

CONTROLLED WAVE PARTICLE INTERACTION STUDIES IN THE RADIATION BELTS

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UMCP**

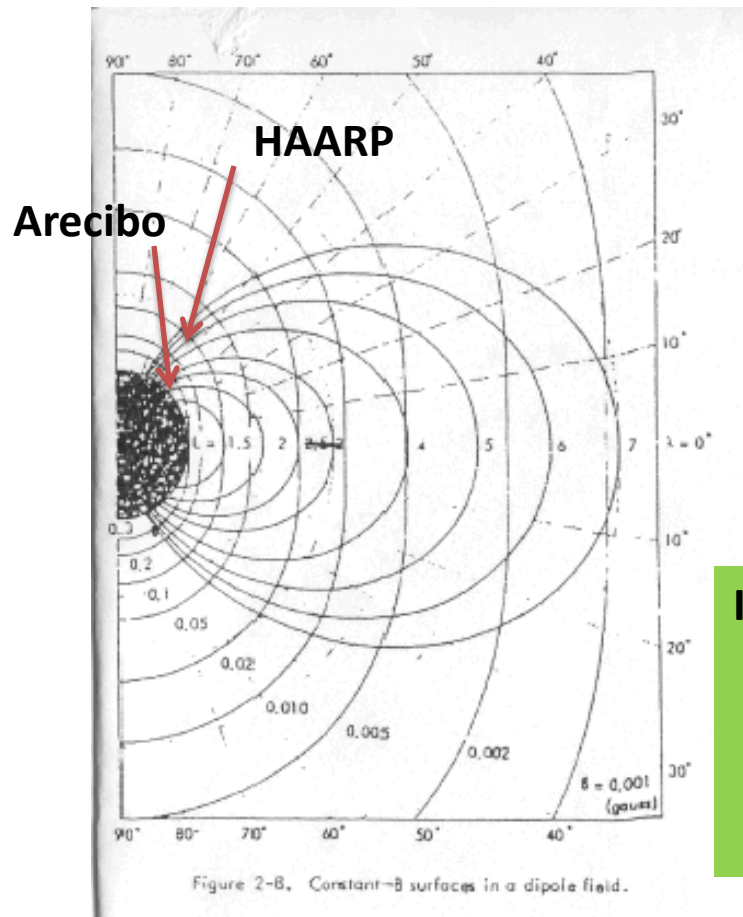
**ACKNOWLEDGE: C.L.CHANG, J.LEBINSKY AT BAE
SYSTEMS**

**XI SHAO, B.ELIASSON, S. SHARMA AND G. MILIKH
AT UMCP**

SUPPORT: MURI/ONR AND BRIOCHE/DARPA

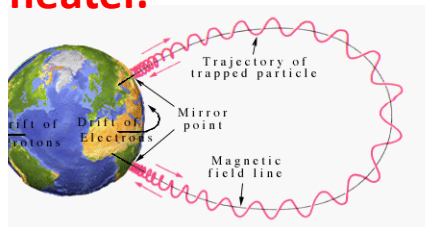
**PRESENTATION TO
HAARP/RESONANCE
WORKSHOP
NOVEMBER, 8,2011
UMCP**

Wave-particle interactions study under controlled wave injection



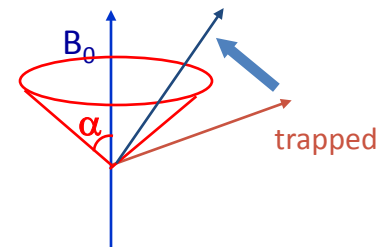
- Inner RB ($1.5 < L < 2$)
- Slot ($2 < L < 3$)
- Outer ($L > 3$)

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



Ionospheric Heaters
 HAARP ($L \approx 4.9$)
 Arecibo ($L \approx 1.4$)
 Tromso ($L \approx 5.9$)
 SURA ($L \approx 2.6$)

Diagnosed by
 RBSP, Resonance, DSX,
 ePOP



Techniques to transform HF to ULF/ELF/VLF frequencies

1. Polar Electrojet Antenna (PEJ)

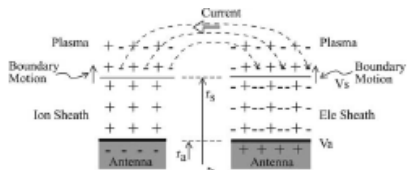
- Requires an electrojet current in the D/E region (70-90 km)- Restricted to high latitudes

- Can inject frequencies up to 20 kHz [Whistlers and Shear Alfvén Waves (SAW)]

2. Ionospheric Current Drive (ICD)

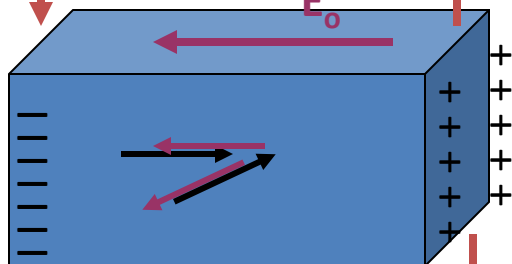
- Does not require electrojet
- Restricted to frequencies below 70 Hz [SAW, EMIC, Magneto-Sonic (MS)]

The Plasma Physics of the PEJ



Injects whistlers and SAW

◀ FAC



$$J_P / J_H = v_{en} / \Omega_e$$

$$v_{en} \propto T_e^\alpha$$

$$\epsilon\omega = \sigma$$

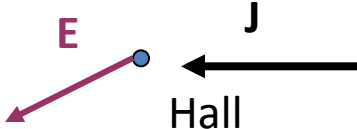
$$E = E_0 \quad 0 < t < T$$

$$E = 0 \quad T < t < 2T$$

$$v \ll \Omega_e$$

$$v = \Omega_e$$

$$v \gg \Omega_e$$



Hall



Pedersen

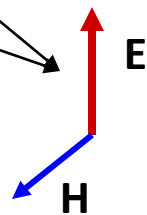
Bottom of the ionosphere

$$\epsilon\omega = \sigma$$

Near field

Far field

Bo

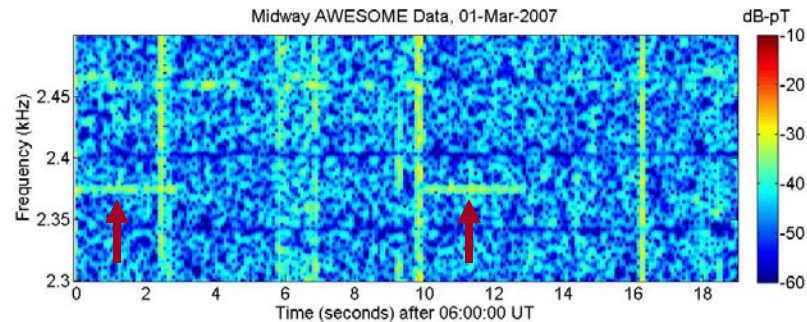
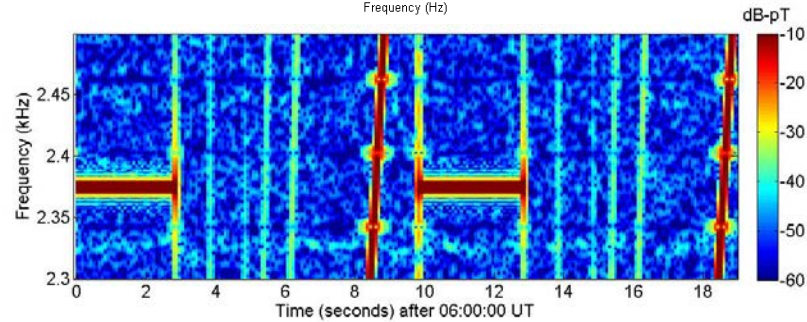
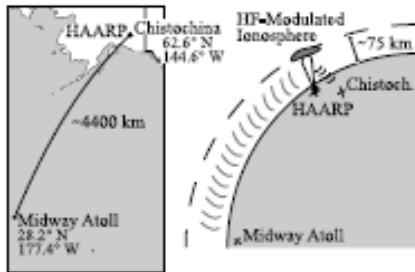
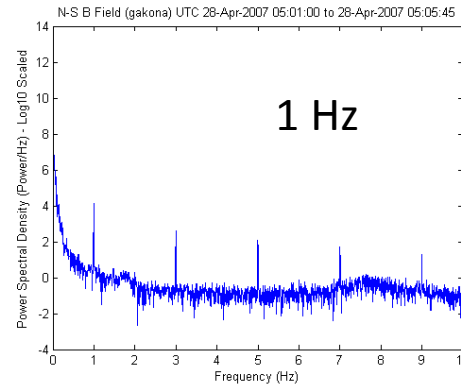
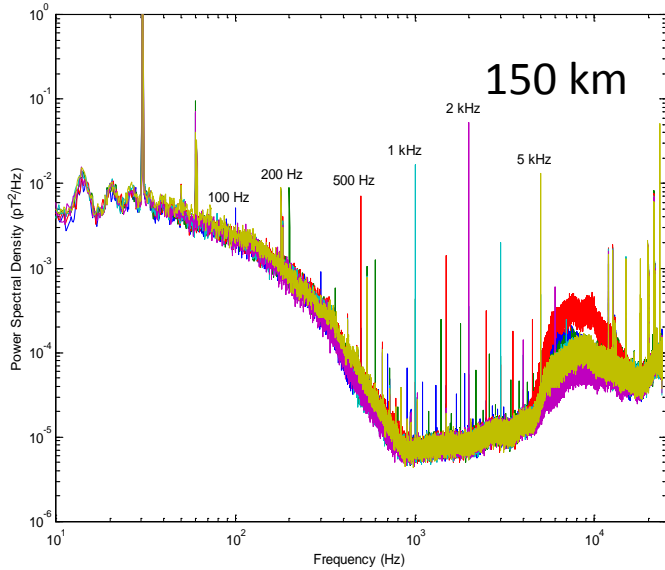


TEM mode

heater



ELF/VLF ground detection and propagation

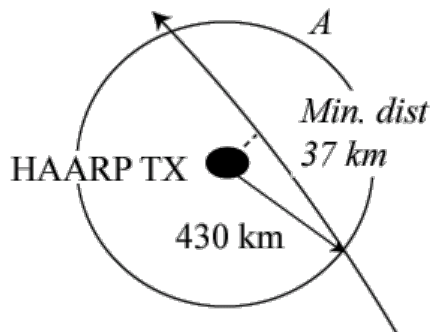
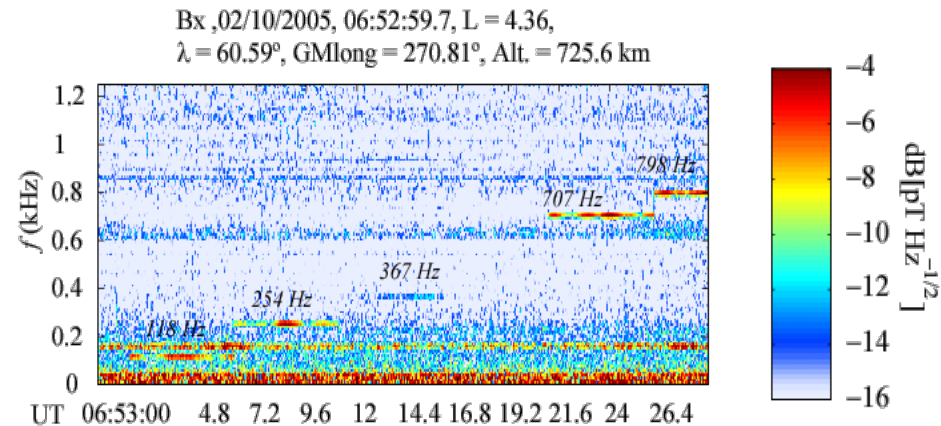
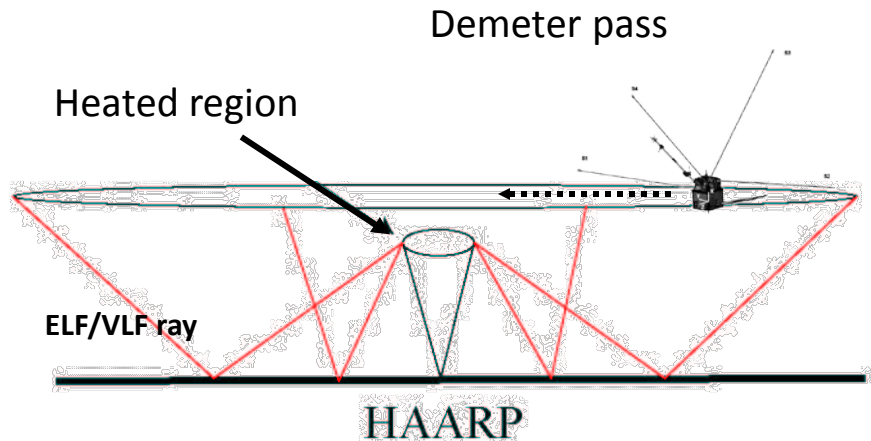


5400
km
away

Midway

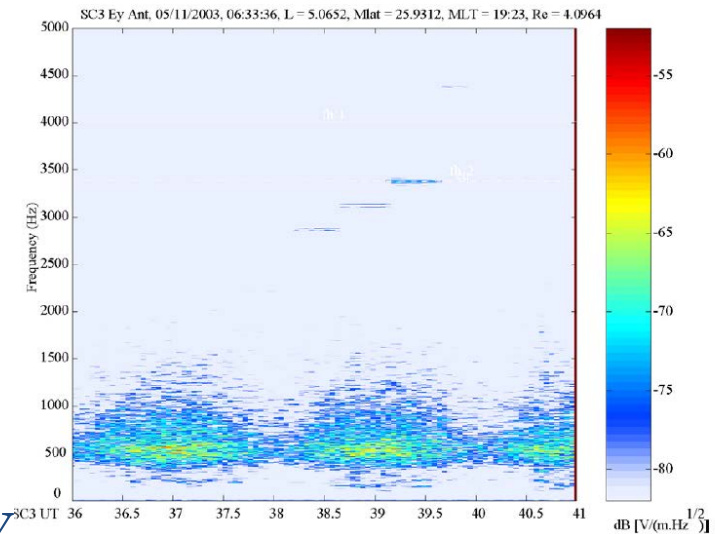
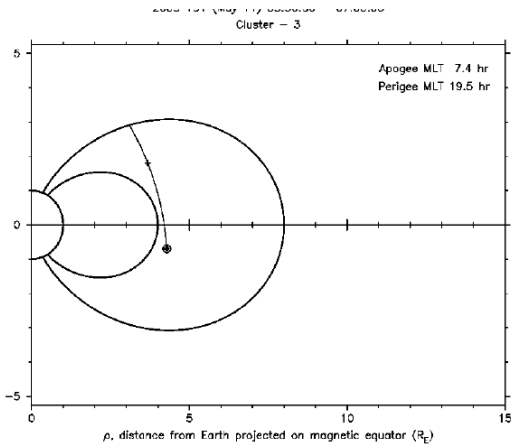
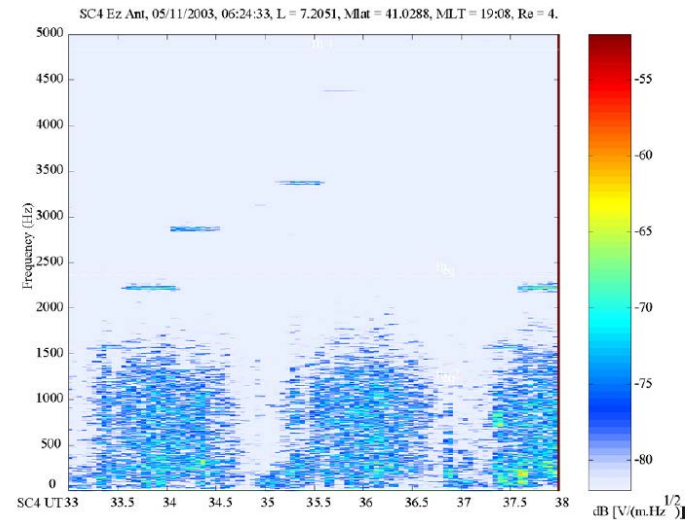
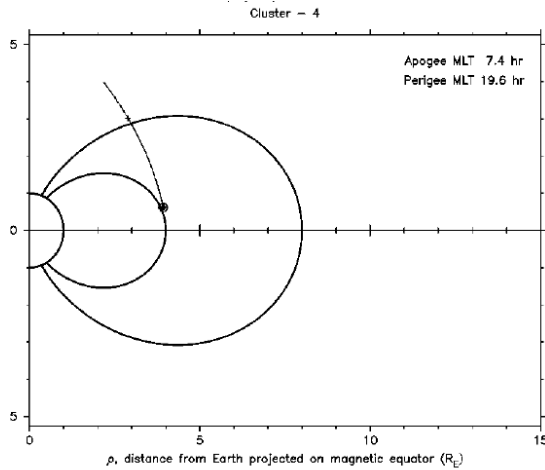
Moore et al.
GRL 2008

