CONTROLLED WAVE PARTICLE INTERACTION STUDIES IN THE RADIATION BELTS

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PRESENTATION TO RESONANCE WORKSHOP
SEPTEBMBER, 19,2012
KIEV, UKRAINE

Wave-particle interactions study under controlled wave injection

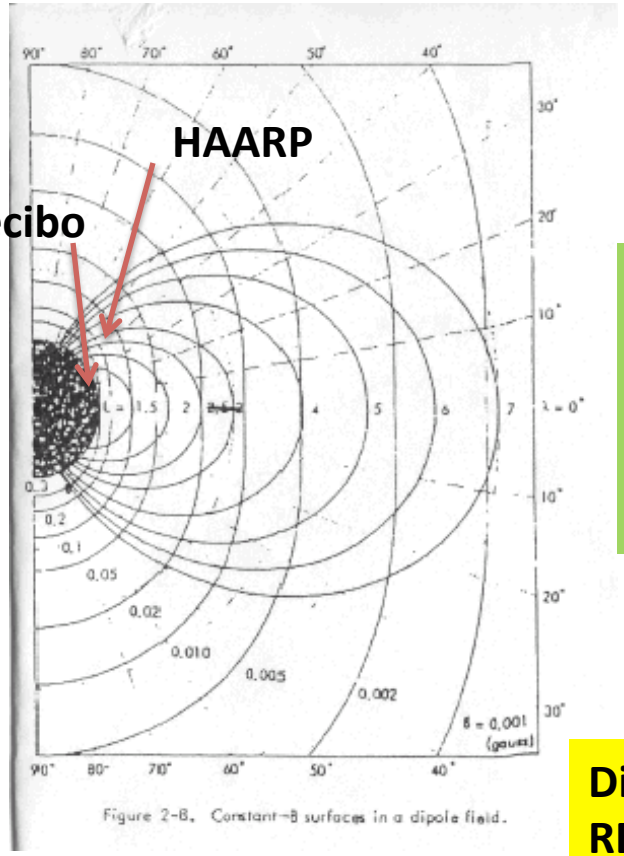


Figure 2-8. Constant-B surfaces in a dipole field.

- 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)

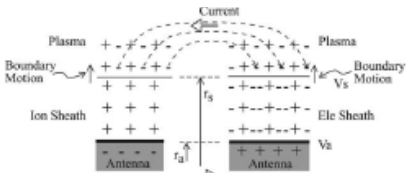
Diagnosed by RBSP ,Resonance, DSX, ePOP

- 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)]

The Plasma Physics of the PEJ



Injects whistlers and SAW

FAC

E_o

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

$\nu_{en} : T_e^{\alpha}$

$\varepsilon\omega = \sigma$

$E = E_o$ 0<t<T

$E = 0$ T<t<2T

E

J

Hall

$\nu << \Omega_e$

$\nu = \Omega_e$

$\nu >> \Omega_e$

J

Pedersen

Bottom of the ionosphere

$\varepsilon\omega = \sigma$

Near field

Far field

Bo

E

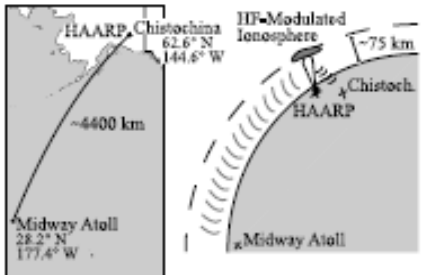
TEM mode

H

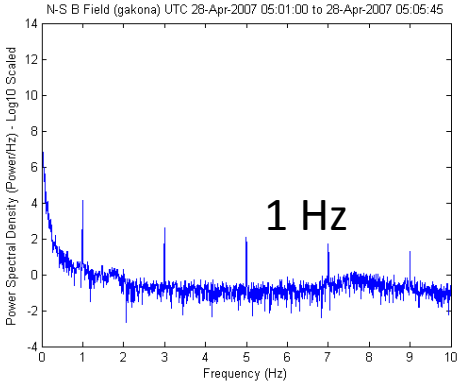
heater

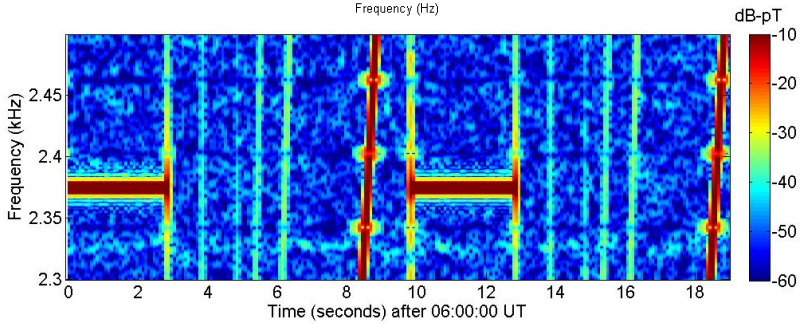
T

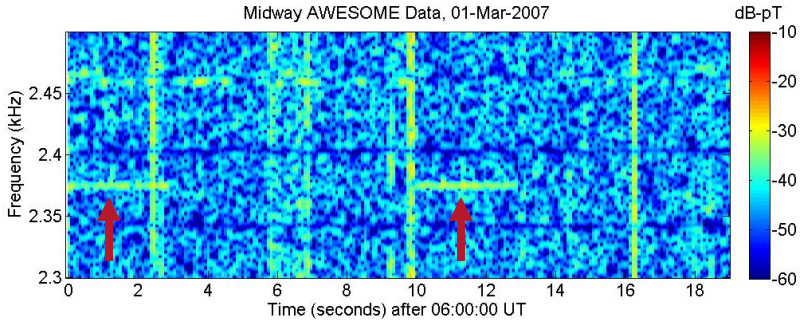
ELF/VLF ground detection and propagation



Moore et al.
GRL 2008



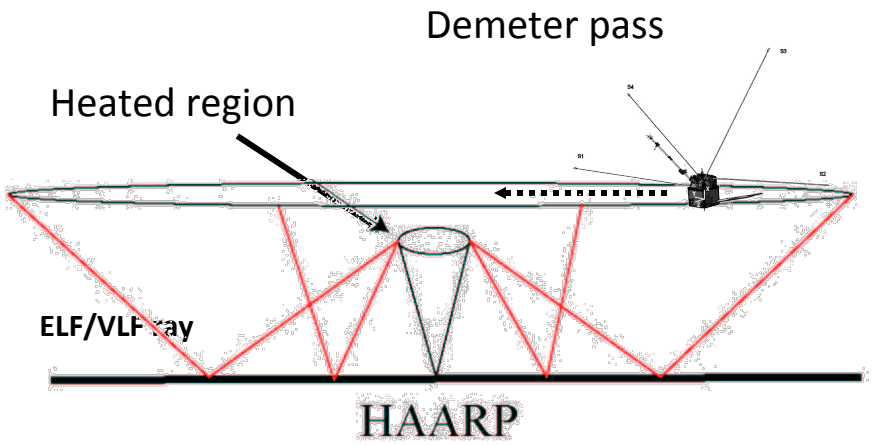


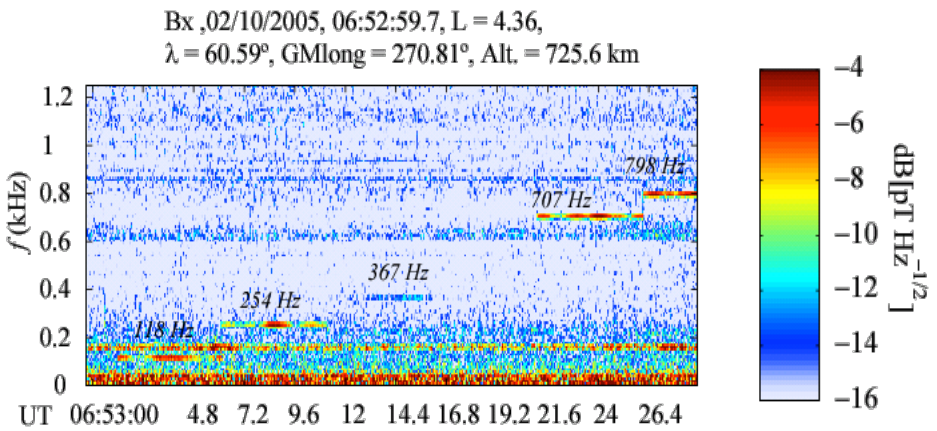


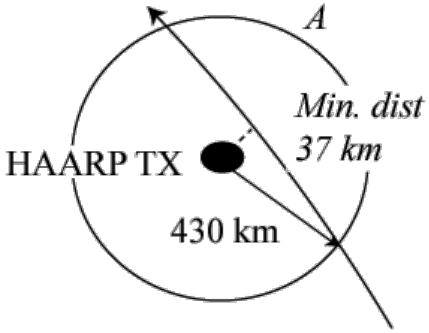
5400 km away

Midway

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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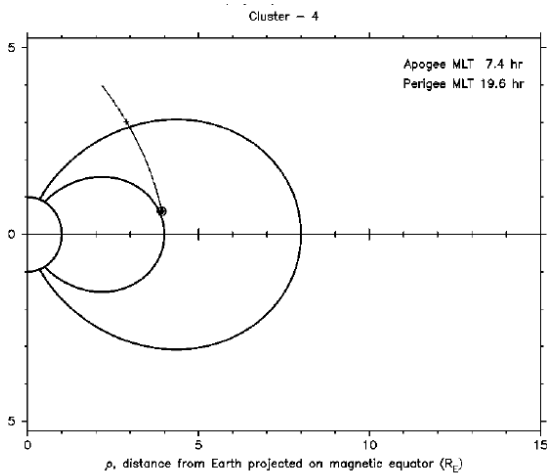
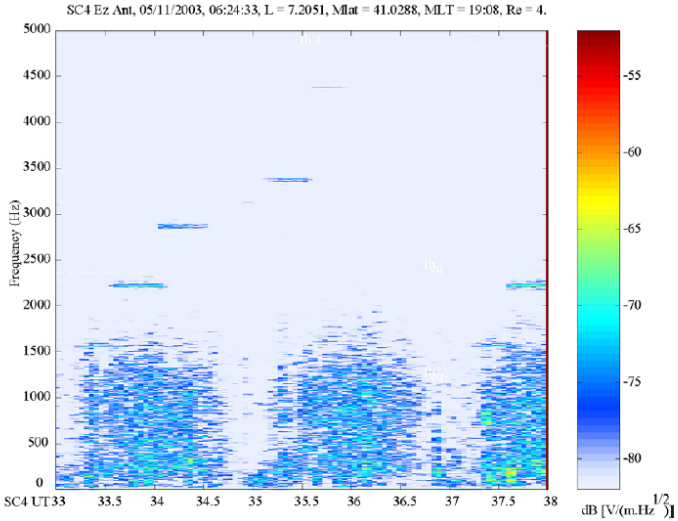
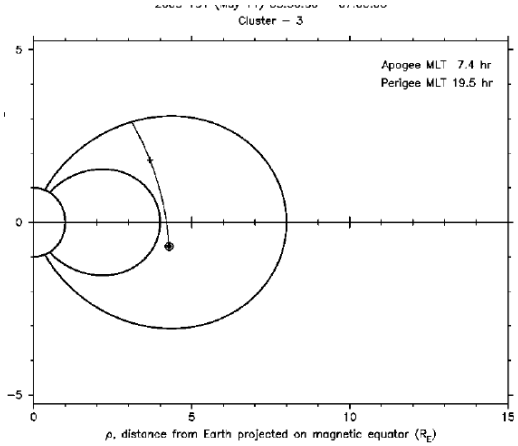
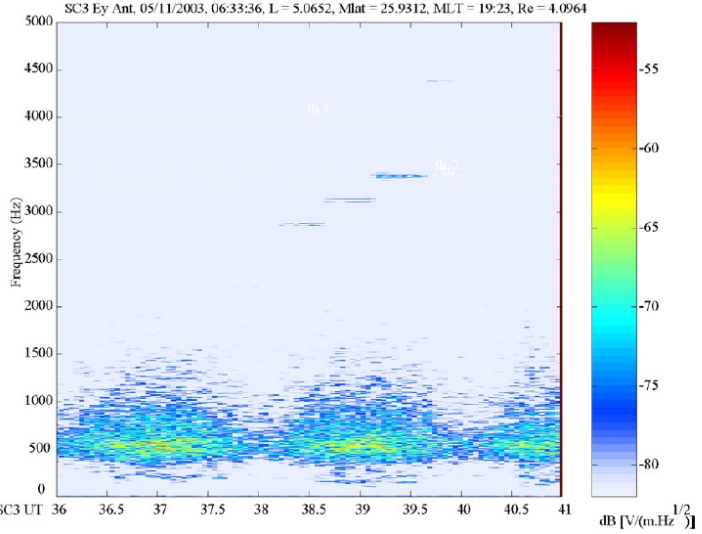
HAARP/CLUSTER INJECTION









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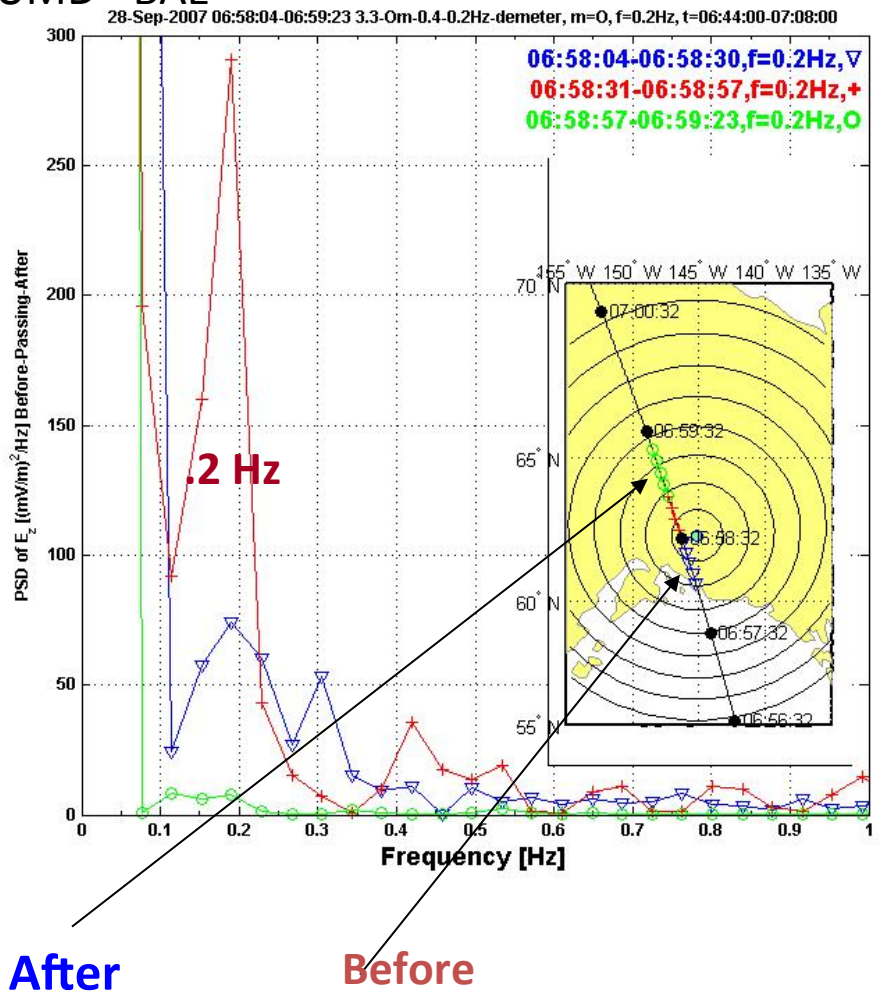
SAW DEMETER Detection

UMD - BAE



Frequency .2 Hz

Closest distance 80 km

Detection time 25 sec

Detection distance 150 km

Maximum E 10 mV/m

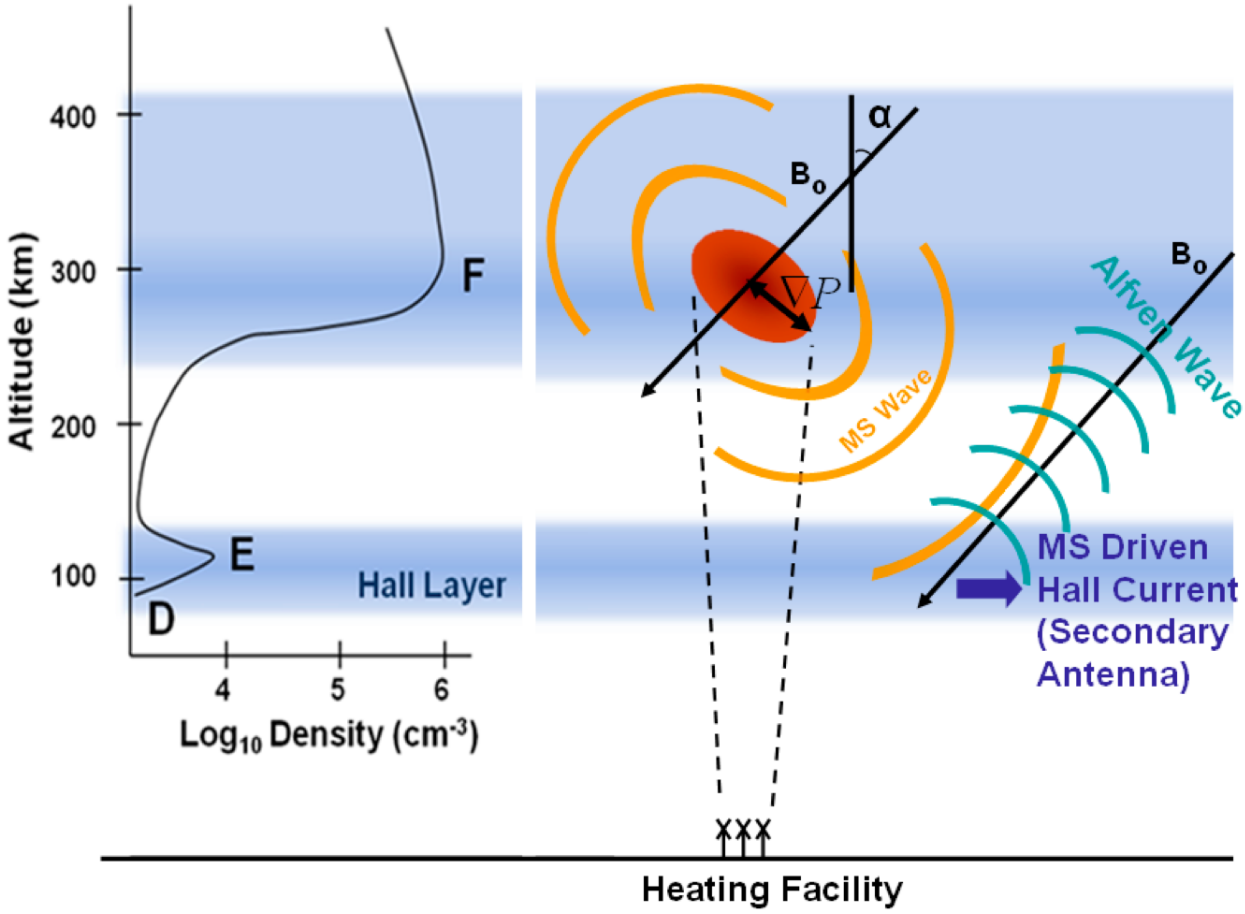
1.5 pT on the ground

Ionospheric Current Drive (ICD) Concept

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

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



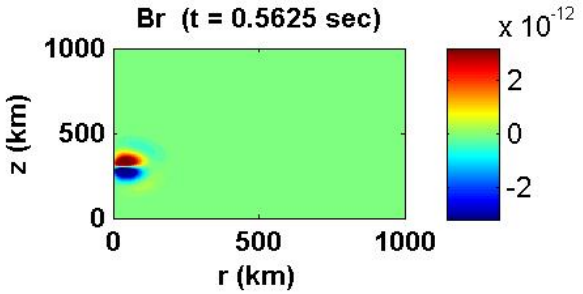
F- region cooling response does not allow frequencies higher than 60-70 Hz

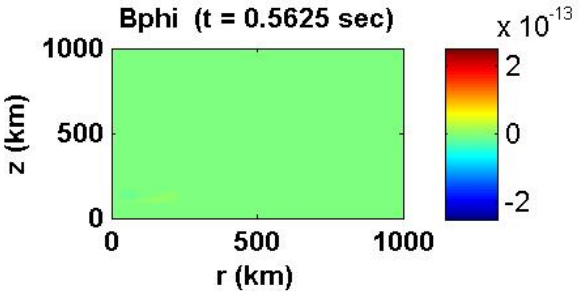
Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

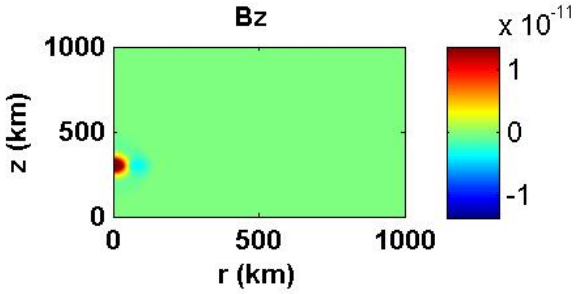
DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

