CONTROLLED WAVE PARTICLE INTERACTION STUDIES IN THE RADIATION BELTS

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UMCP

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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

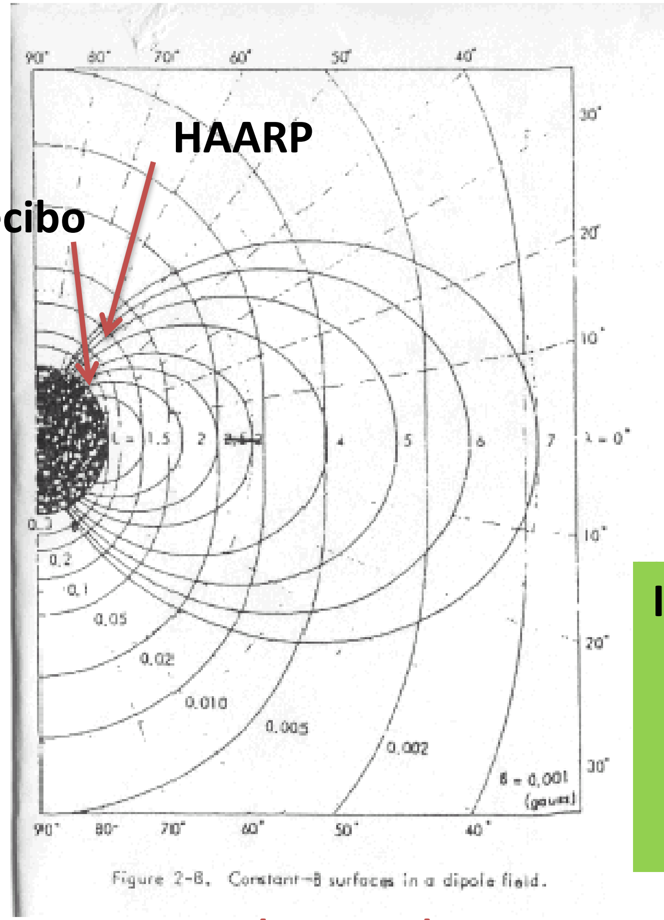
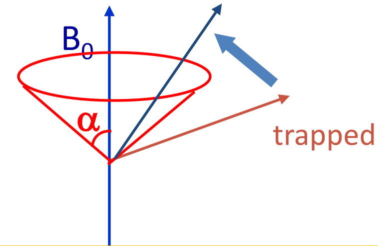
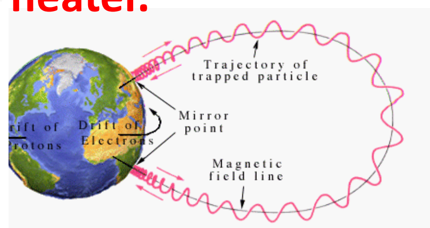


Figure 2-8. Constant-B surfaces in a dipole field.

- 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.





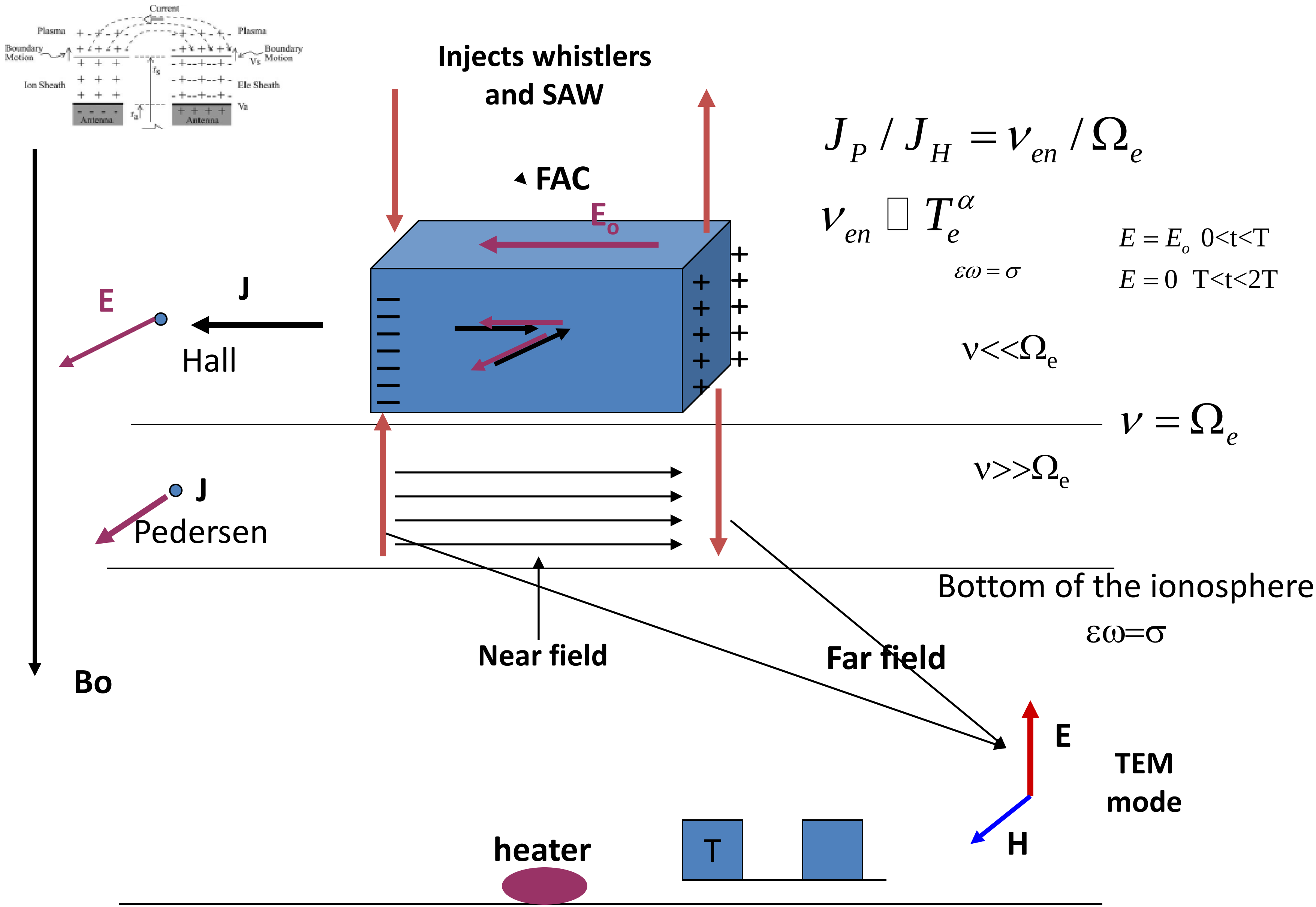
Ionospheric Heaters
HAARP (L≈4.9)
Arecibo (L≈1.4)
Tromso (L≈5.9)
SURA (L≈2.6)

Diagnosed by RBSP ,Resonance, DSX, ePOP

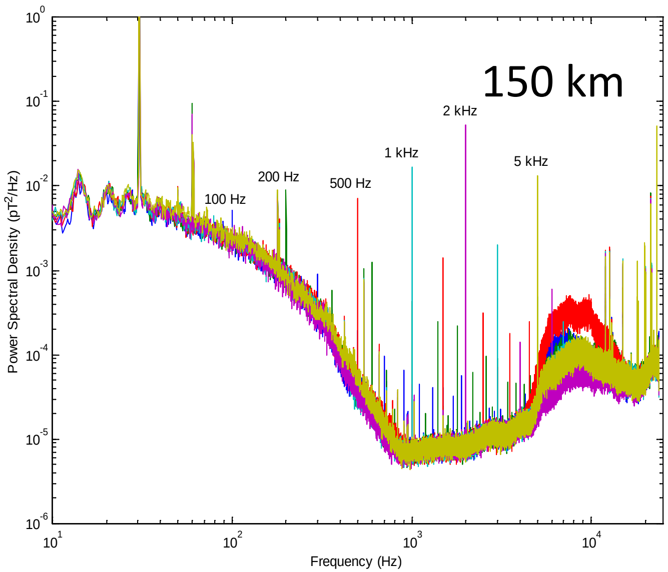
Techniques to transform HF to ULF/ELF/VLF frequencies

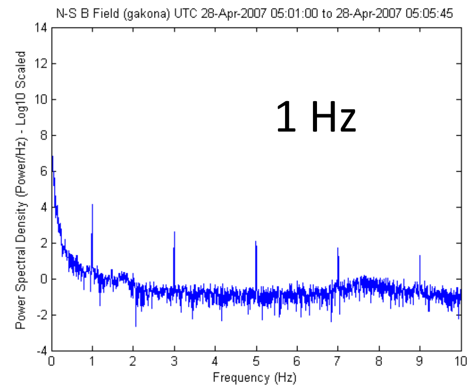
1. Polar Electrojet Antenna (PEJ)
   a. Requires an electrojet current in the D/E region (70-90 km)- Restricted to high latitudes
   b. Can inject frequencies up to 20 kHz [Whistlers and Shear Alfven Waves (SAW)]
2. Ionospheric Current Drive (ICD)
   a. Does not require electrojet
   b. Restricted to frequencies below 70 Hz [SAW, EMIC, Magneto-Sonic (MS)]

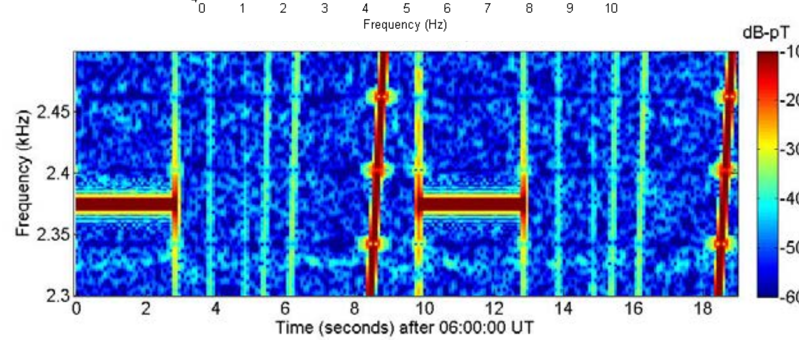
The Plasma Physics of the PEJ



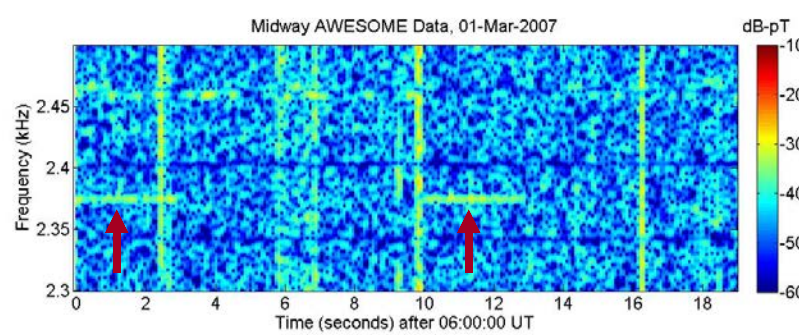
ELF/VLF ground detection and propagation



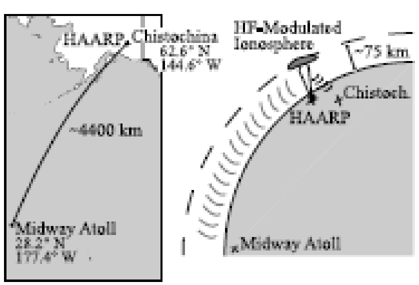




5400 km away

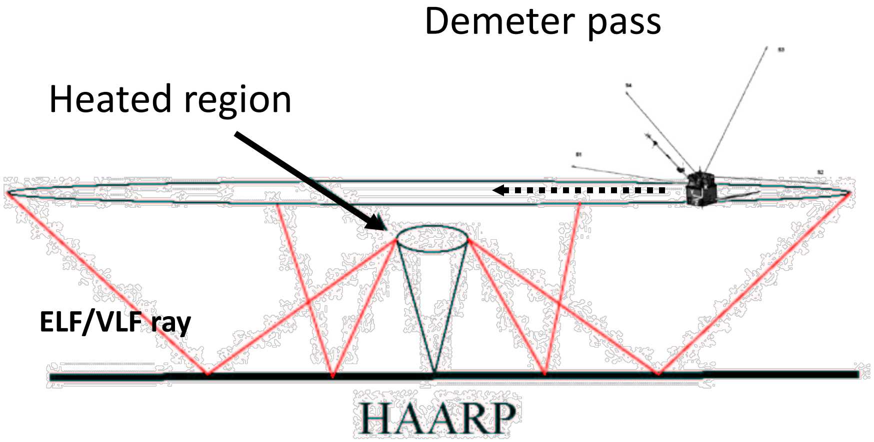


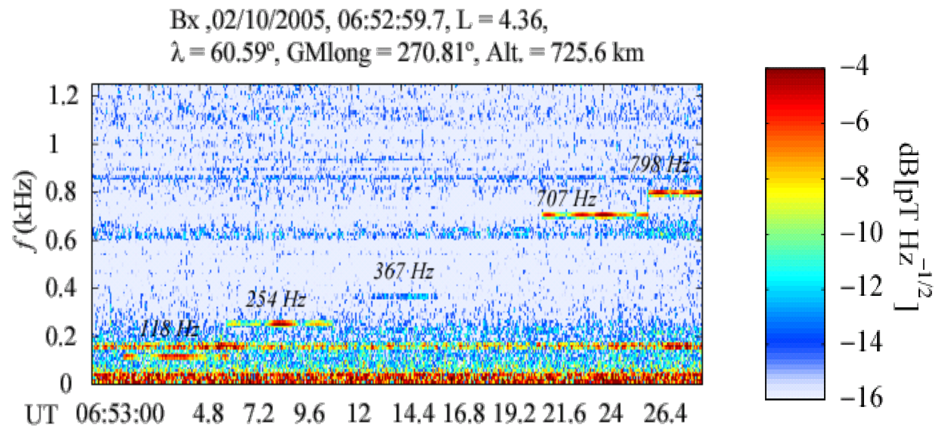
Midway

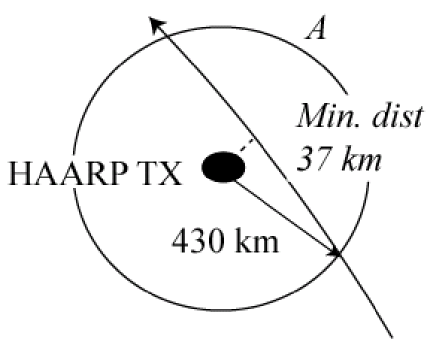


Moore et al. GRL 2008

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 (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.**