HAARP-DEMETER VLF INJECTION

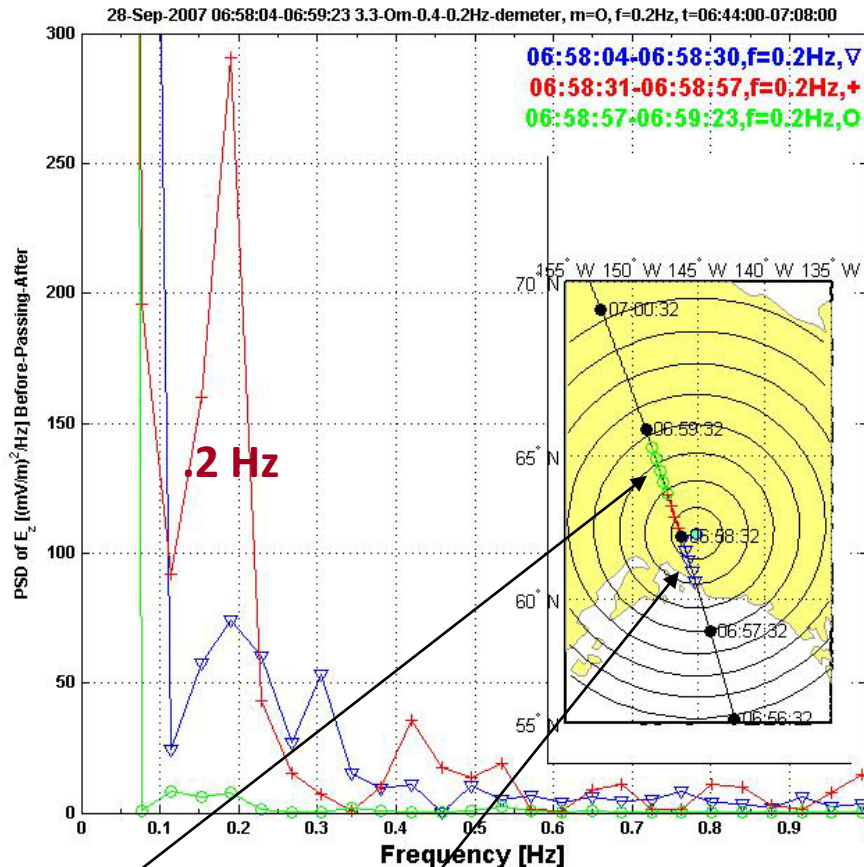


- ELF/VLF signals observed in LEO (~700 km) at lateral distances of >400-km from HAARP
- Simultaneous measurement of all six components (3E, 3B) allows estimation of the Poynting vector
- Total ELF/VLF radiated power estimated to be ~10 to 30 Watts in the range ~100 Hz to 800 Hz.

HAARP/CLUSTER INJECTION



SAW DEMETER Detection



Frequency .2 Hz

Closest distance 80 km

Detection time 25 sec

Detection distance 150 km

Maximum E  10 mV/m

1.5 pT on the ground

After

Before

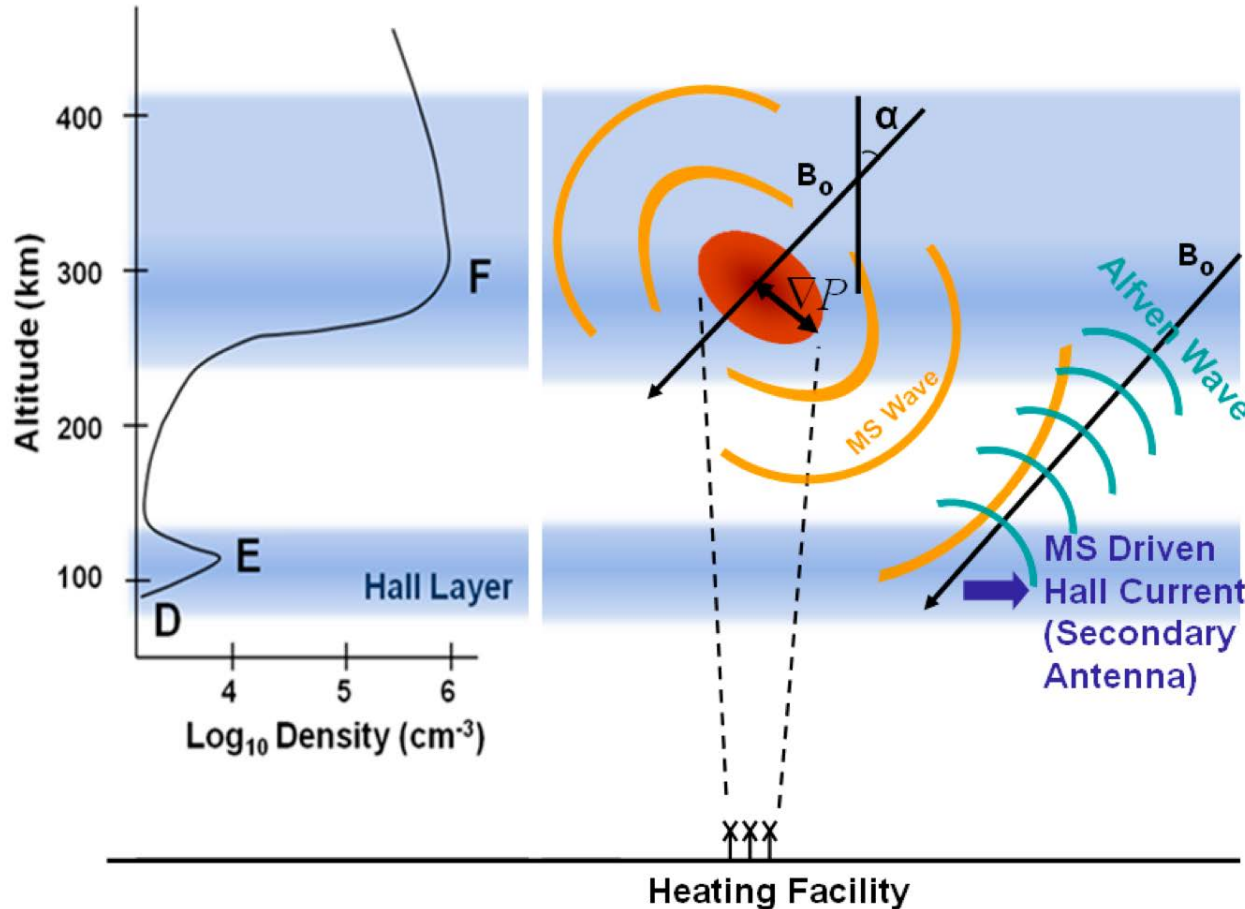
SEPTEMBER 28, 2008

Ionospheric Current Drive (ICD) Concept

Papadopoulos et al.
GRL 2011

Step 1:
$$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t) \quad \text{MS Wave}$$

Step 2: E field of MS wave drives Hall current in E-region resulting in secondary antenna resembling PEJ



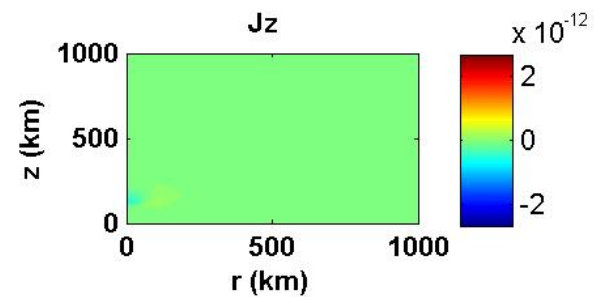
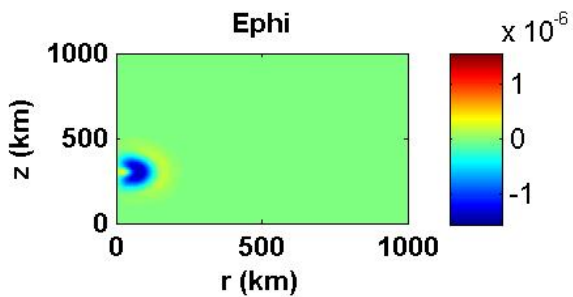
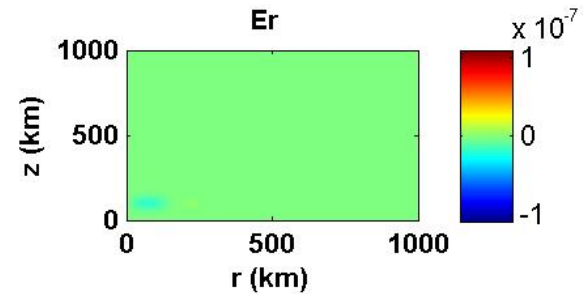
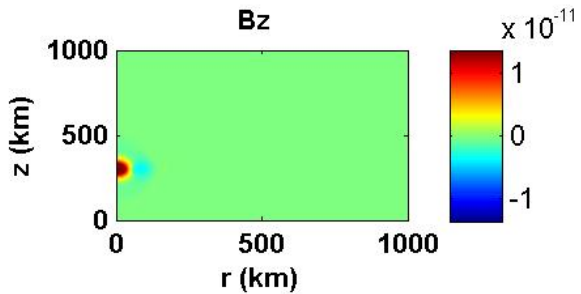
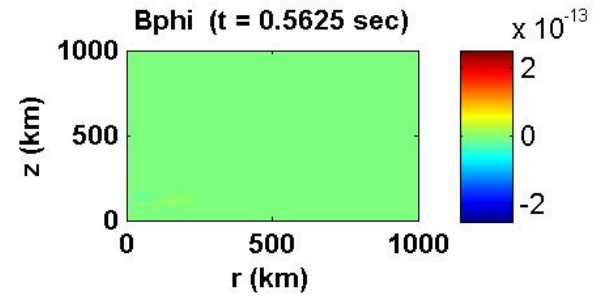
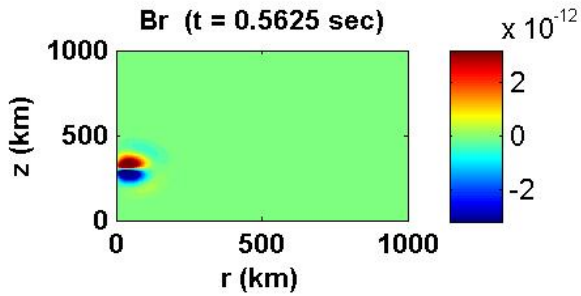
F- region cooling response does not allow frequencies higher than 60-70 Hz

Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

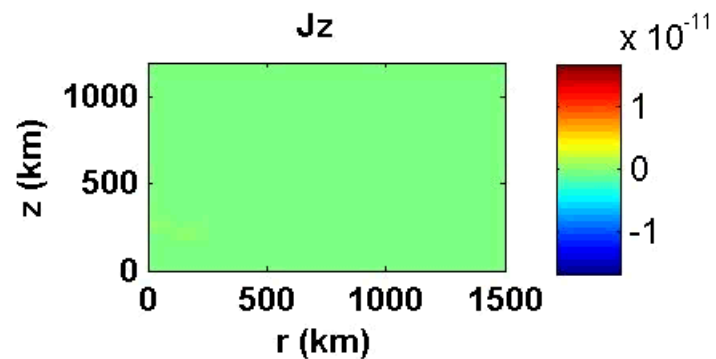
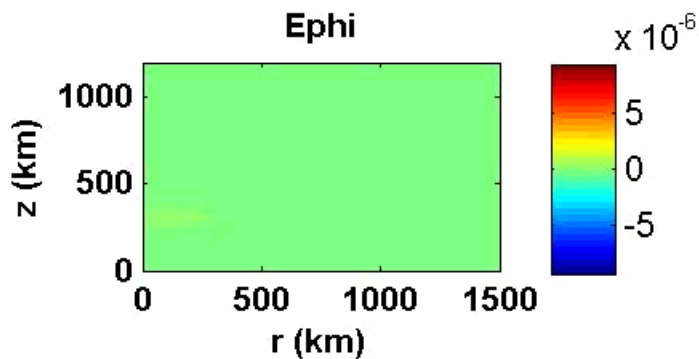
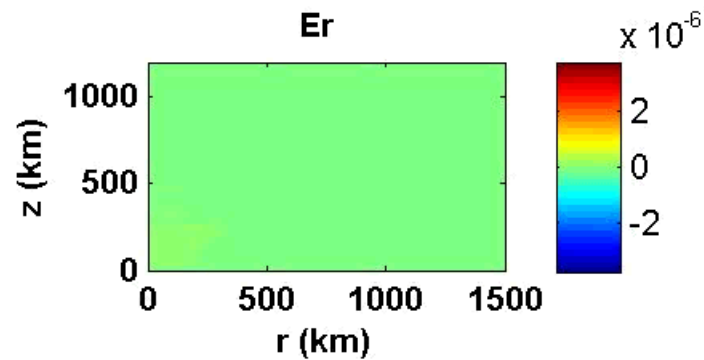
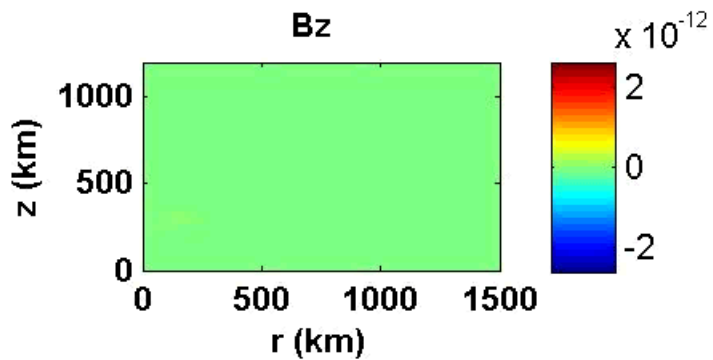
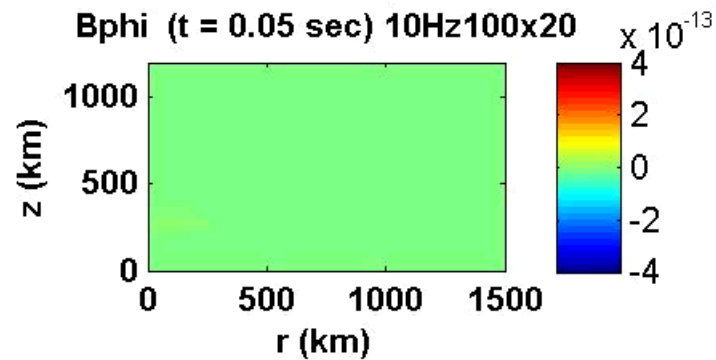
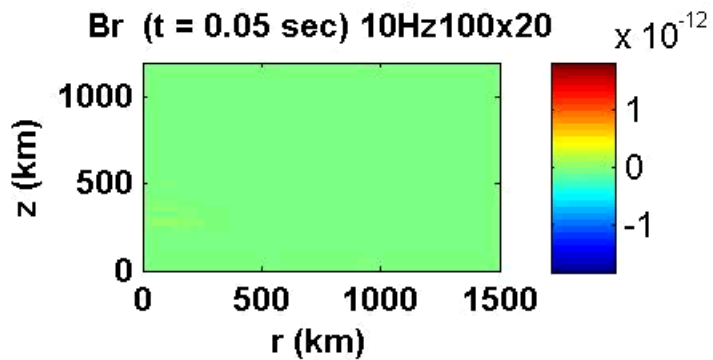
Cylindrical Coordinates