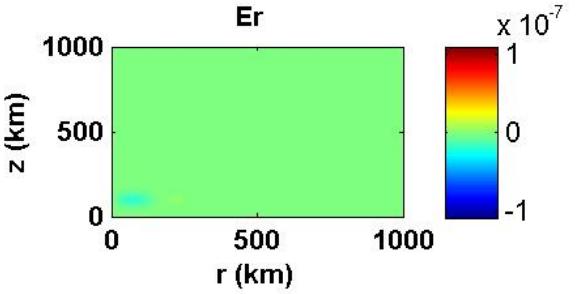
Cylindrical Coordinates

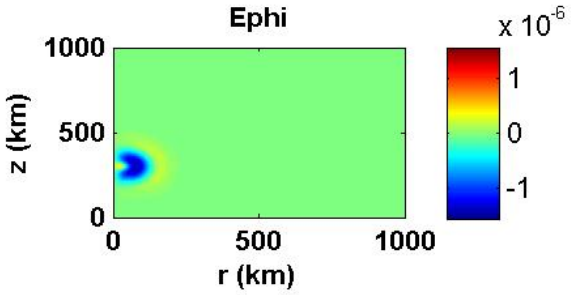
Papadopoulos et al. GRL 2011a

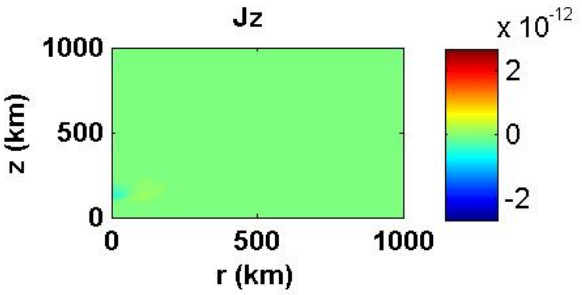






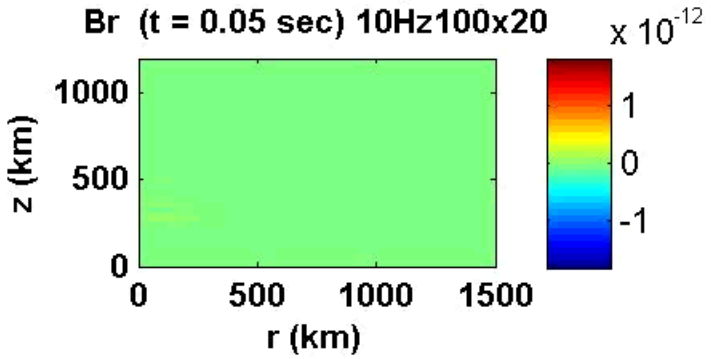


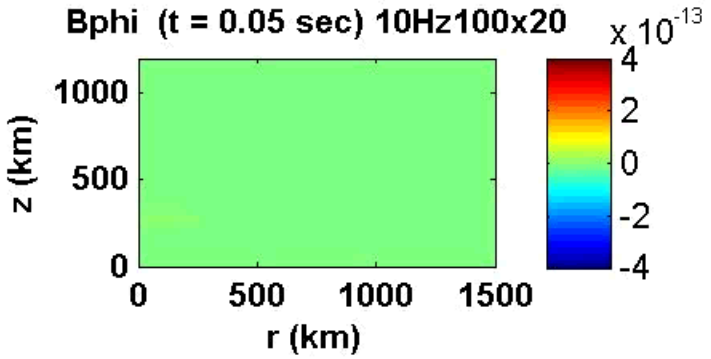


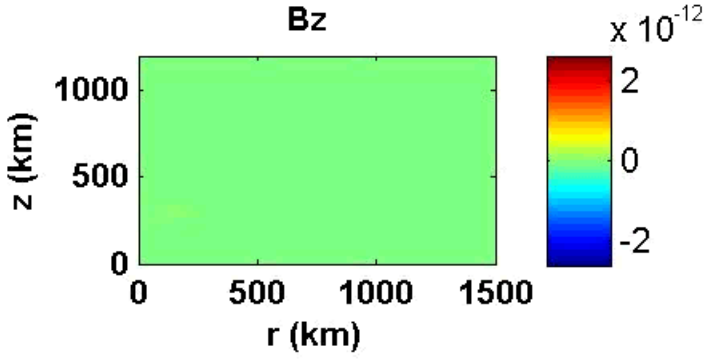


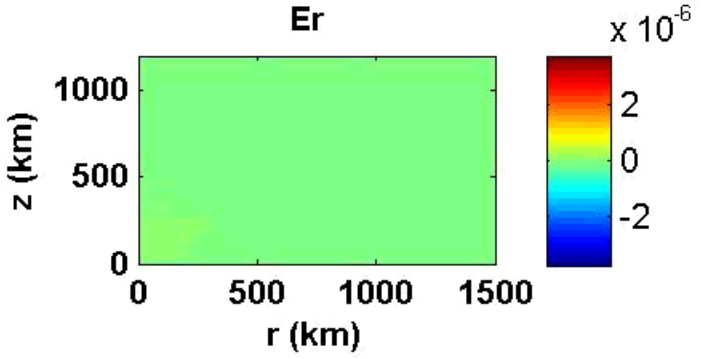
MS

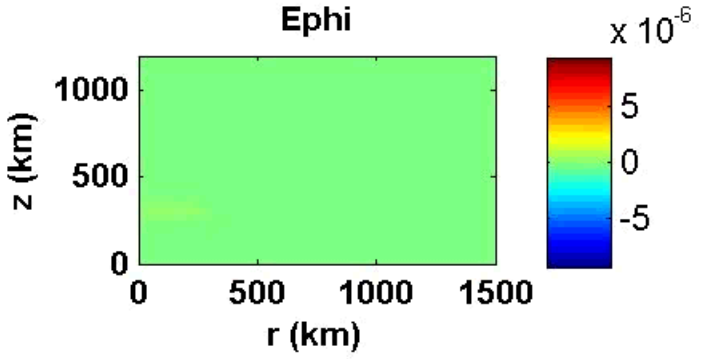
SAW

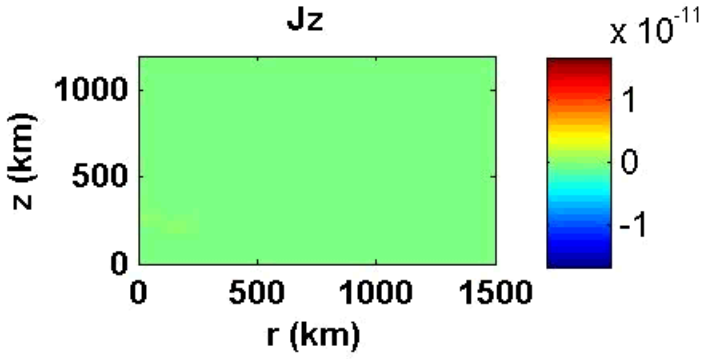

Br (t = 0.05 sec) 10Hz100x20
x 10^-12
1
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)


Bphi (t = 0.05 sec) 10Hz100x20
x 10^-13
4
2
0
-2
-4
1000
500
0
z (km)
0
500
1000
1500
r (km)


Bz
x 10^-12
2
0
-2
1000
500
0
z (km)
0
500
1000
1500
r (km)

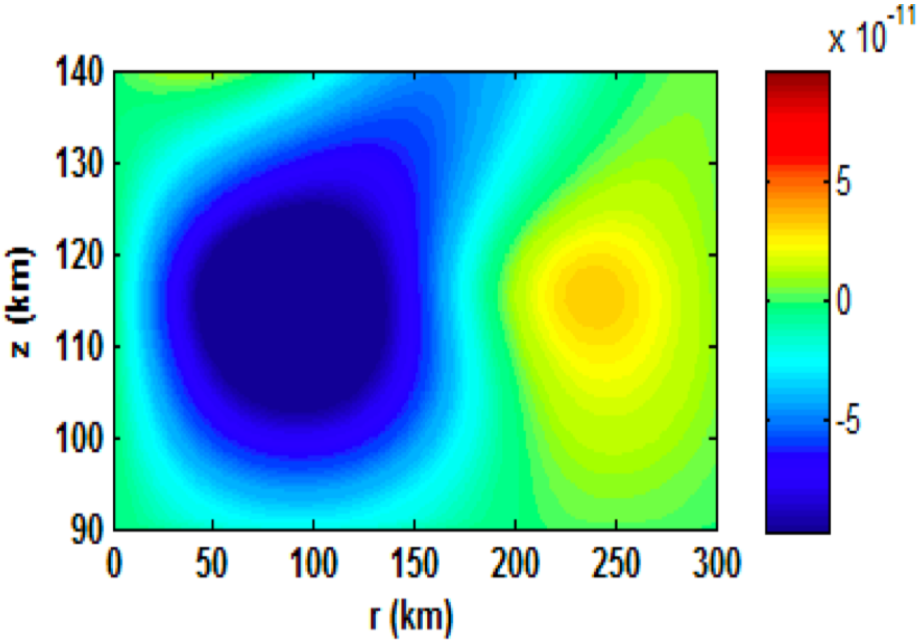

Er
x 10^-6
2
0
-2
1000
500
0
z (km)
0
500
1000
1500
r (km)


Ephi
x 10^-6
5
0
-5
1000
500
0
z (km)
0
500
1000
1500
r (km)


Jz
x 10^-11
1
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)

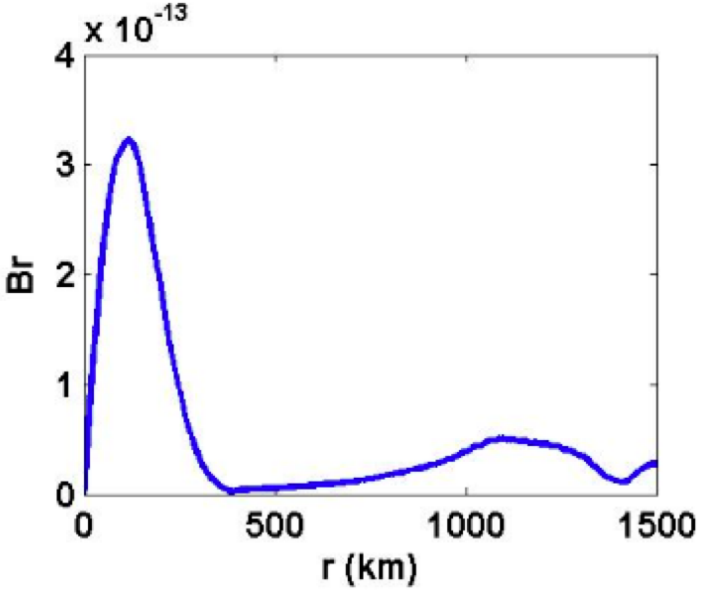
10 Hz

Secondary Antenna Current and Ground Field



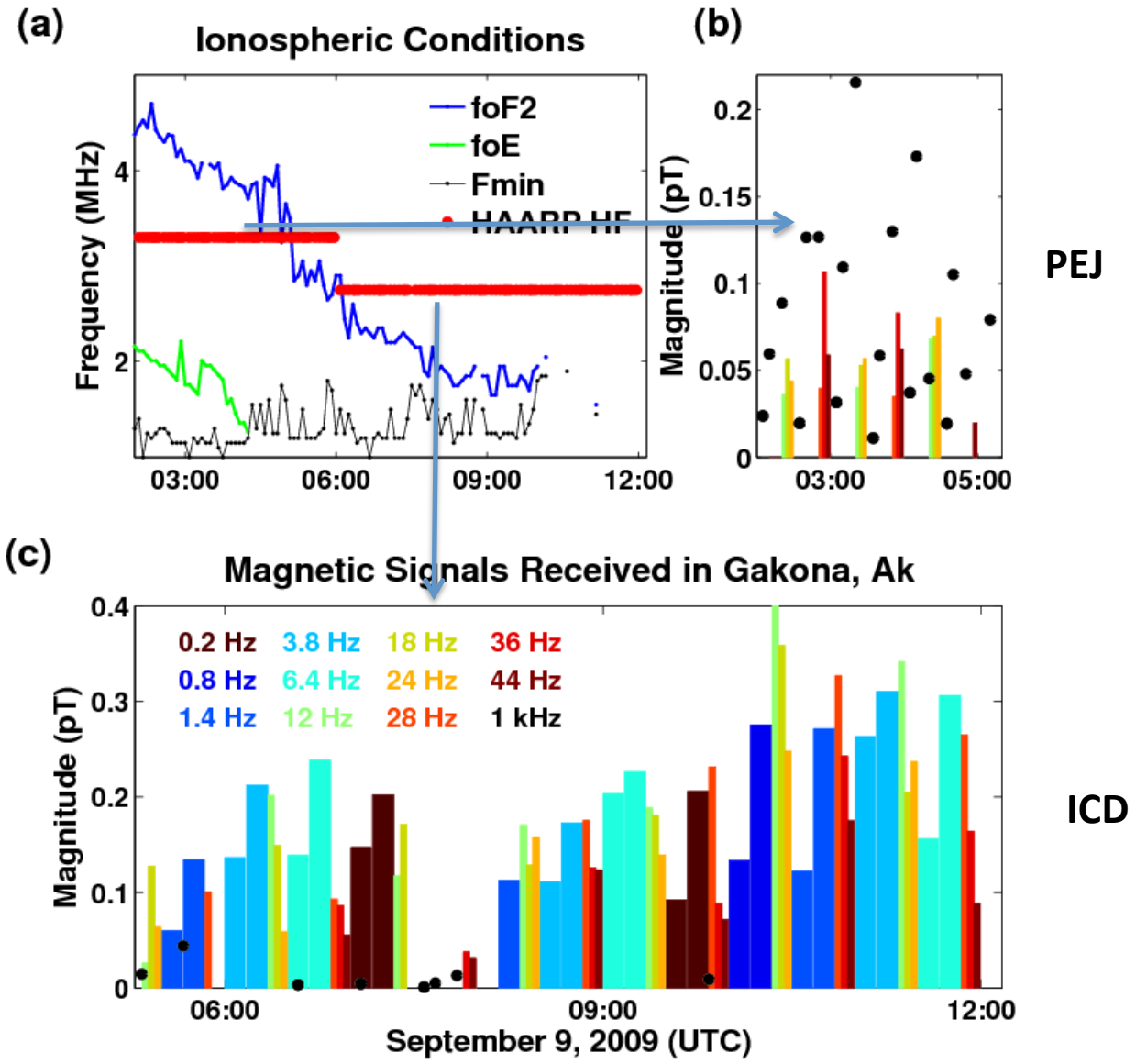
J_θ

Skip distance

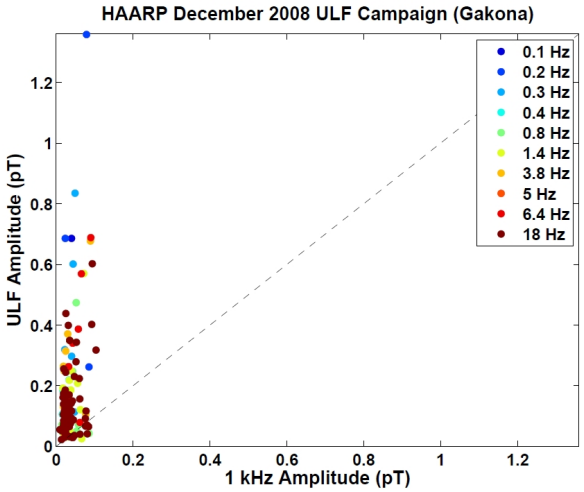


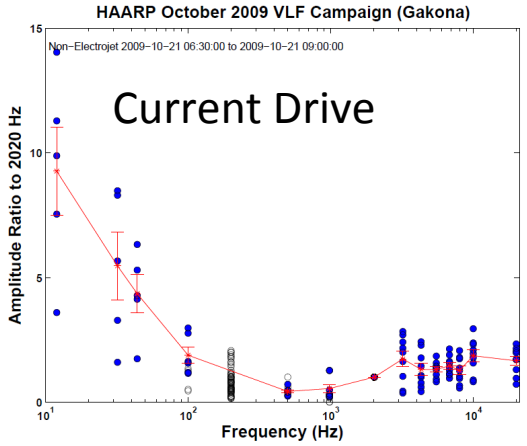
B_r

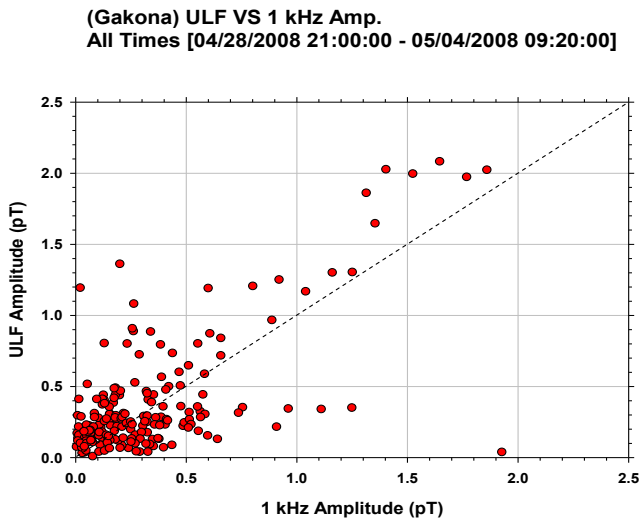
PoP Exps: PEJ to ICD Transition

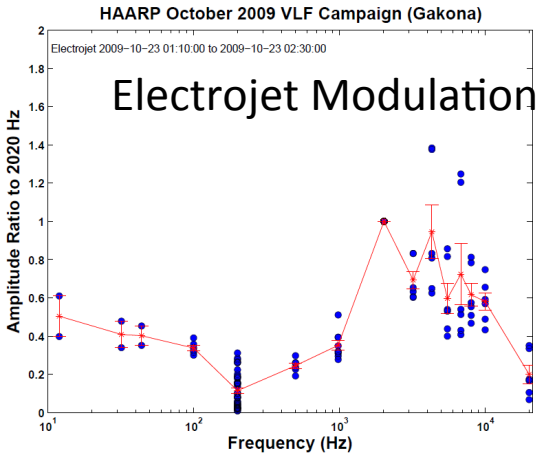


Scaling with power and frequency


HAARP December 2008 ULF Campaign (Gakona)
0.1 Hz
0.2 Hz
0.3 Hz
0.4 Hz
0.8 Hz
1.4 Hz
3.8 Hz
5 Hz
6.4 Hz
18 Hz
ULF Amplitude (pT)
1 kHz Amplitude (pT)

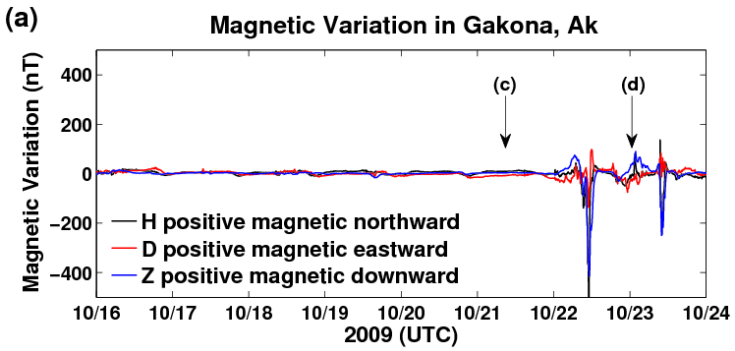

HAARP October 2009 VLF Campaign (Gakona)
Non-Electrojet 2009-10-21 06:30:00 to 2009-10-21 09:00:00
Current Drive
Amplitude Ratio to 2020 Hz
Frequency (Hz)

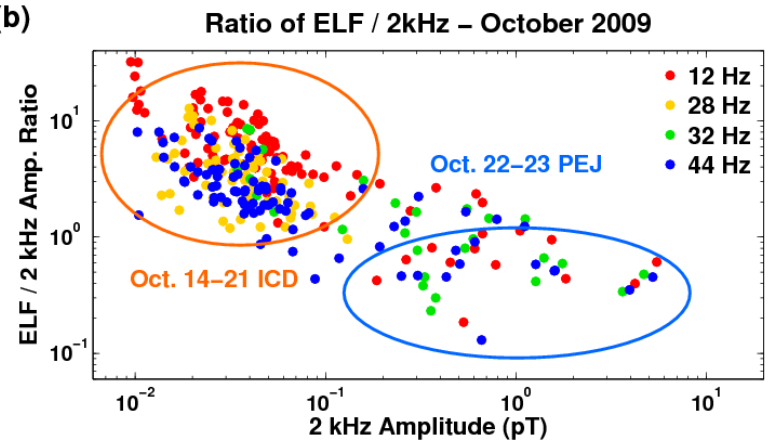

(Gakona) ULF VS 1 kHz Amp.
All Times [04/28/2008 21:00:00 - 05/04/2008 09:20:00]
ULF Amplitude (pT)
1 kHz Amplitude (pT)


HAARP October 2009 VLF Campaign (Gakona)
Electrojet 2009-10-23 01:10:00 to 2009-10-23 02:30:00
Electrojet Modulation
Amplitude Ratio to 2020 Hz
Frequency (Hz)

