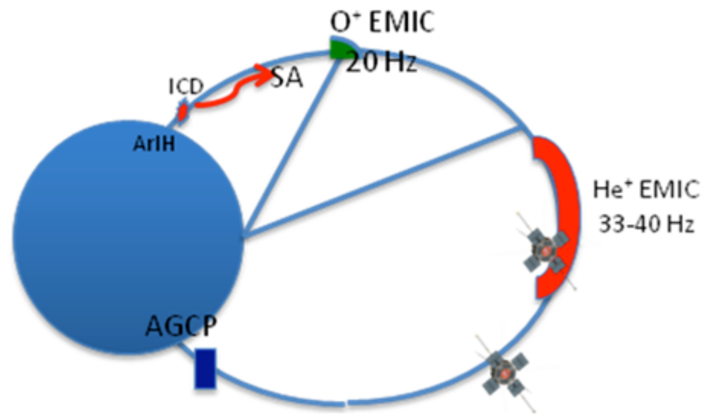
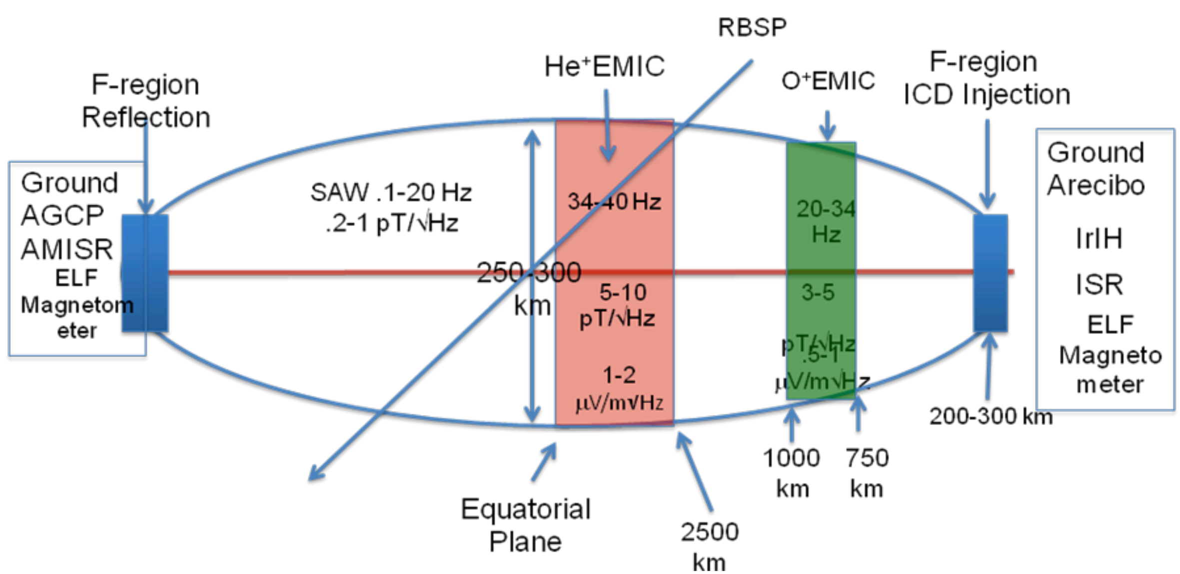
HELIUM BRANCH





Example of study of MHD Wave Propagation in the Inner Belt Using Arecibo and Van Allen Probes