Papadopoulos et al. GRL 2011



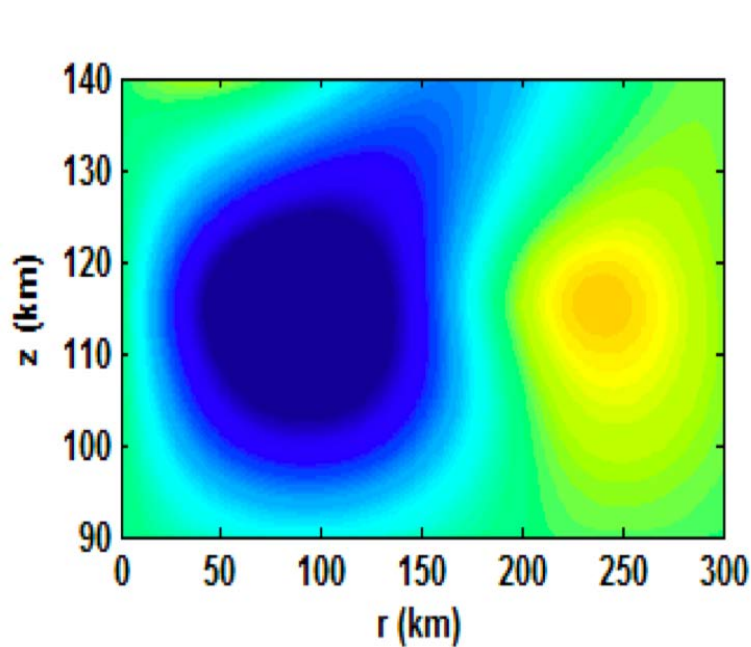
MS

SAW

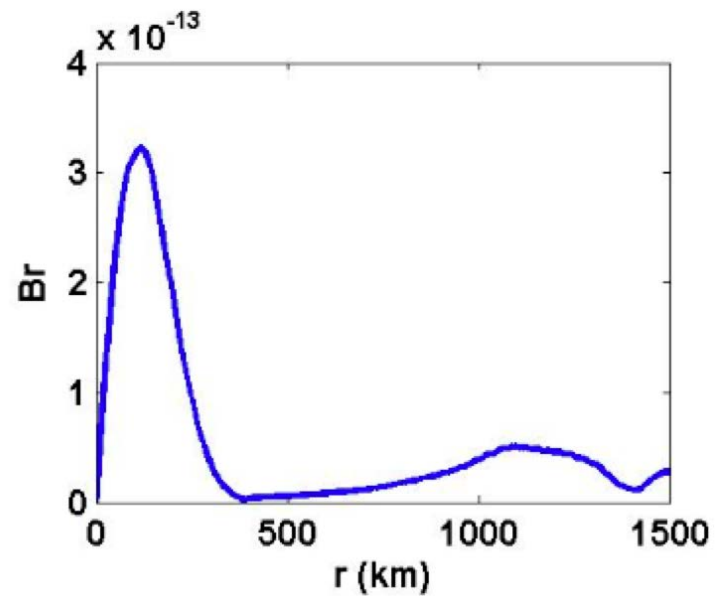


10 Hz

Secondary Antenna Current and Ground Field

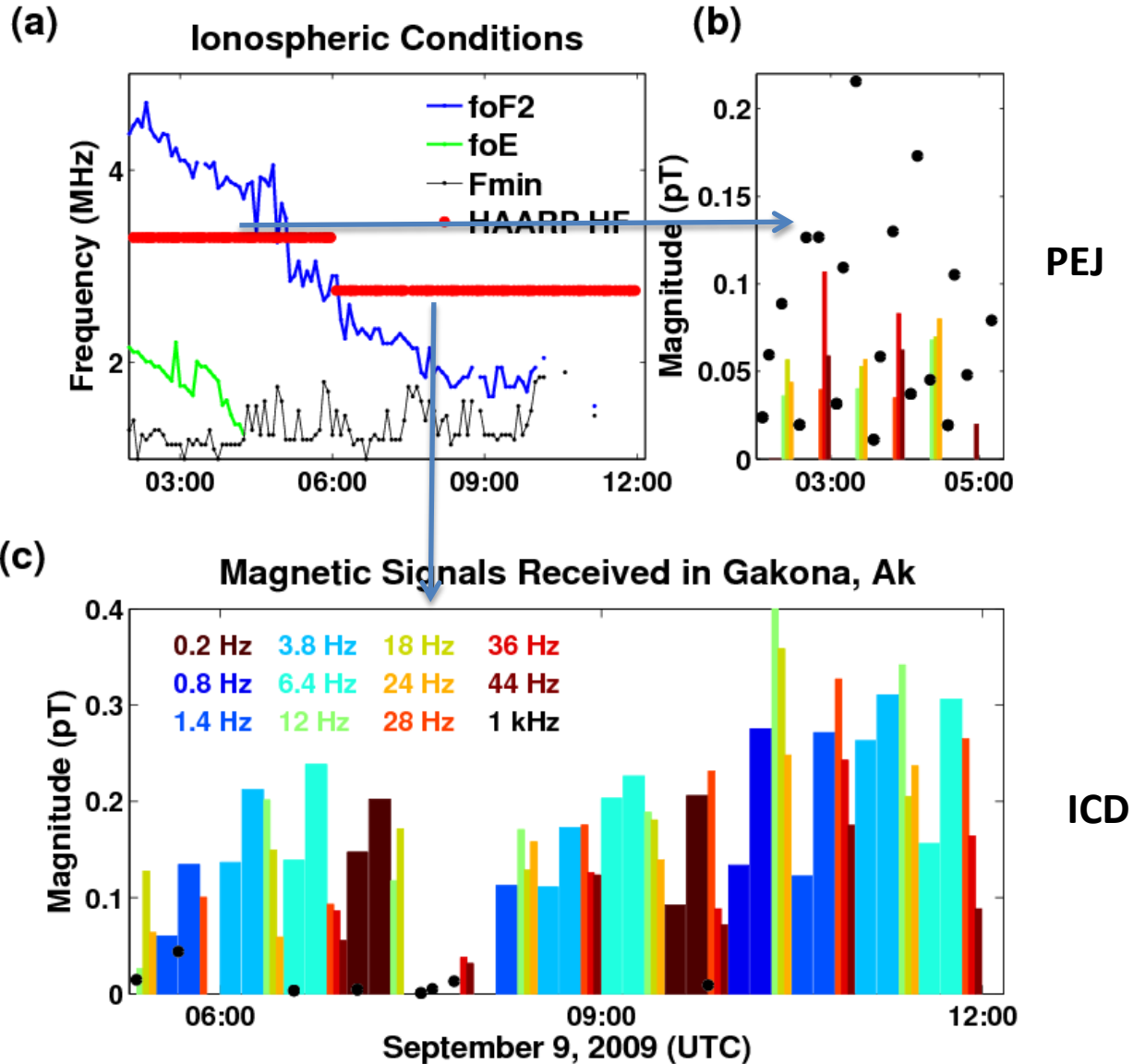


J_θ



B_r

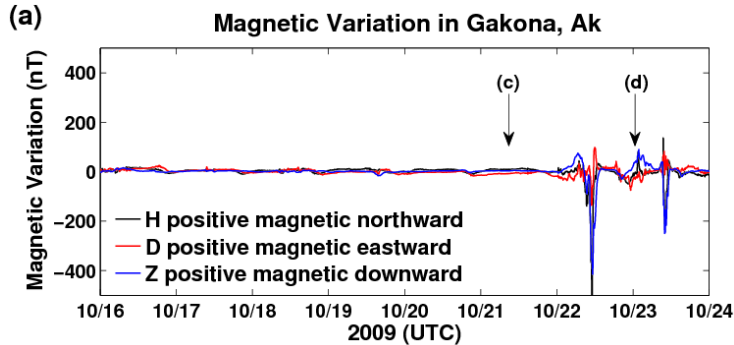
PoP Exps: PEJ to ICD Transition



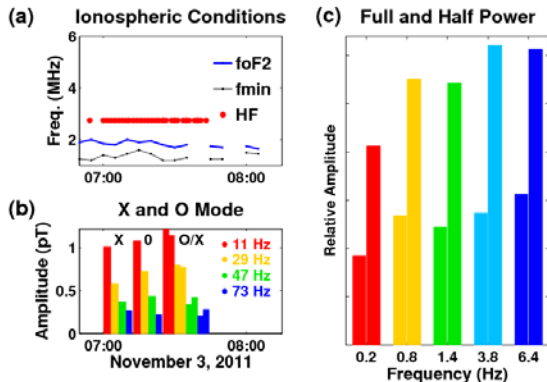
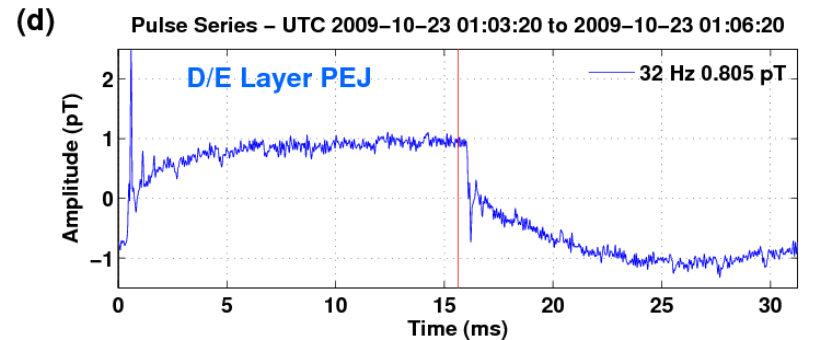
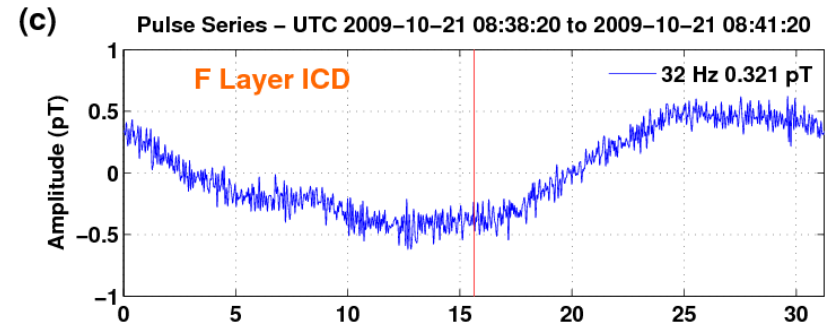
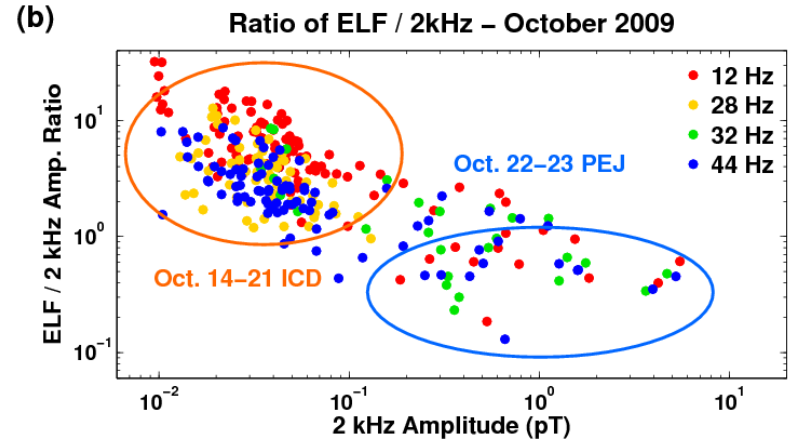
Scaling with power and frequency

ICD PoP Experiments

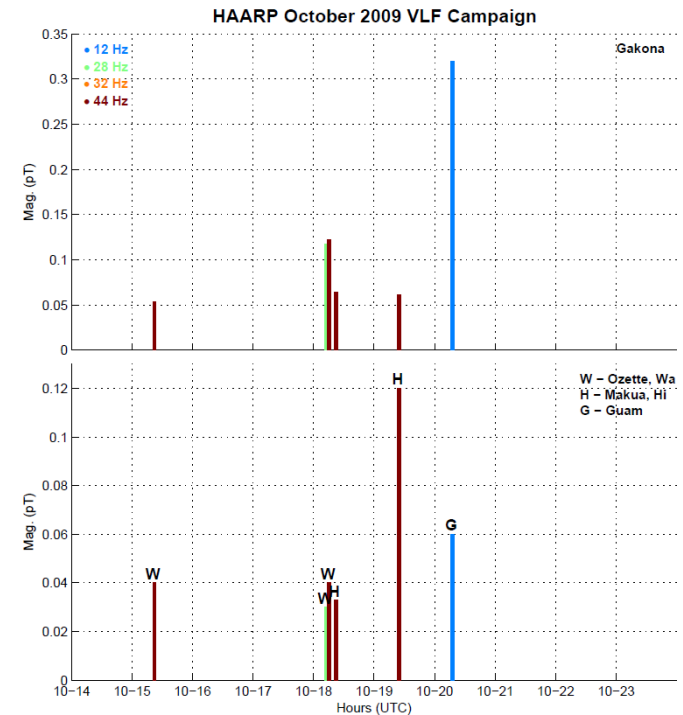
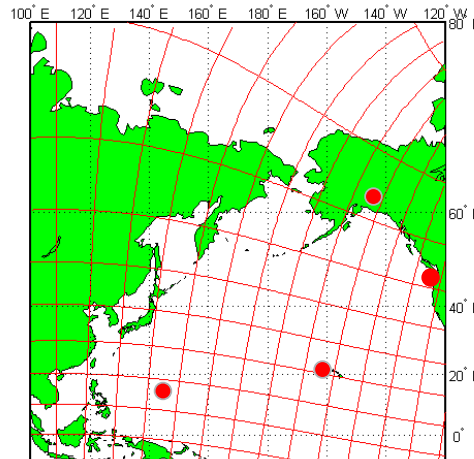
Papadopoulos et al GRL 2011b