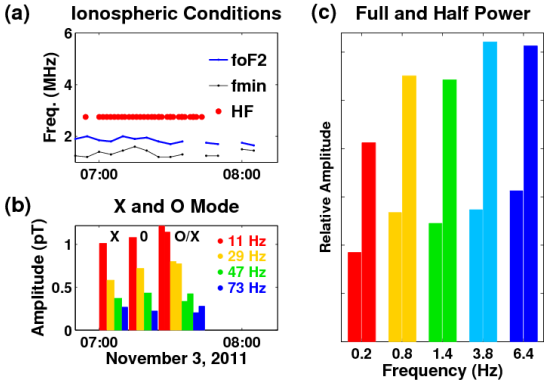
ICD PoP Experiments

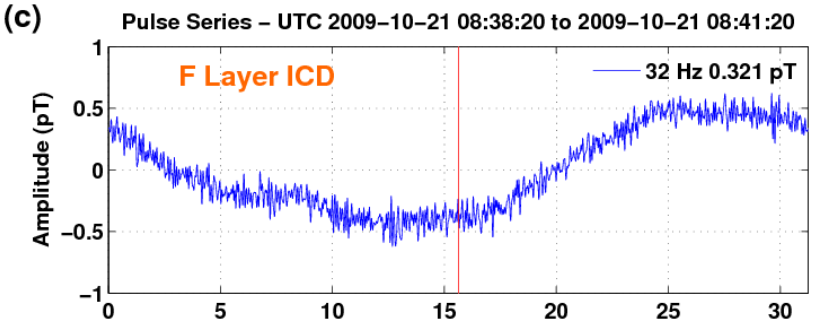
Papadopoulos et al GRL 2011b

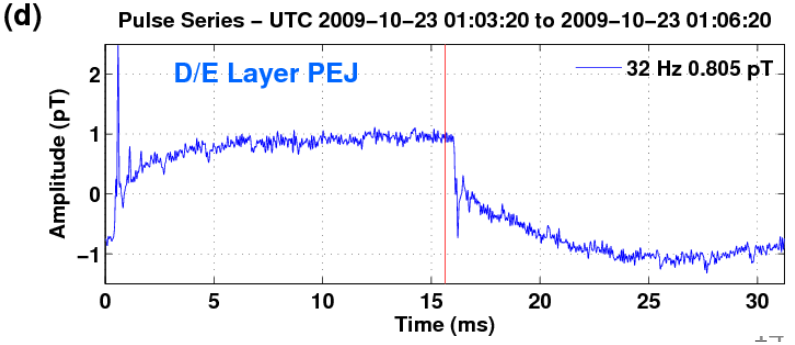


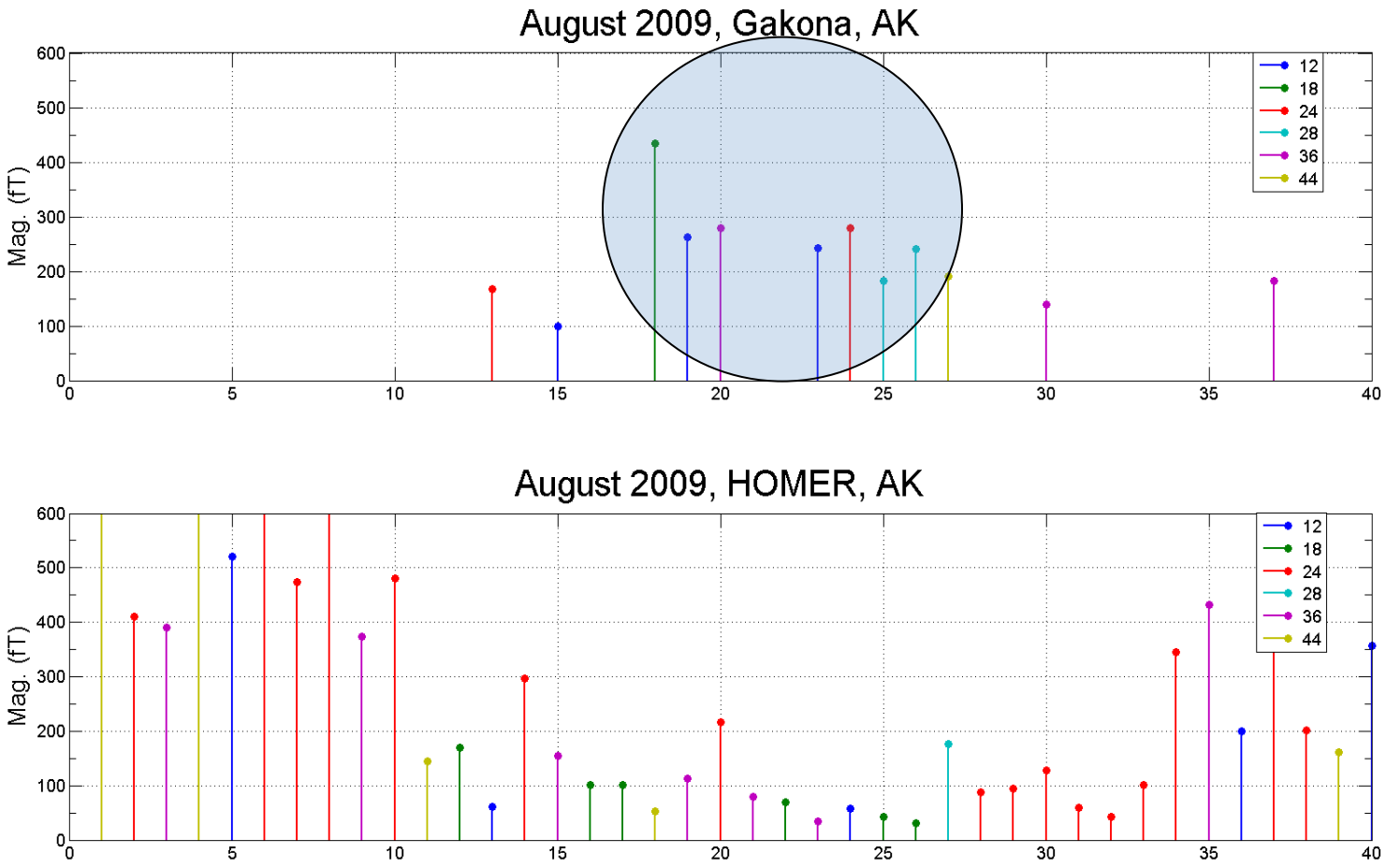


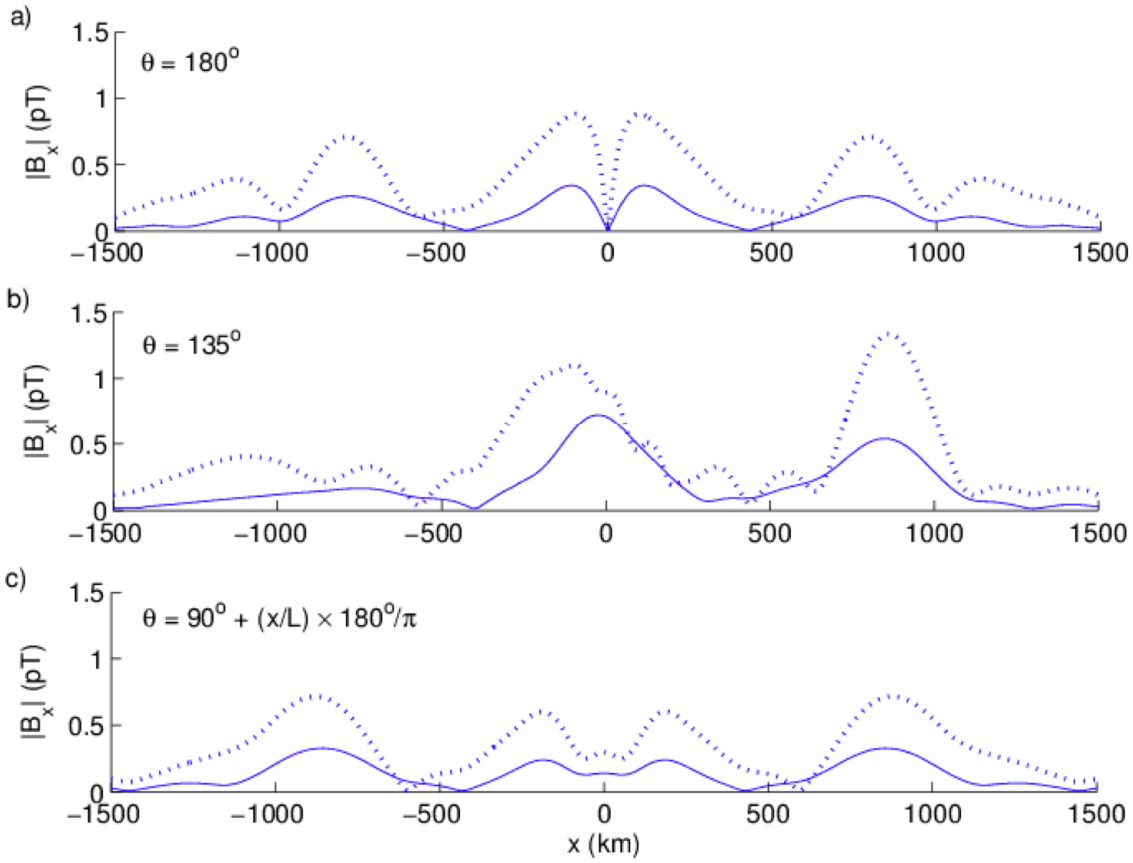
- 10/14-10/21 Magnetometer below 10 nT
- 10/14-10/23 55 hours of VLF/ELF/ULF tests
- 6 hours of VLF ground measurements –PEJ operational
- 51 hours of low ELF/ULF (12-44 Hz) ground measurements



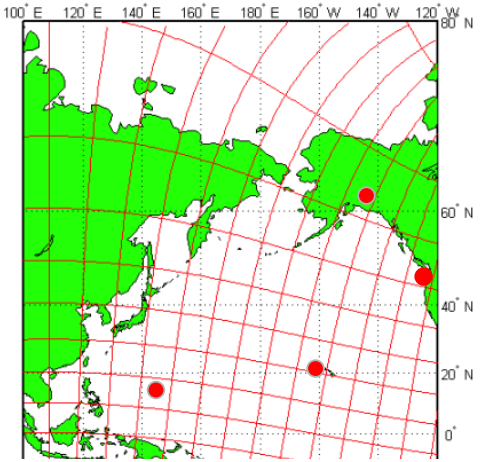


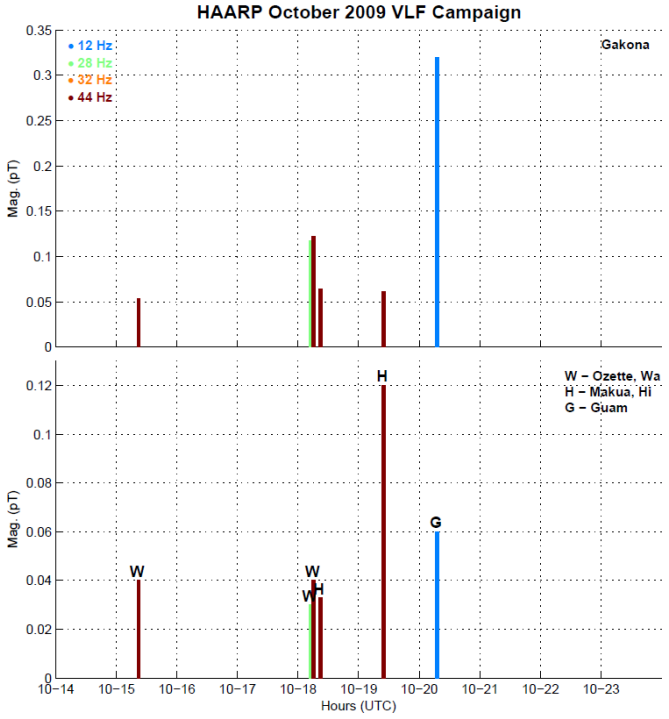



August 2009, Gakona, AK
Mag. (fT)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
12
18
24
28
36
44
August 2009, HOMER, AK
Mag. (fT)
0
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
12
18
24
28
36
44

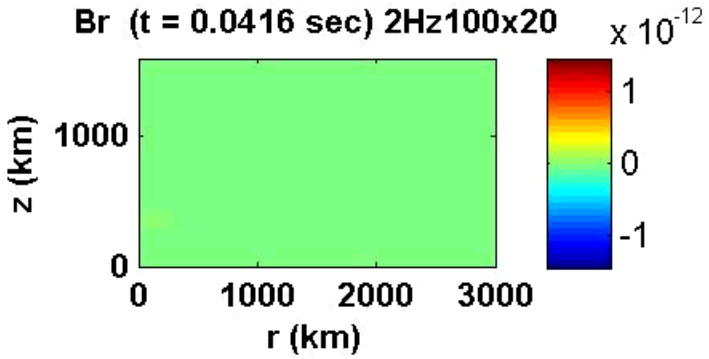

a)
θ = 180°
|B_x| (pT)
b)
θ = 135°
|B_x| (pT)
c)
θ = 90° + (x/L) × 180°/π
|B_x| (pT)
1.5
1
0.5
0
−1500
−1000
−500
0
500
1000
1500
x (km)

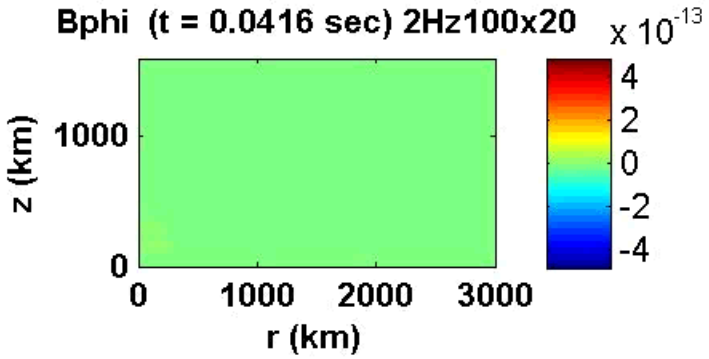
ELF detection at Distant Sites

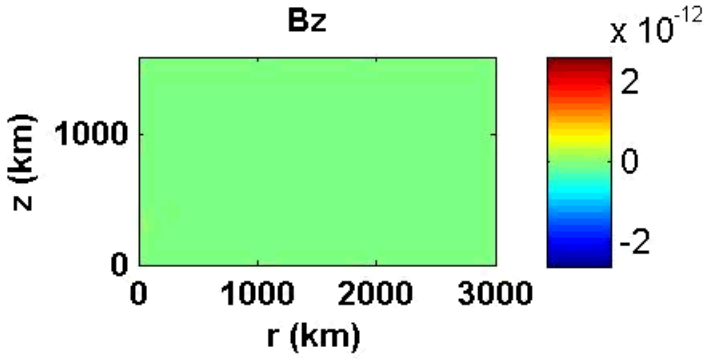


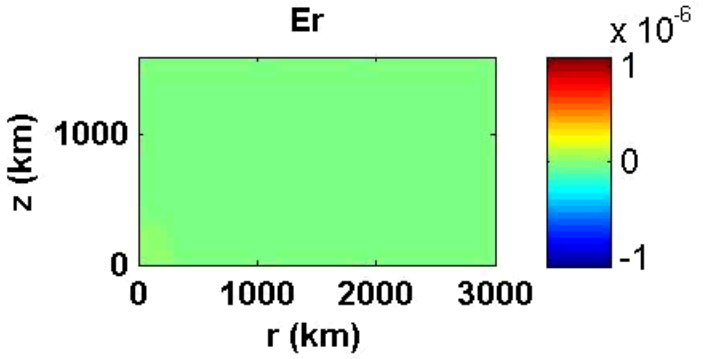


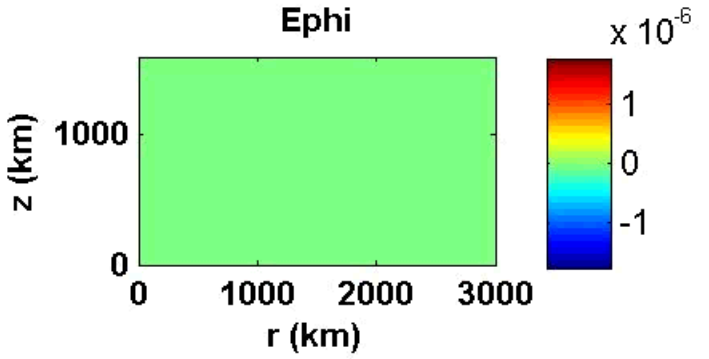
- Distance to Gakona
  - Lake Ozette, WA (W)
    - 1300 mi
  - Hawaii (H)
    - 2900 mi
  - Guam (G)
    - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23

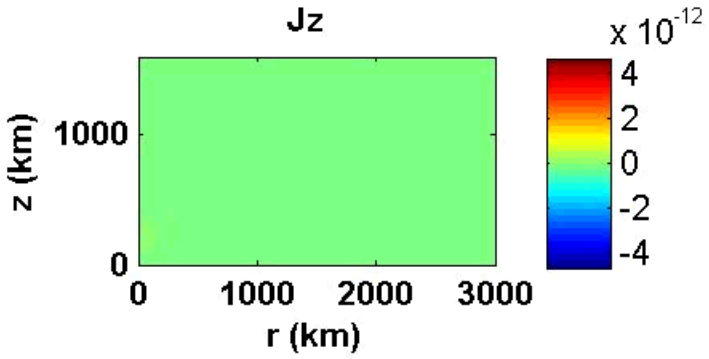

Br (t = 0.0416 sec) 2Hz100x20
x 10^-12
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)


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)

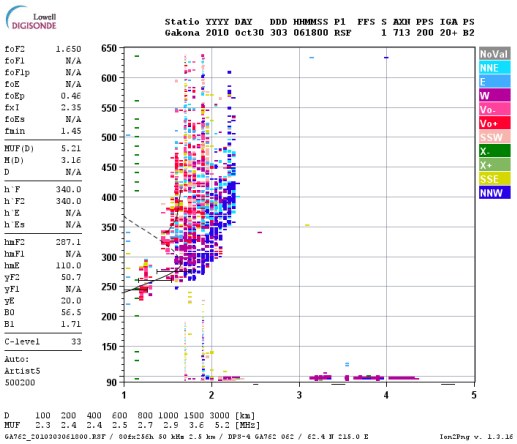

Ephi
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)

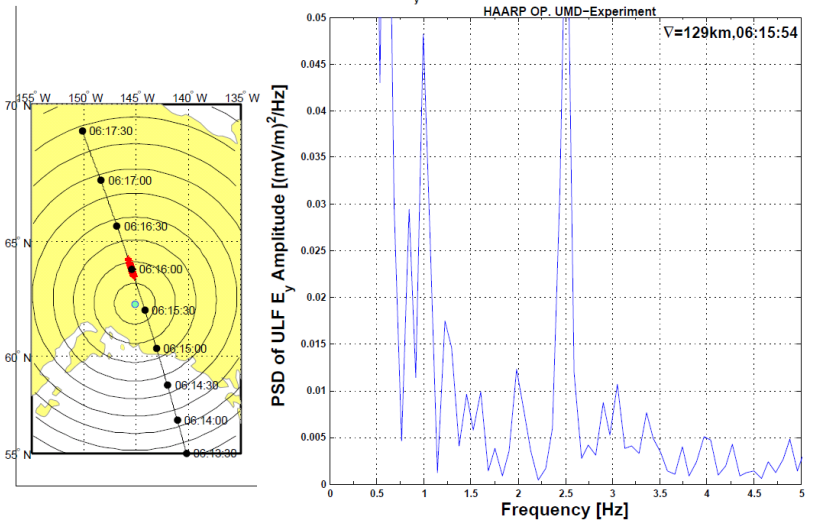

Jz
x 10^-12
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)

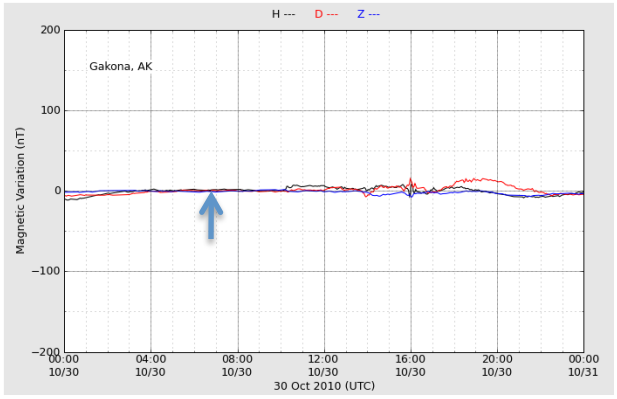
Proof of Concept ICD Experiment – Conducted under DARPA/BRIOCHE

