Shear Alfven Wave Injection in the Magnetosphere by Ionospheric Modifications in the Absence of Electrojet Currents

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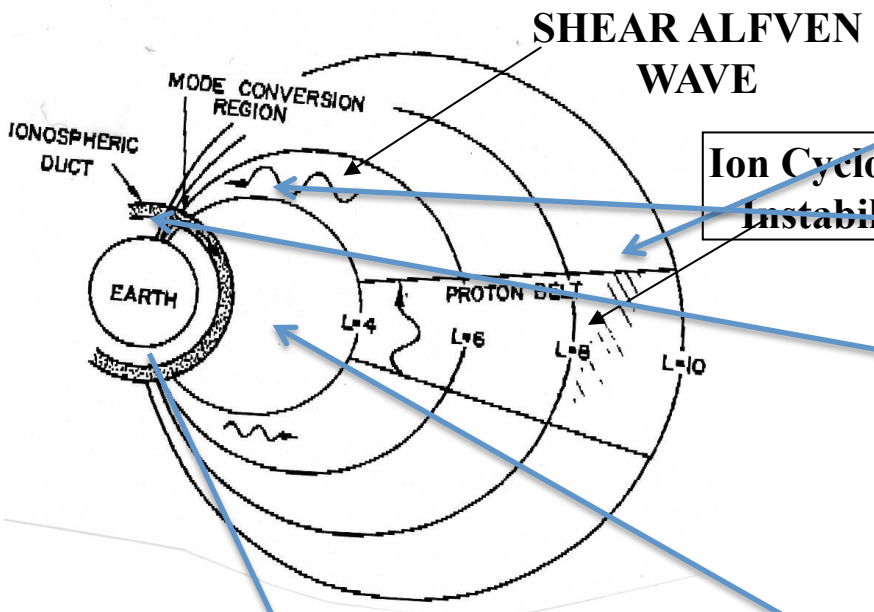
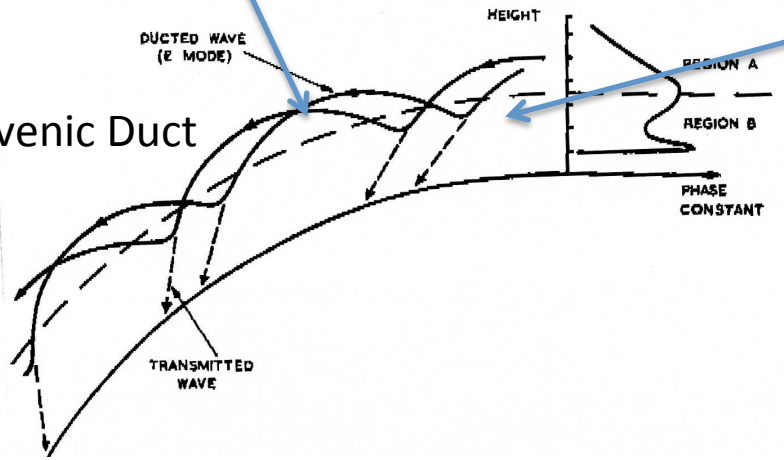
SUPPORT: MURI/ONR AND BRIOCHE/DARPA