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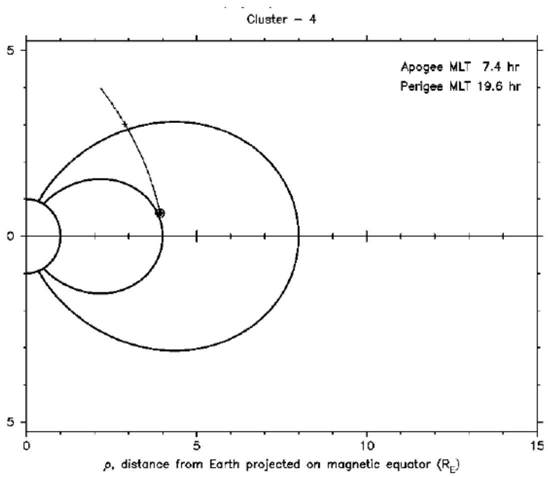
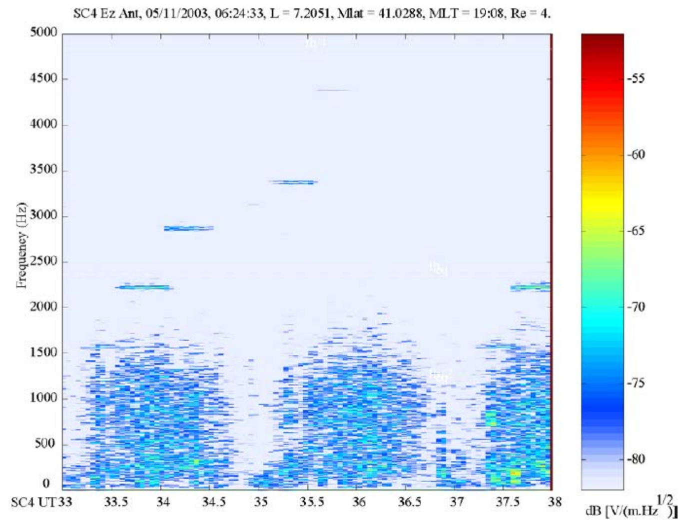
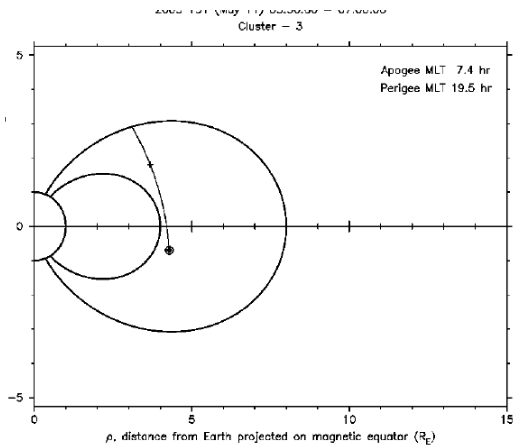
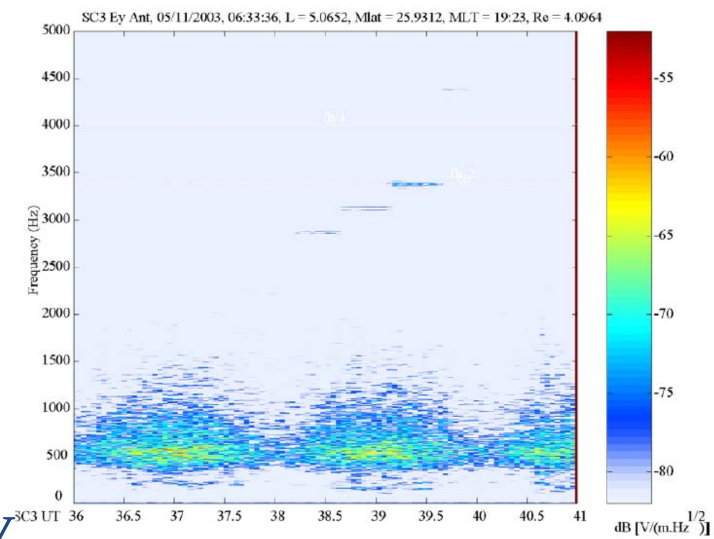
HAARP/CLUSTER INJECTION









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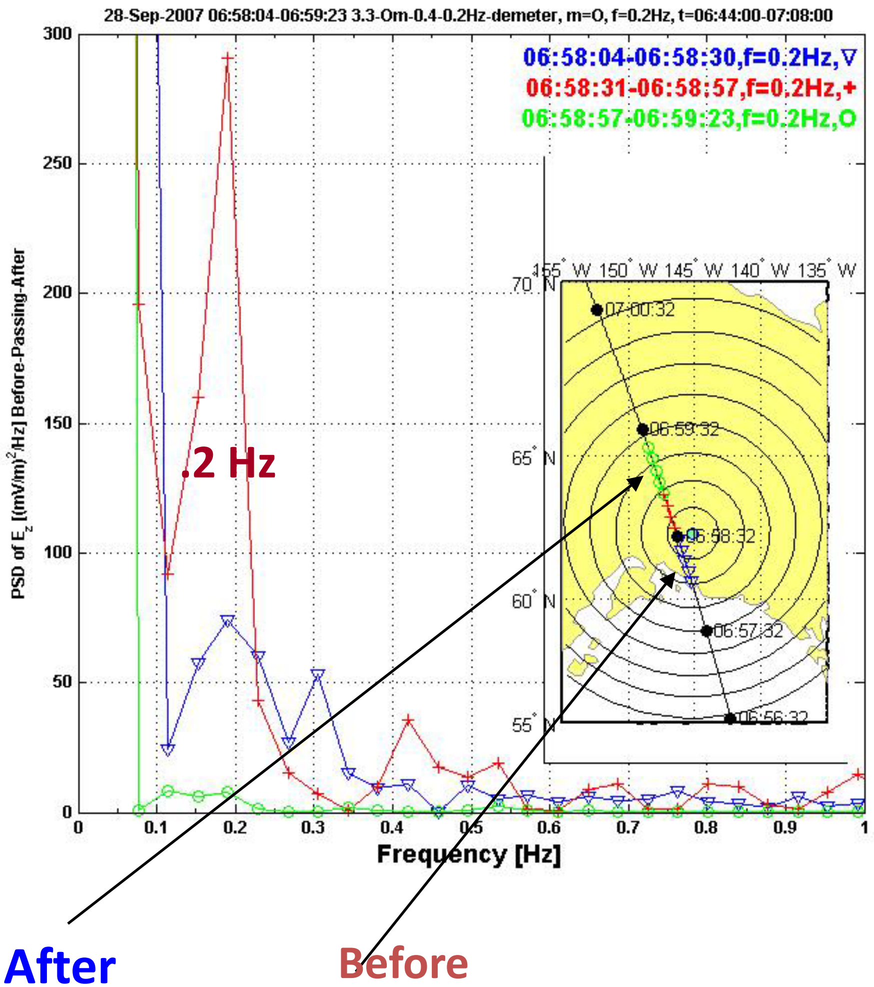
SAW DEMETER Detection



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

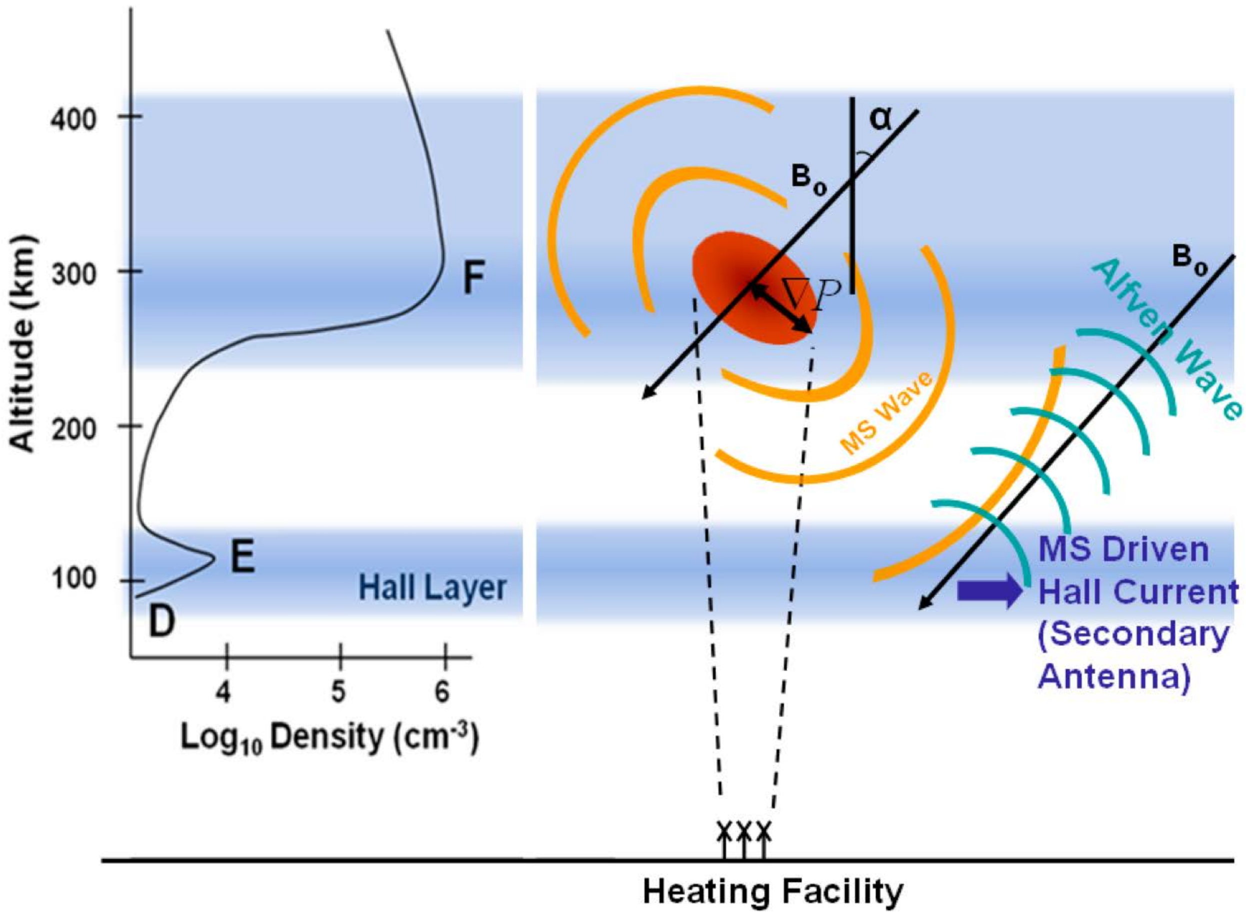
SEPTEMBER 28, 2008

Ionospheric Current Drive (ICD) Concept

Papadopoulos et al.
GRL 2011

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

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



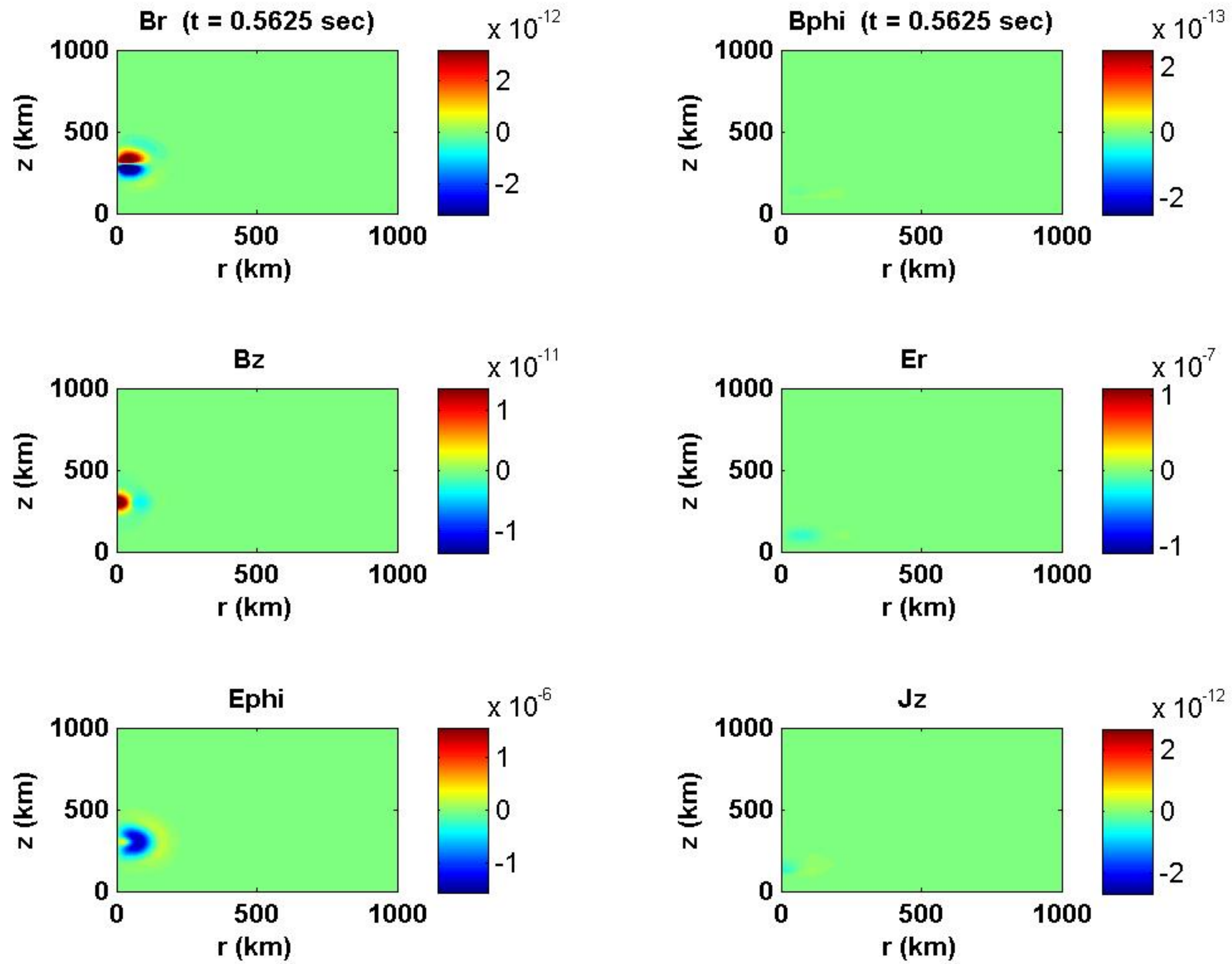
F- region cooling response does not allow frequencies higher than 60-70 Hz

Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

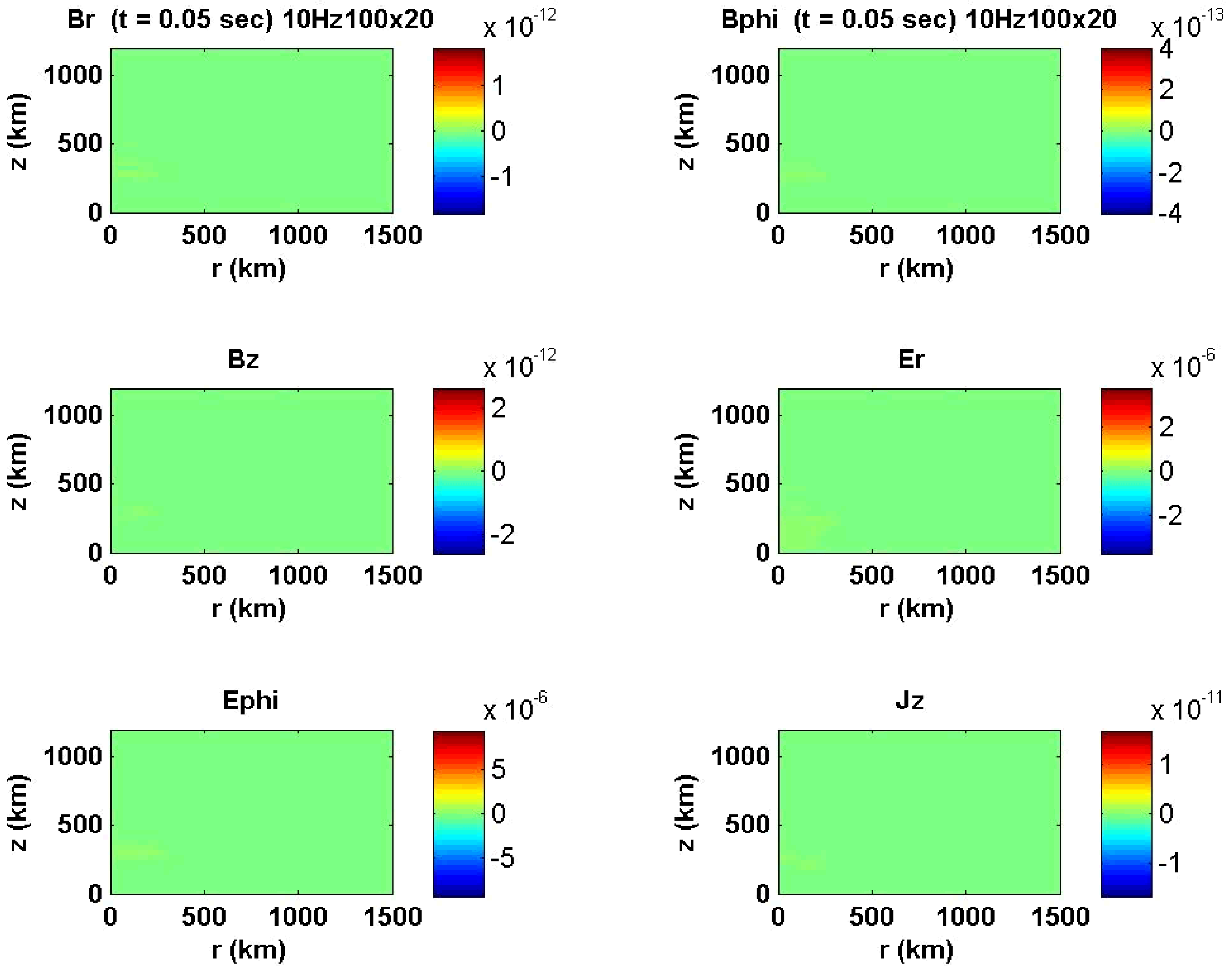
Cylindrical Coordinates

Papadopoulos et al. GRL 2011



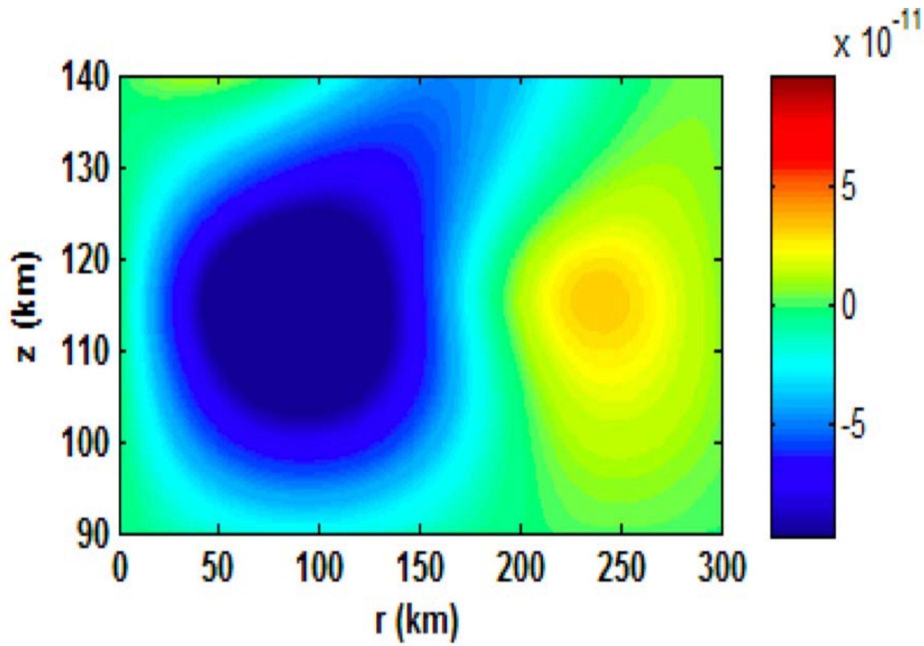
MS

SAW

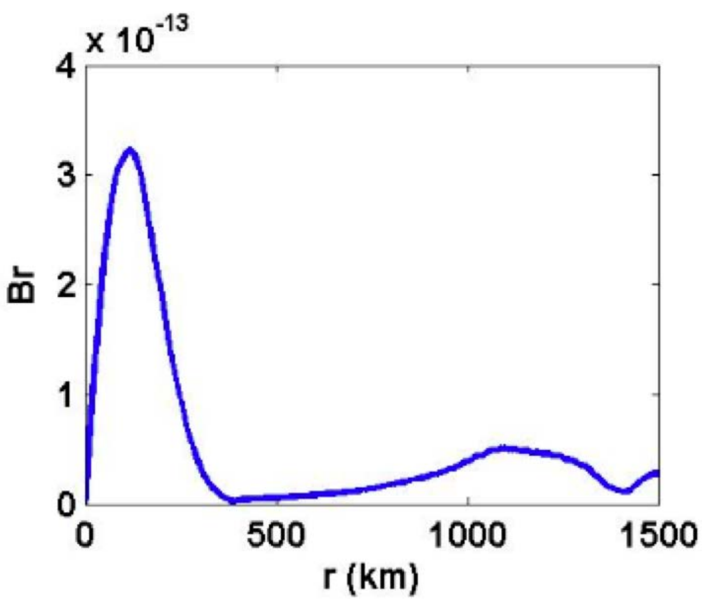

Br (t = 0.05 sec) 10Hz100x20
Bphi (t = 0.05 sec) 10Hz100x20
Bz
Er
Ephi
Jz
z (km)
r (km)
x 10^-12
x 10^-13
x 10^-6
x 10^-11

10 Hz

Secondary Antenna Current and Ground Field

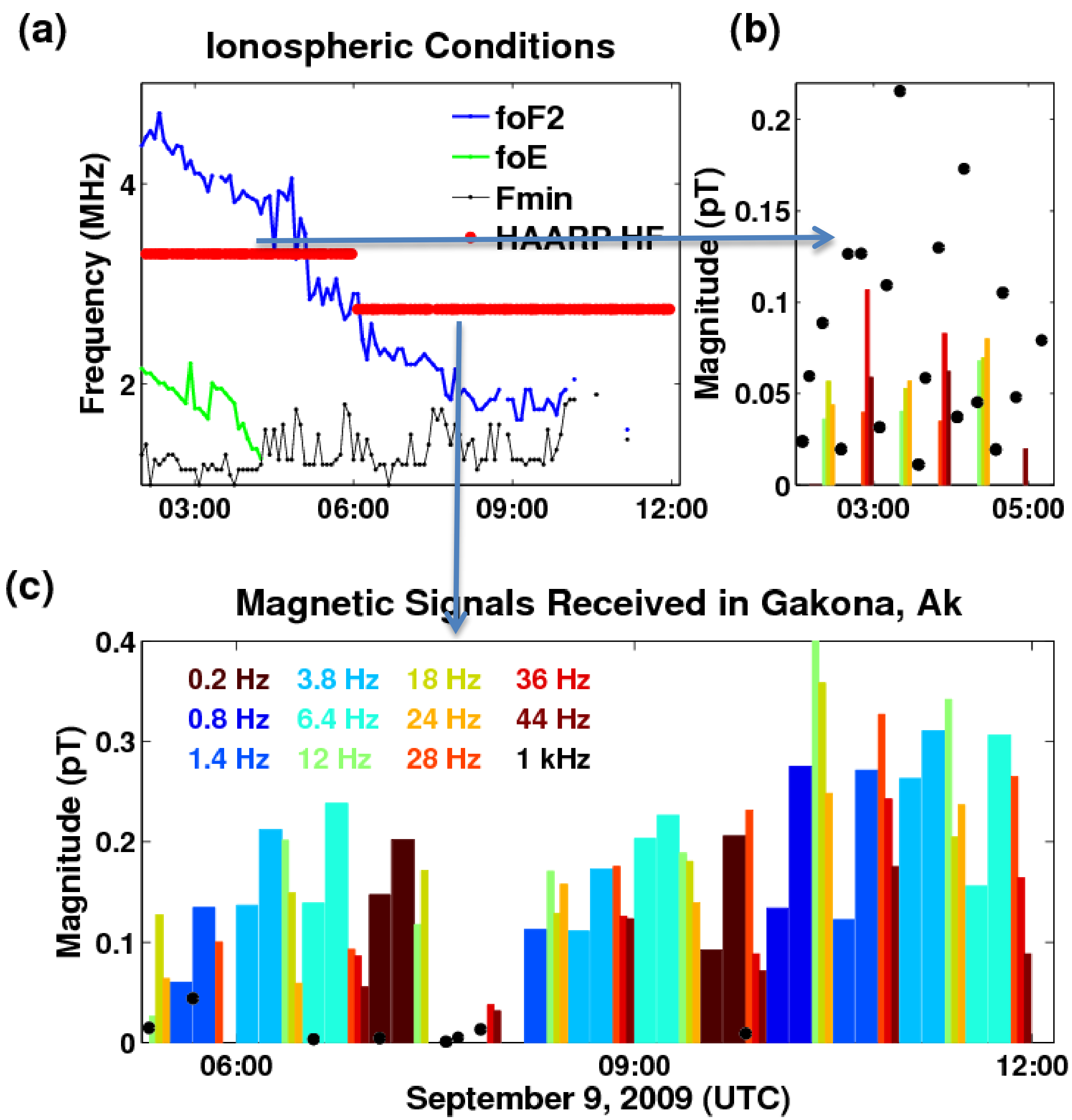


J_θ



B_r

PoP Exps: PEJ to ICD Transition



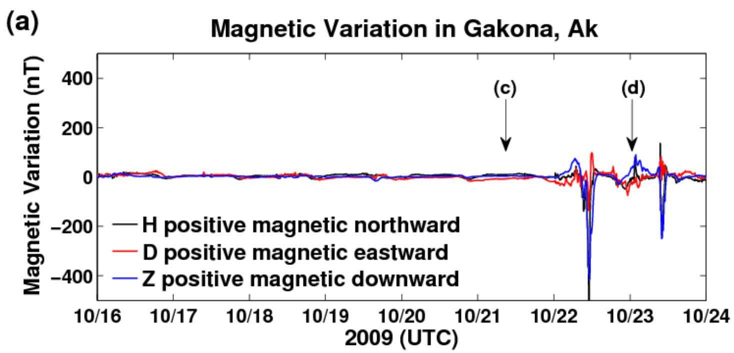
PEJ

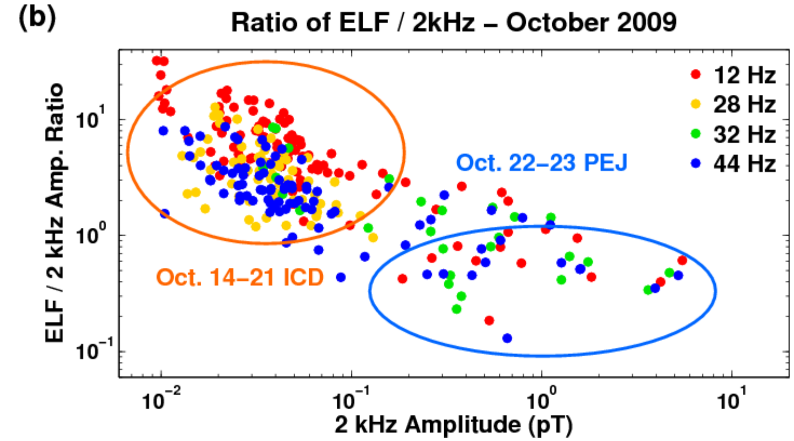
ICD

Scaling with power and frequency

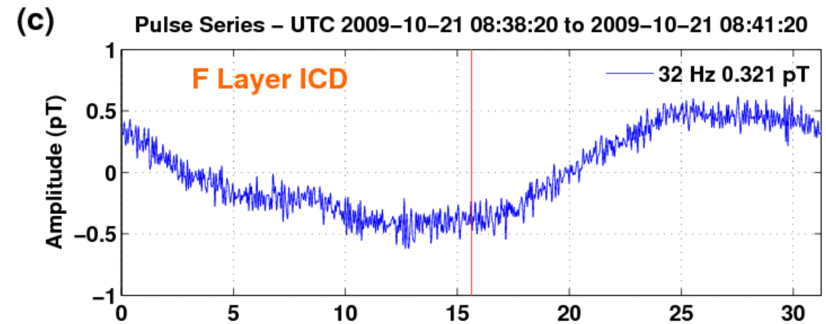
ICD PoP Experiments

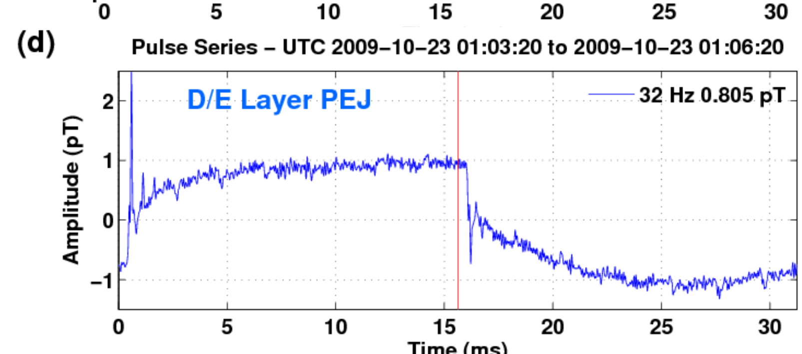
Papadopoulos et al GRL 2011b

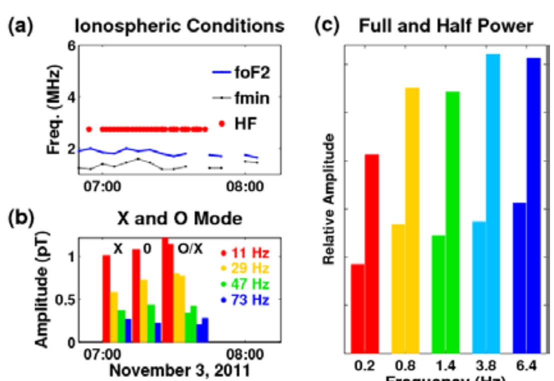




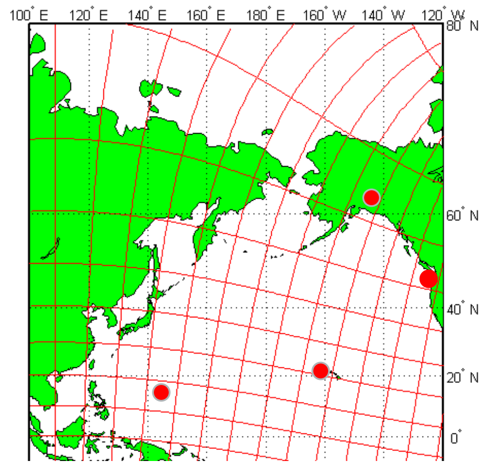
- 10/14-10/21 Magnetometer below 10 nT
- 10/14-10/23 55 hours of VLF/ELF/ULF tests
- 6 hours of VLF ground measurements –PEJ operational
- 51 hours of low ELF/ULF (12-44 Hz) ground measurements