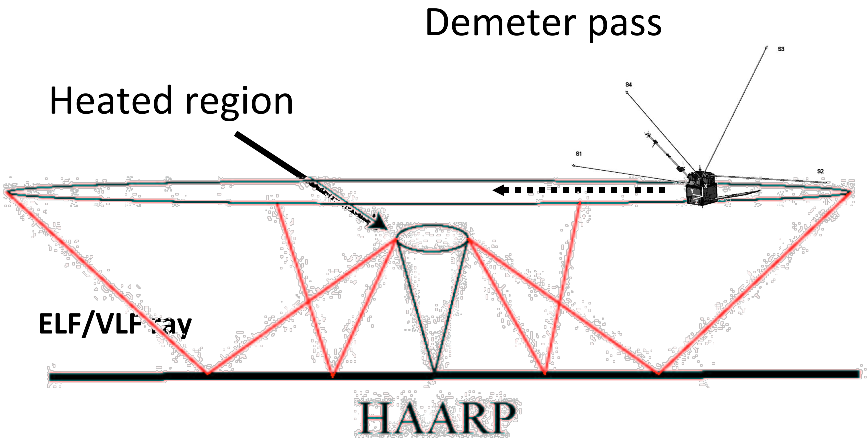


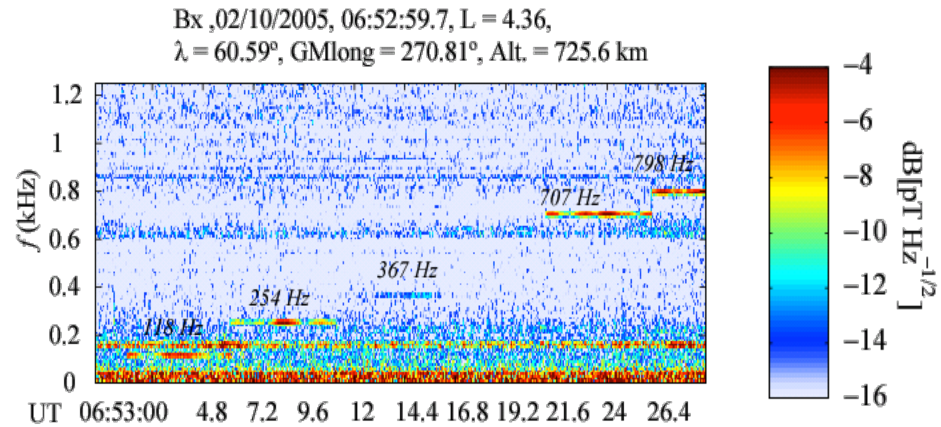


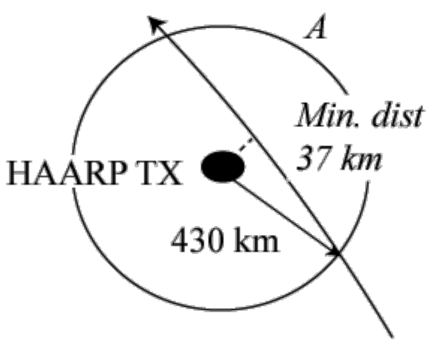
Active experiments vs Resonance mission

- Long-term (0.5–3 hr) multi-spacecraft observations in the flux tube conjugated with a heater (HAARP)
  - Any magnetospheric effect of the heater operation (e.g., ULF/ELF/VLF waves, energetic particle modification, cold plasma updraft) can be studied in detail
- Control of heater operation based on transmitted Resonance data
  - For example, information on natural emissions in the magnetosphere can be useful to choose the modulation frequency
- Artificial feedback in the magnetosphere-ionosphere interaction?
  - Modulating the ionospheric reflection in-phase with the precipitated electron/proton flux can amplify the relaxation oscillations of the cyclotron instability