M-I SAW coupling





Alfvenic Duct

Anisotropic Ions at high L

↓

SAW

↓

Mode convert to MS in Ionosphere

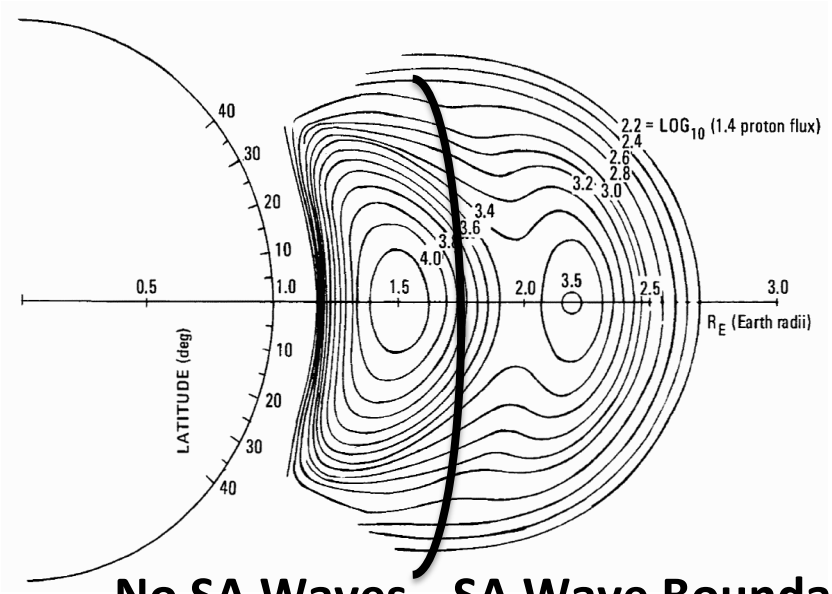
↓

MS waves propagate to mid and equatorial latitudes in Alfven duct

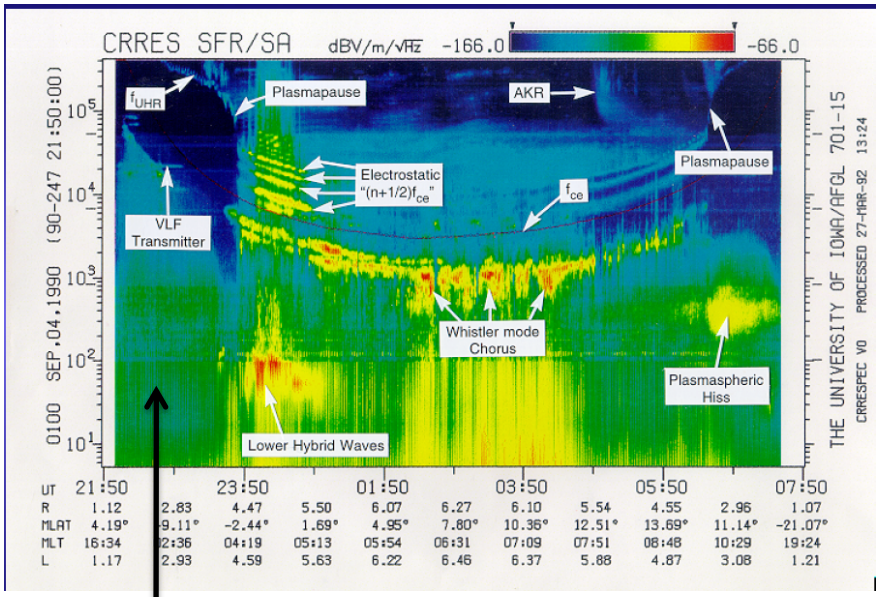
↓

No SAW in inner RB
Long proton lifetime

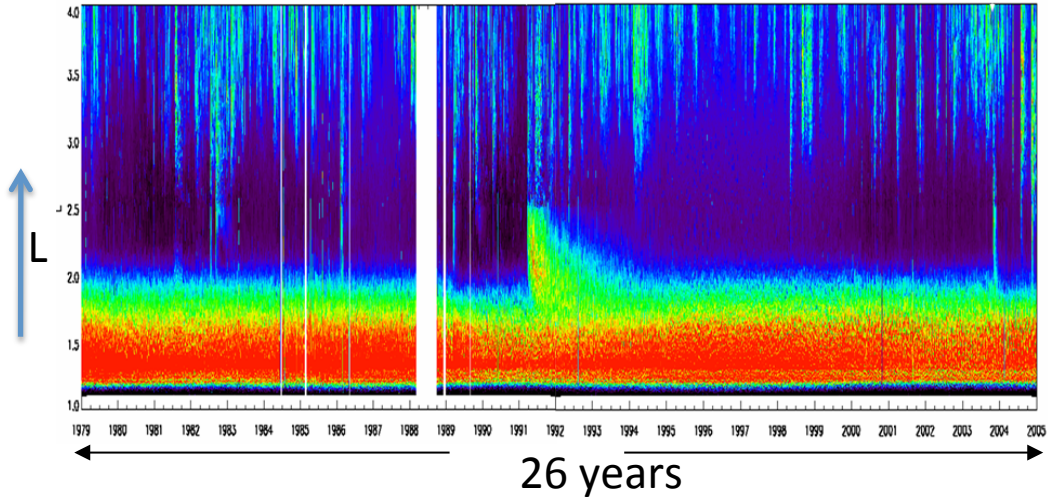
The Inner Proton Belt – Long lifetimes



No SA Waves **SA Wave Boundary**

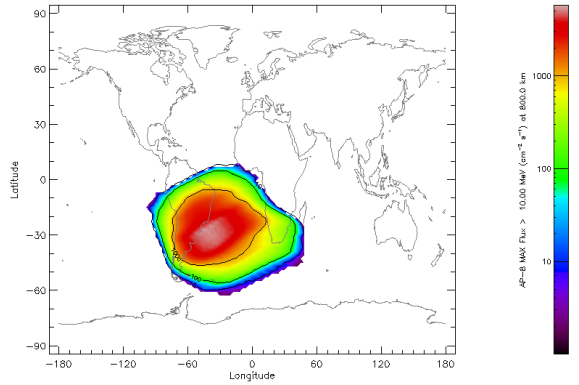


No wave activity at SAW and EMIC branches