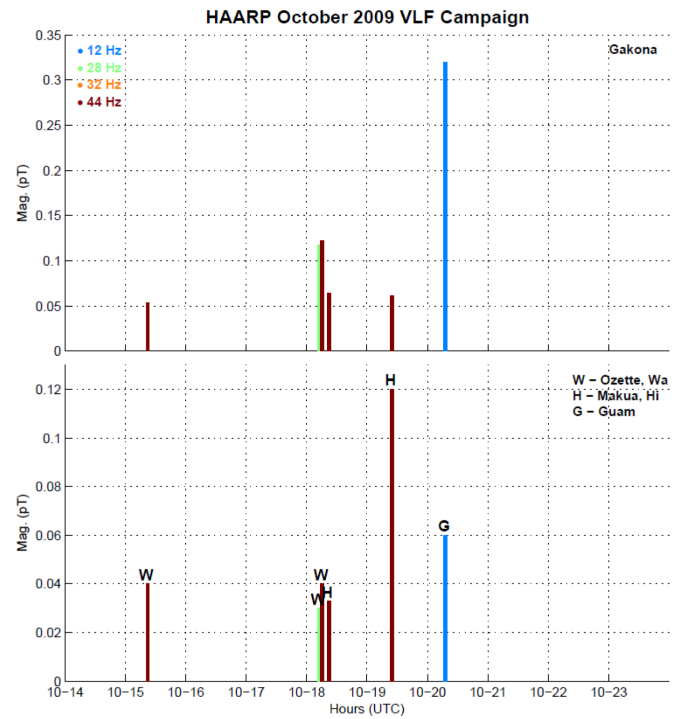




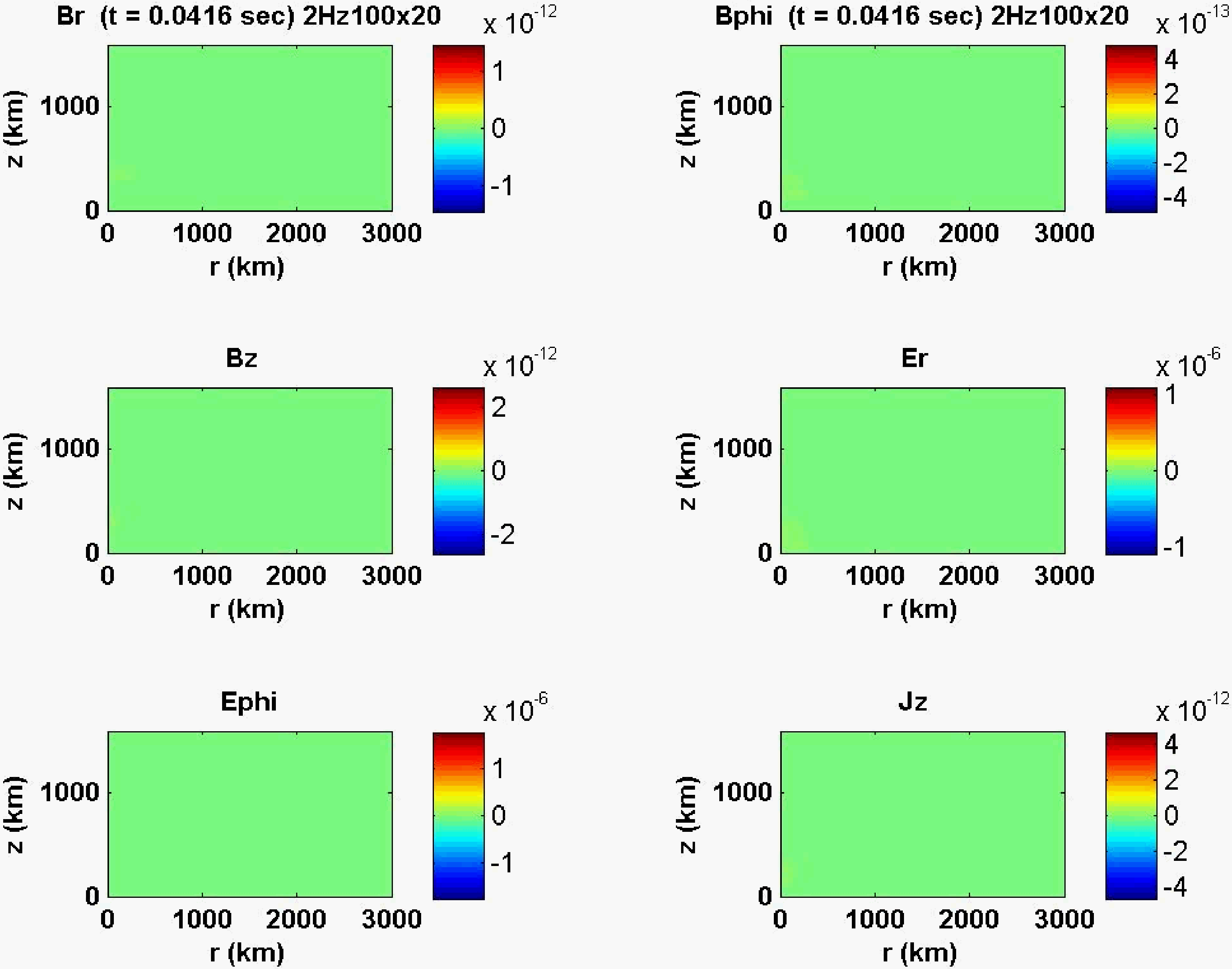


ELF detection at Distant Sites





- 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

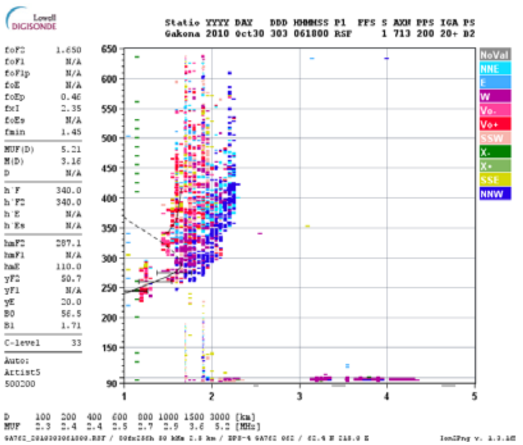


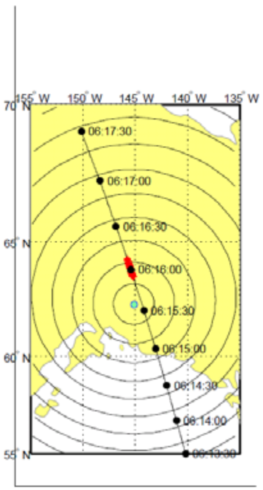
Br (t = 0.0416 sec) 2Hz100x20
x 10^-12
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)
Bphi (t = 0.0416 sec) 2Hz100x20
x 10^-13
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)
Bz
x 10^-12
2
0
-2
z (km)
1000
0
0
1000
2000
3000
r (km)
Er
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)
Ephi
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)
Jz
x 10^-12
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)

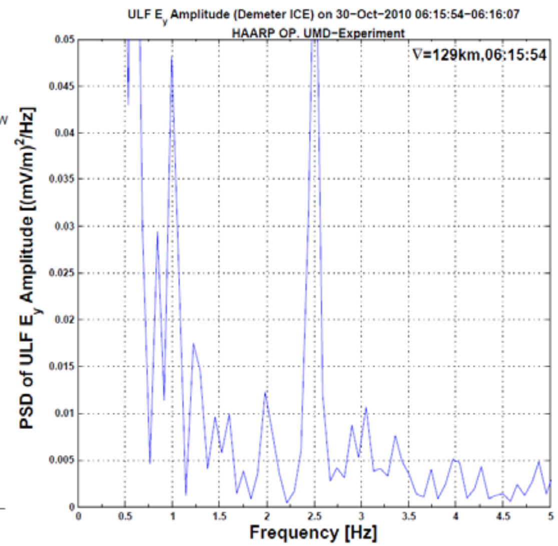
Proof of Concept ICD Experiment – Conducted under DARPA/BRIOCHE

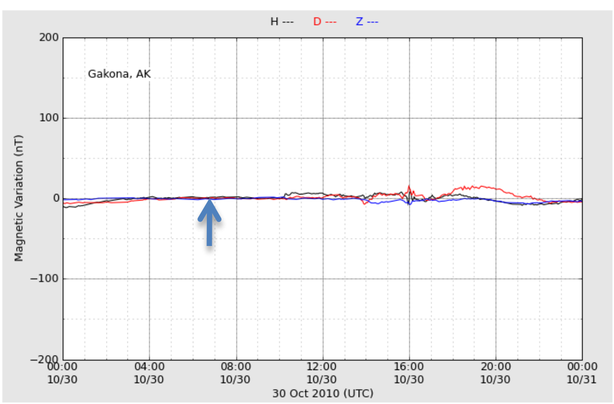
Chang-Lebinsky-Milikh-Papadopoulos

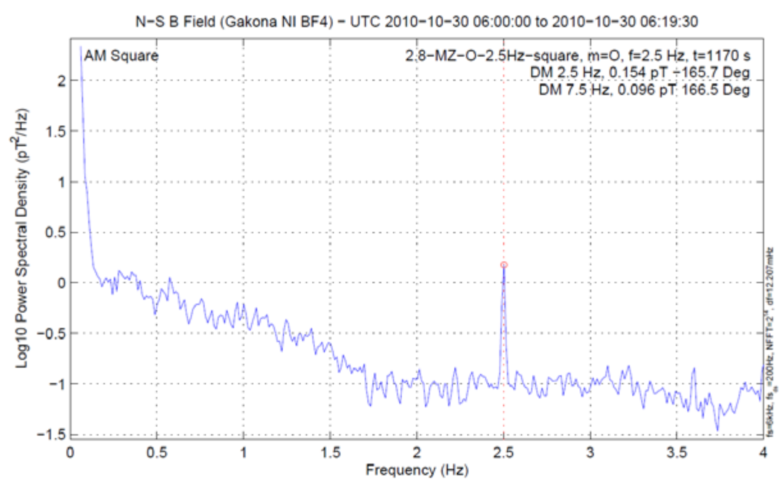
2.8 MHz, O-mode





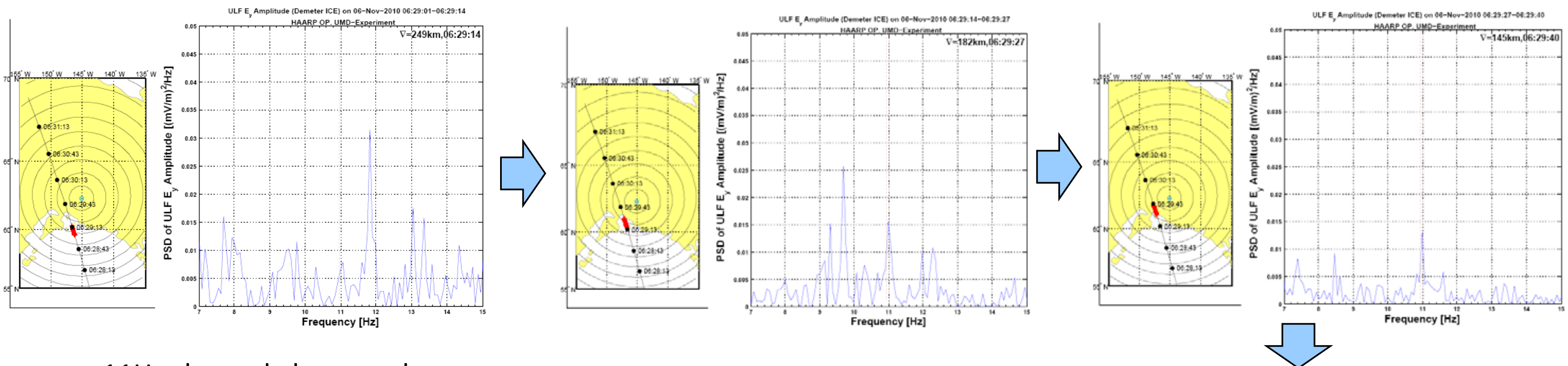




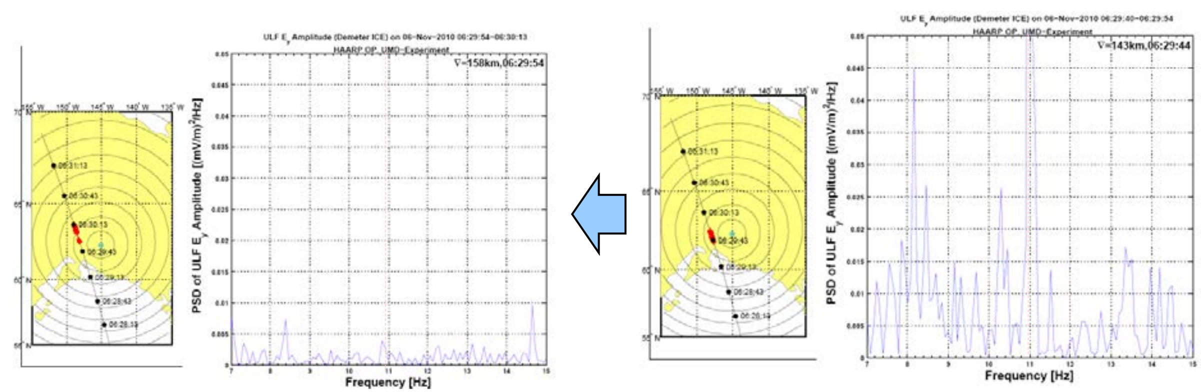


Low ELF Observed by Demeter Satellite

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

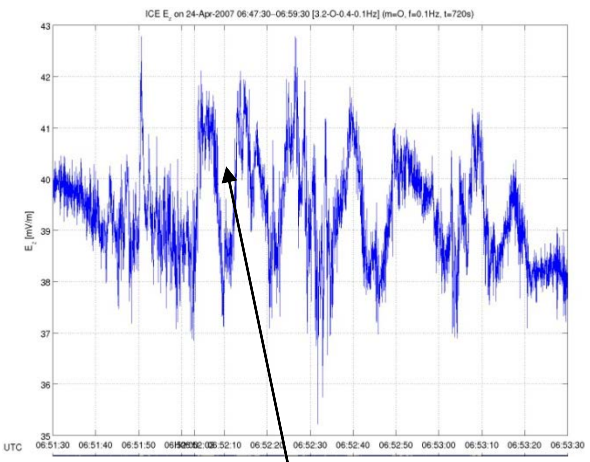


- 11Hz showed along track near HAARP, not before/after
- Duration: 17s or 130 km
- Peak Ey ~ 0.08 (mV/m)²/Hz