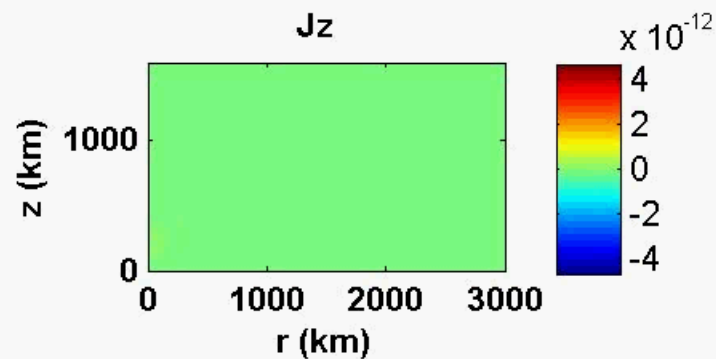
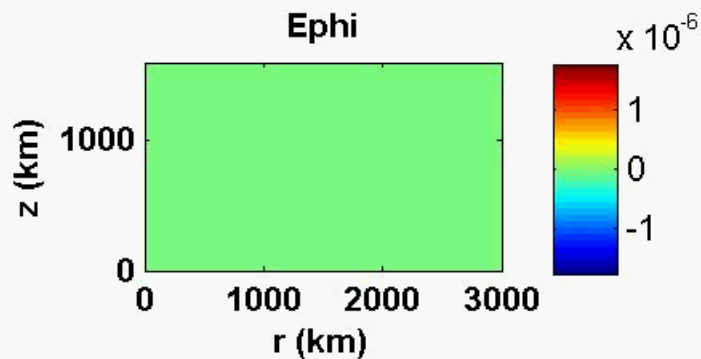
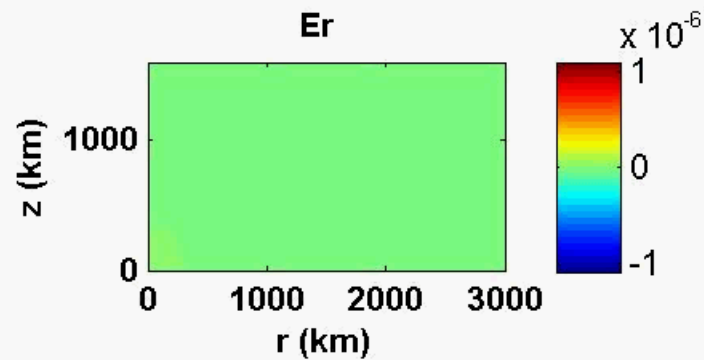
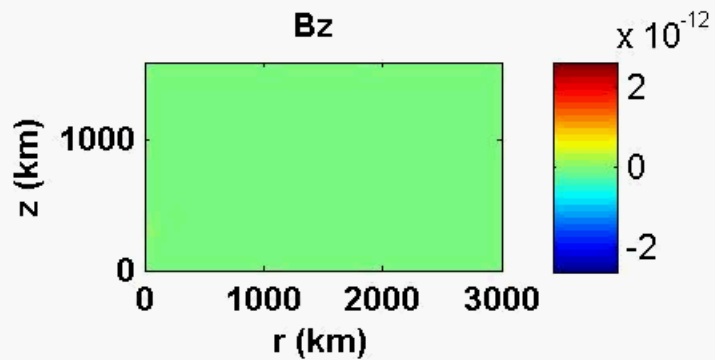
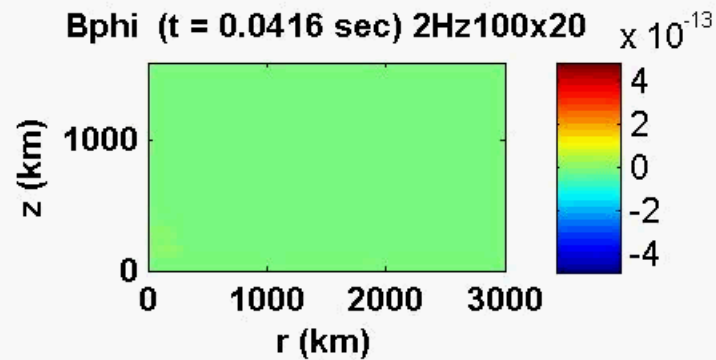
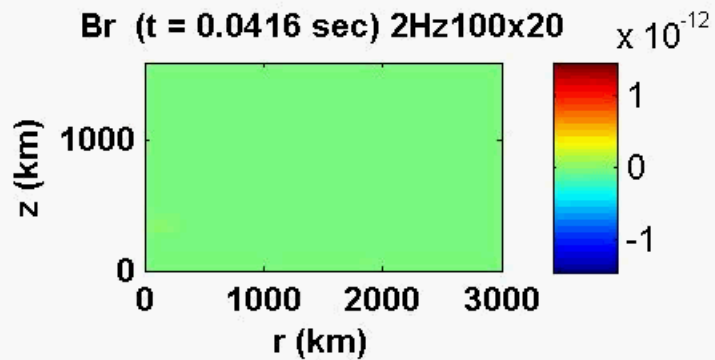
- 10/14-10/21 Magnetometer below 10 nT
- 10/14-10/23 55 hours of VLF/ELF/ULF tests
- 6 hours of VLF ground measurements –PEJ operational
- 51 hours of low ELF/ULF (12-44 Hz) ground measurements



ELF detection at Distant Sites

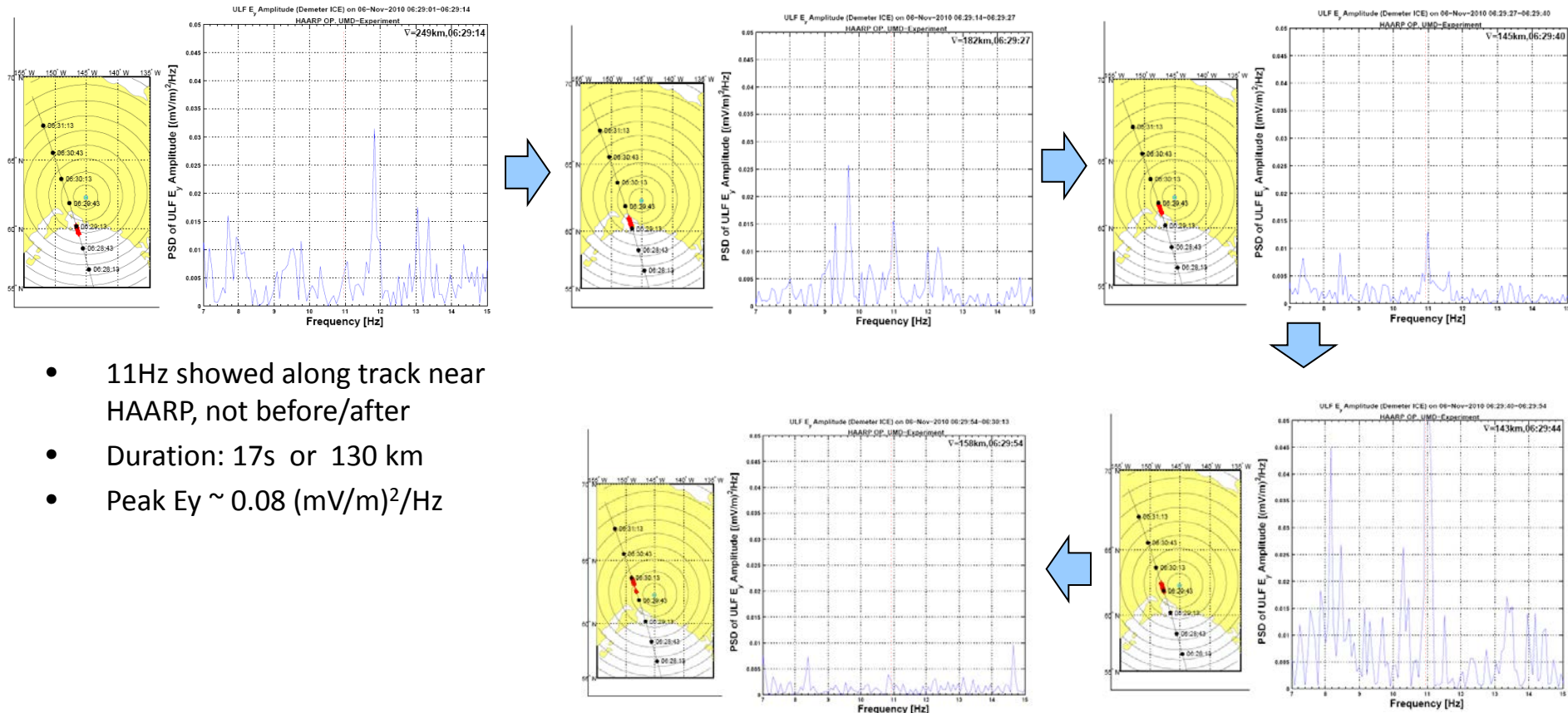


- Distance to Gakona
 - Lake Ozette, WA (W)
 - 1300 mi
 - Hawaii (H)
 - 2900 mi
 - Guam (G)
 - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23



Low ELF Observed by Demeter Satellite

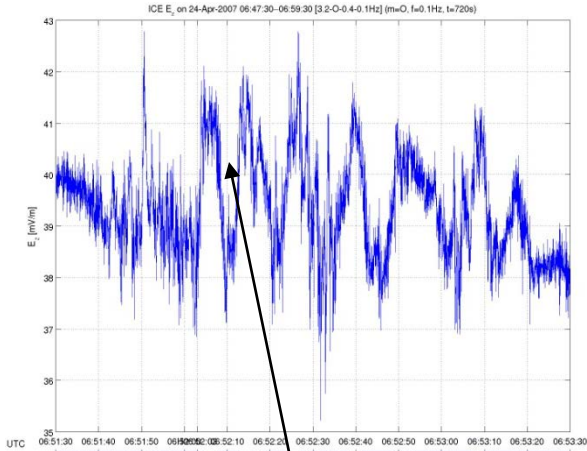
2010-11-06, 06:15:00-06:34:30 ELF 11 Hz modulation (O-MZ)



- 11Hz showed along track near HAARP, not before/after
- Duration: 17s or 130 km
- Peak $E_y \sim 0.08 \text{ (mV/m)}^2/\text{Hz}$