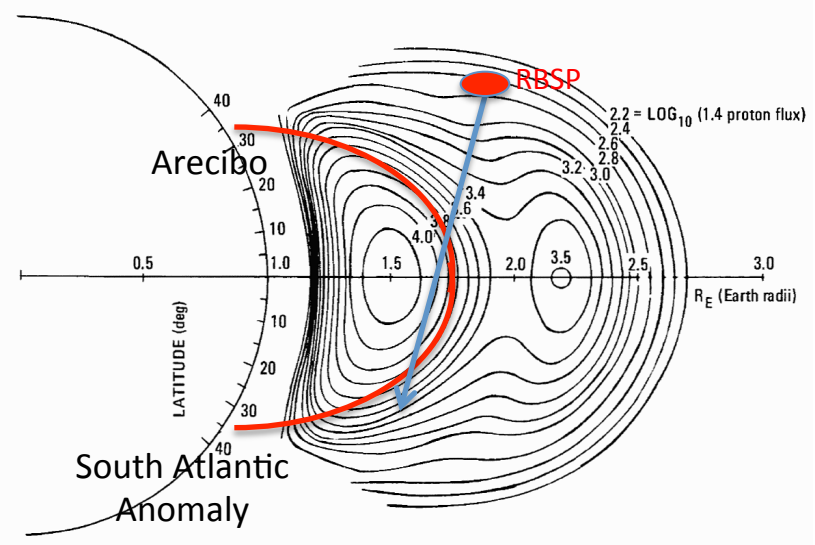
26 years

South Atlantic Anomaly



Injecting ELF Waves from the Ionosphere into the Inner Belt

Major New Research Opportunity



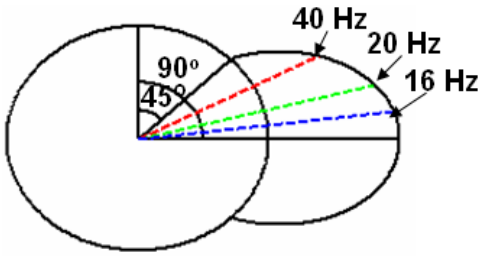
Required ELF Frequencies for protons

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

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

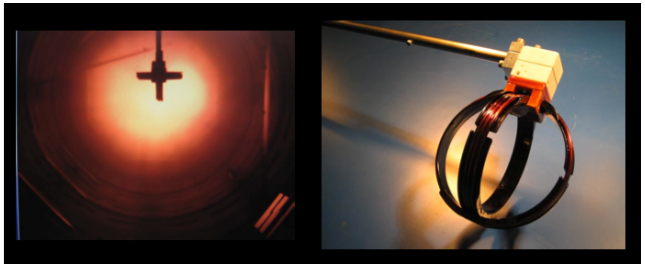
Required ELF Frequencies for MeV electrons – EMIC waves

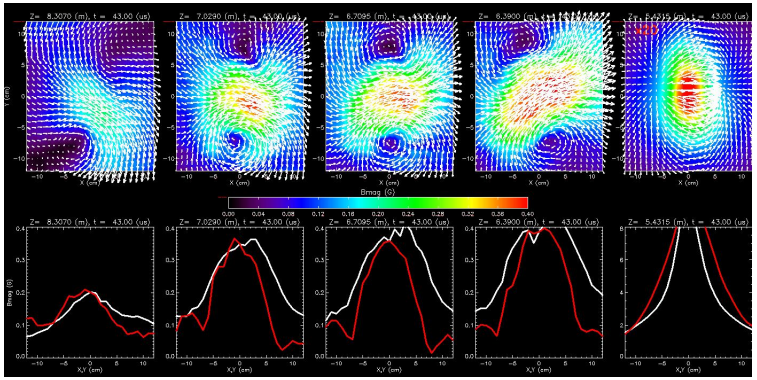