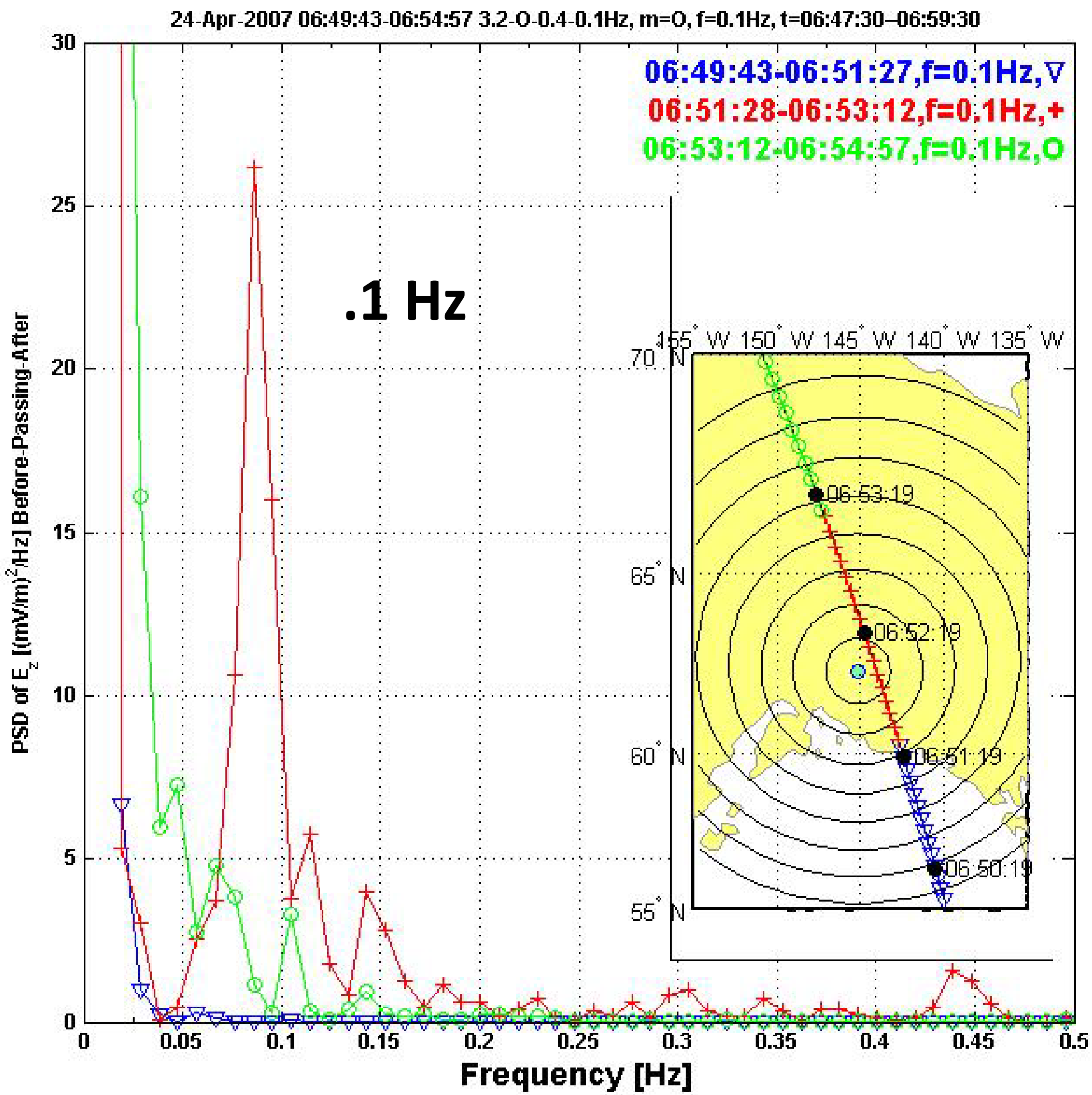
Msonic Wave Injection

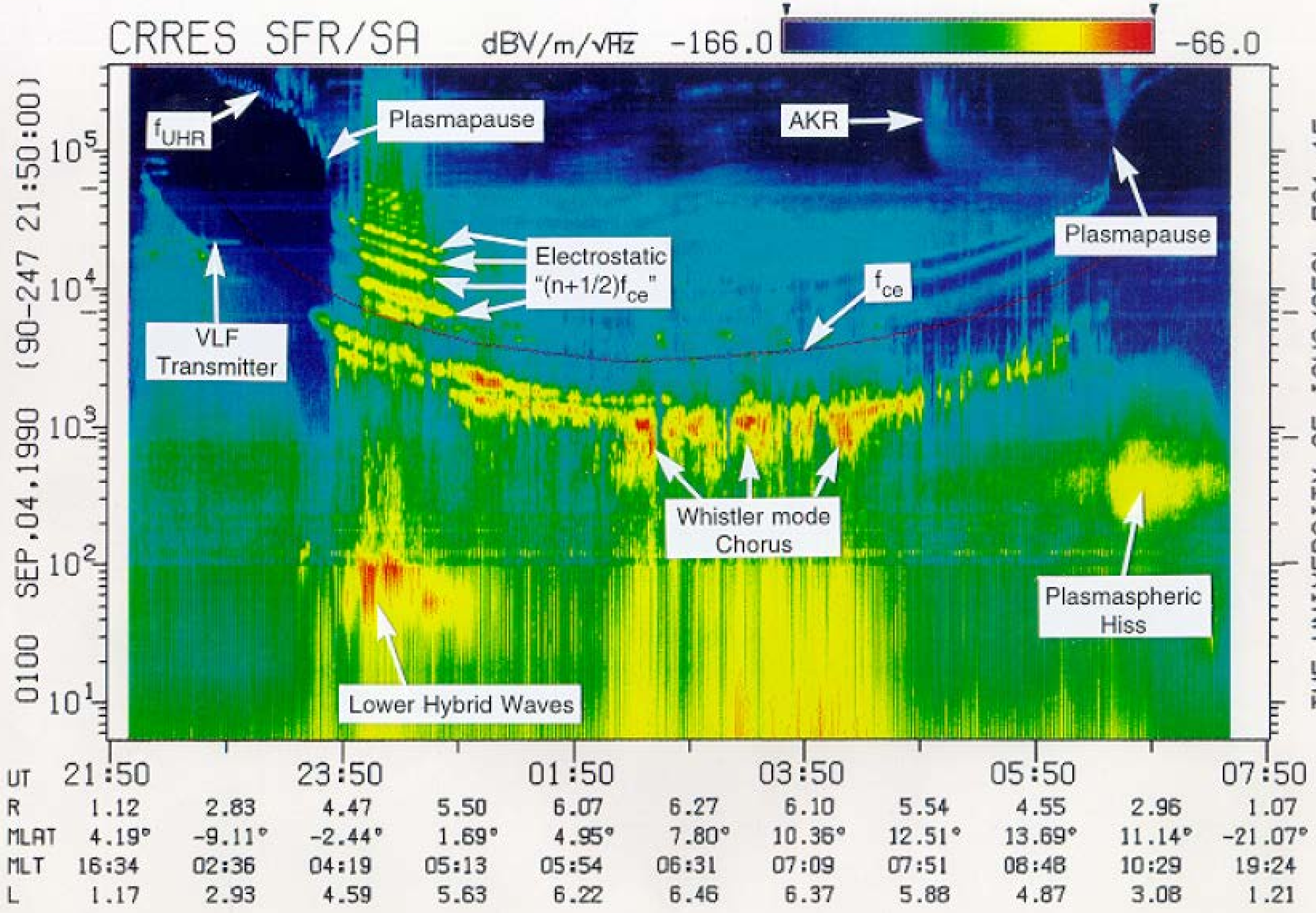
DEMETER



10 sec oscillations

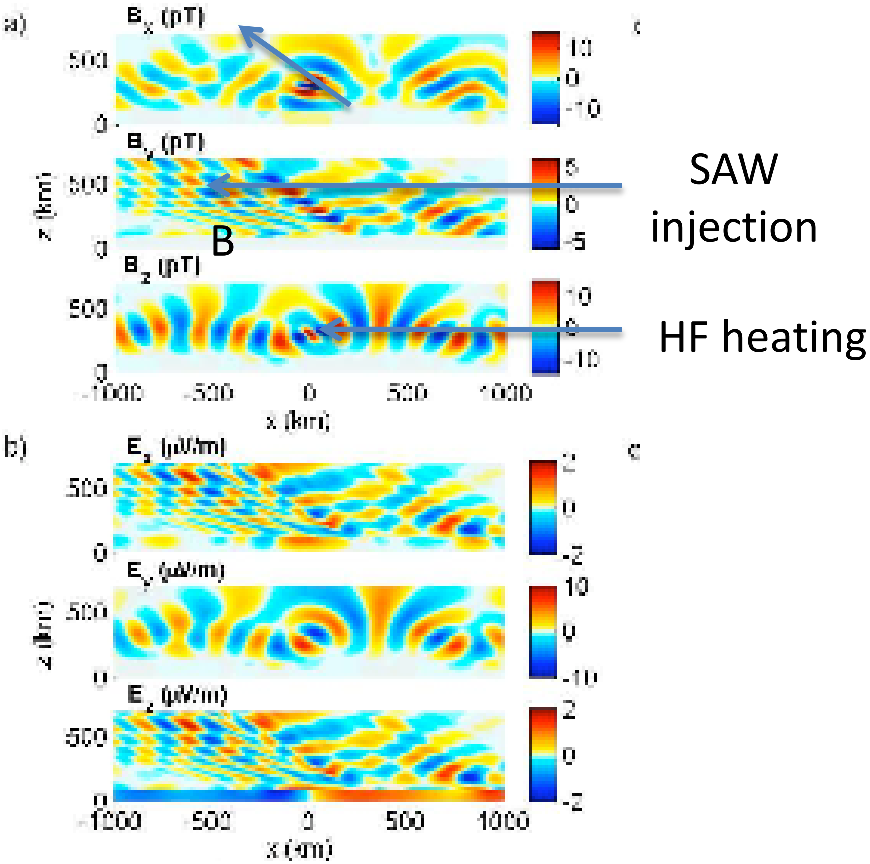
Over 700 km distance

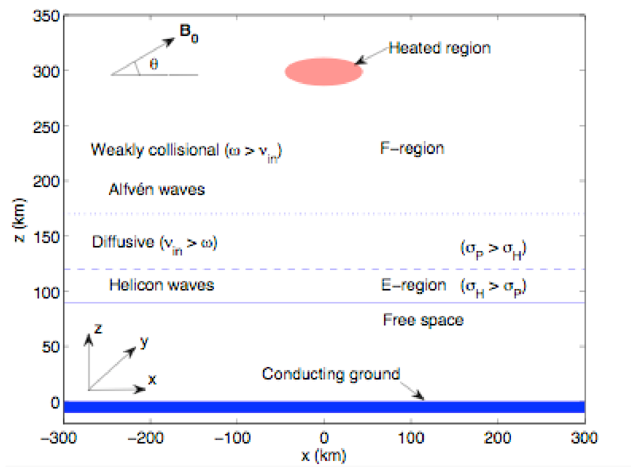


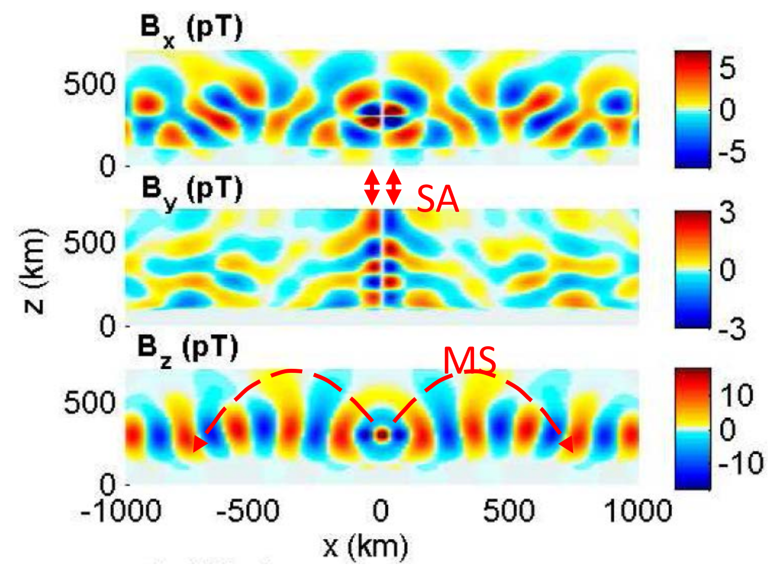


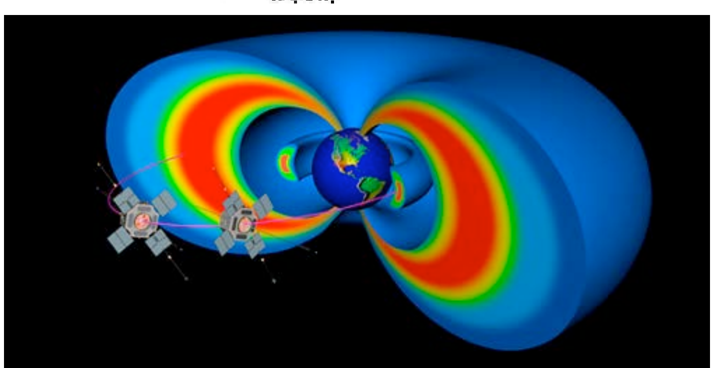
CRRES SFR/SA
dBV/m/√Hz
-166.0
-66.0
fUHR
Plasmapause
AKR
Plasmapause
Electrostatic
"(n+1/2)fce"
fce
VLF
Transmitter
Whistler mode
Chorus
Plasmaspheric
Hiss
Lower Hybrid Waves
0100 SEP.04.1990 (90-247 21:50:00)
THE UNIVERSITY OF IOWA/AFGL 701-15
CRRESPEC V0 PROCESSED 27-MAR-92 13:24
UT 21:50 23:50 01:50 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

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





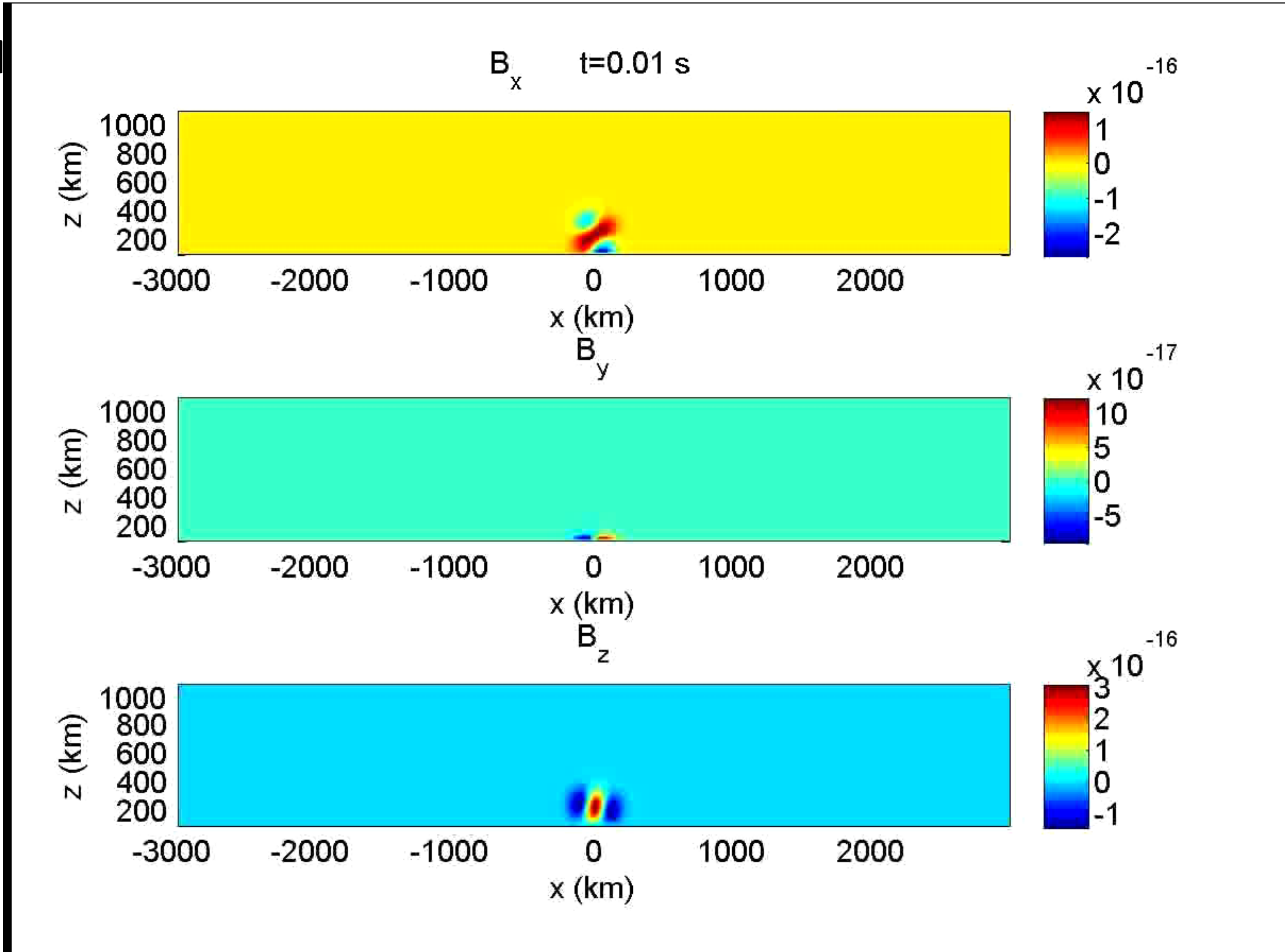




RBSP

ICD - Implications

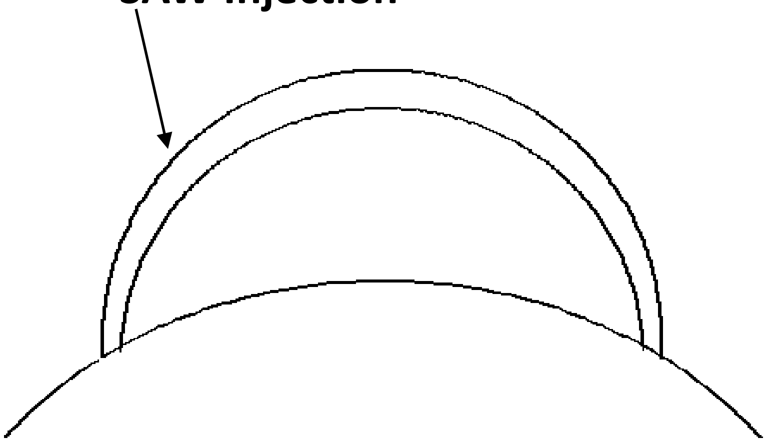
M … on

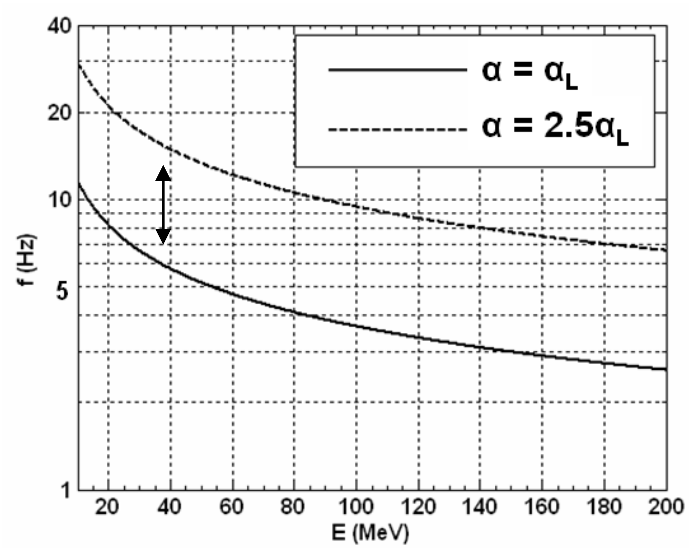


Frequency Selection for Protons

Example for L=1.5

SAW Injection





Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

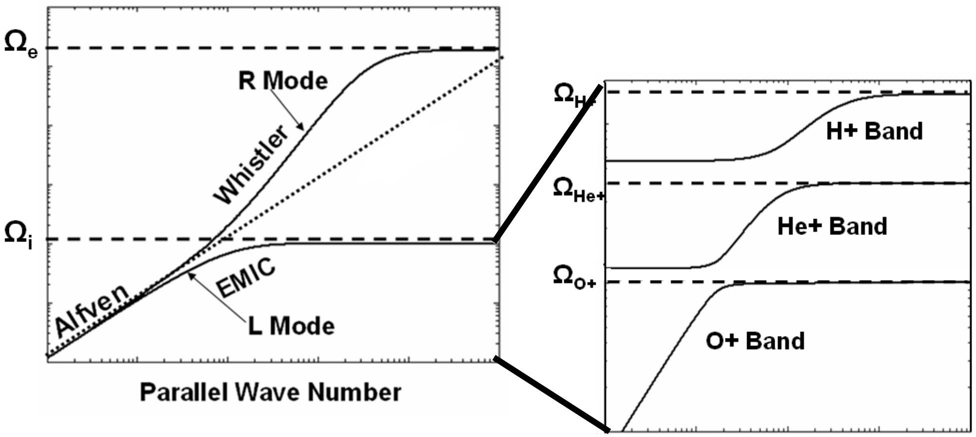
$$\omega = k_z V_A$$

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

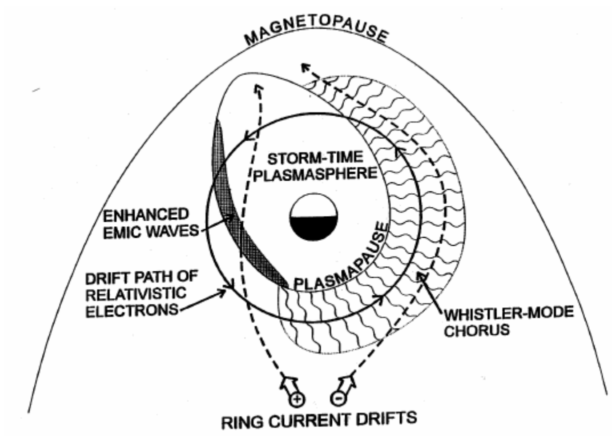
Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz

ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



Outer Belts



Summers et al., 1998, 2000, 2003

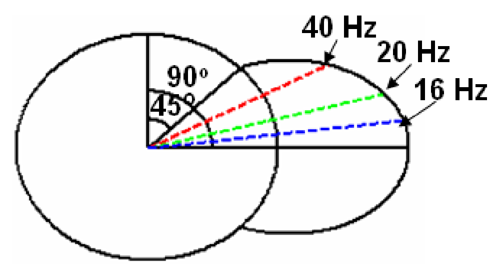
$$-k_z v_z = |\Omega_e| / \gamma$$

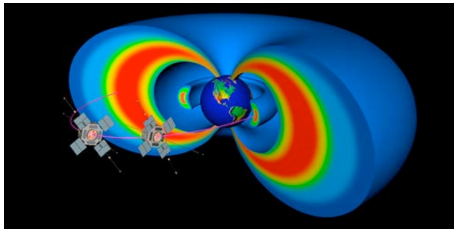
$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3} \frac{\omega\omega_{pj}^2}{(\omega - \Omega_j)}$$

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

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

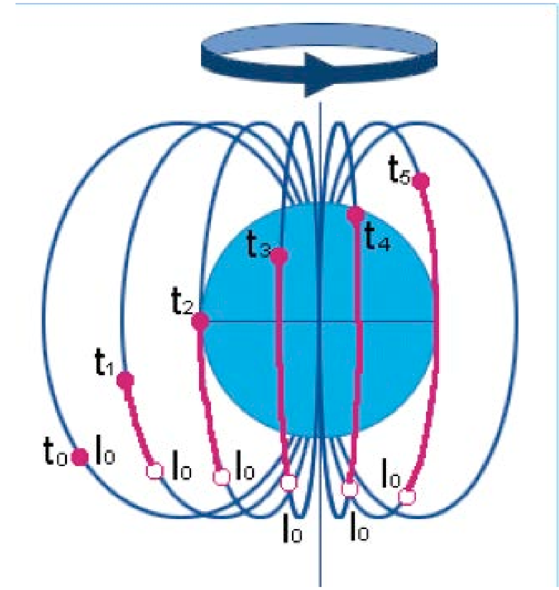
HELIUM BRANCH

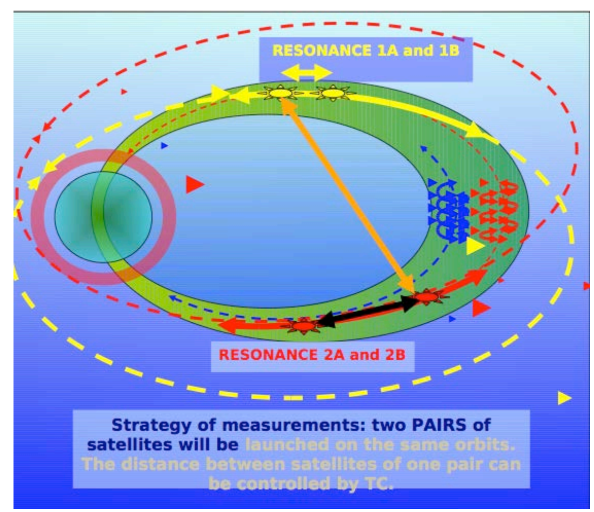




Physics Studies HAARP/Resonance

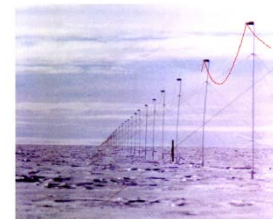
- Wave-particle interactions in the Radiation Belts – Whistler range
  - Artificially Stimulated Emissions (ASE)
- ULF - MHD Study
  - SA ,EMIC and MS wave injection in space. Interactions with trapped electron and ions
  - Excitation of the Ionospheric Alfven Resonator (IAR)
  - SA wave (Pc1) triggering



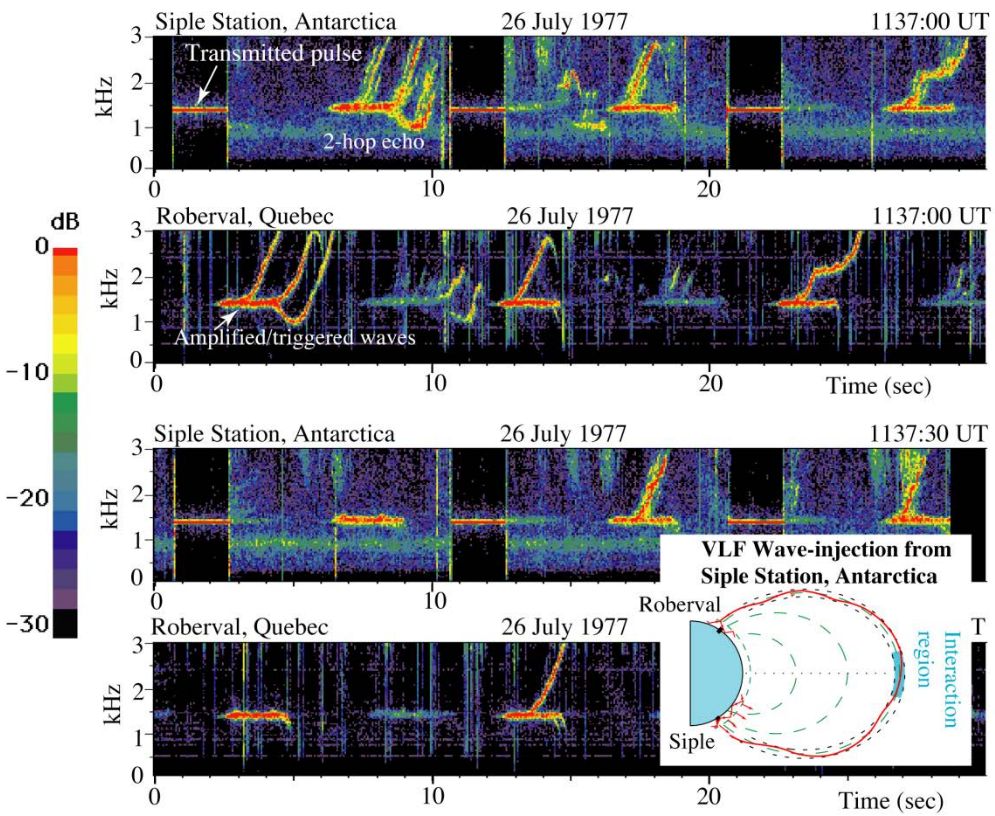


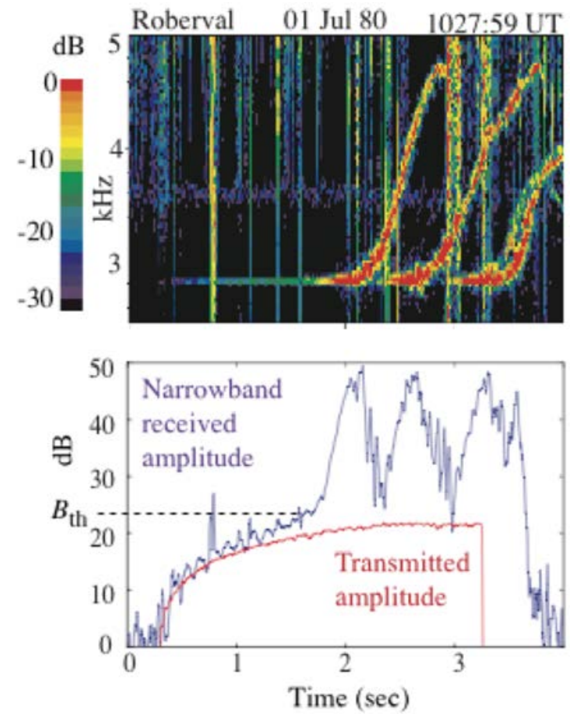
Controlled VLF Wave Injection
Artificially Stimulated Emissions (ASE)

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



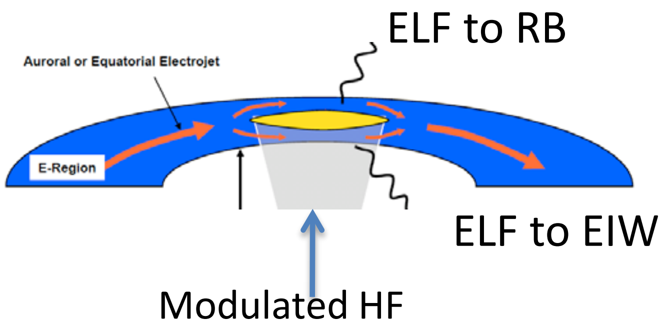
L=4.2, 1.5 MW, 42 km length antenna on 2 km thick ice sheet,
Inject 3-6 kHz –
Very difficult and inefficient to inject ELF/VLF with ground