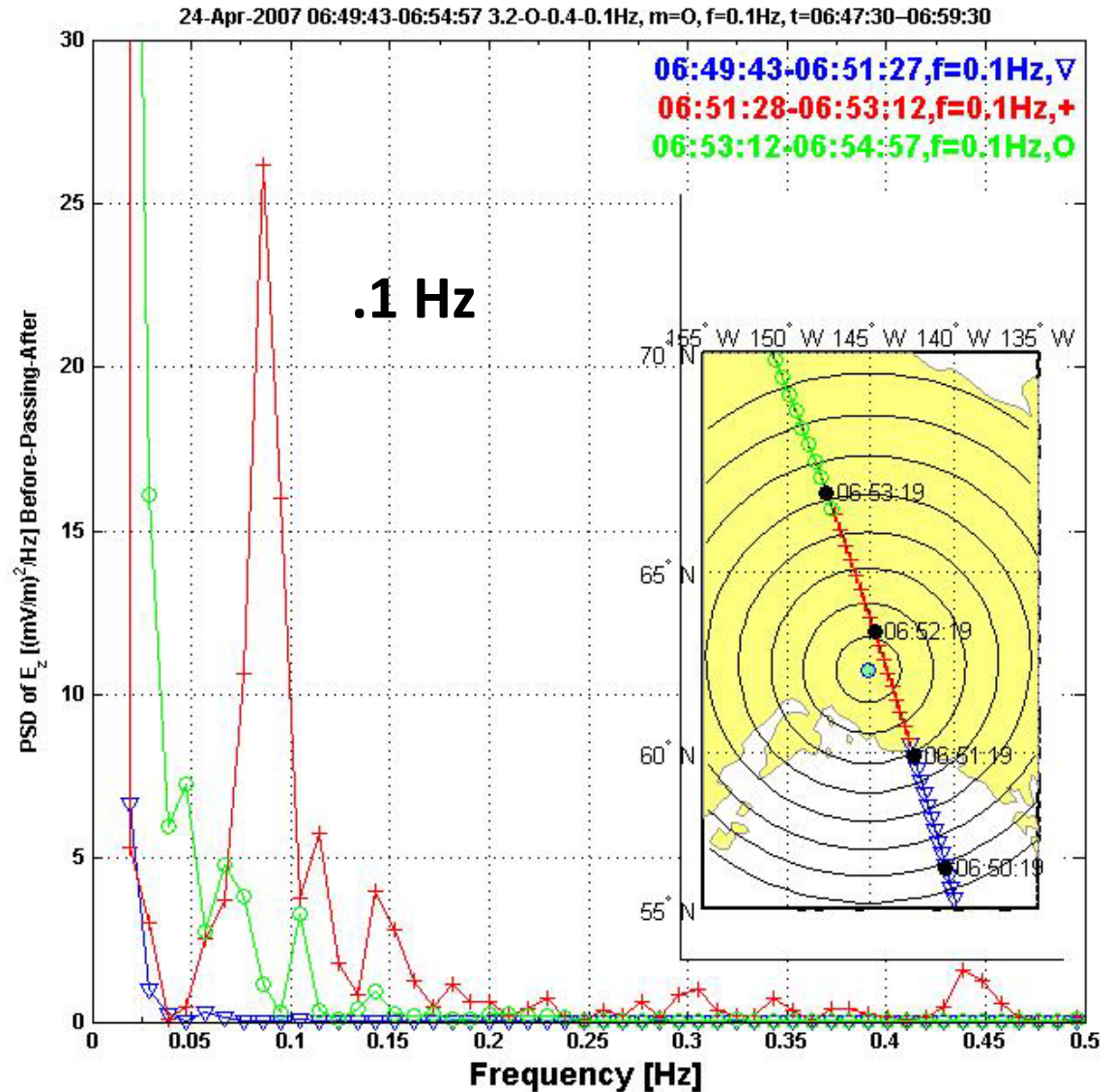
Msonic Wave Injection

DEMETER



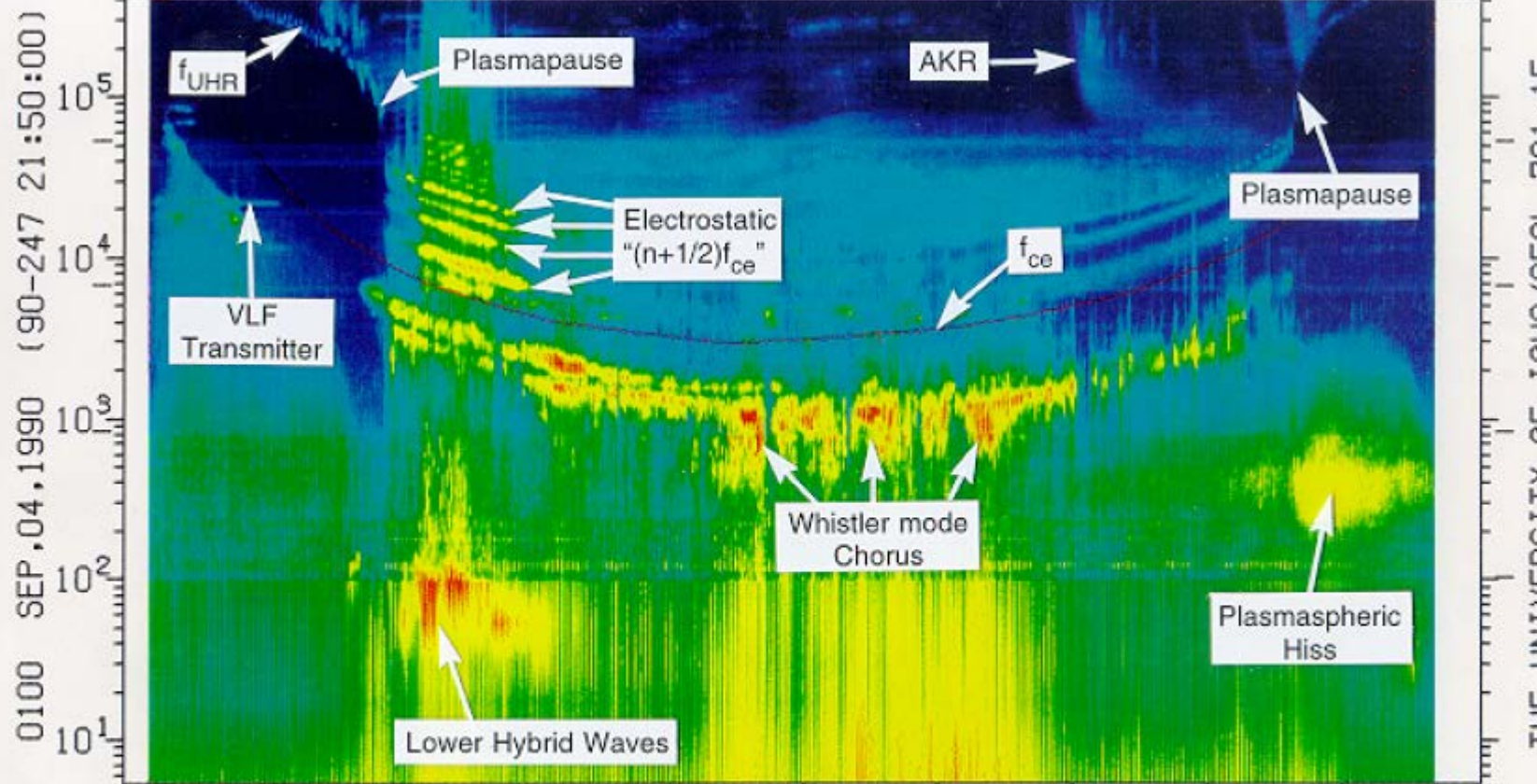
10 sec oscillations

Over 700 km distance



CRRES SFR/SA

dBV/m/√Hz -166.0

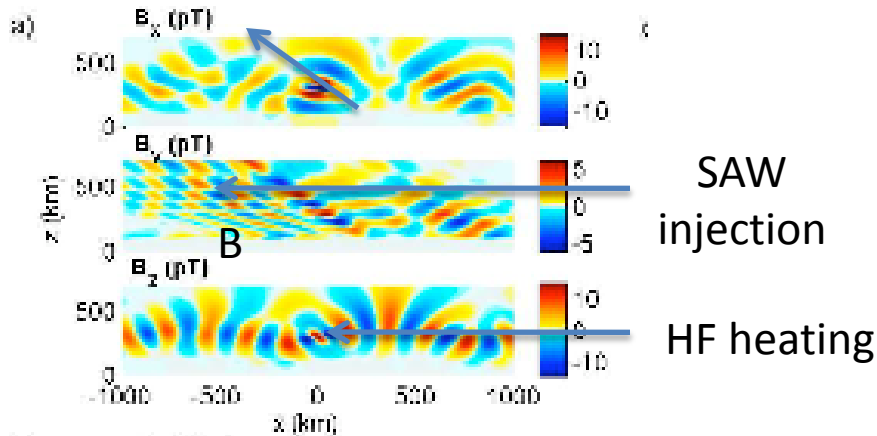


UT	21:50	23:50	01:50	03:50	05:50	07:50					
R	1.12	2.83	4.47	5.50	6.07	6.27	6.10	5.54	4.55	2.96	1.07
MLAT	4.19°	-9.11°	-2.44°	1.69°	4.95°	7.80°	10.36°	12.51°	13.69°	11.14°	-21.07°
MLT	16:34	02:36	04:19	05:13	05:54	06:31	07:09	07:51	08:48	10:29	19:24
L	1.17	2.93	4.59	5.63	6.22	6.46	6.37	5.88	4.87	3.08	1.21

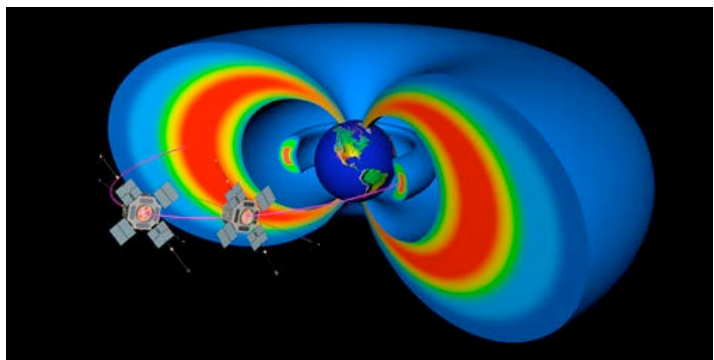
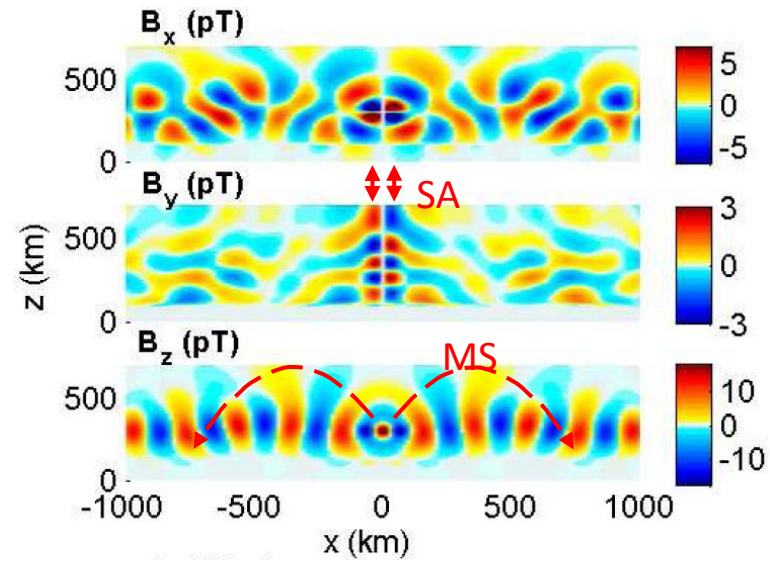
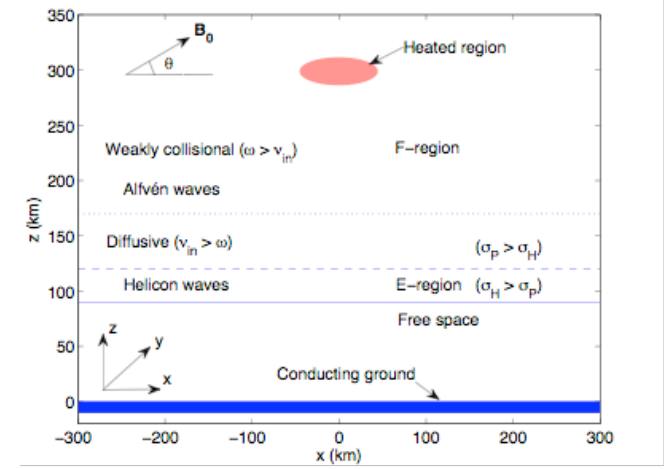
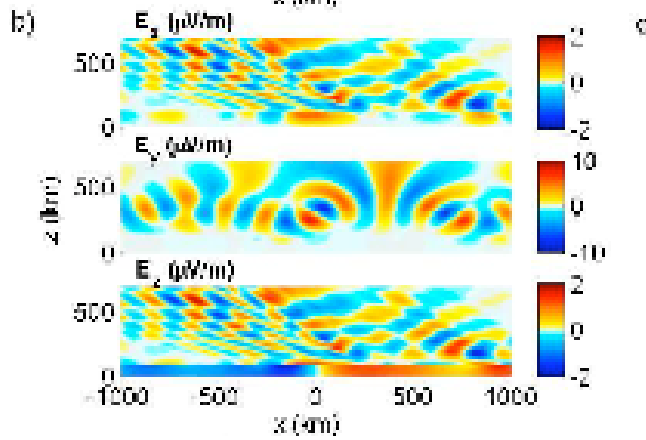
THE UNIVERSITY OF IOWA/AFGL 701-15

CRRESPEC V0 PROCESSED 27-MAR-92 13:24

Implications of ICD to RB and RBR – Potential Arecibo/RBSP Tests



SAW injection
HF heating

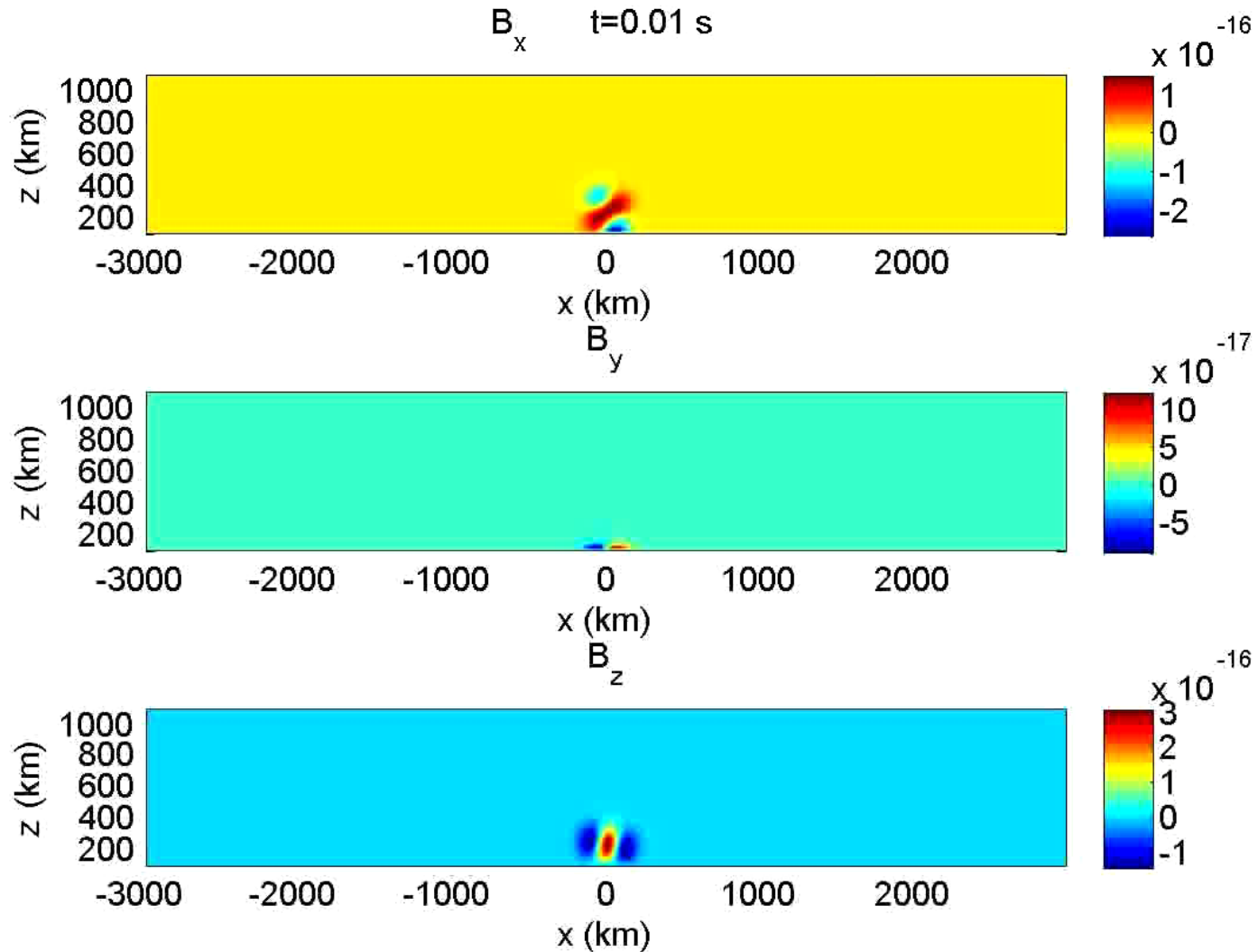


RBSP

ICD - Implications

M

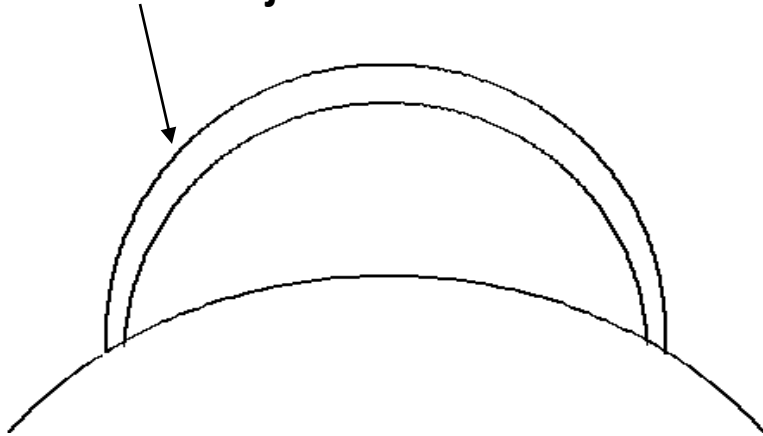
on



Frequency Selection for Protons

Example for L=1.5

SAW Injection

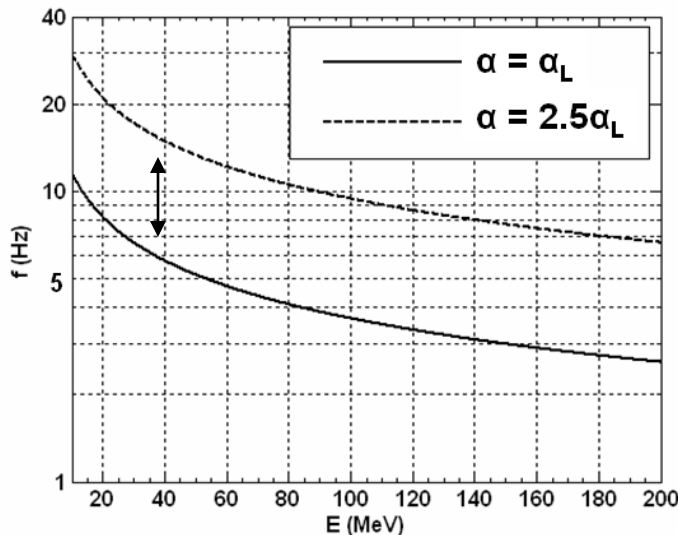


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

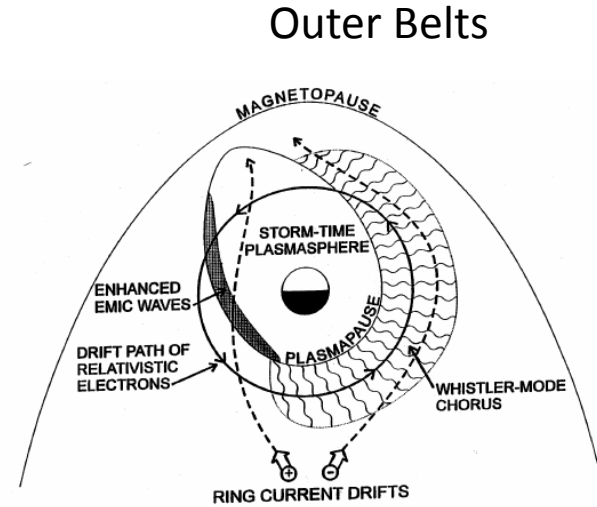
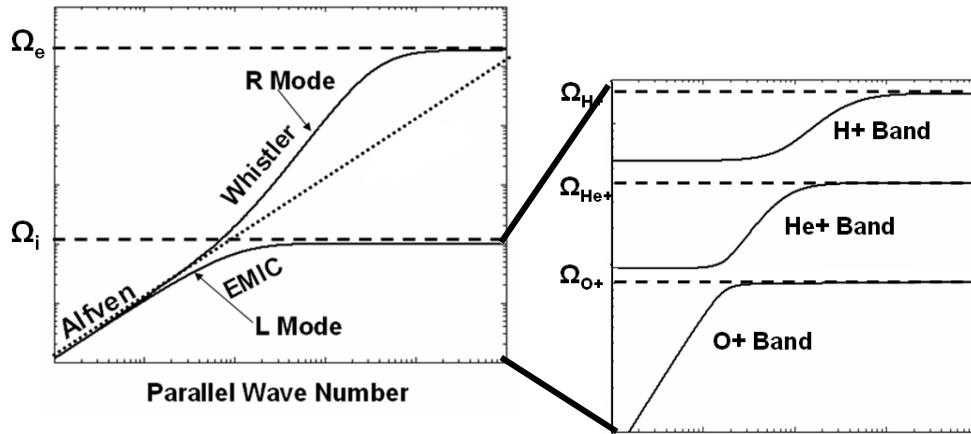
$$\omega(E, \alpha) \approx \frac{\Omega}{\cos \alpha} \sqrt{\frac{M V_A^2}{2E}}$$



Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz

ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



Summers et al., 1998, 2000, 2003

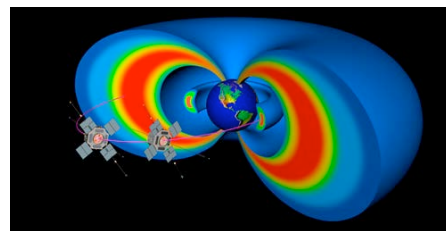
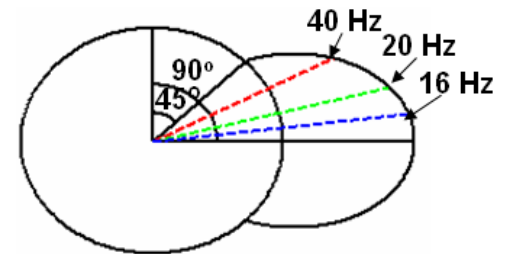
$$-k_z v_z = |\Omega_e| / \gamma$$

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

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

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

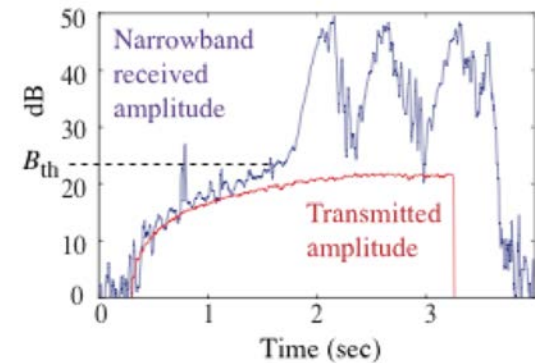
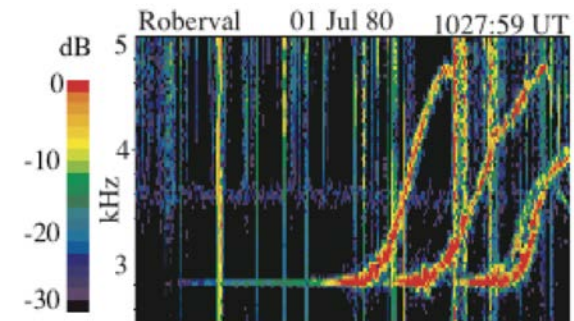
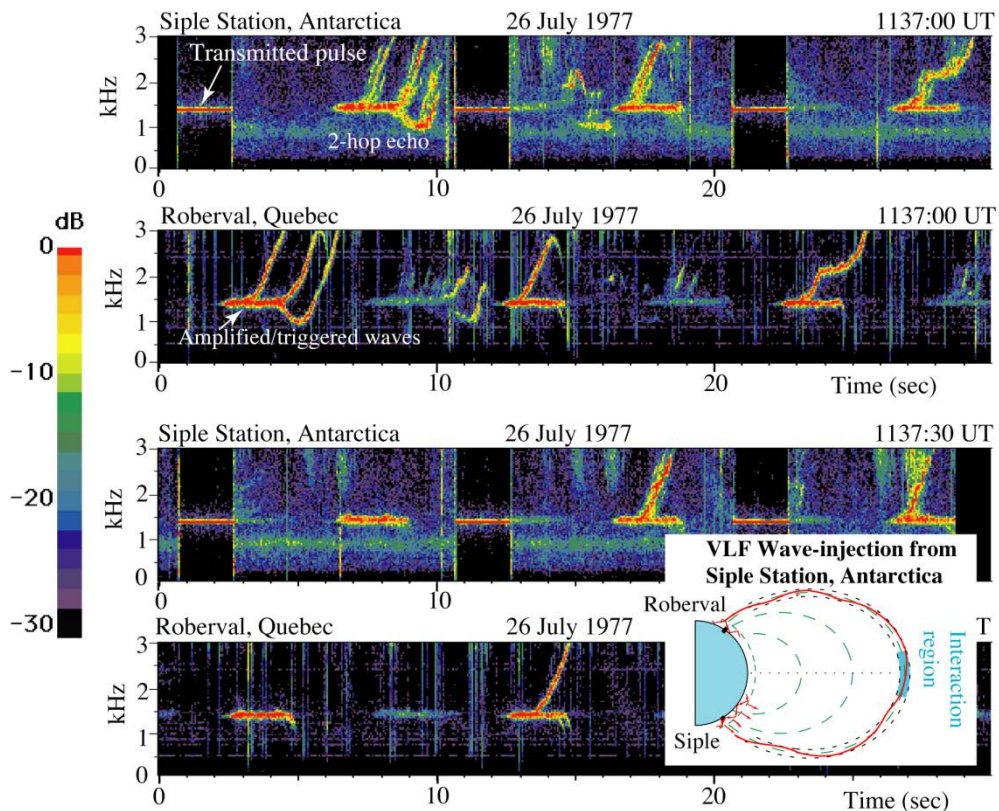
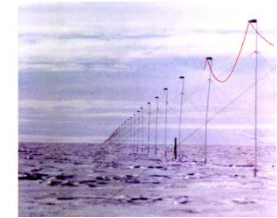
HELIUM BRANCH



Controlled VLF Wave Injection Artificially Stimulated Emissions (ASE)

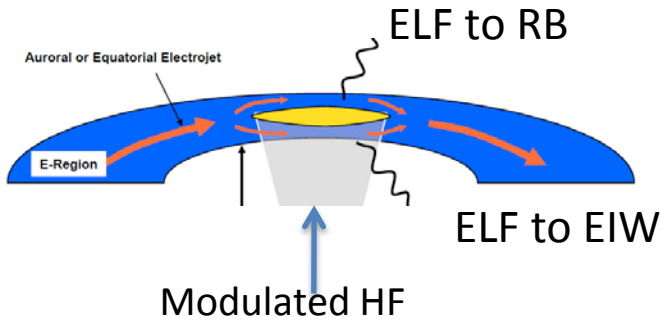
Siple Station Antarctica – (Stanford – NSF) Helliwell (1973-1987):

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

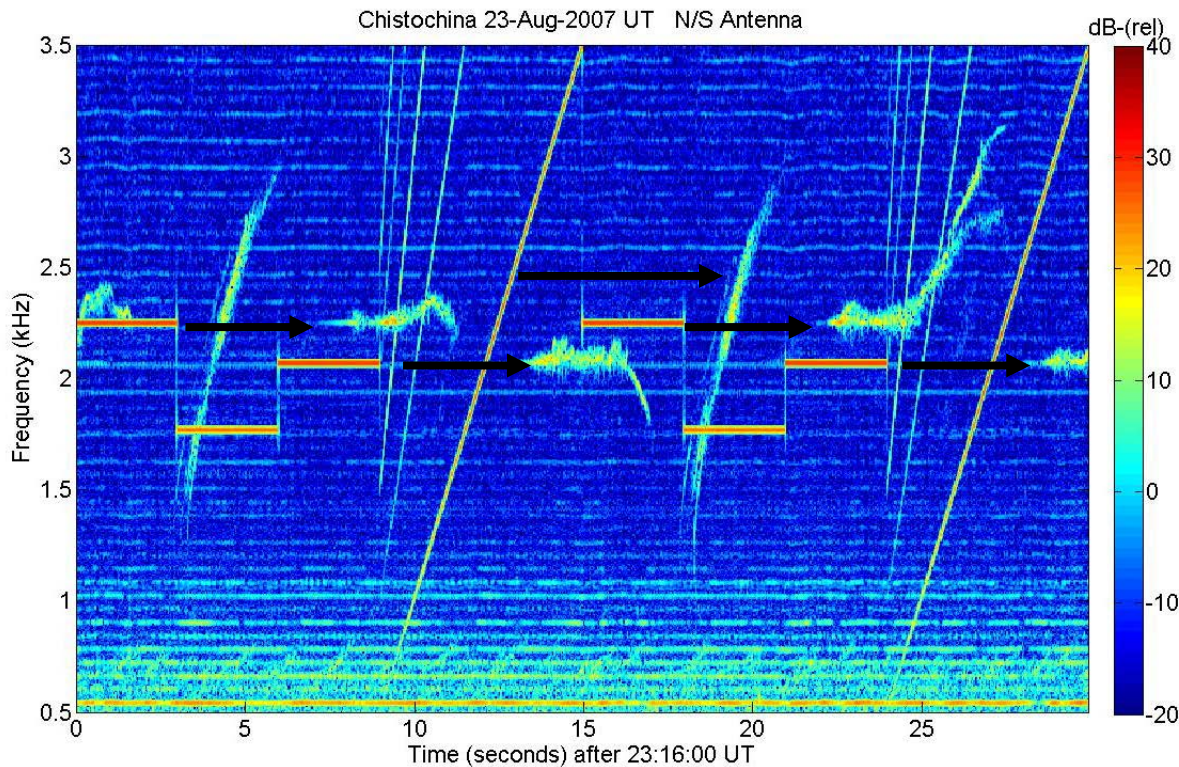
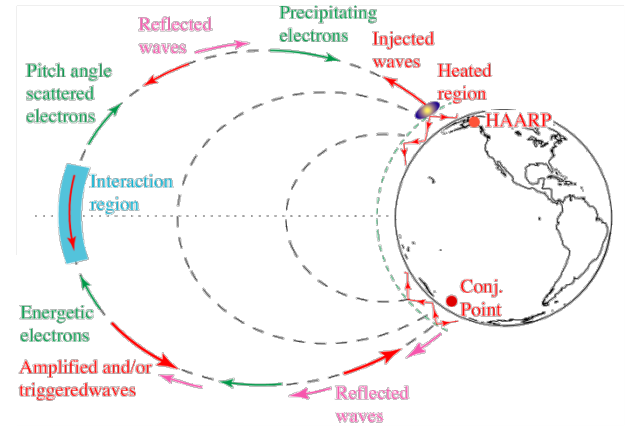


Triggered Emissions

ASE – HAARP Tests



ASE Studies

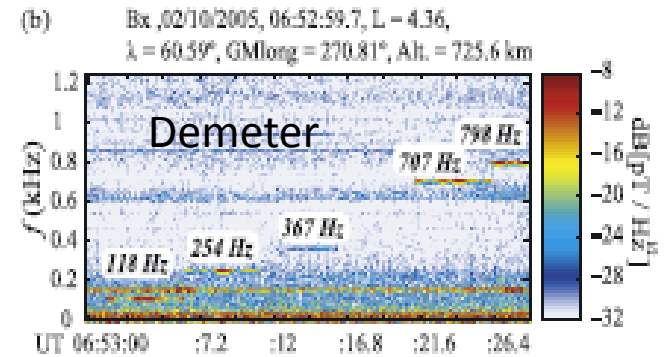
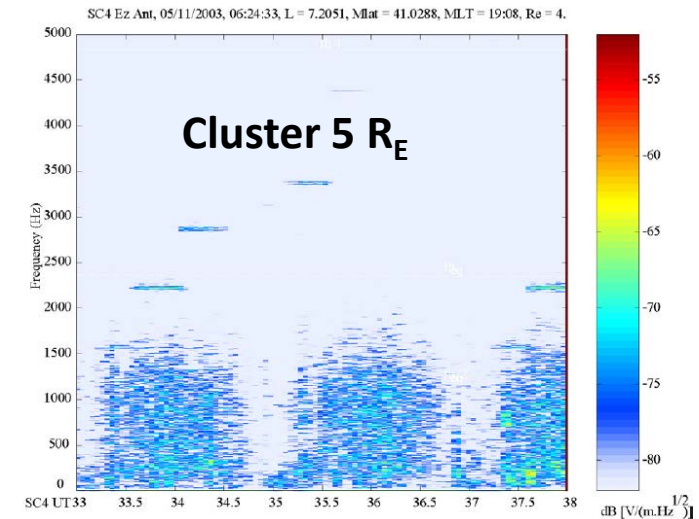
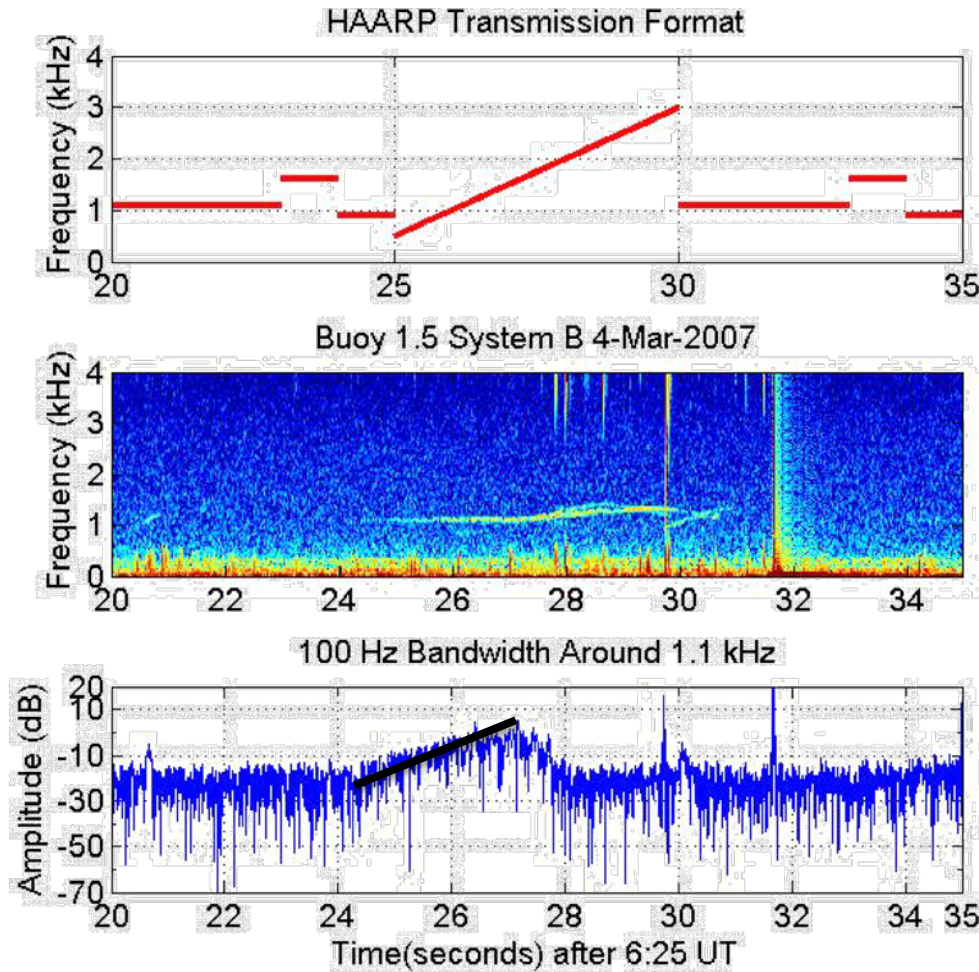