HAARP-DEMETER VLF INJECTION



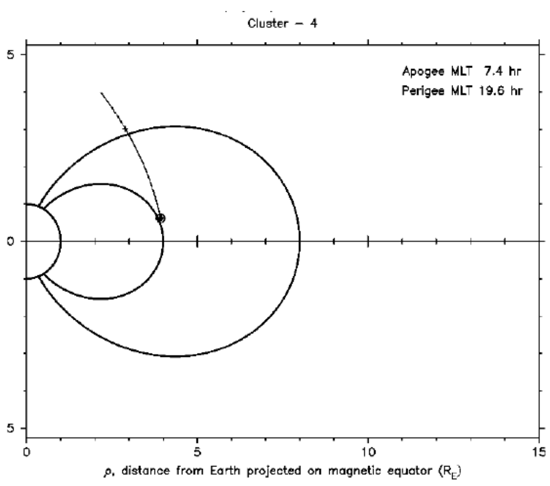


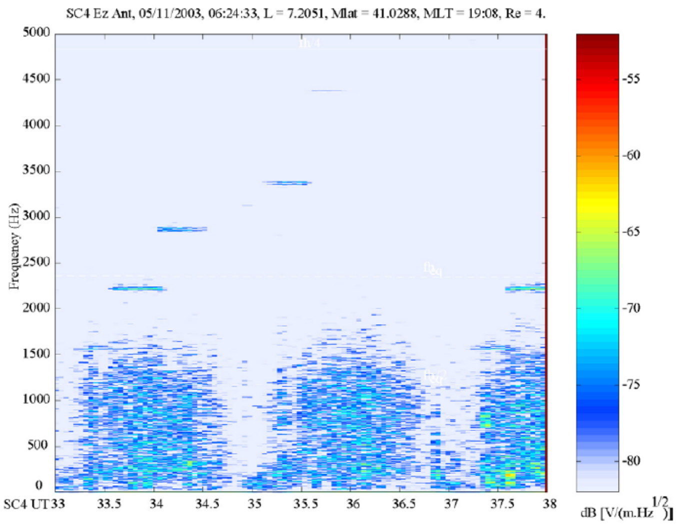


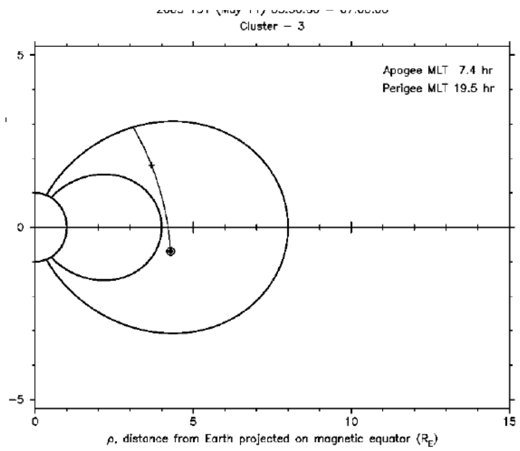
- ELF/VLF signals observed in LEO (~700 km) at lateral distances of >400-km from HAARP
- Simultaneous measurement of all six components (3*E*, 3*B*) allows estimation of the Poynting vector
- Total ELF/VLF radiated power estimated to be ~10 to 30 Watts in the range ~100 Hz to 800 Hz.