Proton Energy	Resonance Frequencies
30 MeV	6-16 Hz
50 MeV	5-15 Hz
100 MeV	3.5-9.5Hz

Techniques for Injecting 1-40 Hz Waves

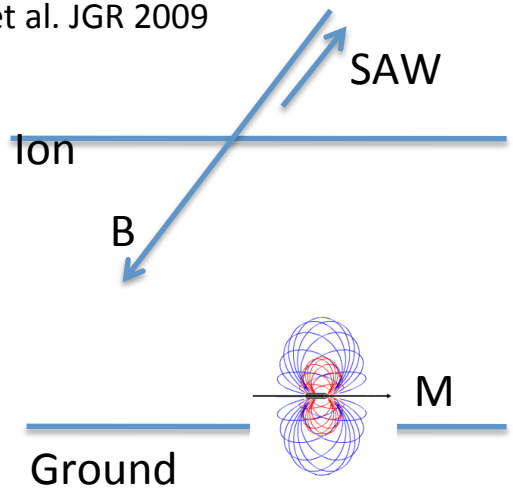
1. Rotating Magnetic Fields (RMF) – PoP using UCLA/LAPD Chamber



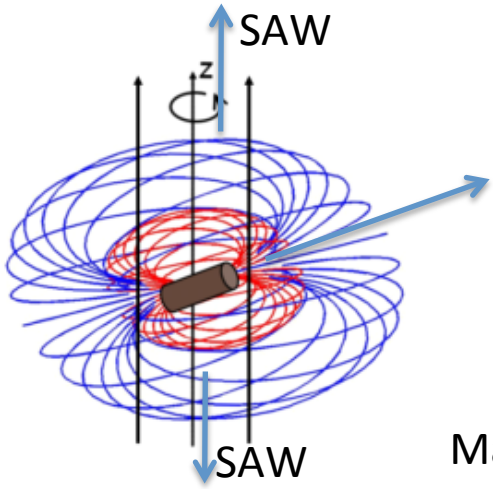


Karavaev et al. PoP, 2010; Giglioti et al. PoP, 2009

Shao et al. JGR 2009



RMF Injection from Ground



Orbiting satellite carrying superconducting or permanent magnet Controlling its spin results in injection of SAW in the RB