Conjugate



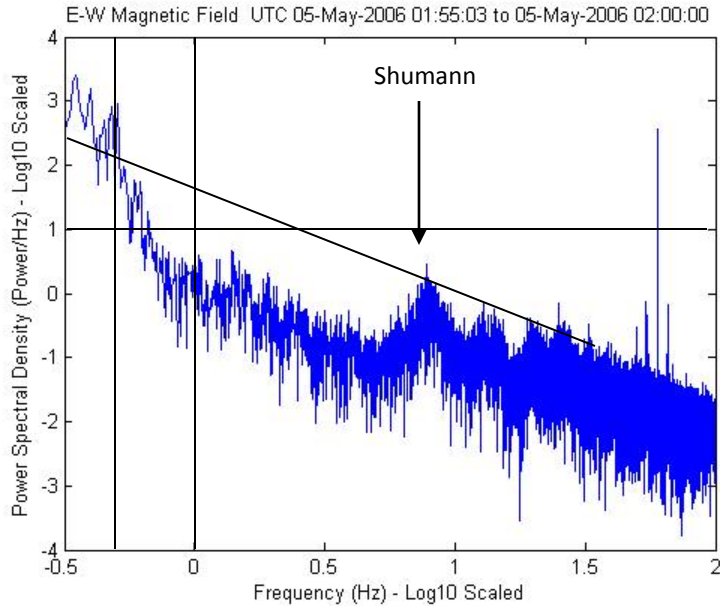
Pulses above 2 kHz have 1-hop echoes with triggered emissions
Pulse near 1.7 kHz does not; ramps have echoes with no emissions

15 dB/s Amplification & Triggered Emissions

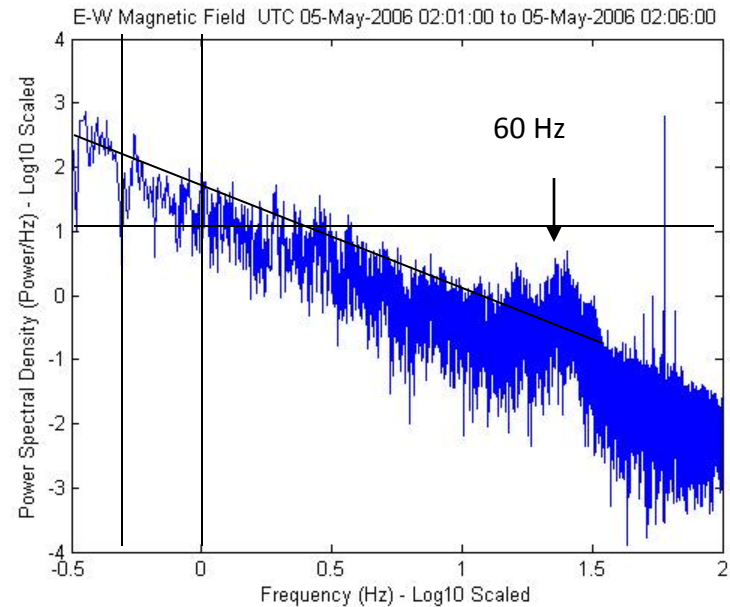


Only the pulse at 1100 Hz is amplified

Pc1 Triggered Emissions ?



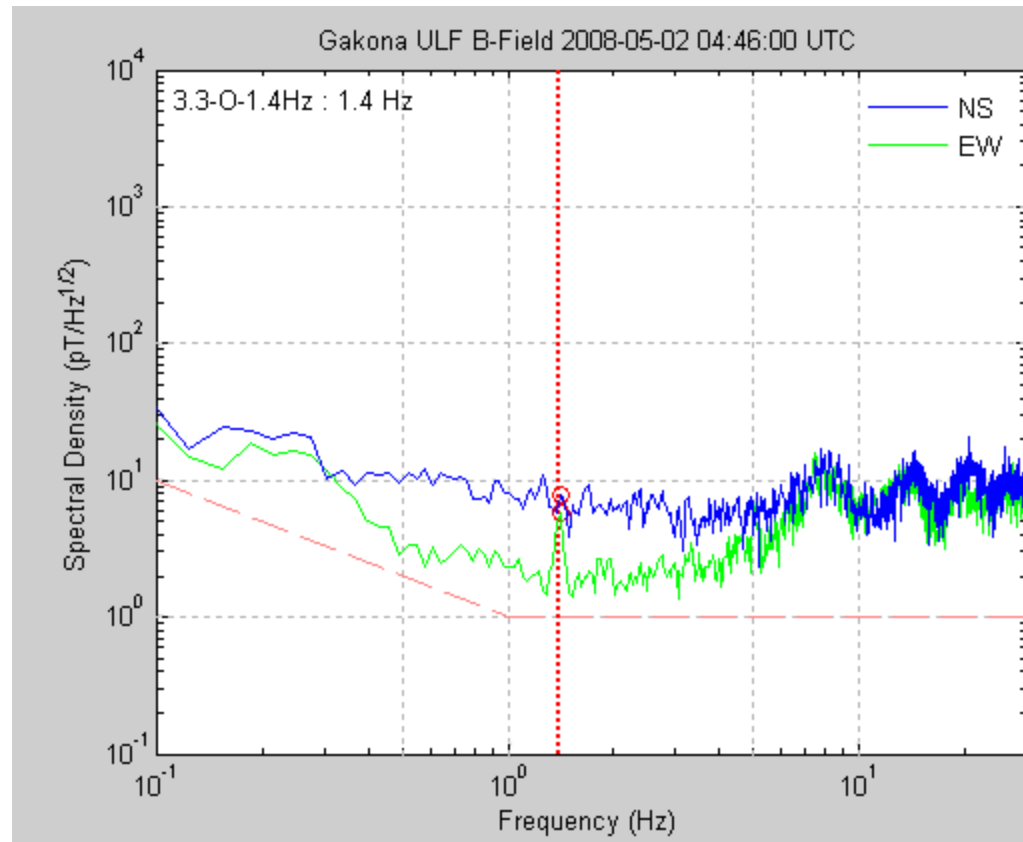
Spectrum before HAARP ULF Start Experiment – Ambient Noise



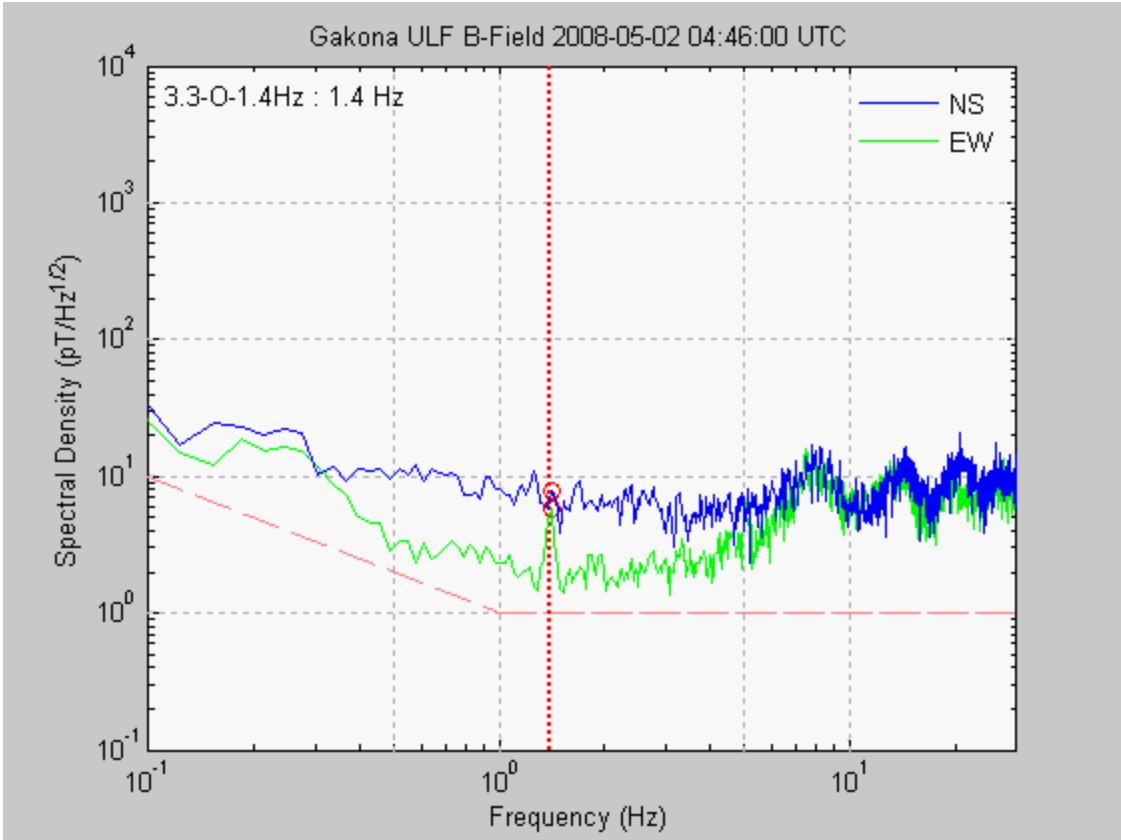
Spectrum after HAARP ULF Start
Noise Increase by more than 10-20 dB between .7-10 Hz

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



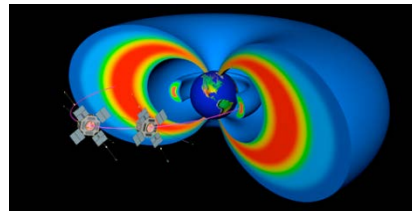
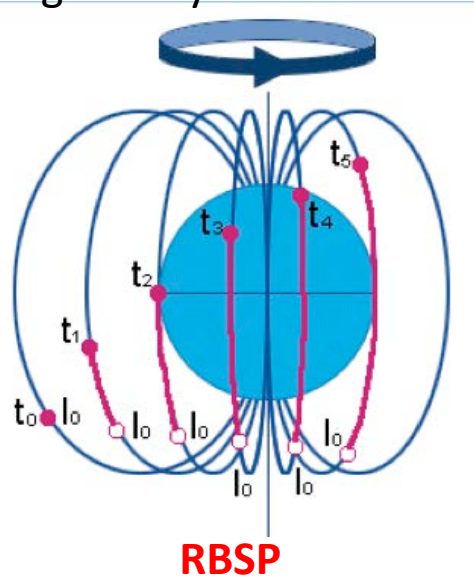
**Triggered Pc1
broadband**



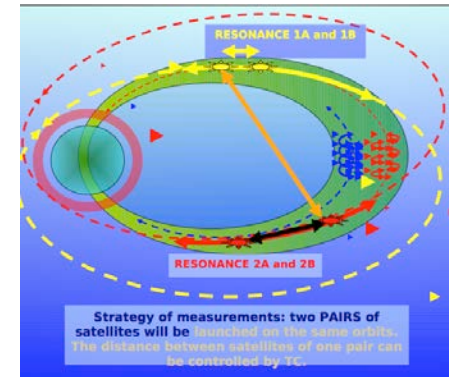
The Future

- Use Ionospheric heaters (HF) to inject ULF/ELF/VLF waves in the L-shell that spans the heater and diagnose it with RBSP, Resonance, DSX, ePOP

Magneto-synchronous



Launch May 18, 2012
 2 probes, <1500 kg for both
 10° inclination, 9 hr orbits
 ~ 500 km x 30,600 km

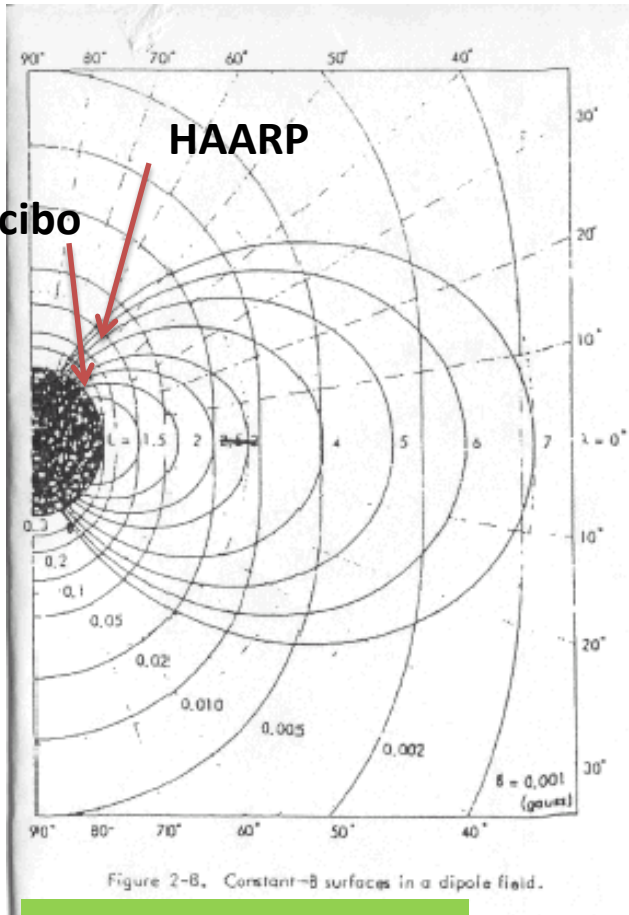
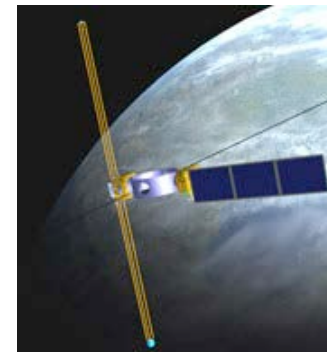


RESONANCE (Russia)

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

DSX (AFRL)

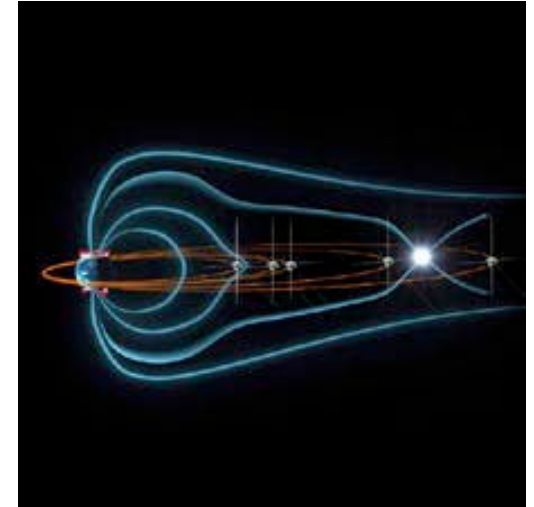
Launch ~2012
 MEO,
 wave/particle



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

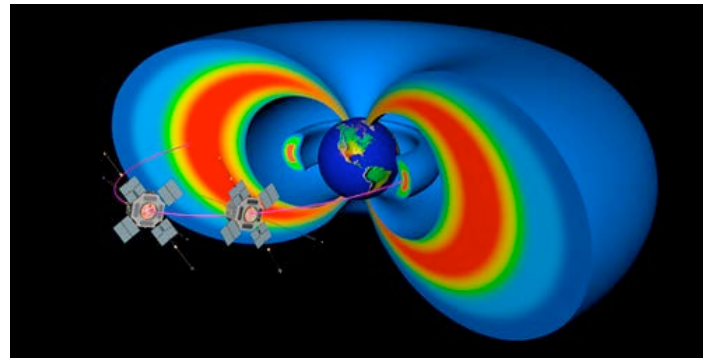
RESONANCE (Russia)