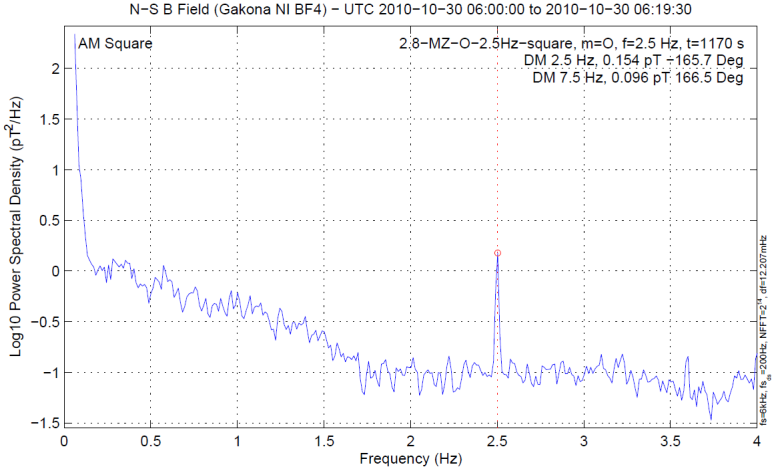
Chang-Lebinsky-Milikh-Papadopoulos

2.8 MHz, O-mode



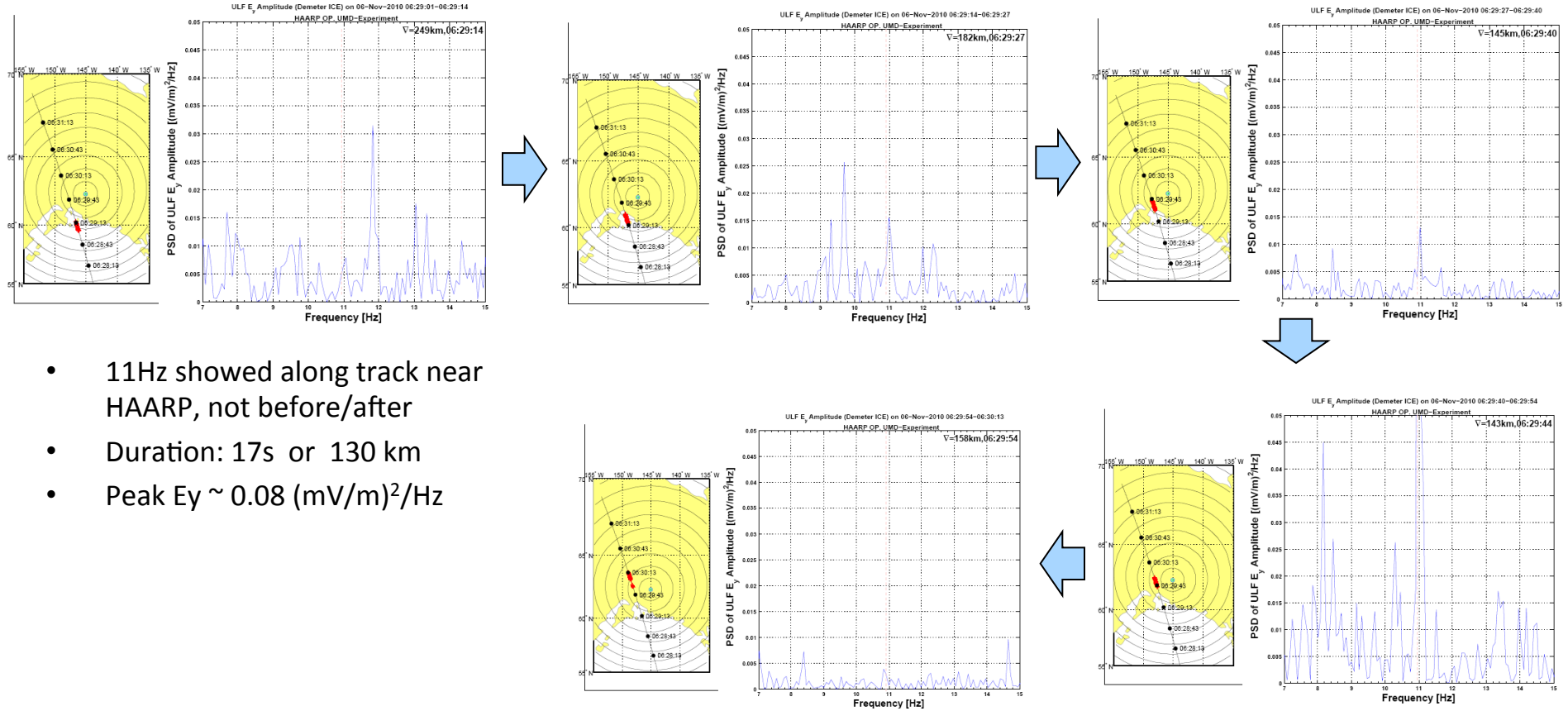






Low ELF Observed by Demeter Satellite

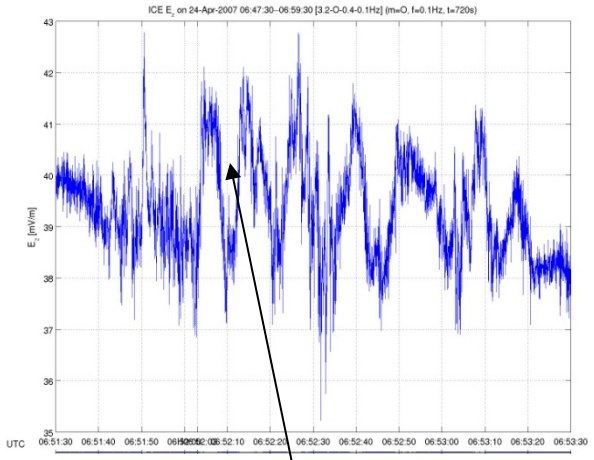
2010-11-06, 06:15:00-06:34:30 ELF 11 Hz modulation (O-MZ)



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

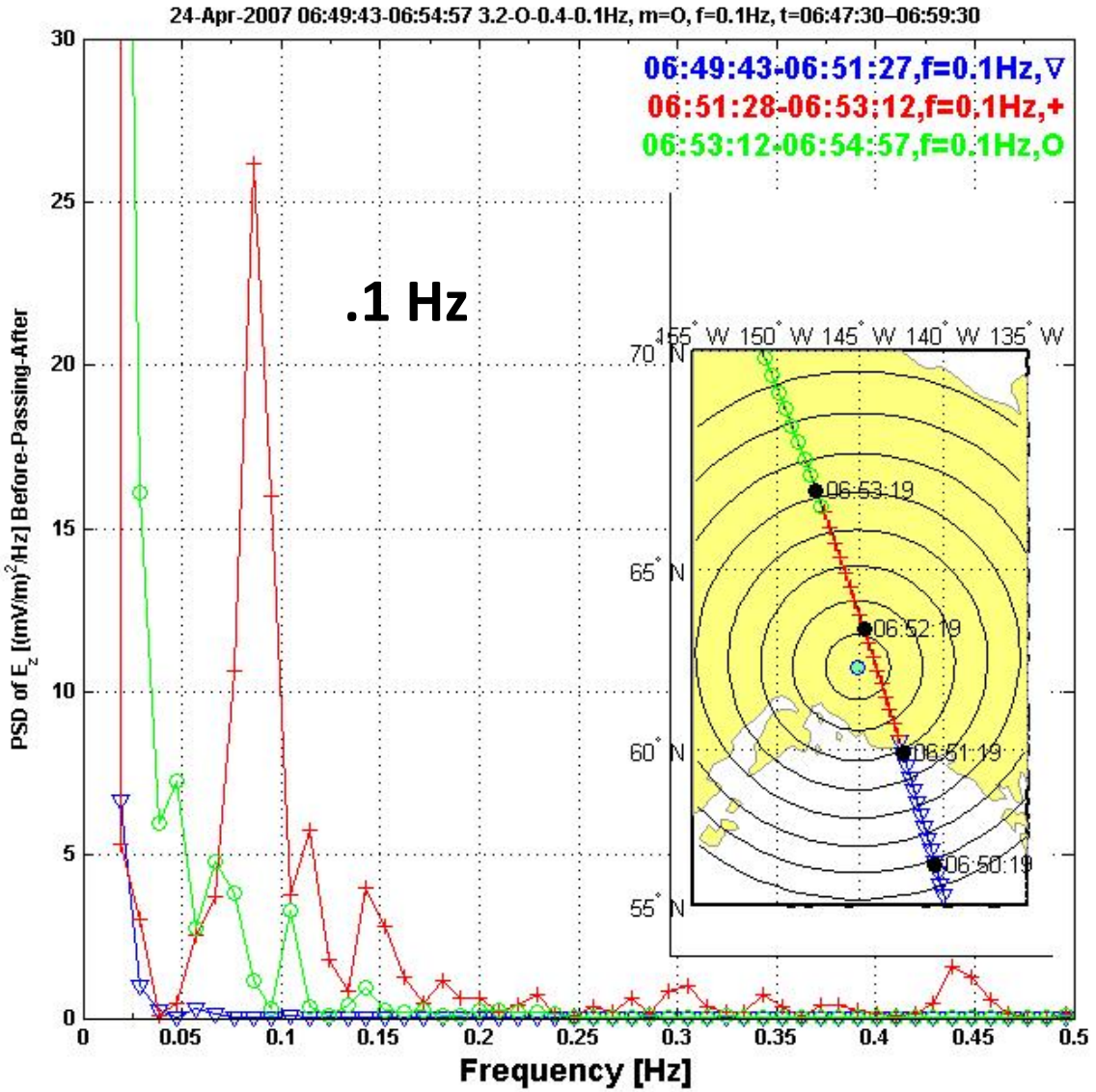
Msonic Wave Injection

DEMETER

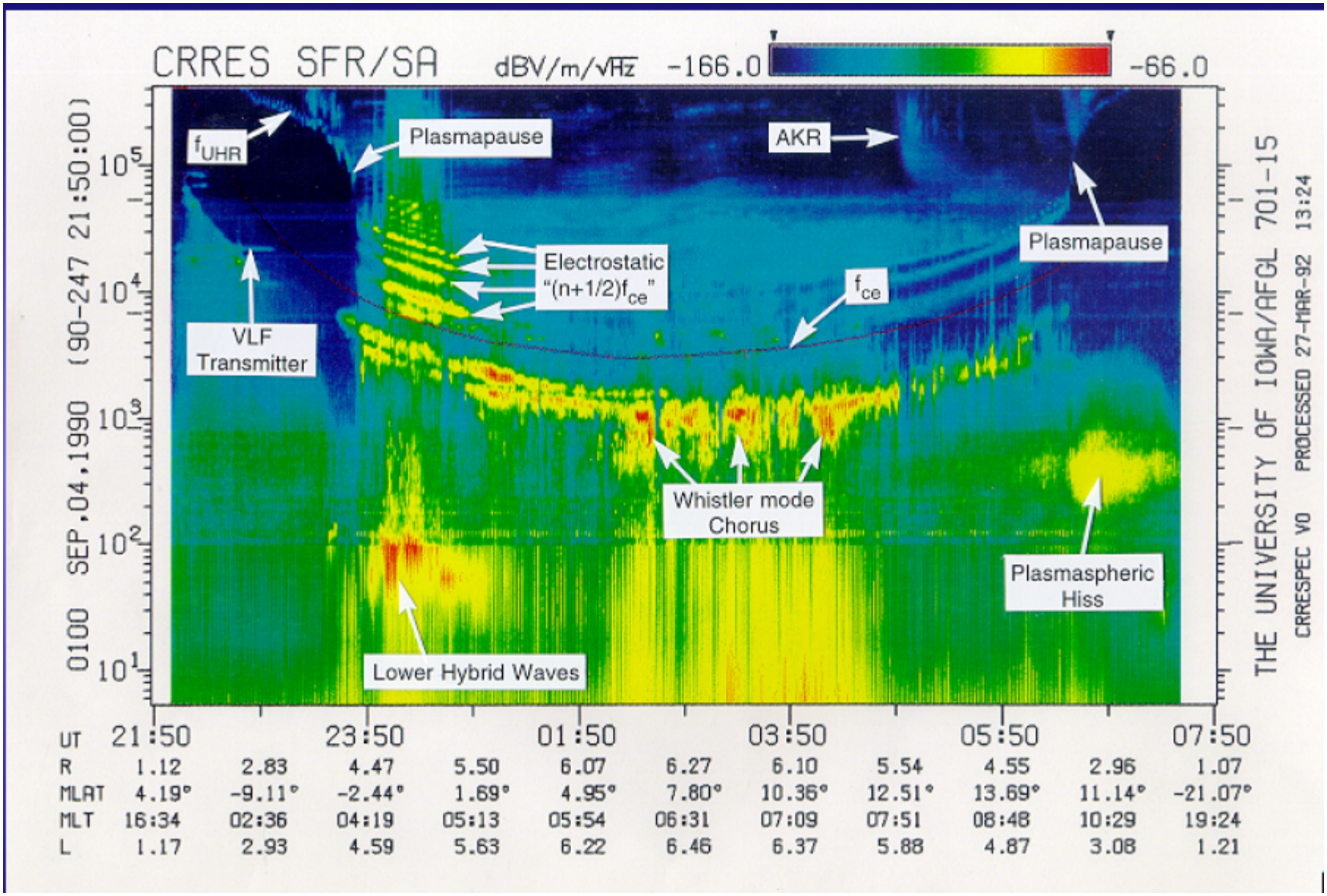


10 sec oscillations

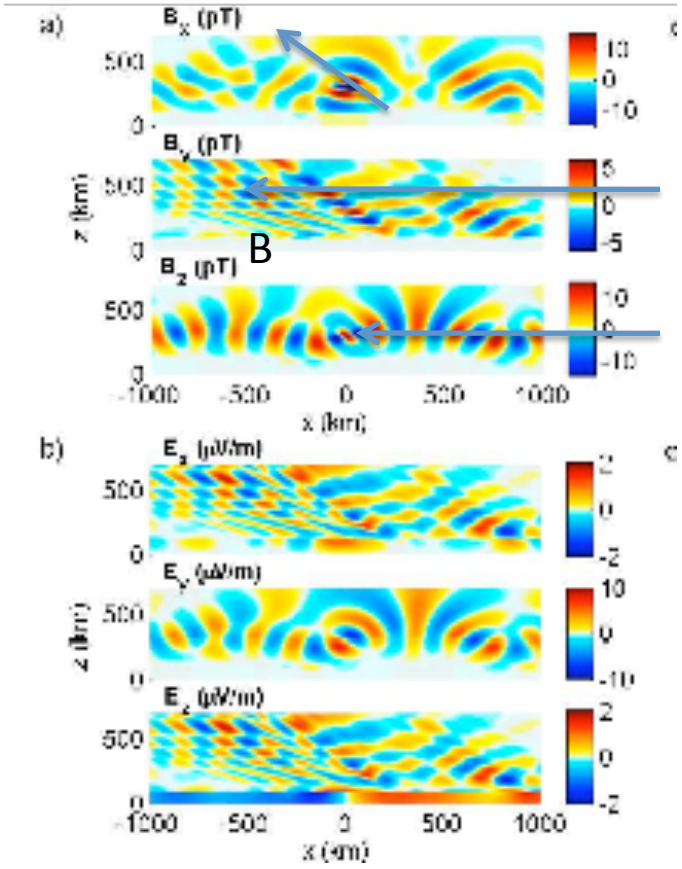
Over 700 km distance



Inner RB

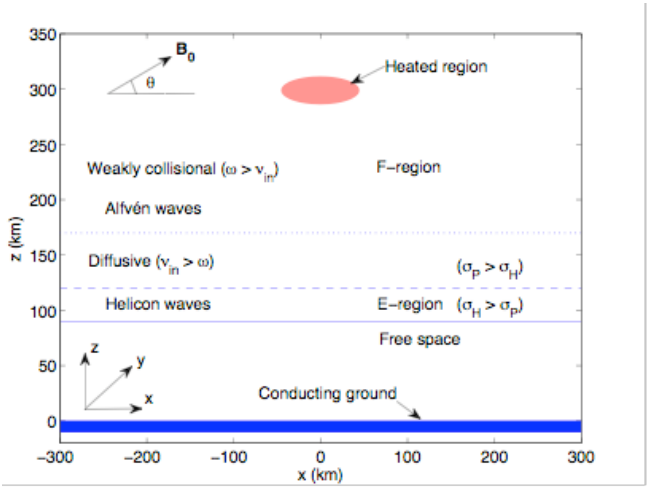

CRRES SFR/SA
dBV/m/√Hz
-166.0
-66.0
f_{UHR}
Plasmapause
AKR
Plasmapause
Electrostatic
"(n+1/2)f_{ce}"
f_{ce}
VLF
Transmitter
Whistler mode
Chorus
Plasmaspheric
Hiss
Lower Hybrid Waves
0100 SEP.04.1990 (90-247 21:50:00)
THE UNIVERSITY OF IOWA/AFGL 701-15
CRRESPEC V0 PROCESSED 27-MAR-92 13:24
UT 21:50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

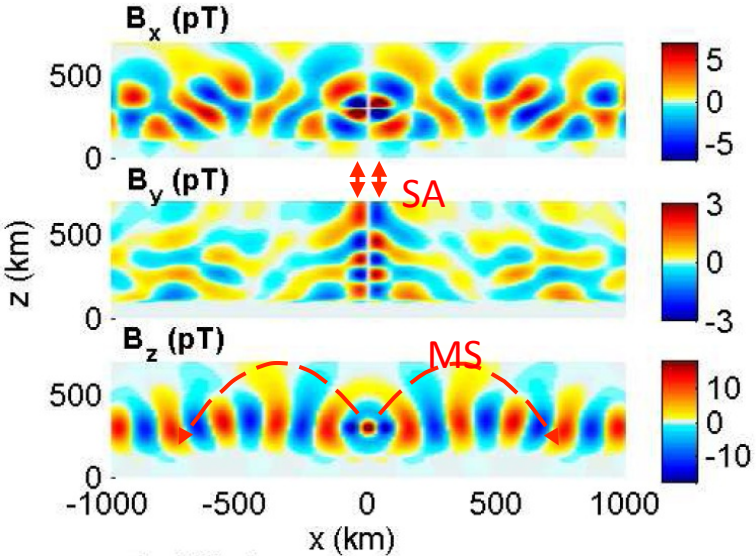
Implications of ICD to RB and RBR – Potential Arecibo/RBSP Tests