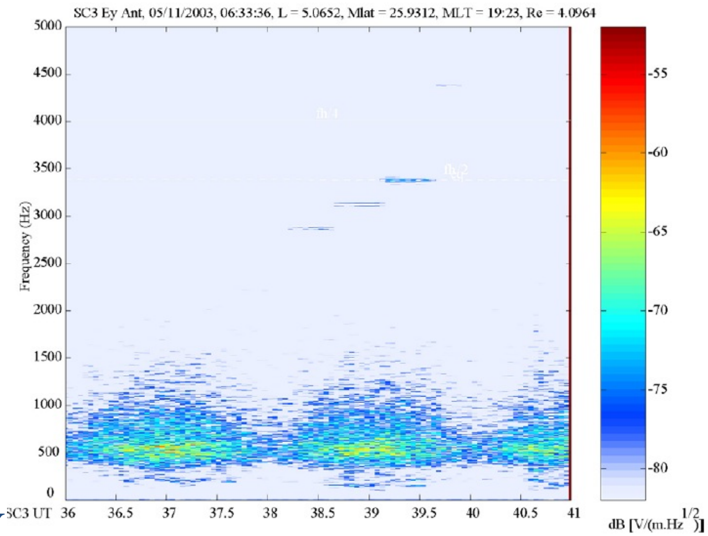
COURTESY STANFORD UNIVERSITY

HAARP/CLUSTER INJECTION

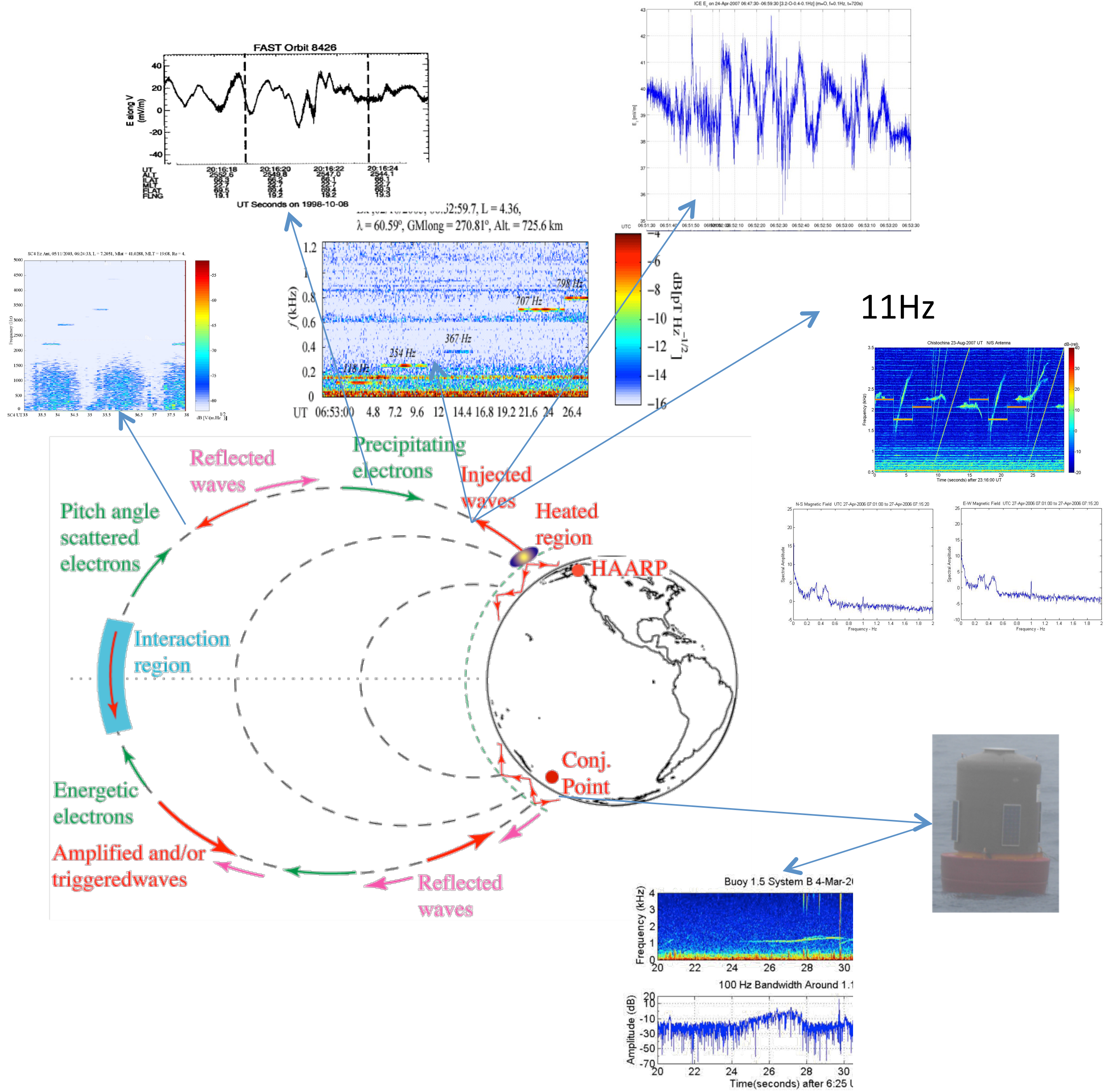






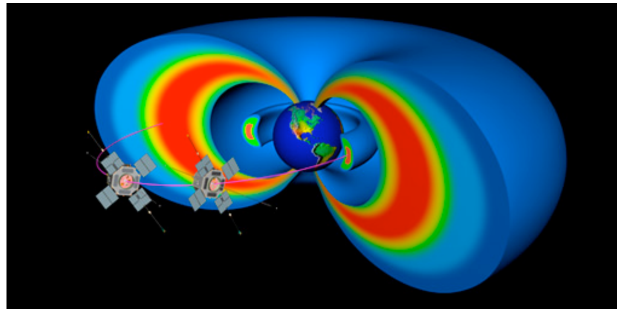


COURTESY STANFORD UNIVERSITY



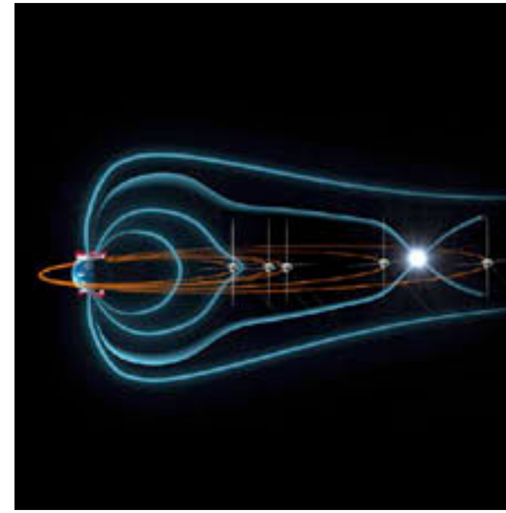
FAST Orbit 8426
E along V (mV/m)
UT Seconds on 1998-10-08
λ = 60.59°, GMlong = 270.81°, Alt. = 725.6 km
f (kHz)
798 Hz
707 Hz
367 Hz
254 Hz
118 Hz
dB[pT Hz^-1/2]
11Hz
Reflected waves
Precipitating electrons
Injected waves
Heated region
HAARP
Pitch angle scattered electrons
Interaction region