Magneto-synchronous orbit

RMF Satellite Injection

Techniques for Injecting 1-40 Hz Waves

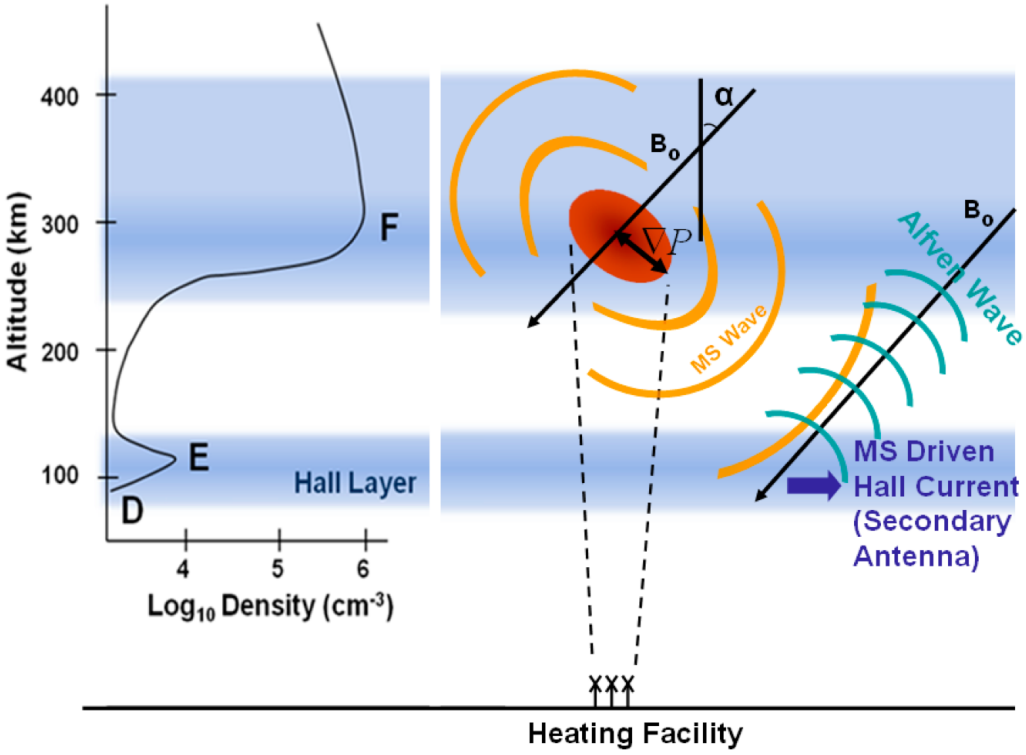
2. Ionospheric Current Drive (ICD)

Papadopoulos et al. GRL 2011 a,b

I-M SAW Coupling – Requires Ionospheric Heater – Available at Arecibo

Step 1: F-Region HF Heating -gradp $\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$ MS Wave