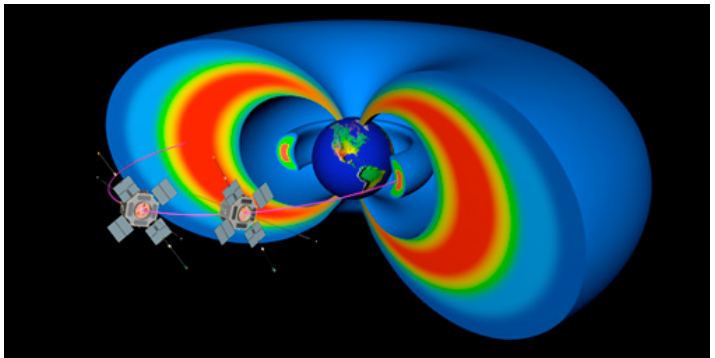


SAW injection

HF heating



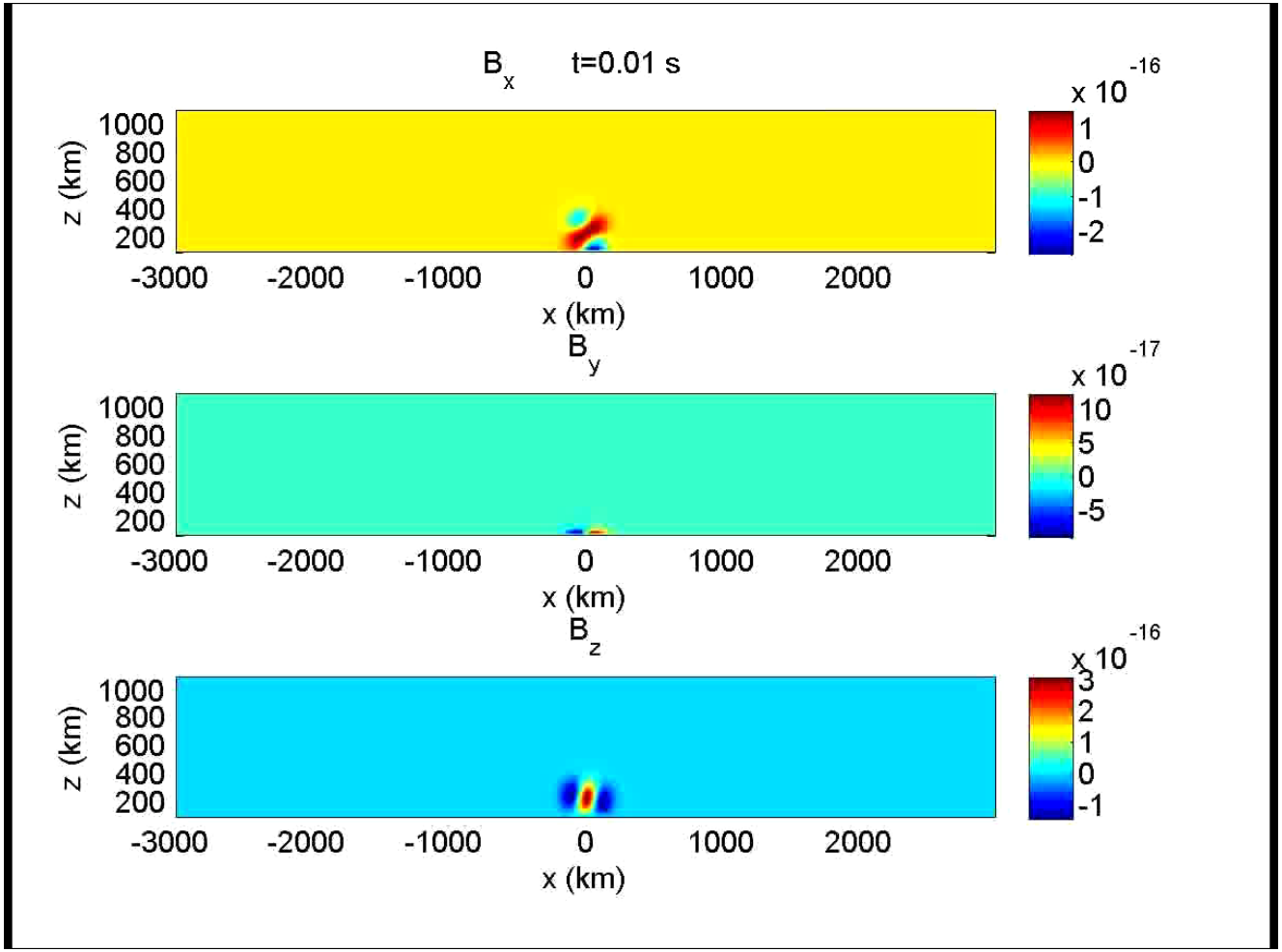




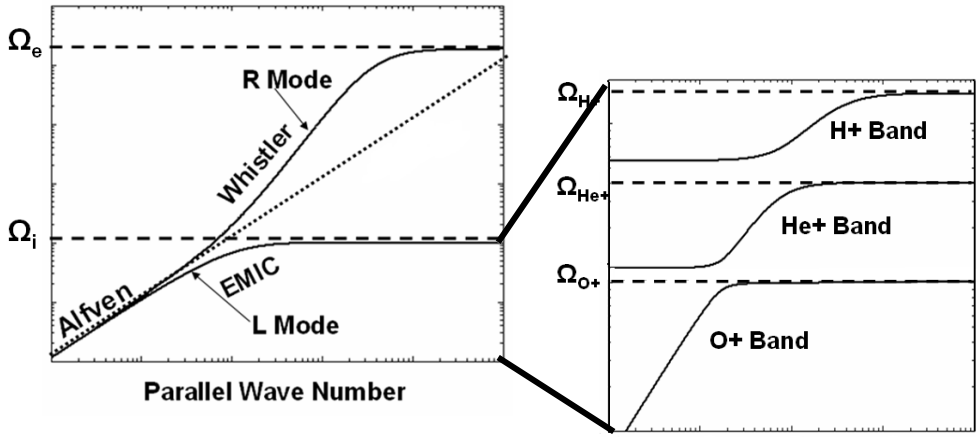
RBSP

ICD - Implications

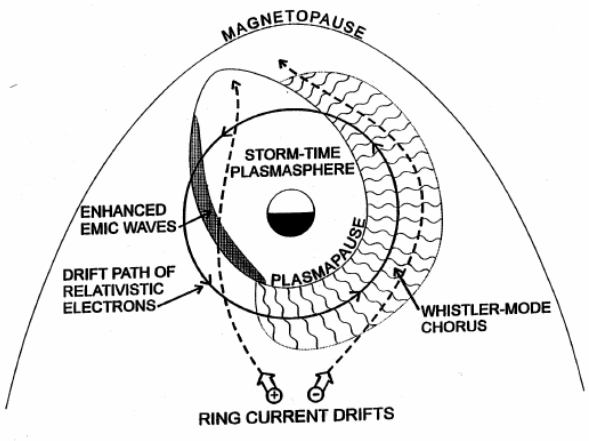
Mid-latitude Heaters – Arecibo , SURA : Wave Particle Interaction Studies in the inner Belt



ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



Outer Belts



Summers et al., 1998, 2000, 2003

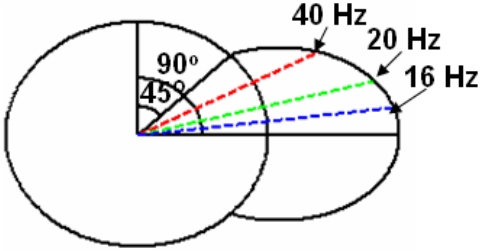
$$-k_z v_z = |\Omega_e| / \gamma$$

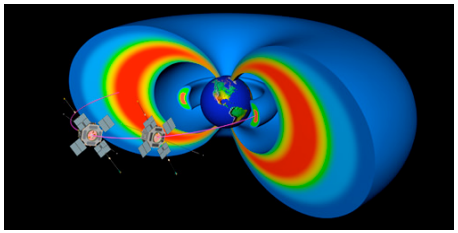
$$\frac{k^2 c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{j=1}^{3} \frac{\omega \omega_{pj}^2}{(\omega - \Omega_j)}$$

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

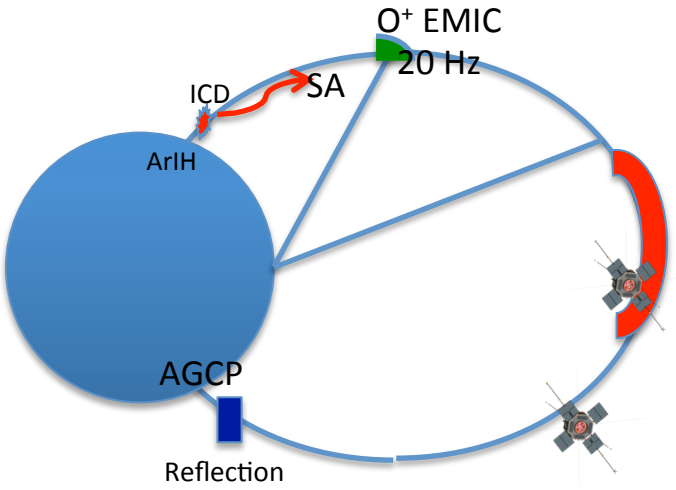
As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance $(1/k_z \to 0)$

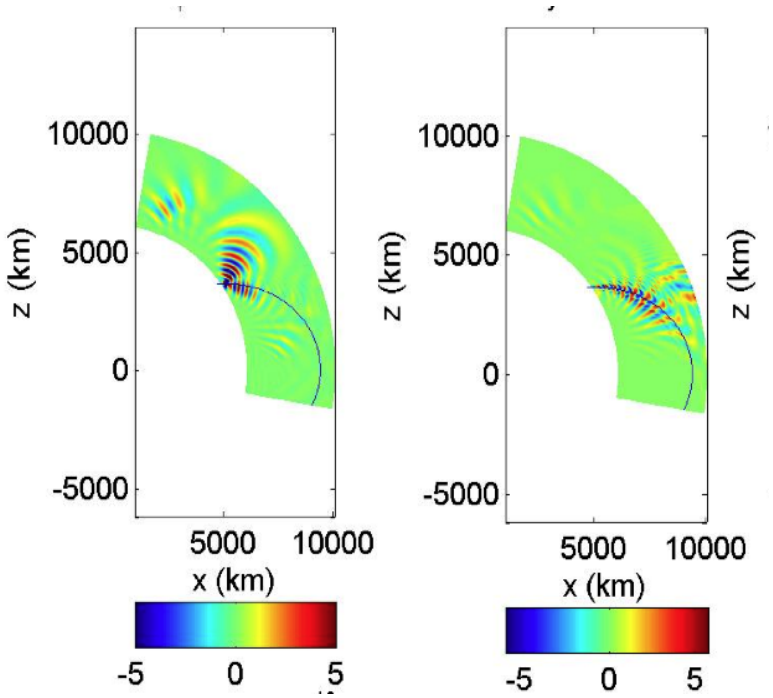
HELIUM BRANCH

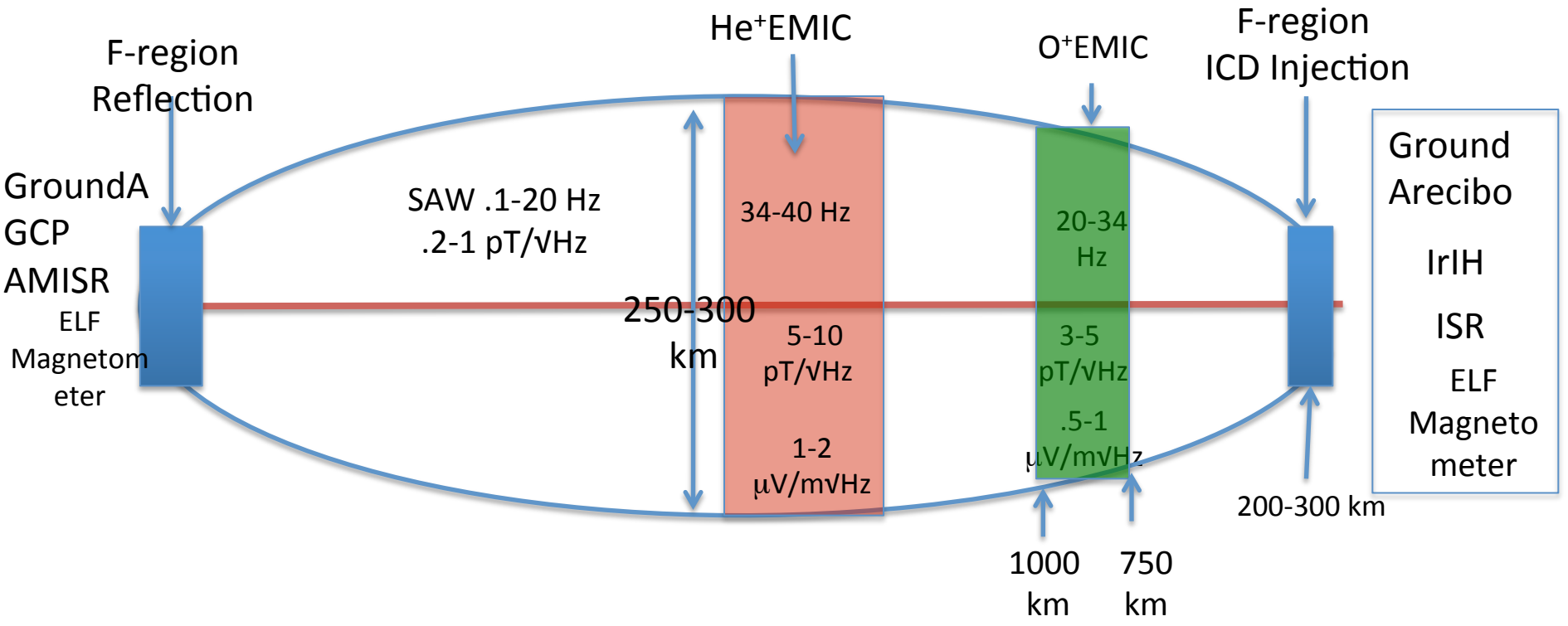


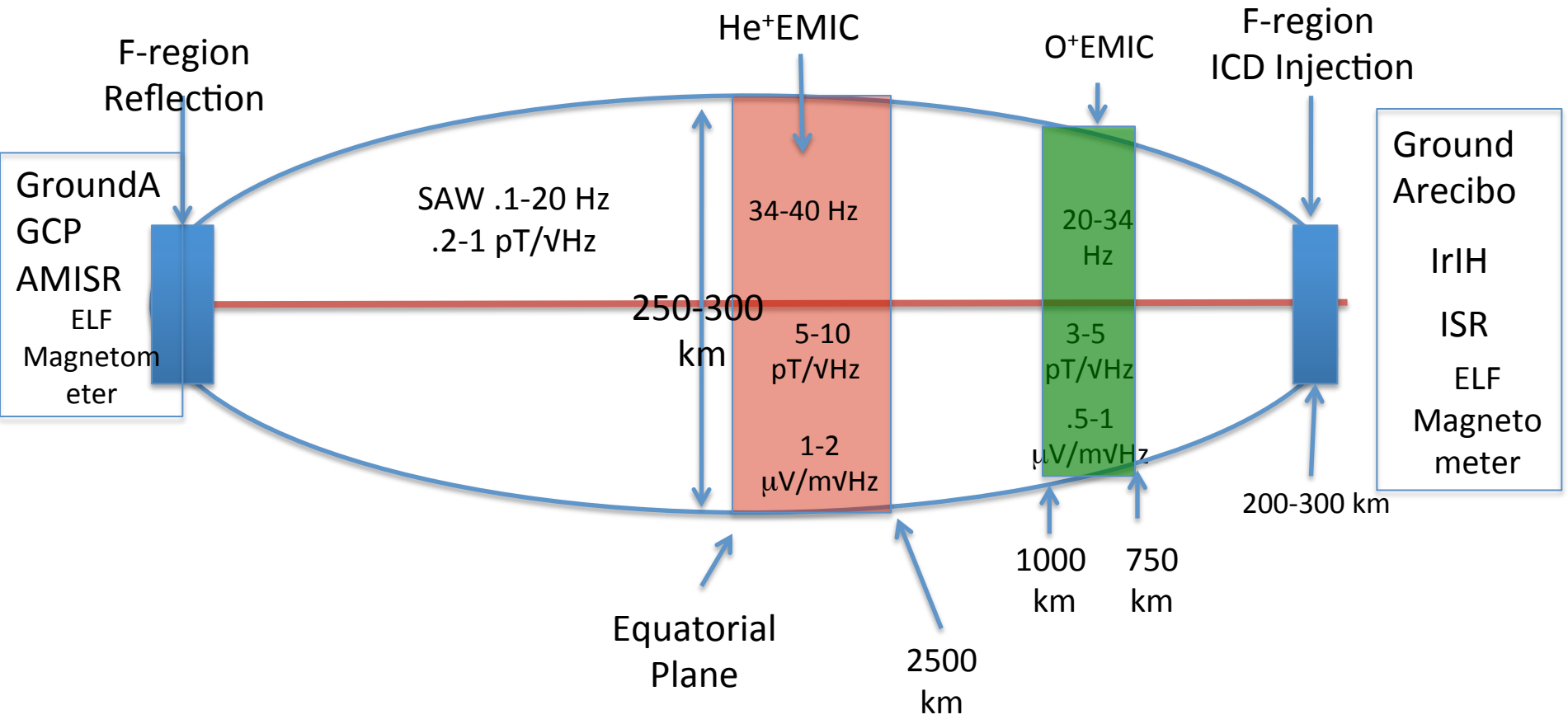


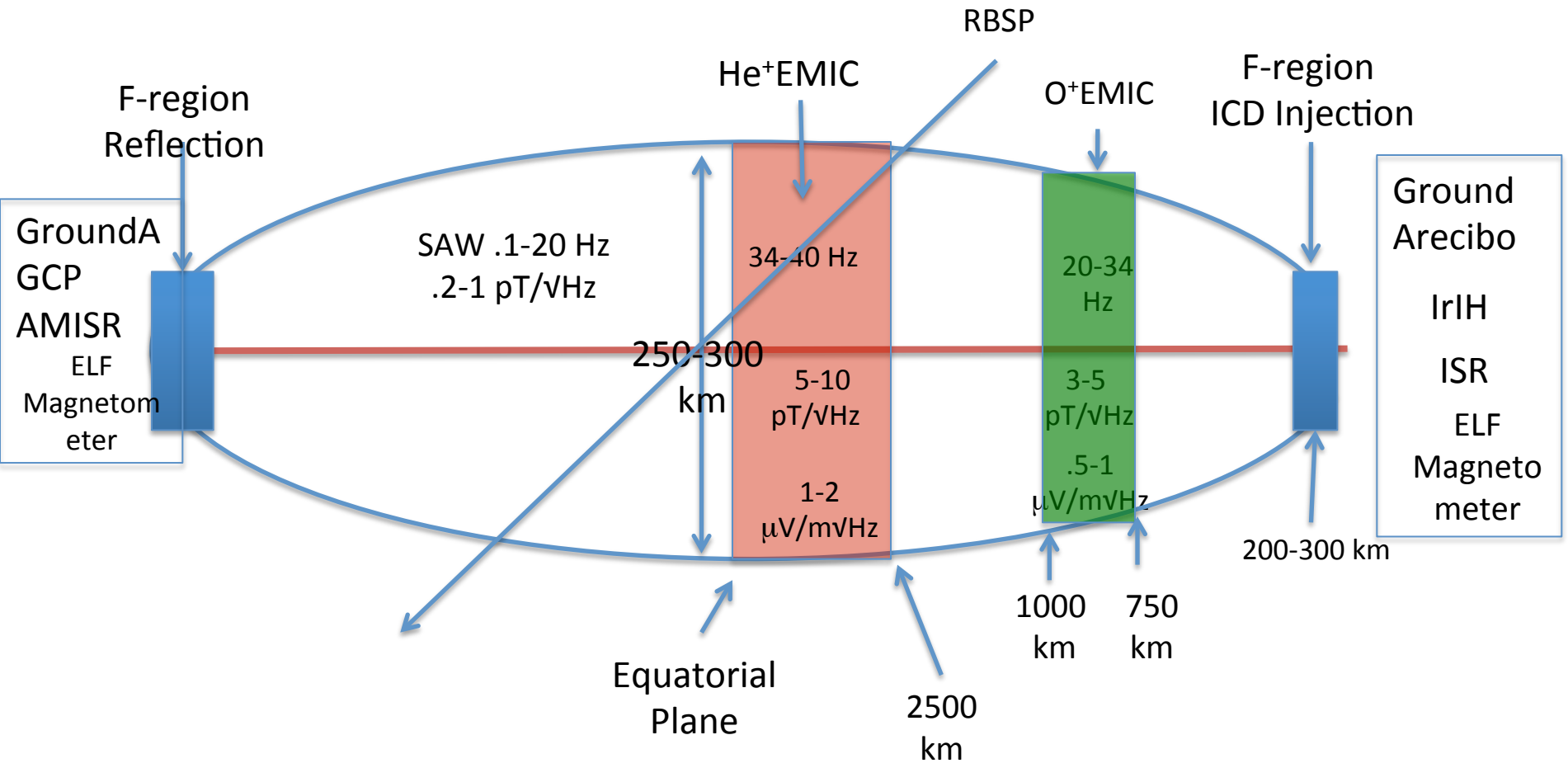
Arecibo Heater Experiments






F-region
Reflection
He+EMIC
O+EMIC
F-region
ICD Injection
GroundA
GCP
AMISR
ELF
Magnetom
eter
SAW .1-20 Hz
.2-1 pT/√Hz
250-300
km
34-40 Hz
5-10
pT/√Hz
1-2
μV/m√Hz
20-34
Hz
3-5
pT/√Hz
.5-1
μV/m√Hz
Ground
Arecibo
IrIH
ISR
ELF
Magneto
meter
200-300 km
1000
km
750
km


F-region
Reflection
He+EMIC
O+EMIC
F-region
ICD Injection
GroundA
GCP
AMISR
ELF
Magnetom
eter
SAW .1-20 Hz
.2-1 pT/√Hz
250-300
km
34-40 Hz
5-10
pT/√Hz
1-2
μV/m√Hz
20-34
Hz
3-5
pT/√Hz
.5-1
μV/m√Hz
Ground
Arecibo
IrIH
ISR
ELF
Magneto
meter
200-300 km
1000
km
750
km
Equatorial
Plane
2500
km

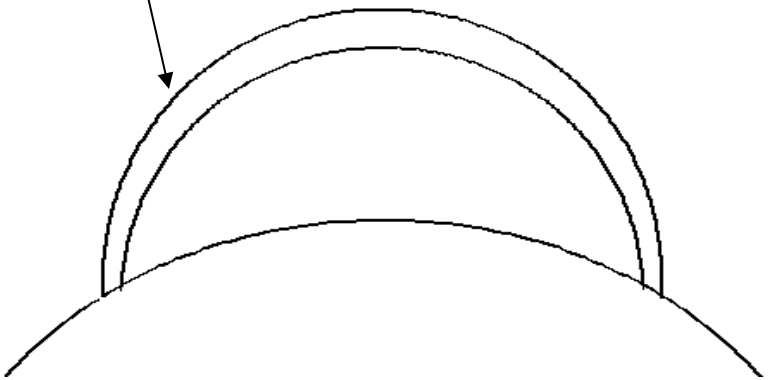


Back of the envelope schematic of experiments with approximate amplitudes to be verified in the experiments. Better calculations to be included in the proposal are in progress. In all experiments the ionospheric state will be measured by the ISRs. The field amplitudes will be recorded on the ground in Arecibo and conjugate (AGCP)