Conj. Point
Energetic electrons
Amplified and/or triggeredwaves
Reflected waves
Buoy 1.5 System B 4-Mar-2
Frequency (kHz)
100 Hz Bandwidth Around 1.1
Amplitude (dB)
Time(seconds) after 6:25 U

RBSP



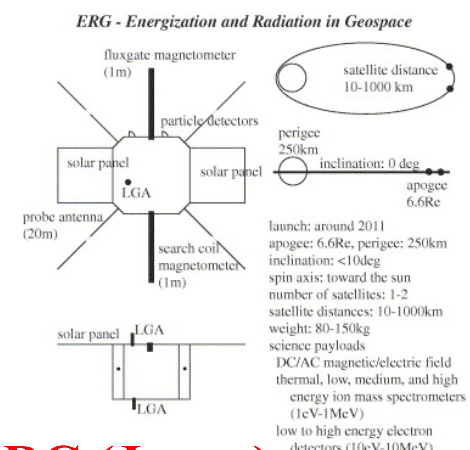
RESONANCE (Russia)

Launch ~2012-14, 4-spacecraft
Orbit:1800x30,000km, ~63° incl.



BARREL (NASA)

Launch ~2013
2 campaigns, 5-8 balloons each

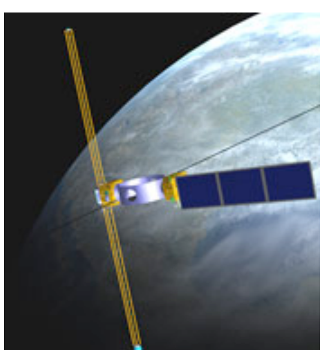


THEMIS (NASA)

Launch Feb 17, 2007
5 identical probes (3)

ERG (Japan)

Launch ~2014, GTO



DSX (AFRL)