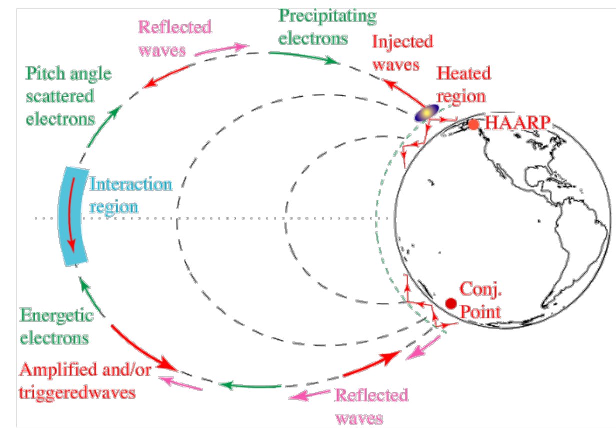


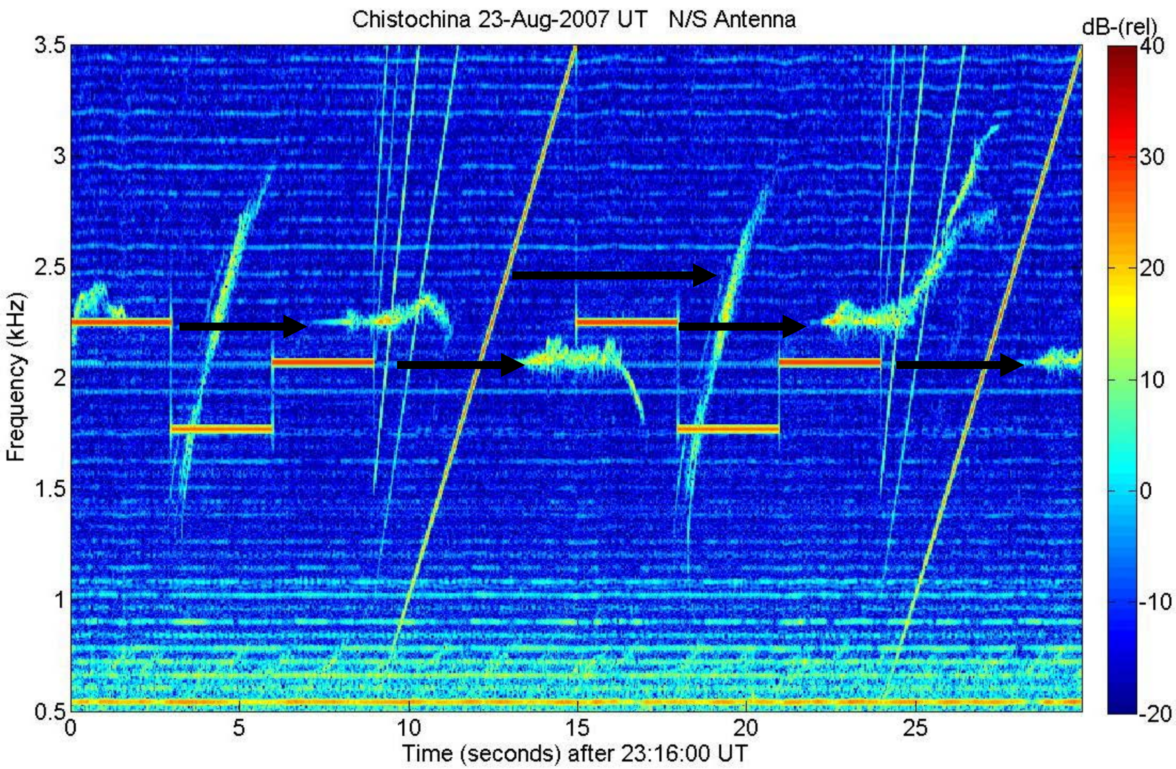
Triggered Emissions

ASE – HAARP Tests



ASE Studies

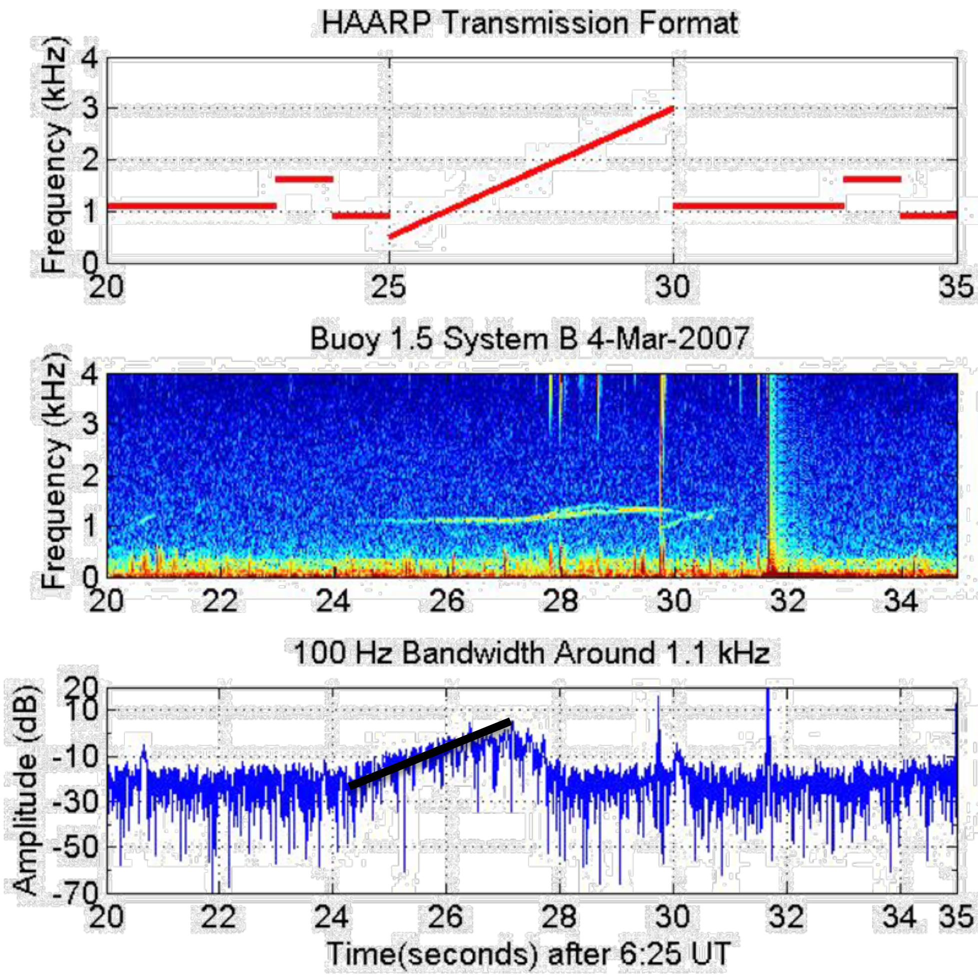


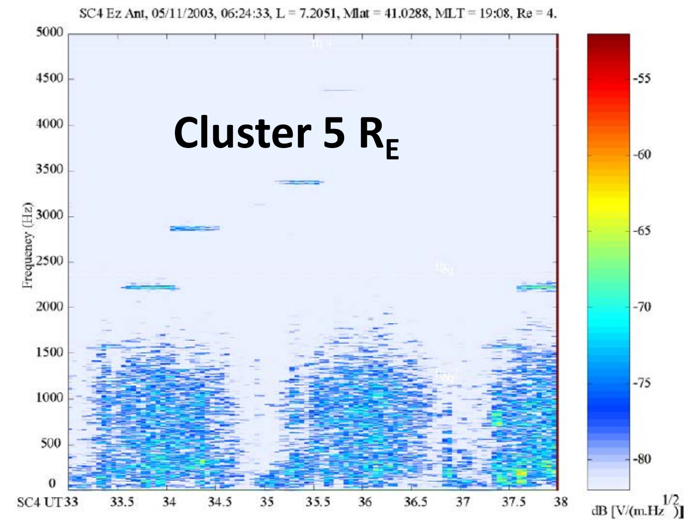


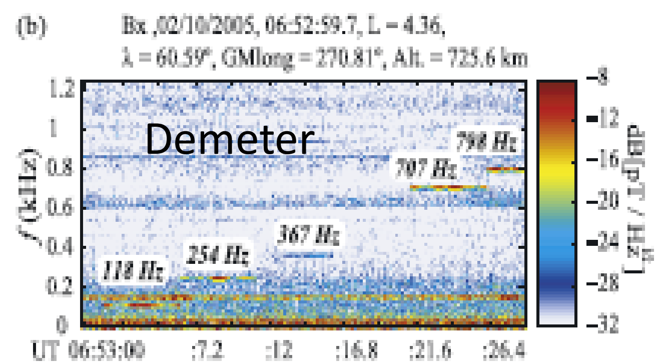
Conjugate

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



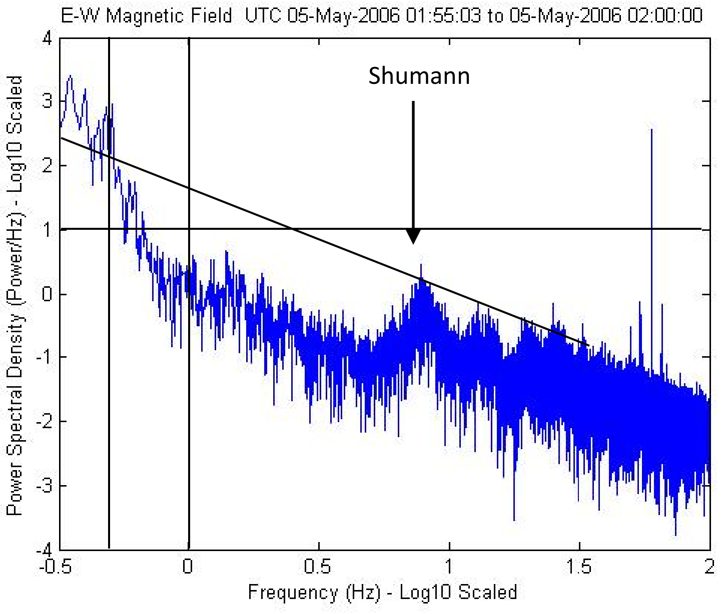


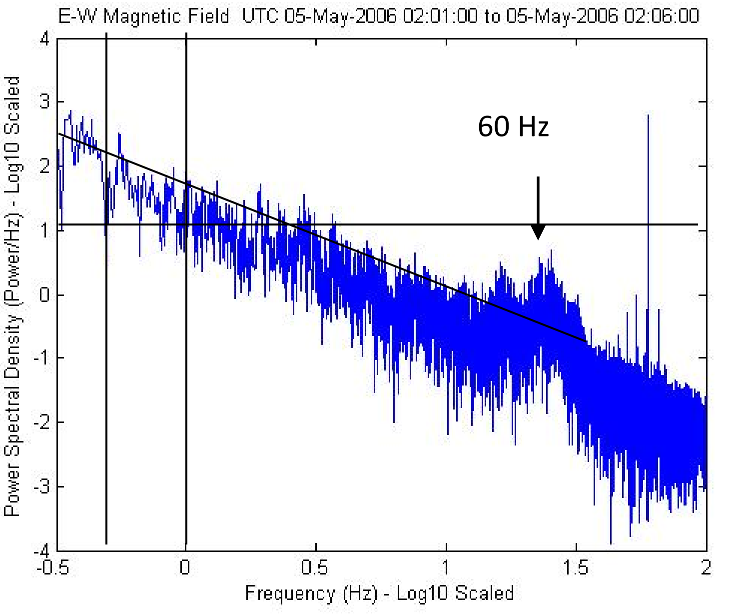


Only the pulse at 1100 Hz is amplified

BAE SYSTEMS

Pc1 Triggered Emissions ?



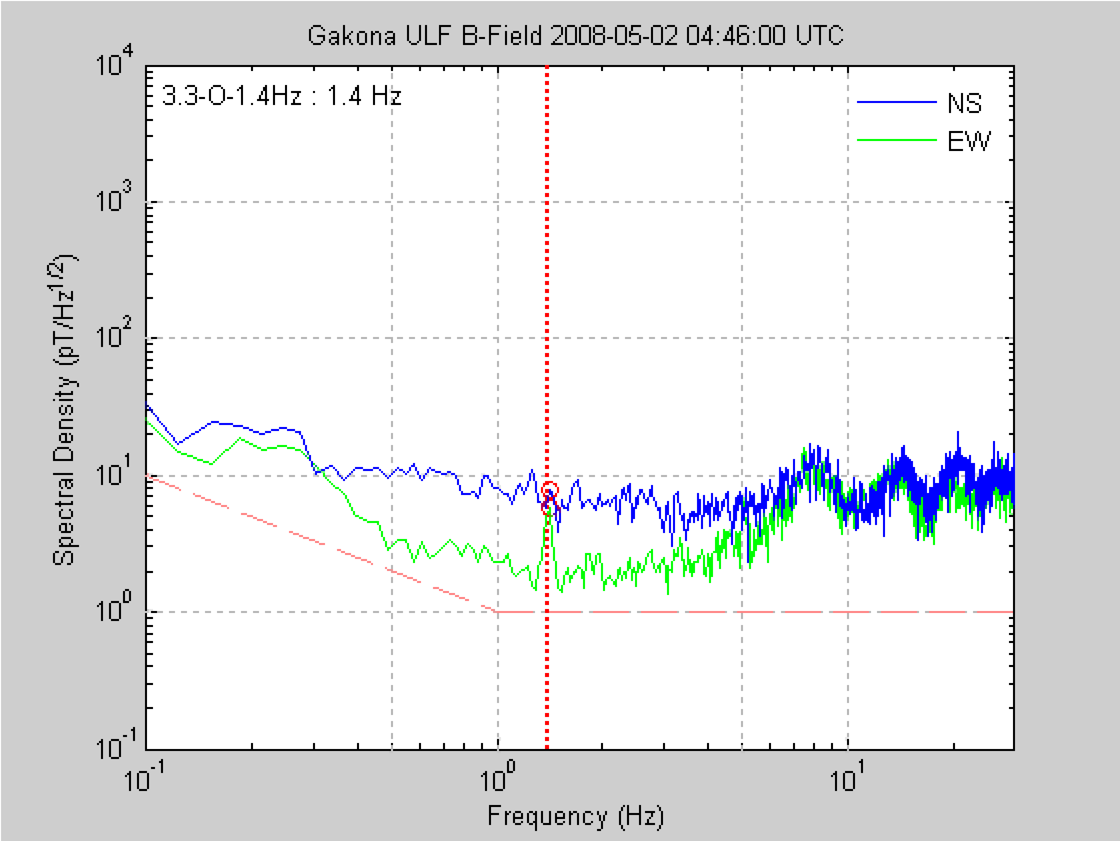


Spectrum before HAARP ULF Start Experiment – Ambient Noise

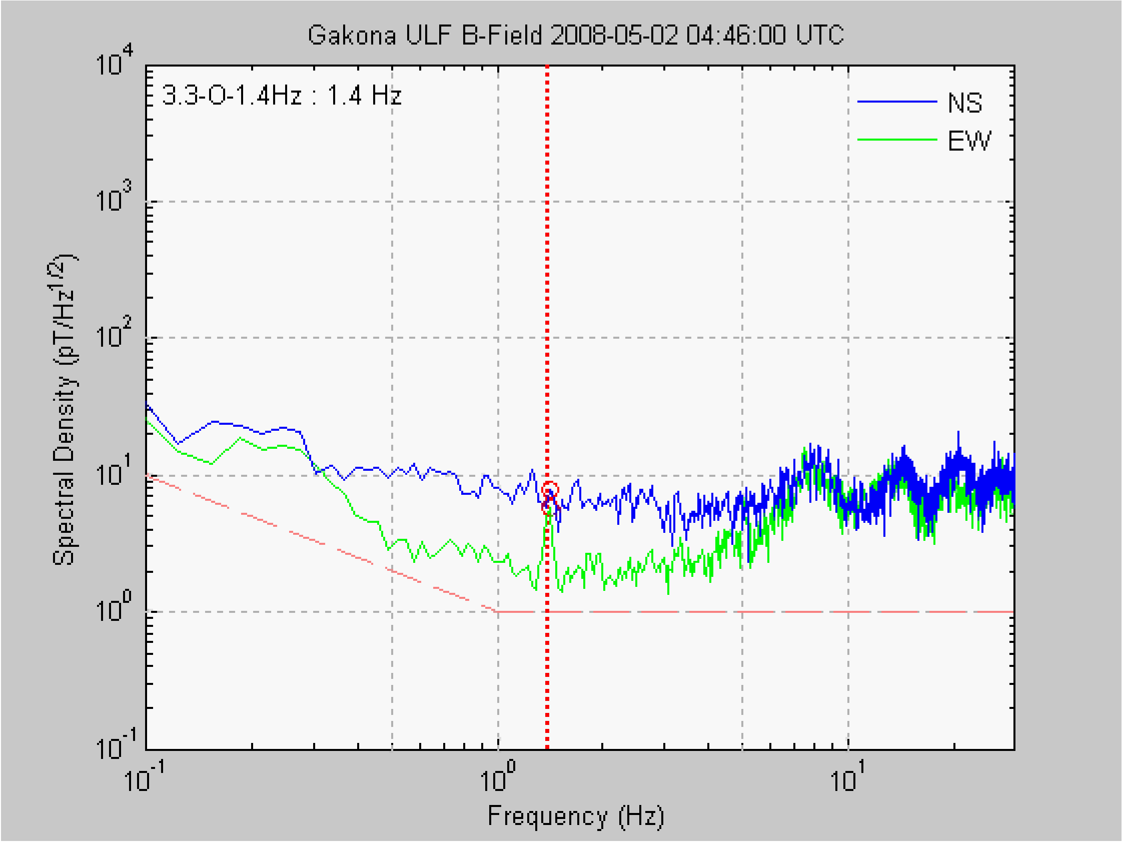
Spectrum after HAARP ULF Start Noise Increase by more than 10-20 dB between .7-10 Hz

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



Gakona ULF B-Field 2008-05-02 04:46:00 UTC
3.3-O-1.4Hz : 1.4 Hz
NS
EW
Spectral Density (pT/Hz^1/2)
Frequency (Hz)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-1
10^0
10^1

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**

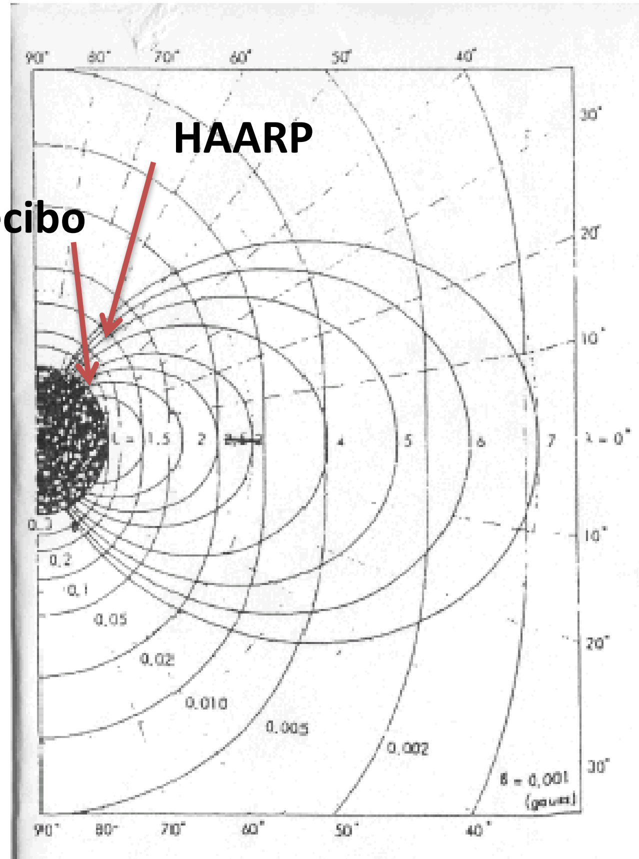
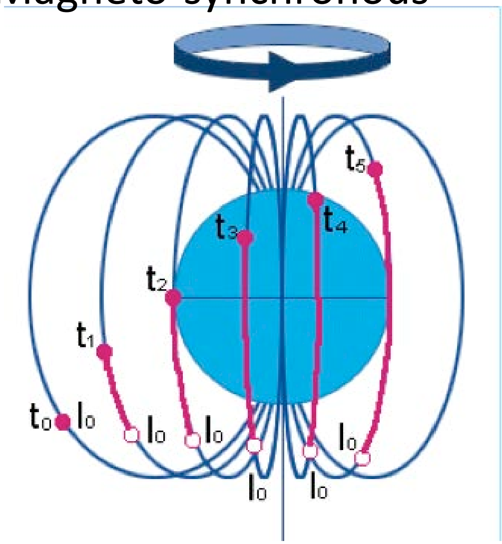


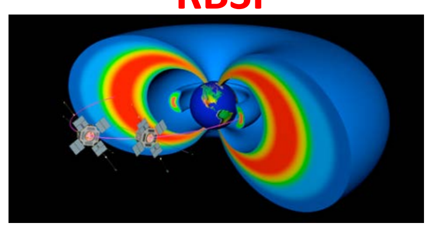
Figure 2-8. Constant-B surfaces in a dipole field.