Frequency Selection for Protons

Example for L=1.5

SAW Injection

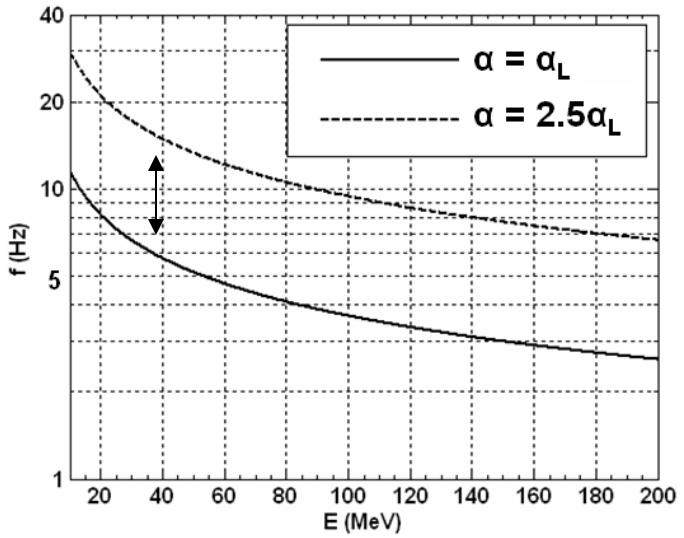


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

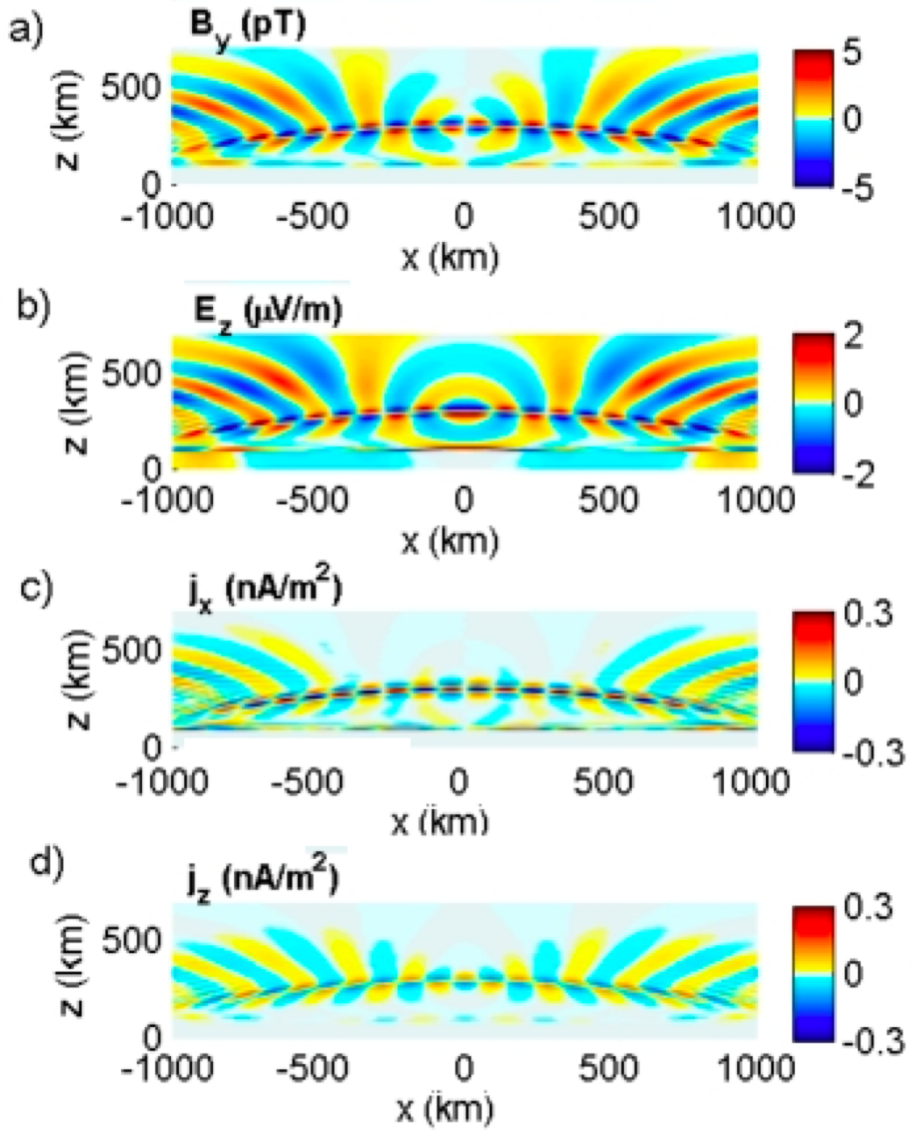
$$\omega = k_z V_A$$

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



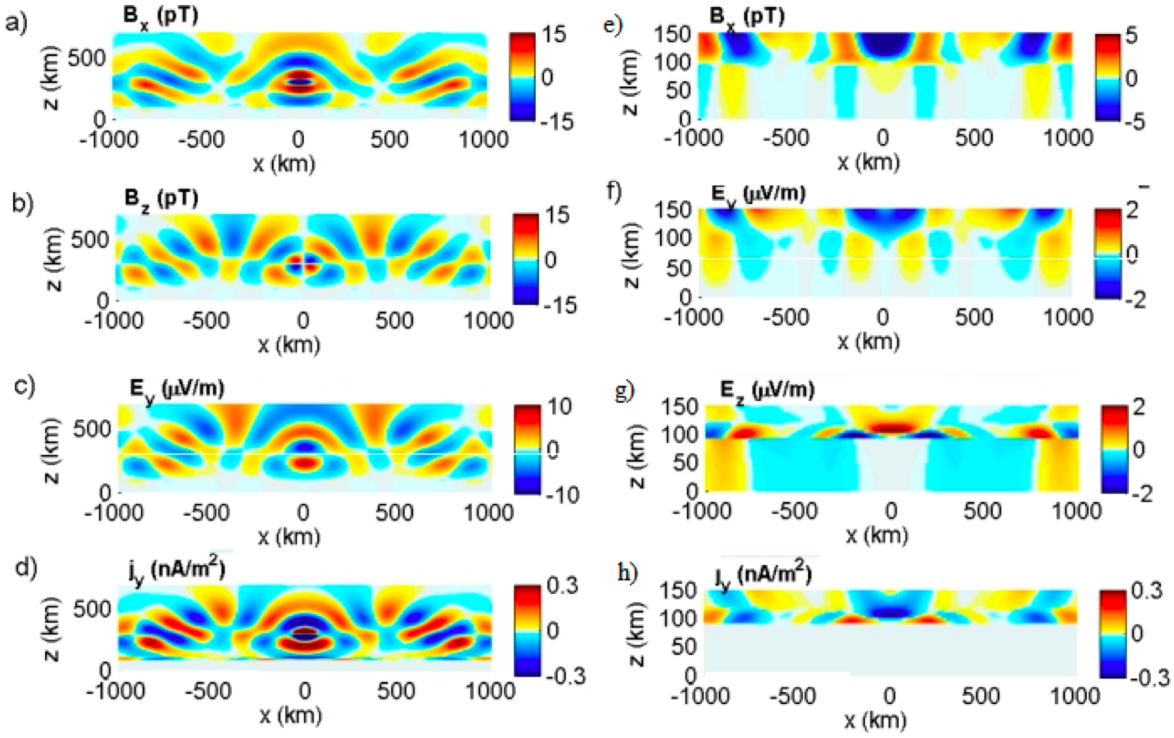
Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz



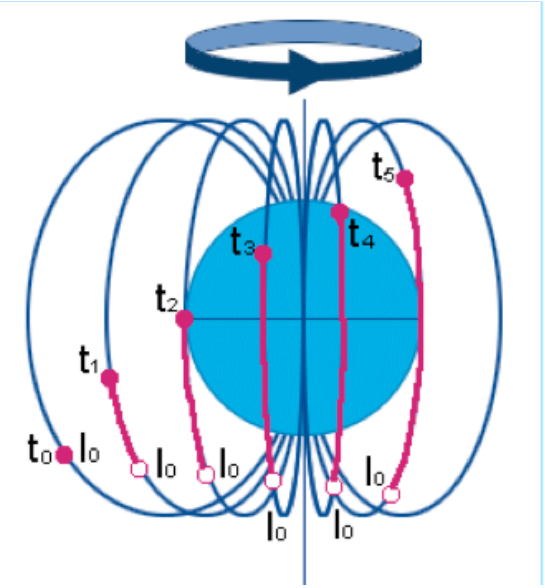
Dip Equator

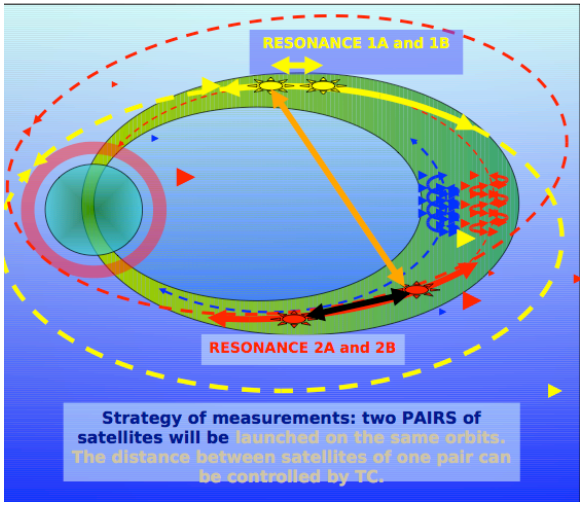
Eliasson et al., 2012


a)
B_x (pT)
15
0
-15
b)
B_z (pT)
15
0
-15
c)
E_y (μV/m)
10
0
-10
d)
j_y (nA/m^2)
0.3
0
-0.3
e)
B_x (pT)
5
0
-5
f)
E_y (μV/m)
2
0
-2
g)
E_z (μV/m)
2
0
-2
h)
j_y (nA/m^2)
0.3
0
-0.3
z (km)
x (km)
-1000
-500
0
500
1000
0
50
100
150
500

Physics Studies HAARP/Resonance

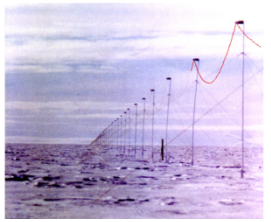
- Wave-particle interactions in the Radiation Belts – Whistler range
  - Artificially Stimulated Emissions (ASE)
- ULF - MHD Study
  - SA ,EMIC and MS wave injection in space. Interactions with trapped electron and ions
  - Excitation of the Ionospheric Alfven Resonator (IAR)
  - SA wave (Pc1) triggering



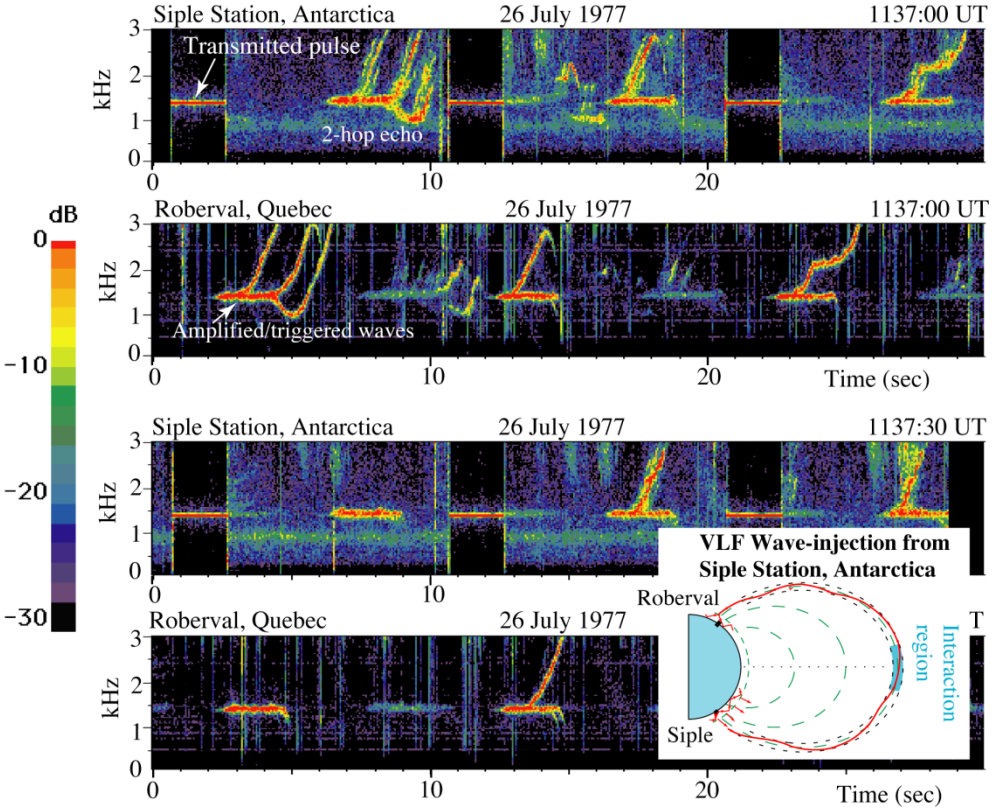


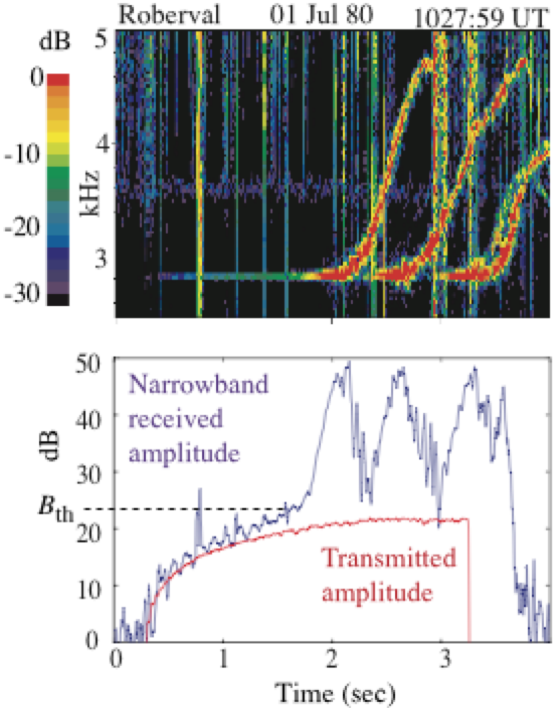
Controlled VLF Wave Injection Artificially Stimulated Emissions (ASE)

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



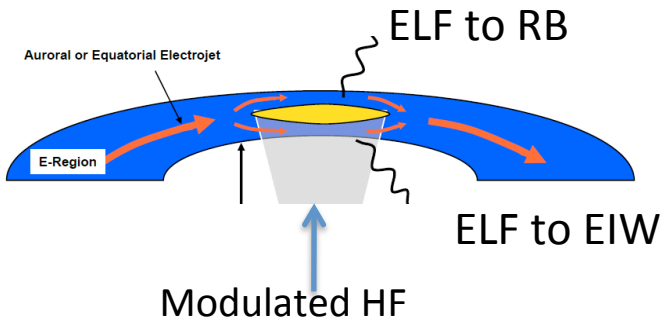
L=4.2, 1.5 MW, 42 km length antenna on 2 km thick ice sheet,
Inject 3-6 kHz –
Very difficult and inefficient to inject ELF/VLF with ground



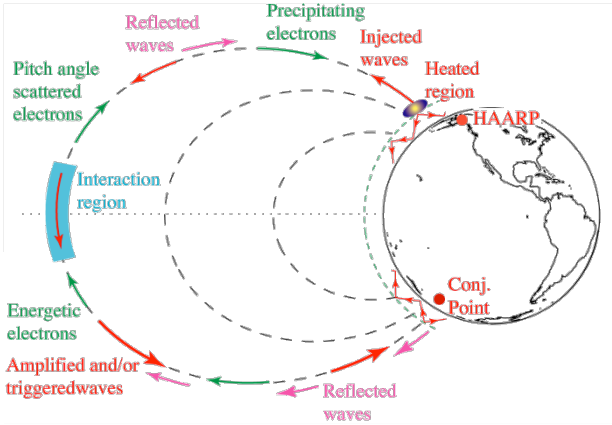


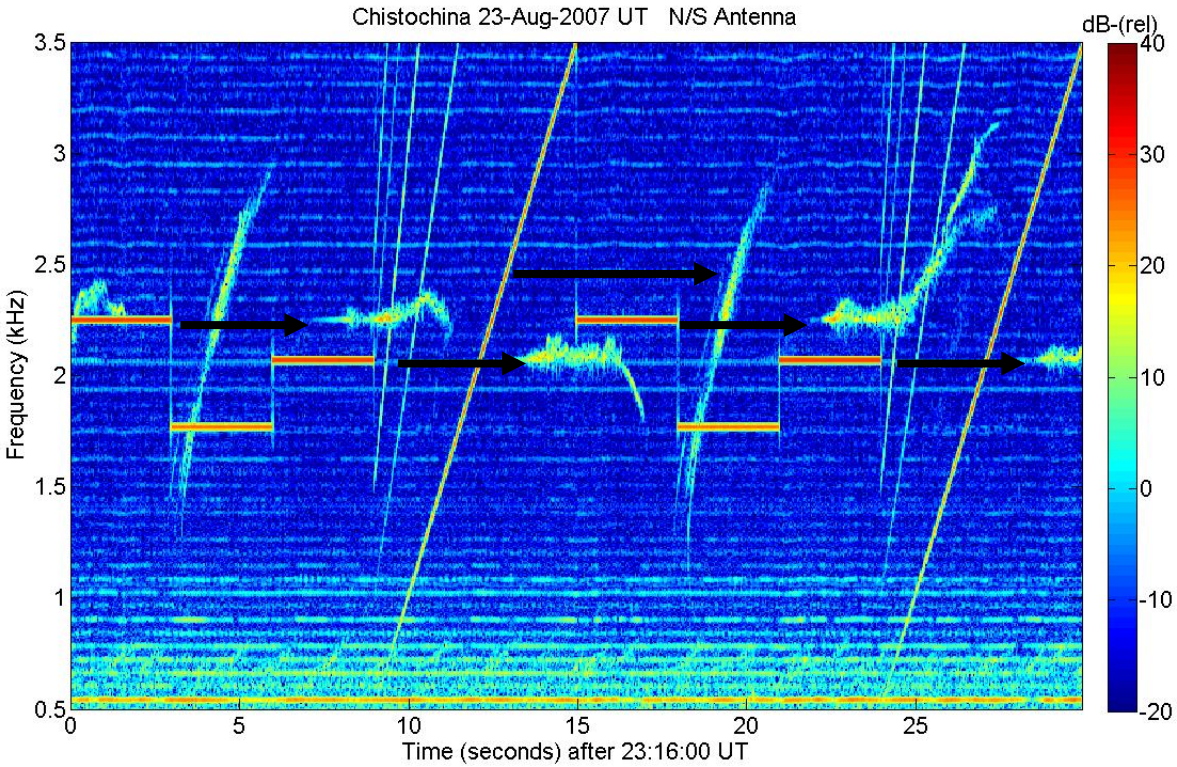
Triggered Emissions

ASE – HAARP Tests

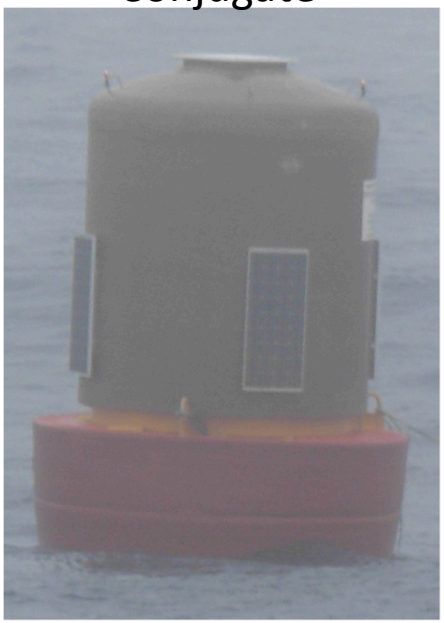


ASE Studies



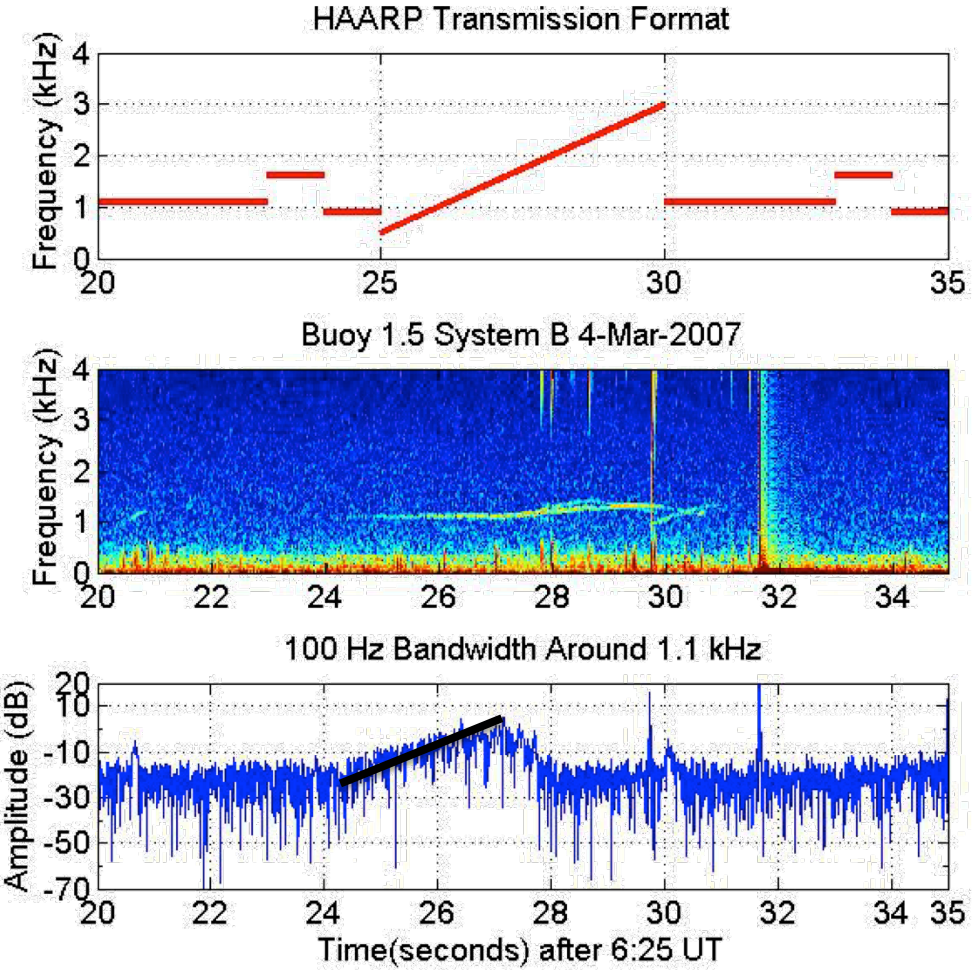


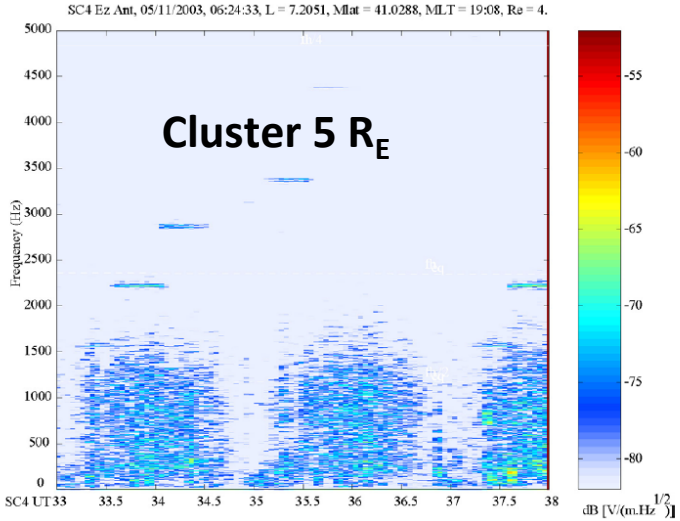
Conjugate

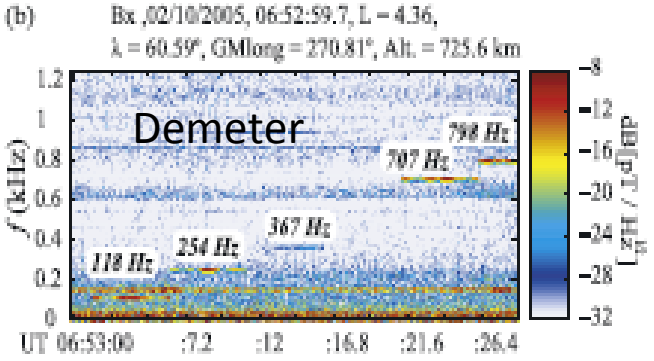


Pulses above 2 kHz have 1-hop echoes with triggered emissions
Pulse near 1.7 kHz does not; ramps have echoes with no emissions