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



THEMIS (NASA)

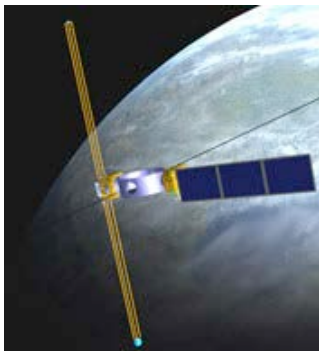
Launch Feb 17, 2007
5 identical probes (3)



- Launch May 18, 2012
- 2 probes, <1500 kg for both
- ~10° inclination, 9 hr orbits
- ~500 km x 30,600 km

DSX (AFRL)

Launch ~2012
MEO, wave/particle

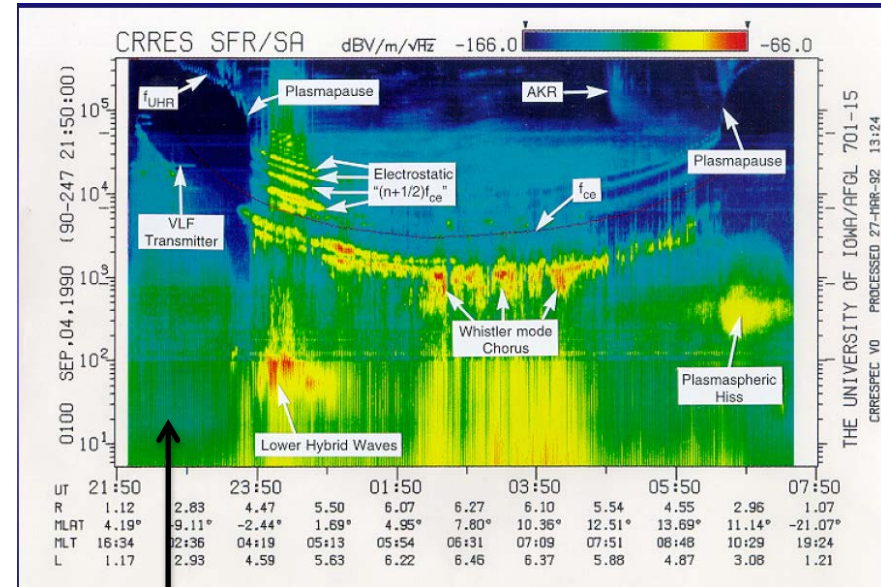
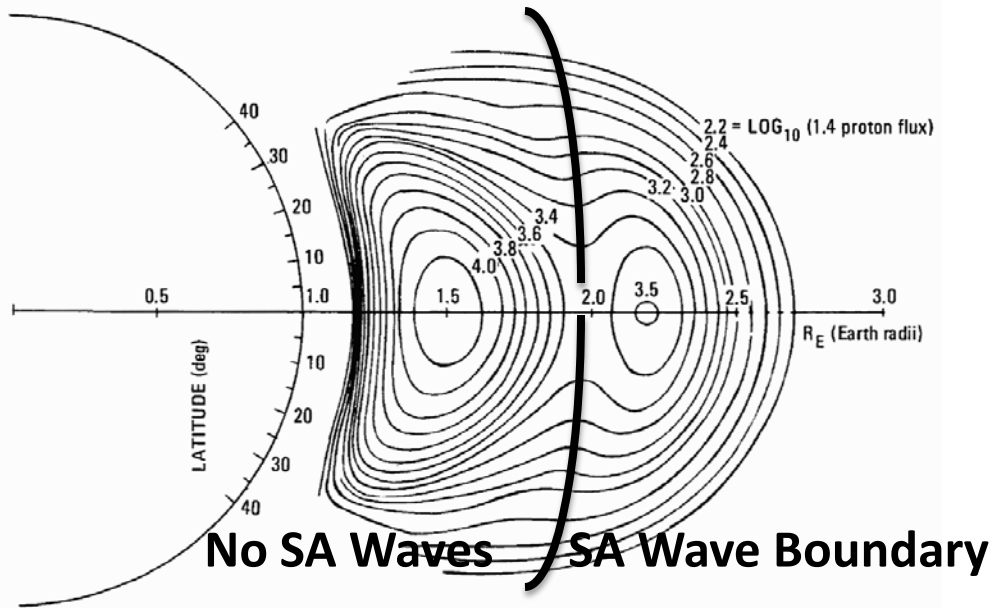


ORBITALS (CSA)

Launch 2012-2013
Orbit(?) ~L=2 to L=6



Inner Proton Belt – Accessible from Arecibo



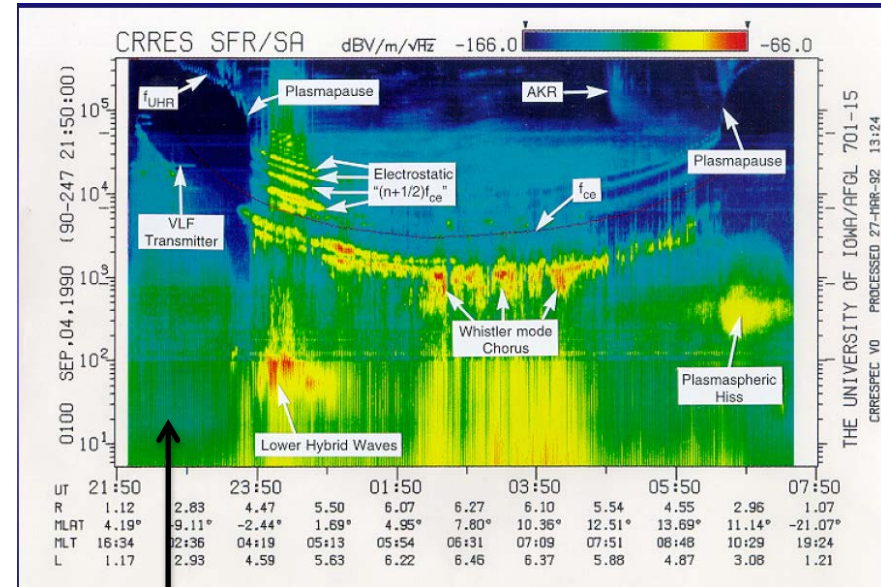
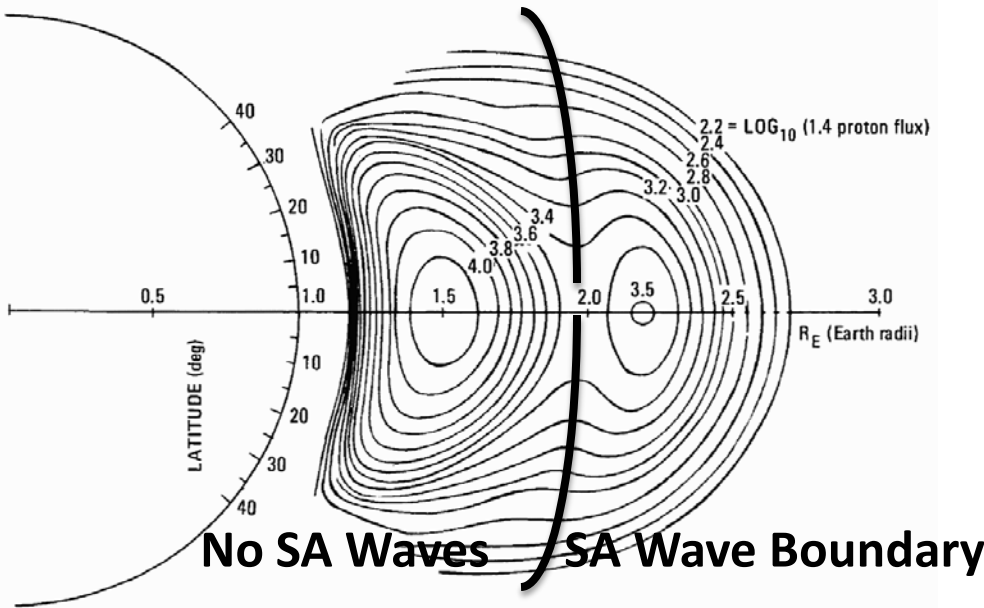
Typical inner belt proton lifetimes:

10 MeV – decades

50 MeV – century

No wave activity at SAW and EMIC branches

Inner Proton Belt – Accessible from Arecibo



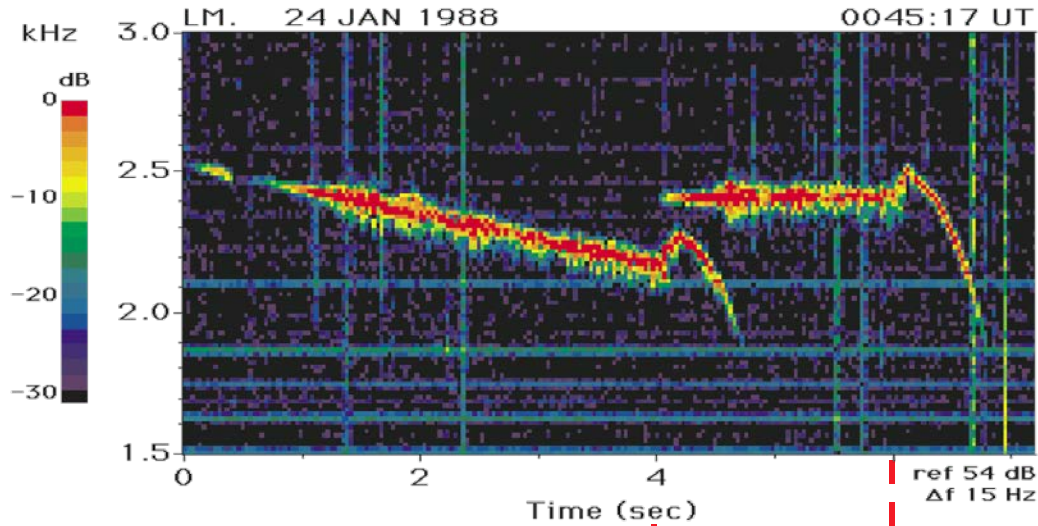
Typical inner belt proton lifetimes:

10 MeV – decades

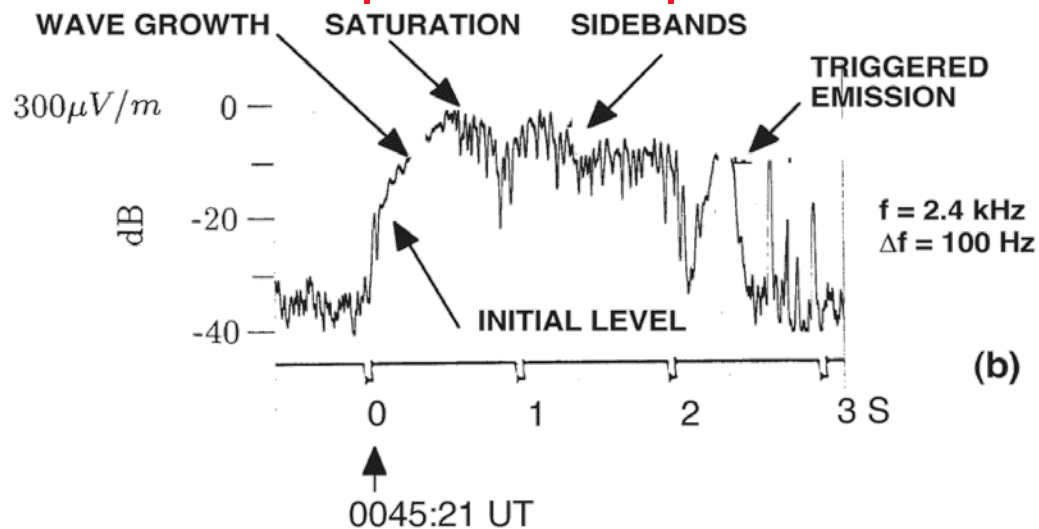
50 MeV – century

No wave activity at SAW and EMIC branches

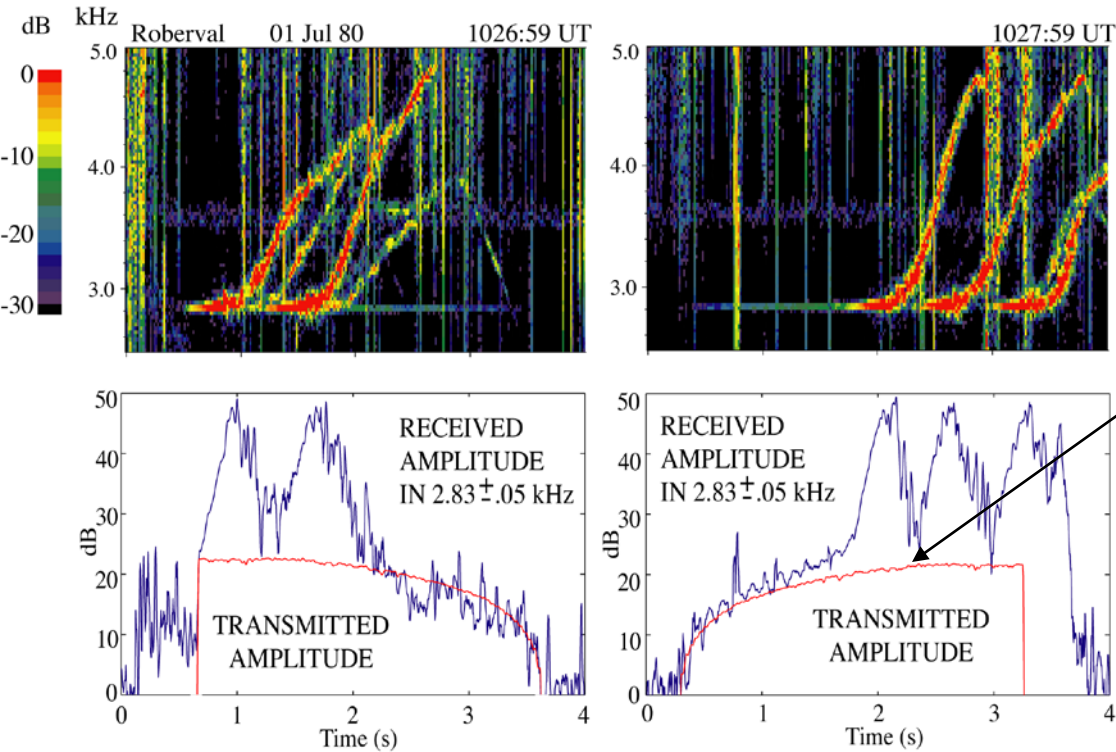
Growth & Saturation



Amplitude in
~100 Hz band



Amplitude Effect on Growth



COHERENT GROWTH 20-30 dB

- **THRESHOLD**
- **SIGNAL SATURATION**
- **TRIGGERED EMISSIONS – risers, fallers, hooks**
- **ENTRAINMENT**

TRANSITION TO OSCILLATOR BEHAVIOR