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

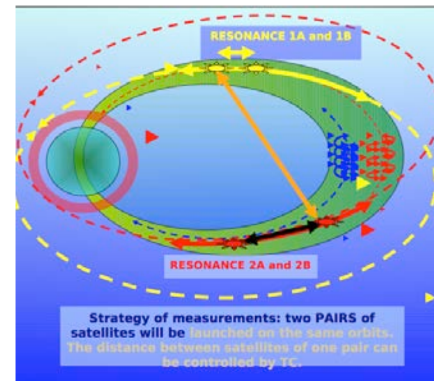
Magneto-synchronous



RBSP

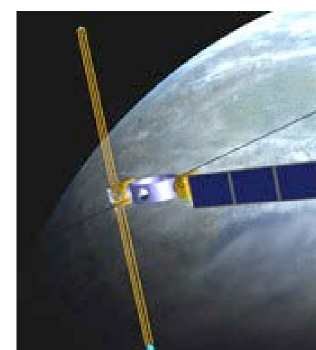


Launch May 18, 2012
2 probes, <1500 kg for both
10° inclination, 9 hr orbits
~500 km x 30,600 km



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

DSX (AFRL)
Launch ~2012
MEO,
wave/particle



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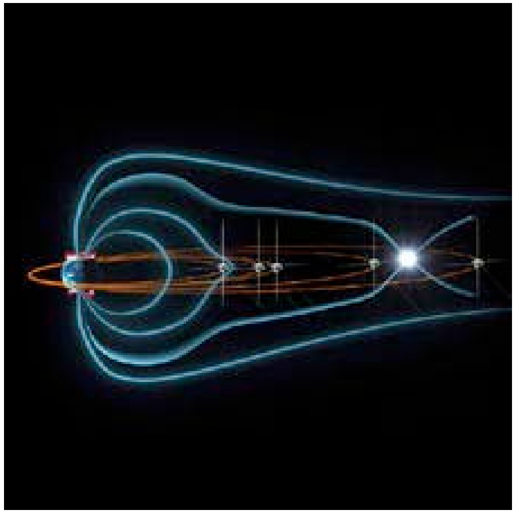
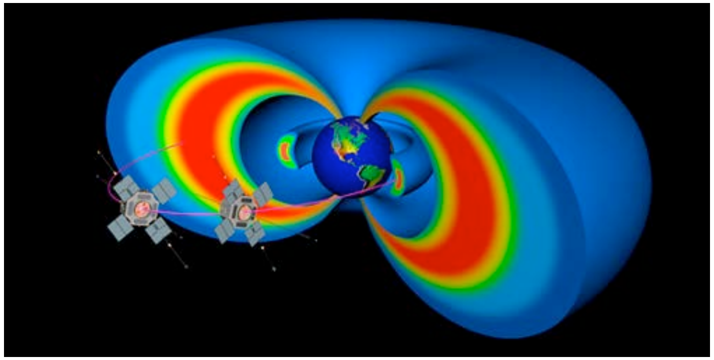


THEMIS (NASA)

Launch Feb 17, 2007

5 identical probes (3)



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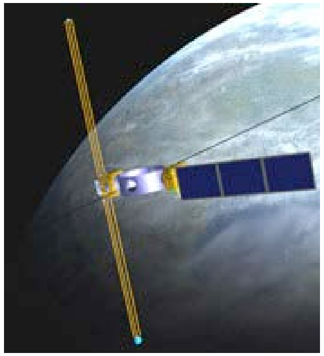


DSX (AFRL)

Launch ~2012

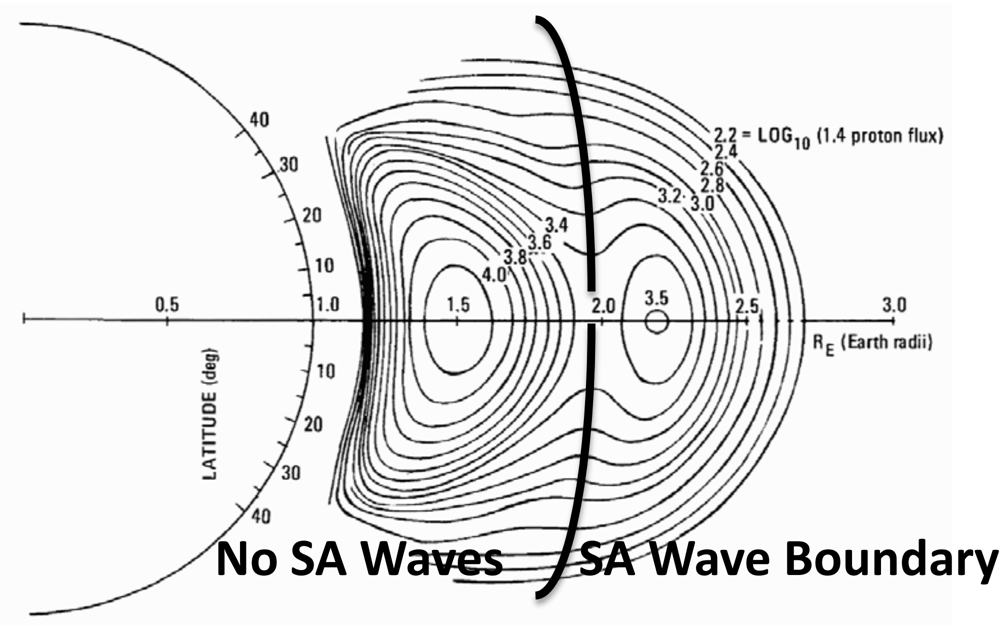
MEO, wave/particle

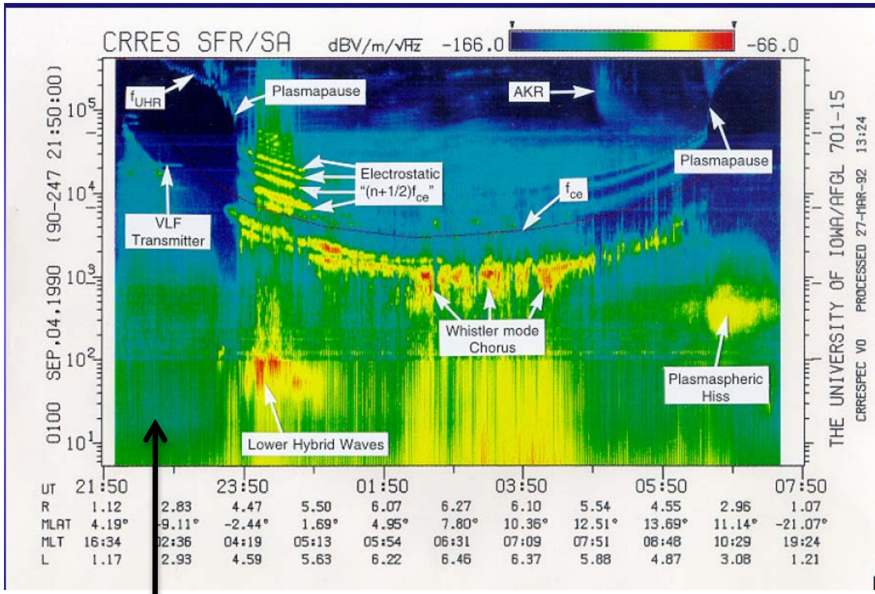
ORBITALS (CSA)

Launch 2012-2013

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

Inner Proton Belt – Accessible from Arecibo





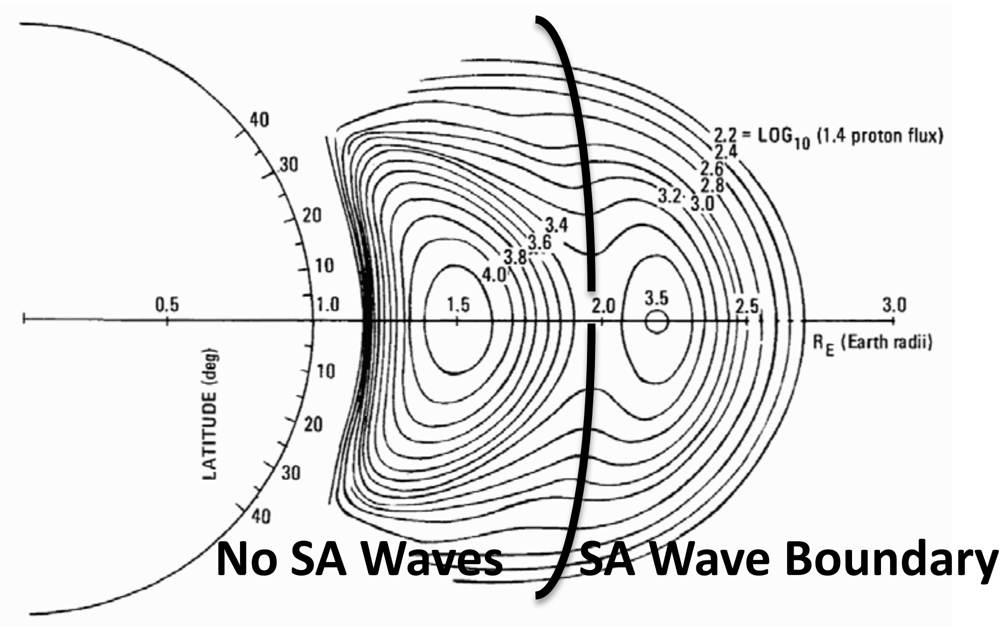
No wave activity at SAW and EMIC branches

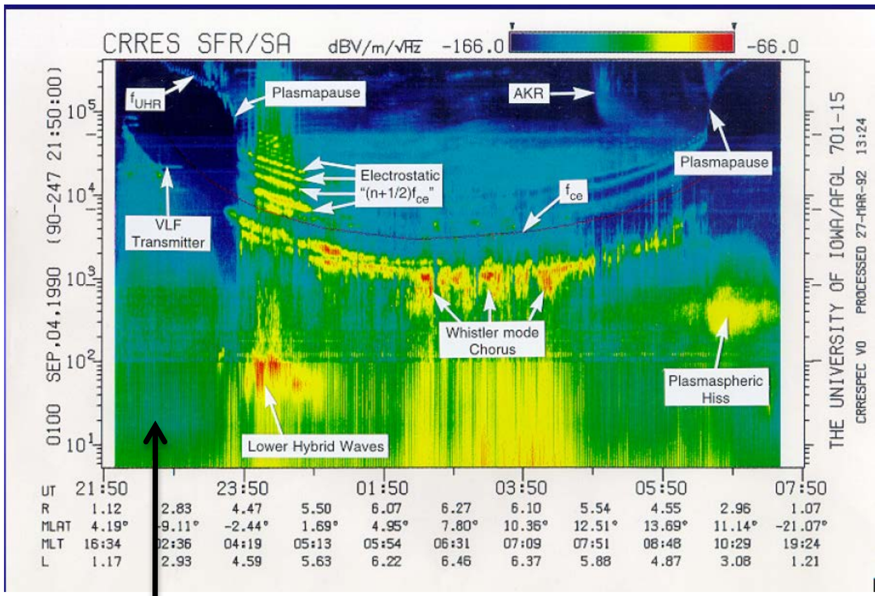
Typical inner belt proton lifetimes:

10 MeV – decades

50 MeV – century

Inner Proton Belt – Accessible from Arecibo





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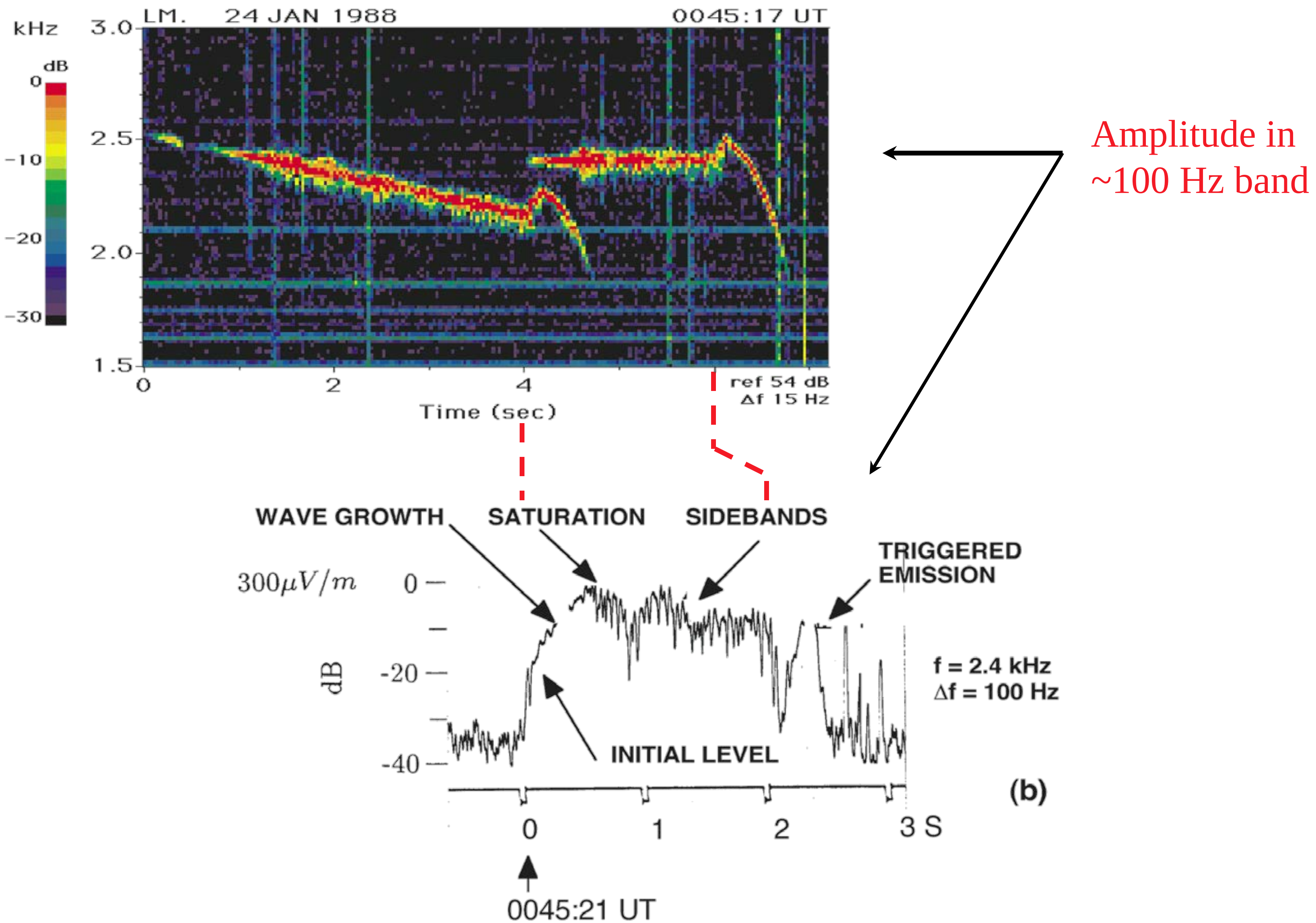
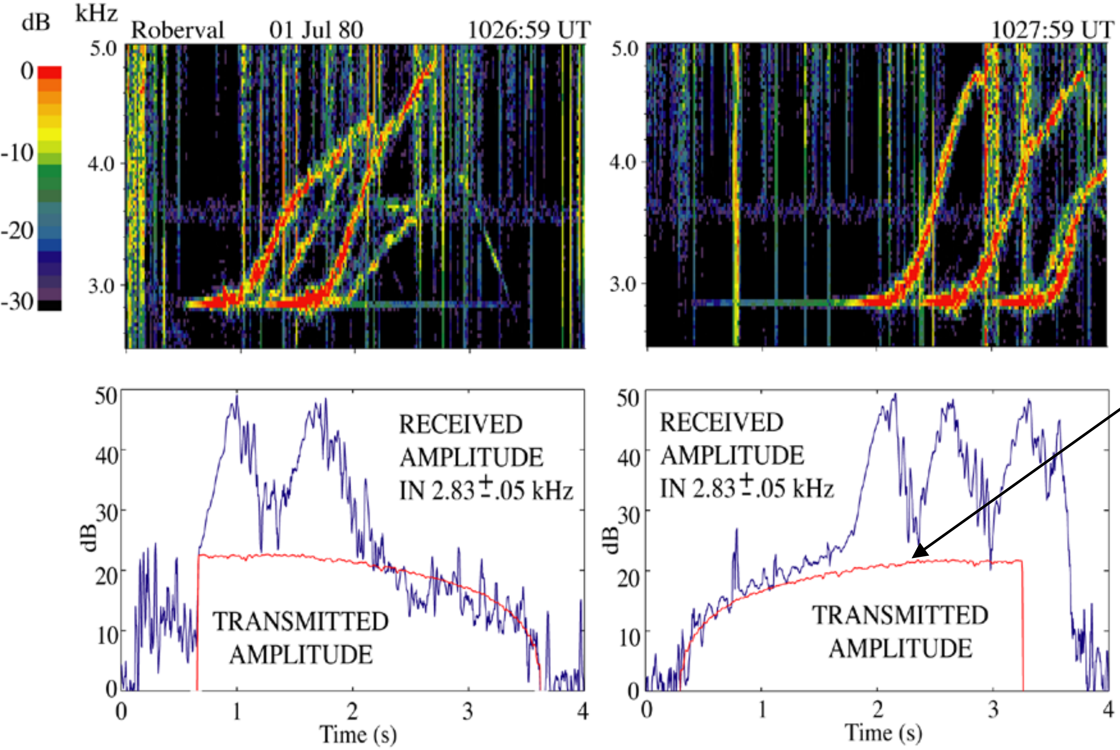
Growth & Saturation



Amplitude Effect on Growth



COHERENT GROWTH 20-30 dB

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

TRANSITION TO OSCILLATOR BEHAVIOR