15 dB/s Amplification & Triggered Emissions



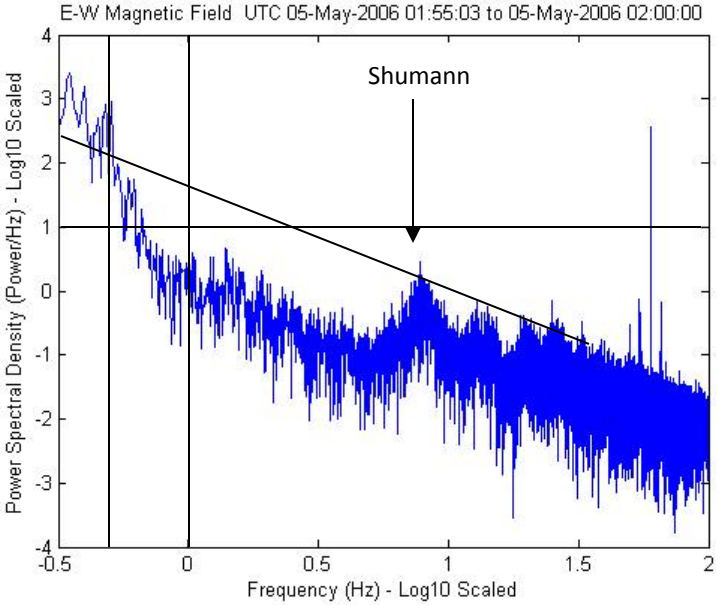




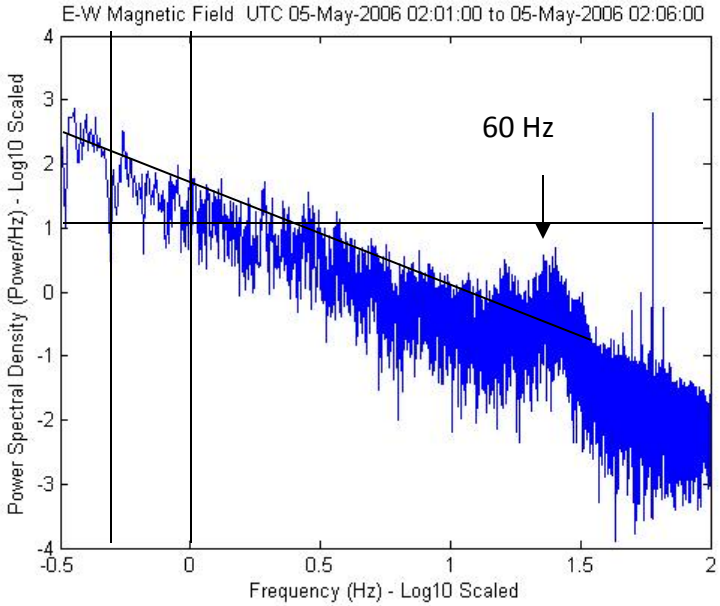
Only the pulse at 1100 Hz is amplified

BAE SYSTEMS

Pc1 Triggered Emissions ?



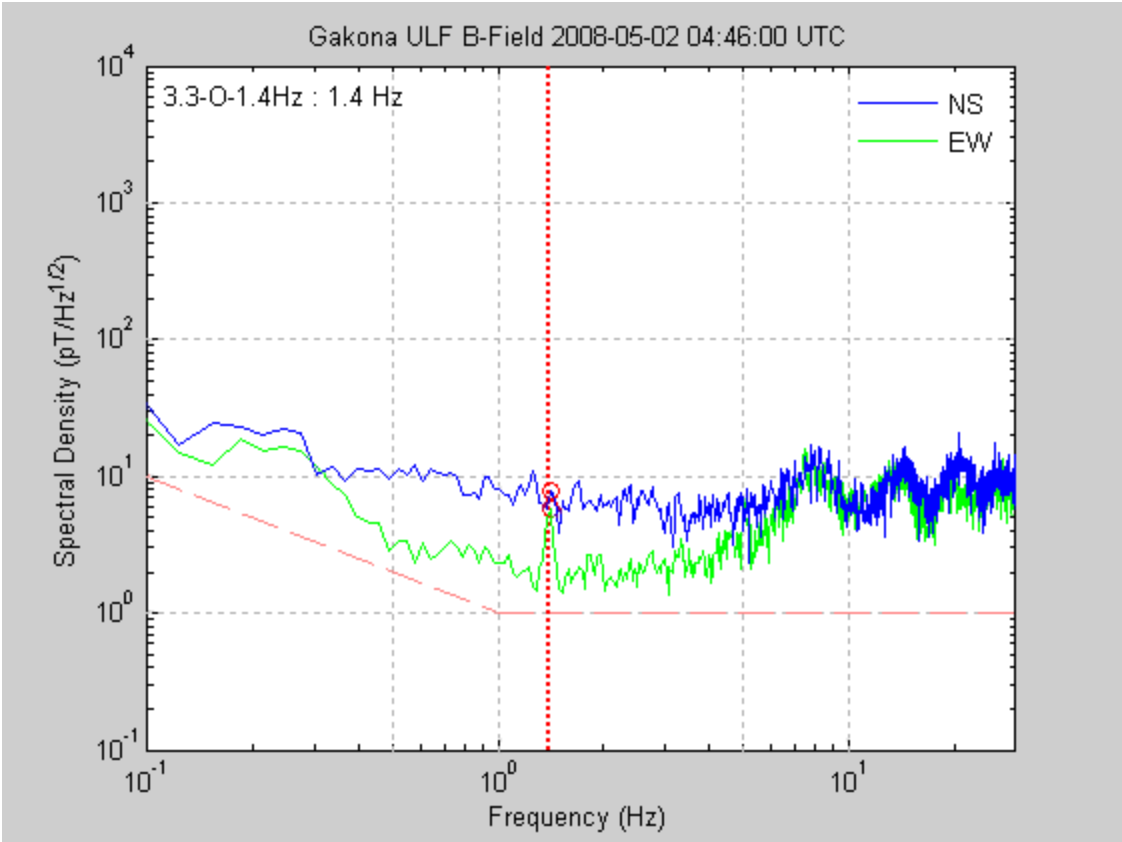
Spectrum before HAARP ULF Start Experiment – Ambient Noise



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

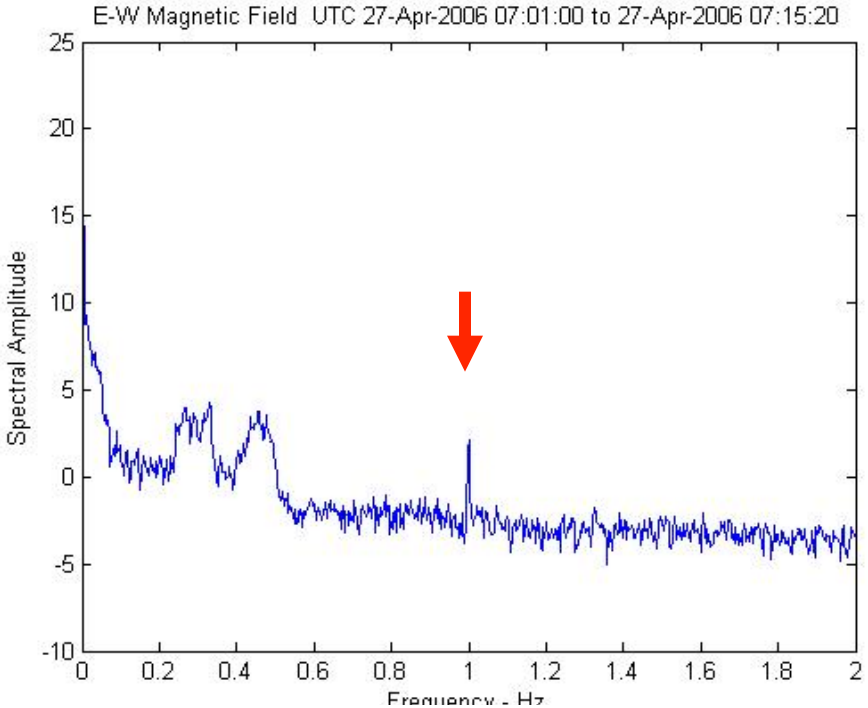
ULF at Gakona – Power Spectral Density (PSD)

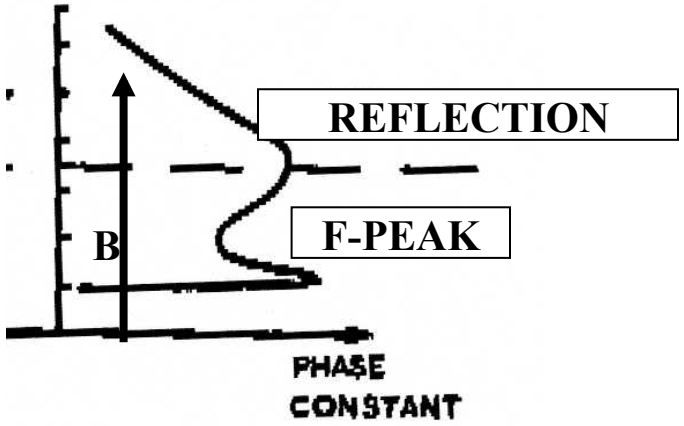
- Frequency spectrum in a moving time window
- Clear Schumann resonances at 8, 14, .. Hz
- Signals emerge as freq. peaks in sync with HAARP ULF operation
- Greatly varying background below 1 Hz

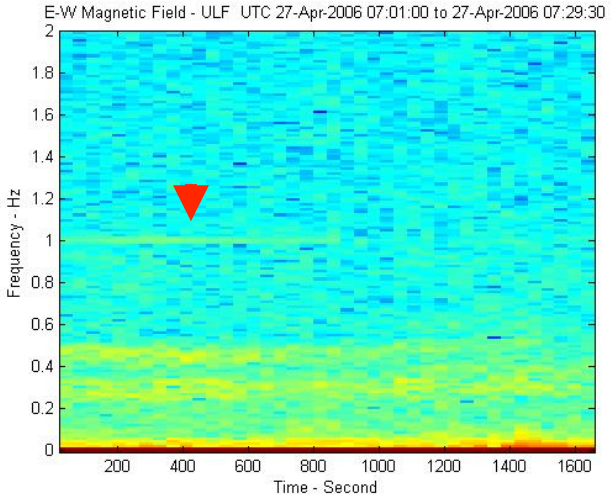


Triggered Pc1 broadband

IAR Excitation by the HAARP







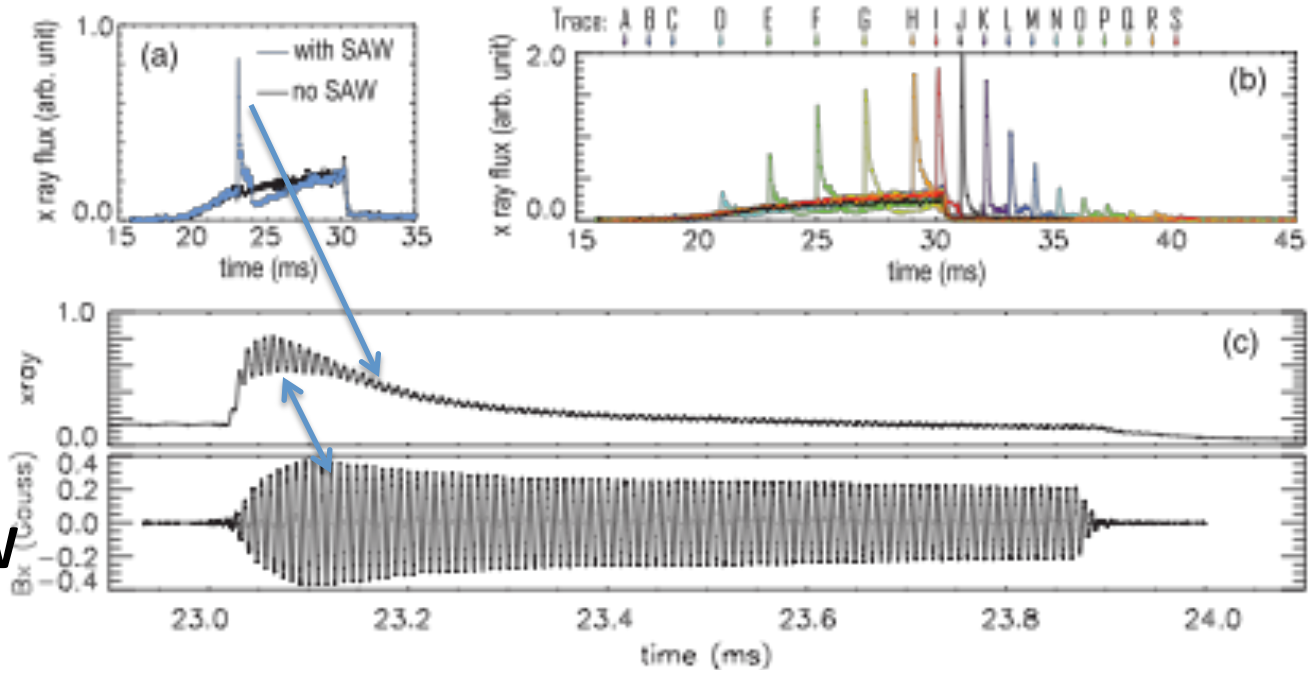
Excitation of the IAR due naturally excited waves at .25 Hz and .5 Hz and by HAARP generated SA at 1.0 Hz.

LAPD Experiment

SAW cannot break μ

Single pulse X-rays

Injected SAW



Physics hypothesis: Loss cone drives whistlers leading to steady state loss (KP)- Injection of SAW couples (?) to whistlers giving enhanced spiky loss

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**

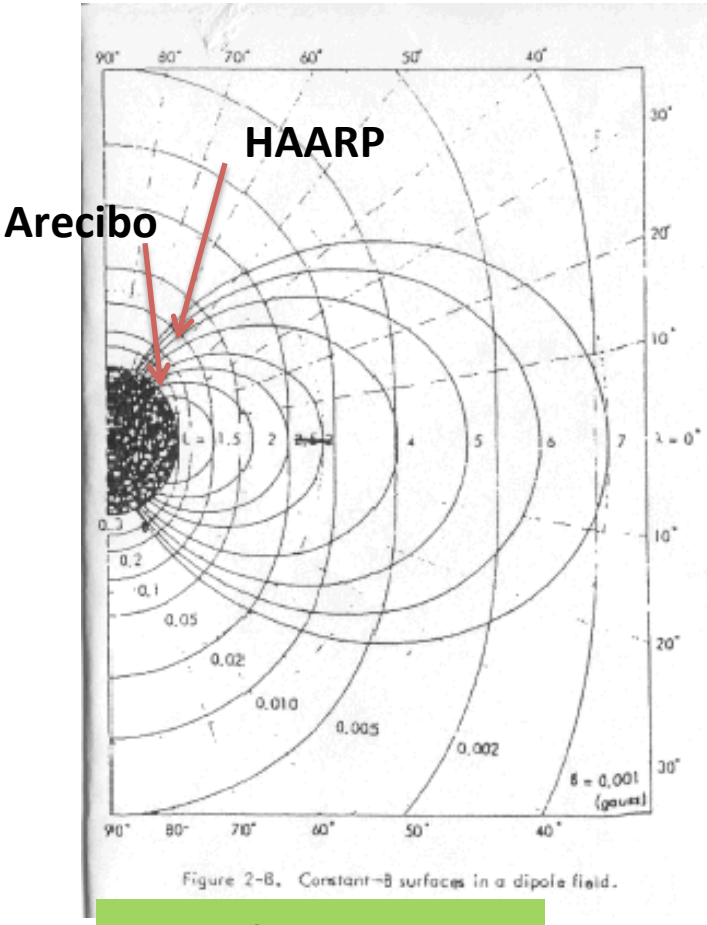
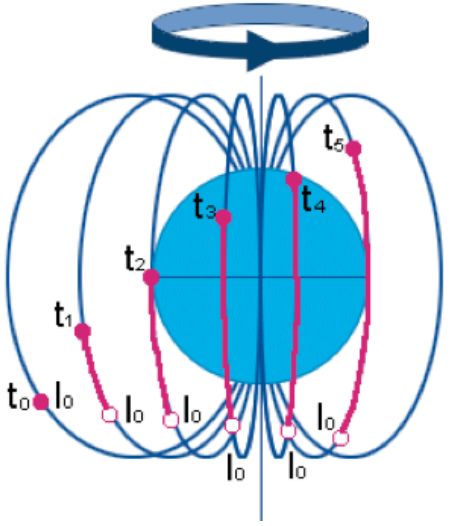
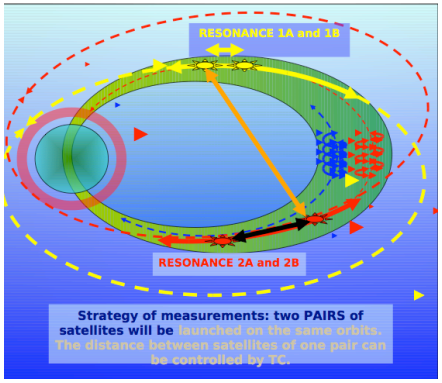


Figure 2-8. Constant-B surfaces in a dipole field.

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

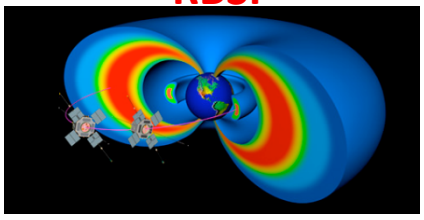
Magneto-synchronous





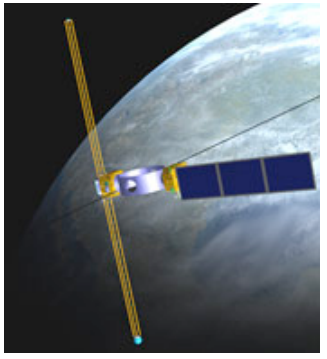
RESONANCE (Russia)
Launch ~2012-14, 4-spacecraft
Orbit:1800x30,000km, ~63° incl.