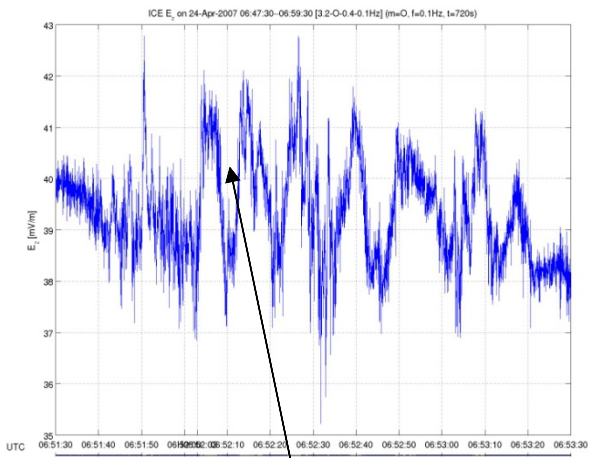
Launch ~2015
MEO, wave/particle

ORBITALS (CSA)

Launch ?
Orbit(?) ~L=2 to L=6

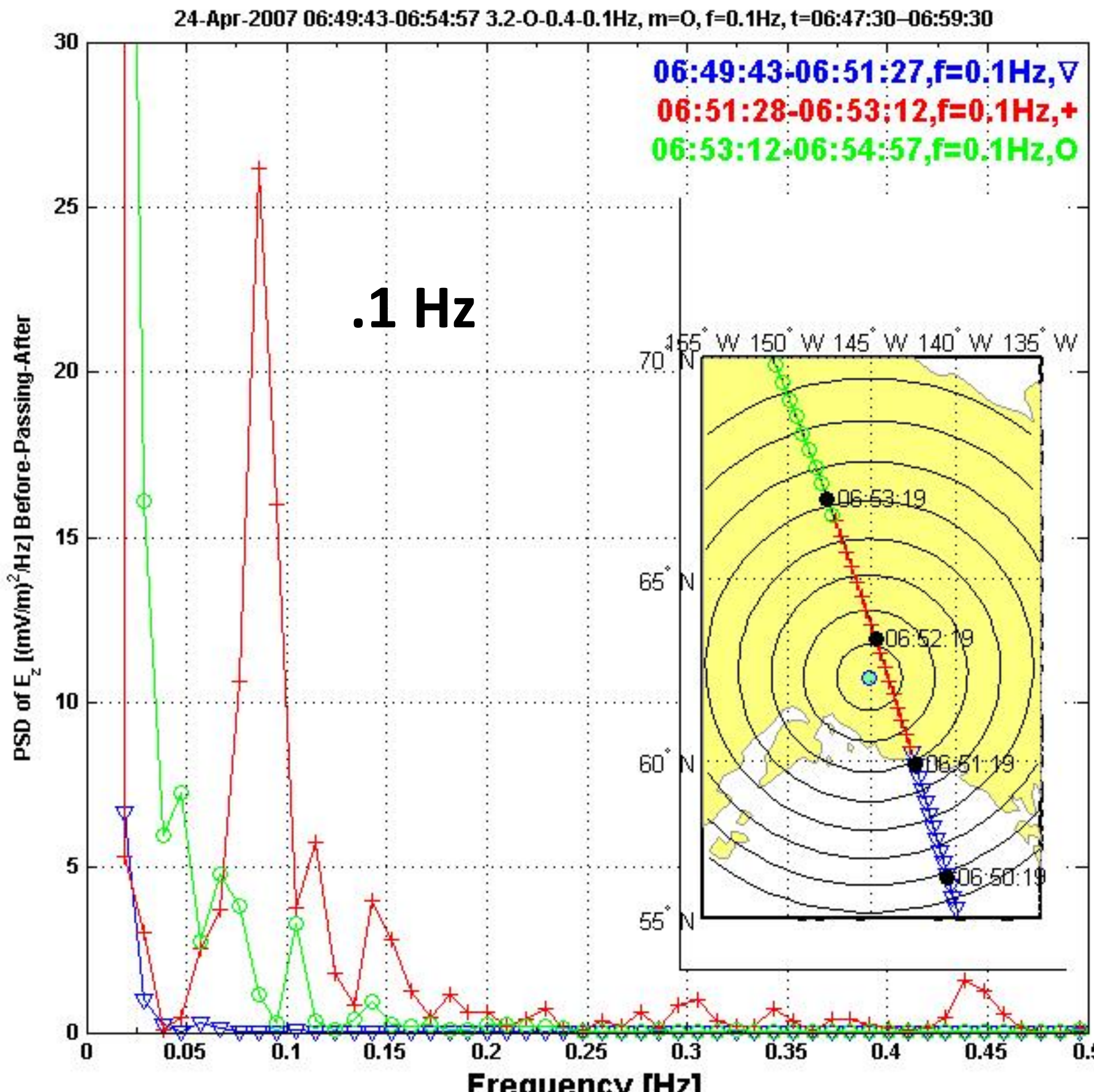
Msonic Wave Injection

DEMETER



10 sec oscillations

Over 700 km distance



Wave-particle interactions study under controlled wave injection

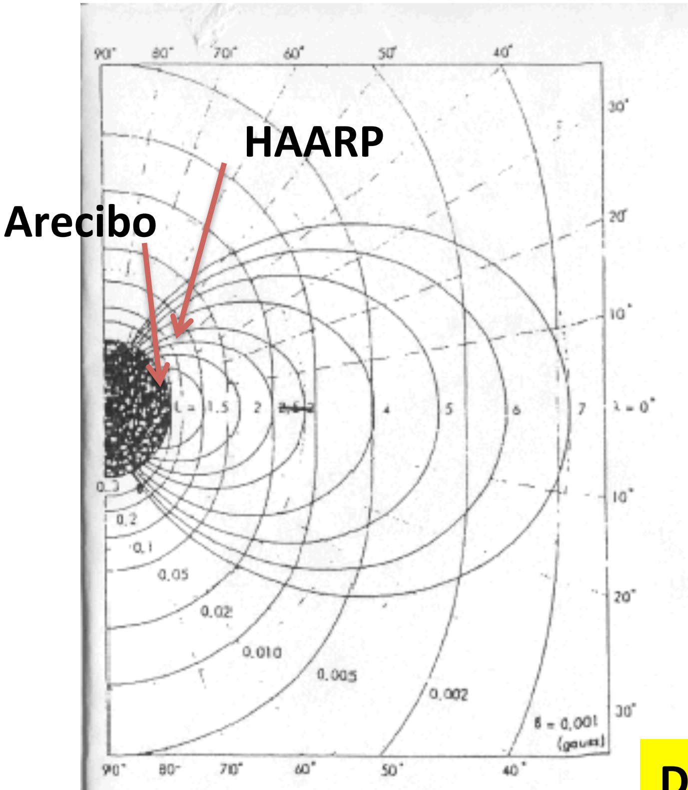


Figure 2-8. Constant-B surfaces in a dipole field.

- Use Ionospheric heaters (HF) to inject ULF/ELF/VLF waves in the L-shell that spans the heater.

Ionospheric Heaters
HAARP (L≈4.9)
Arecibo (L≈1.4)
Tromso (L≈5.9)
SURA (L≈2.6)

Diagnosed by RBSP ,Resonance, DSX, ePOP

- Inner RB (1.5<L<2)
- Slot (2<L<3)
- Outer (L>3)

Techniques to transform HF to ULF/ELF/VLF frequencies

1.Polar Electrojet Antenna (PEJ)

a. Requires an electrojet current in the D/E region (70-90 km)-Restricted to high latitudes

b. Can inject frequencies up to 20 kHz [Whistlers and Shear Alfven Waves (SAW)]

2. Ionospheric Current Drive (ICD)

a. Does not require electrojet

b. Restricted to frequencies below 70 Hz [SAW, EMIC, Magneto-Sonic (MS)]