RBSP



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



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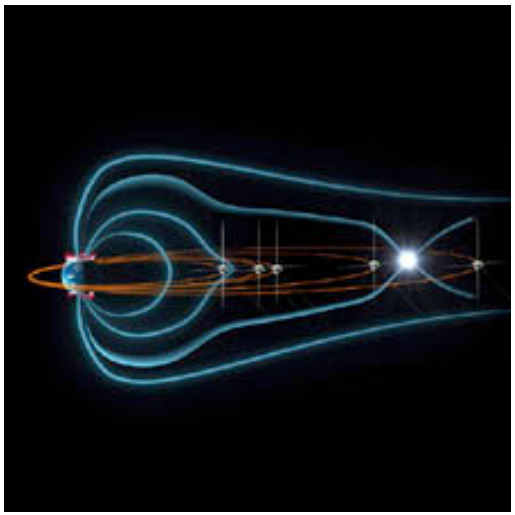
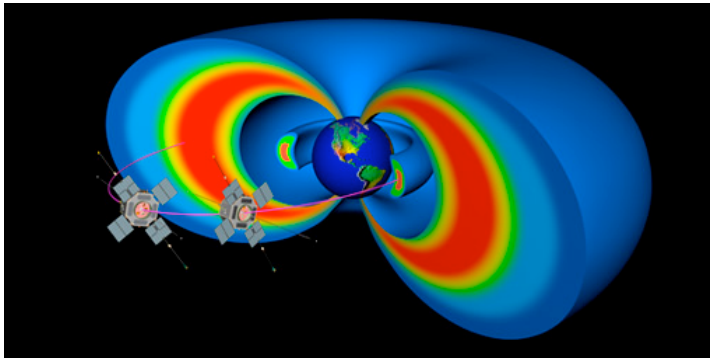


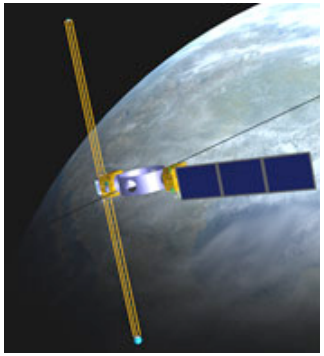


THEMIS (NASA)

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

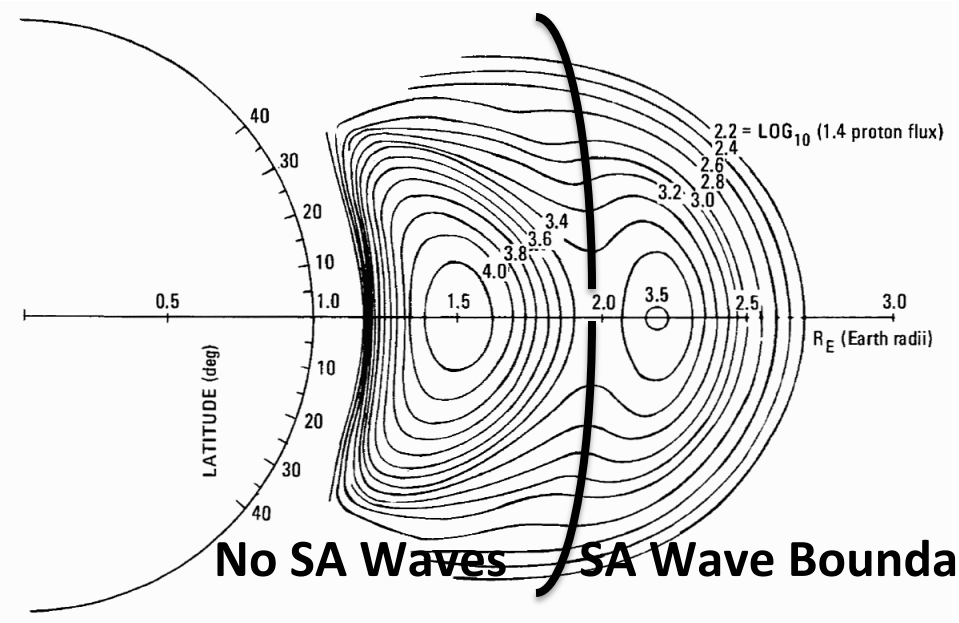
MEO, wave/particle

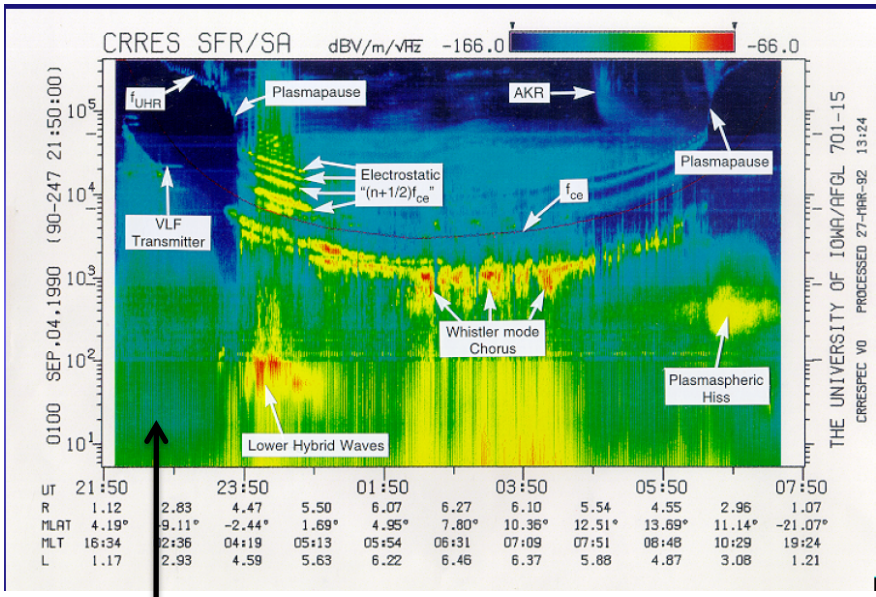
ORBITALS (CSA)

Launch 2012-2013

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

Inner Proton Belt – Accessible from Arecibo



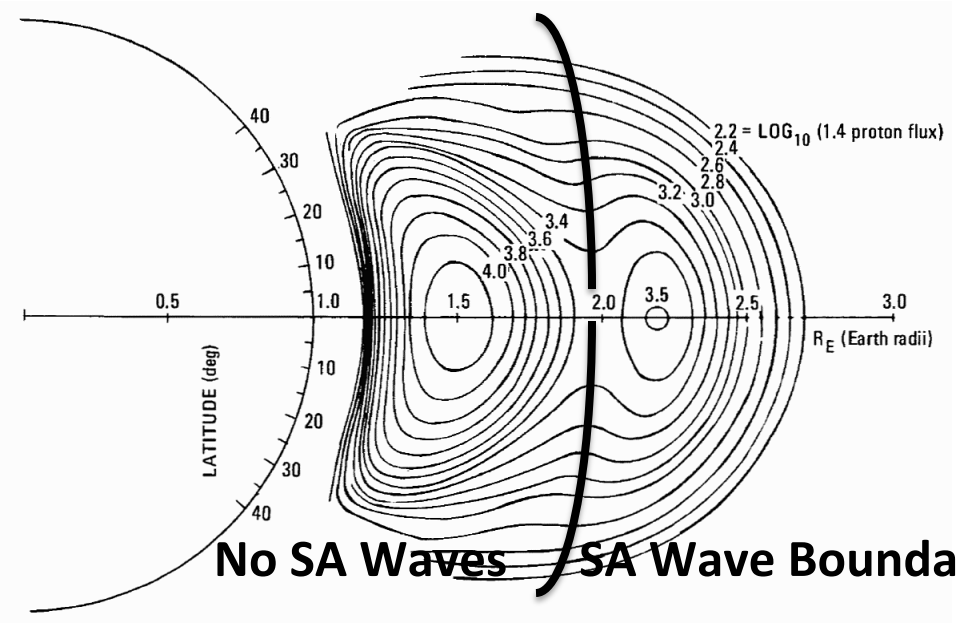


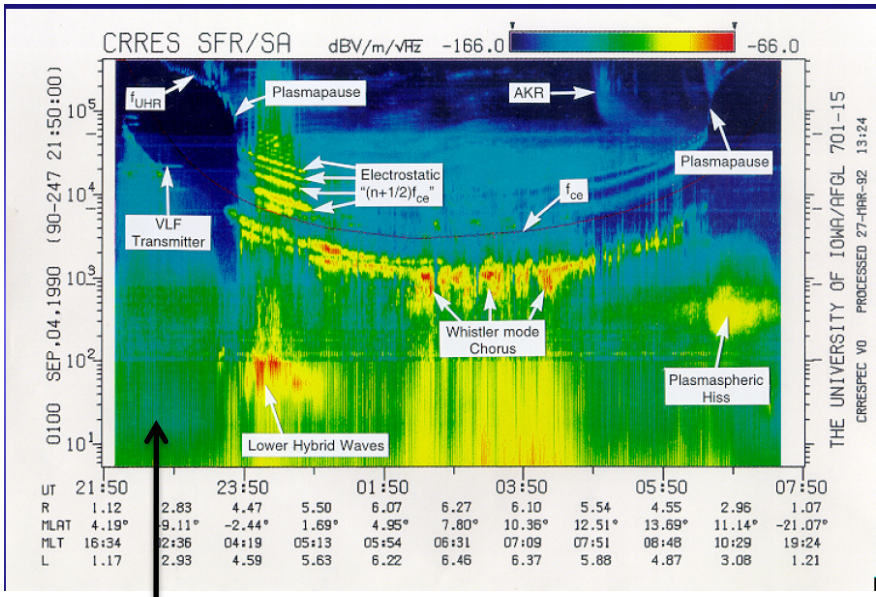
Typical inner belt proton lifetimes:

- **10 MeV – decades**
- **50 MeV – century**

No wave activity at SAW and EMIC branches

Inner Proton Belt – Accessible from Arecibo





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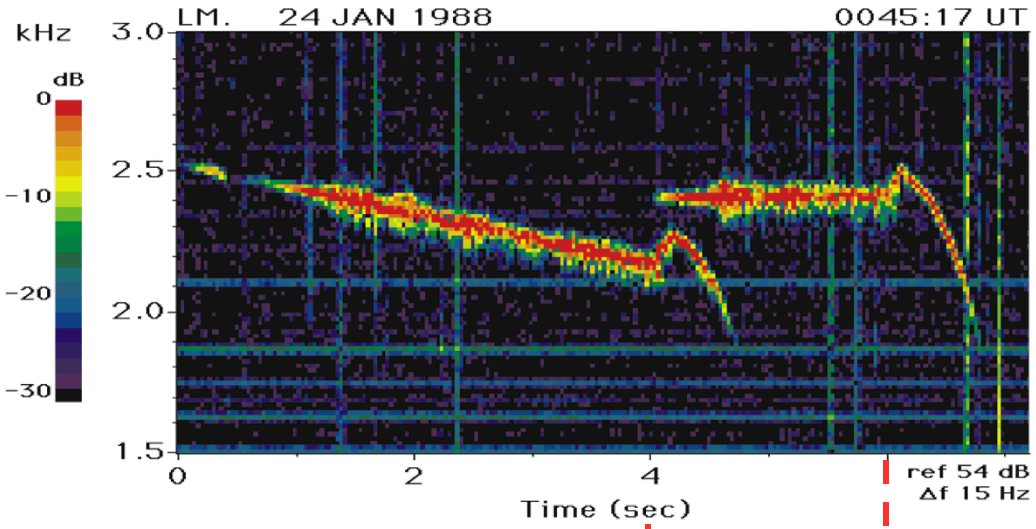
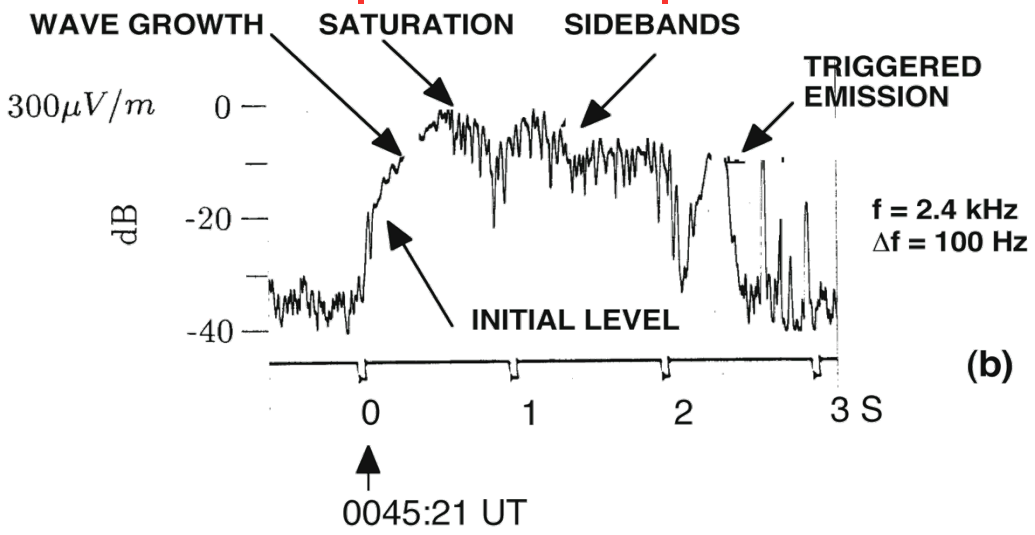
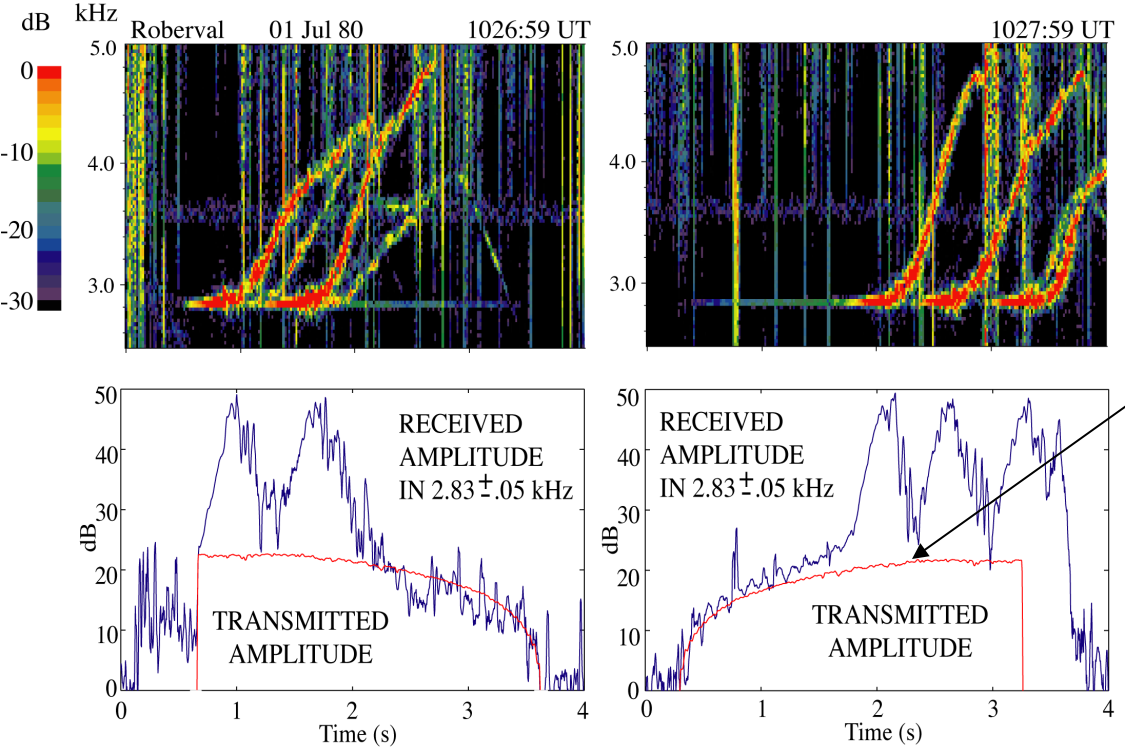
Growth & Saturation



Amplitude in ~100 Hz band



Amplitude Effect on Growth

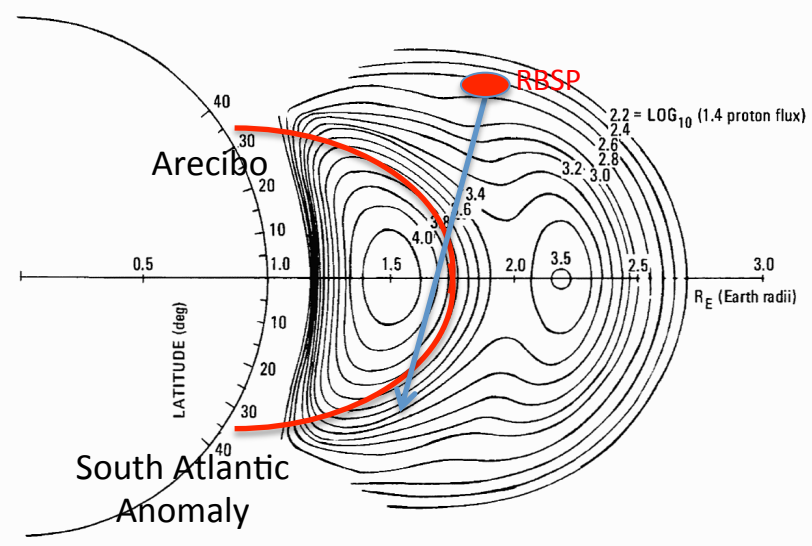


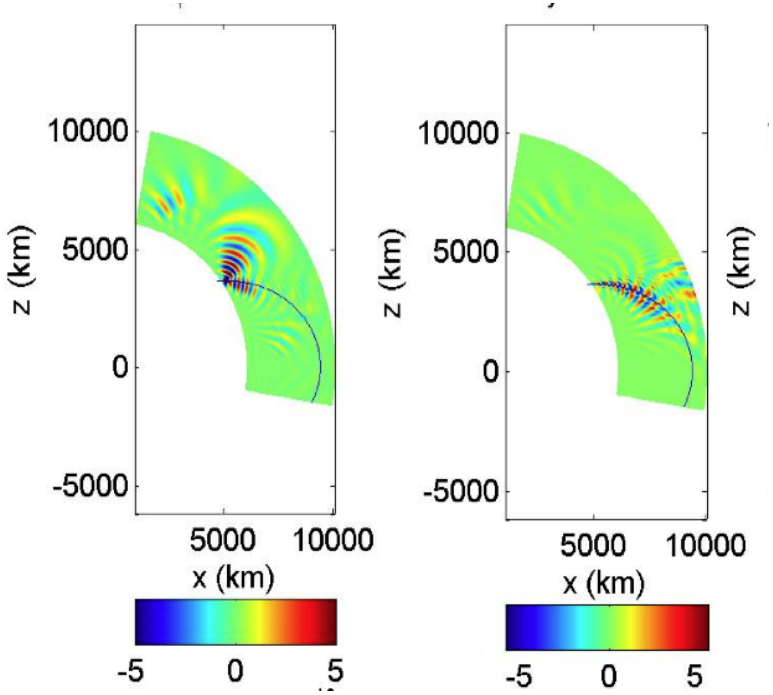
COHERENT GROWTH 20-30 dB

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

TRANSITION TO OSCILLATOR BEHAVIOR

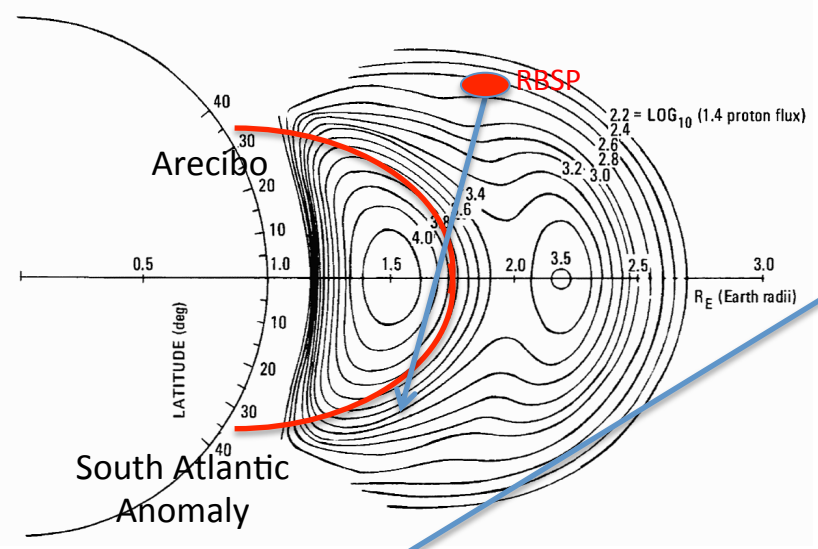
Next Step - Active SAW Probing of Inner RB Using the Arecibo Heater





Focus on SAW for protons and EMIC for electrons

Active Probing of Inner RB Using the Arecibo Heater Using ICD – Triggered EMIC



Focus on SAW for protons and EMIC for electrons

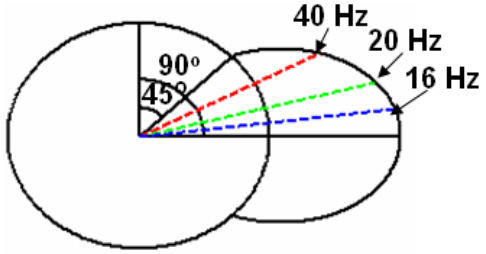
Proton Energy	Resonance Frequencies
30 MeV	6-16 Hz
50 MeV	5-15 Hz
100 MeV	3.5-9.5Hz

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

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

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

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



HELIUM BRANCH