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

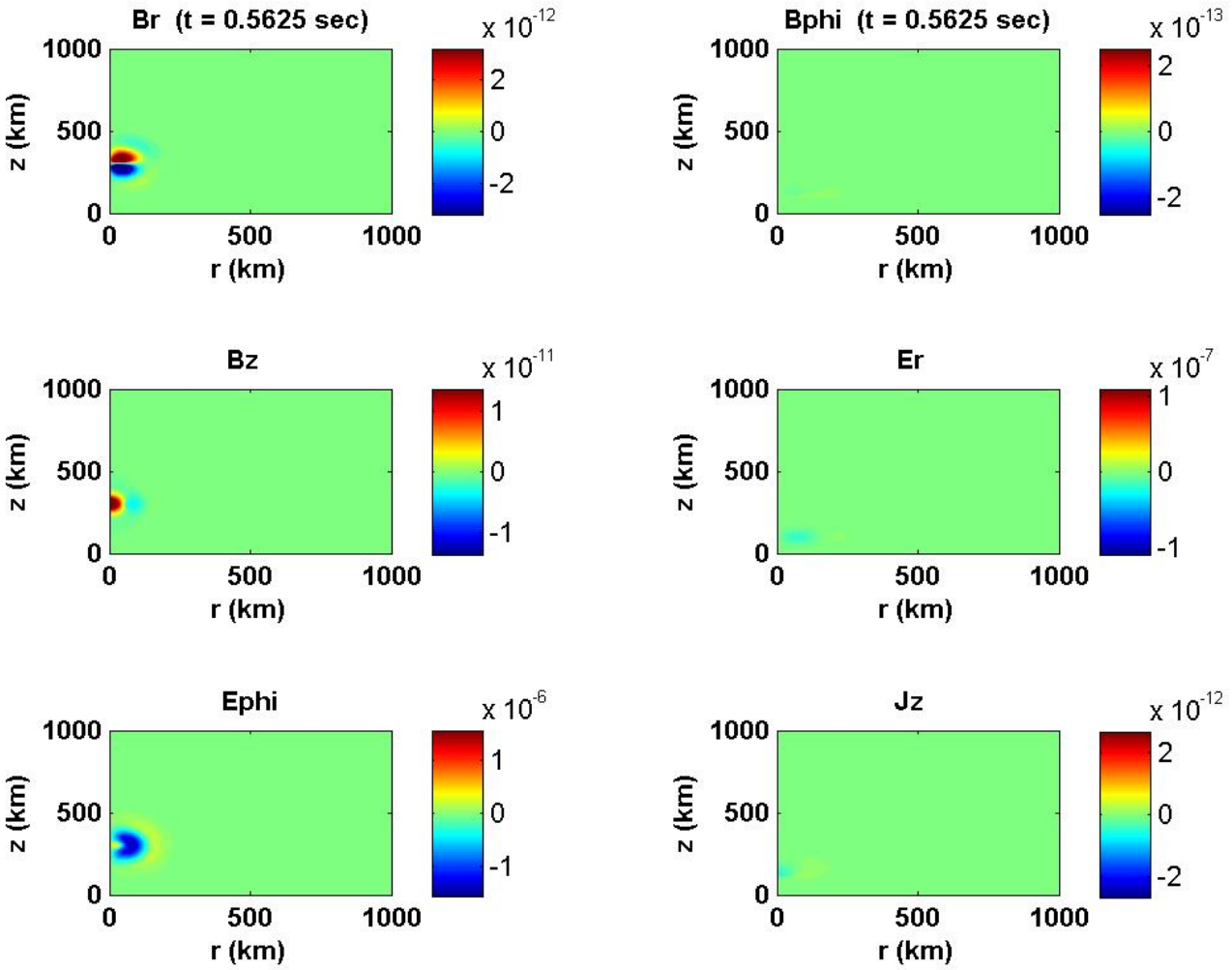


F- region cooling response does not allow frequencies higher than 60-70 Hz

Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

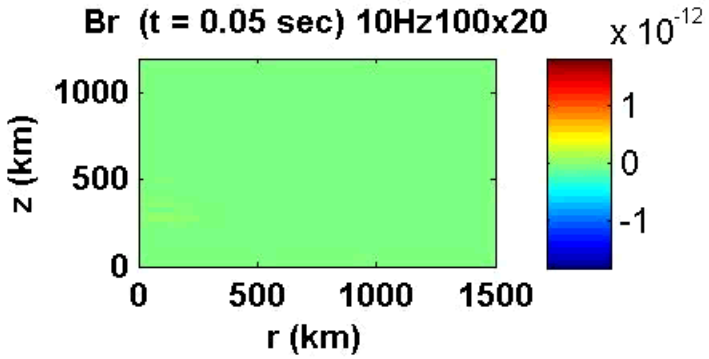
Concept reverses M-I SAW coupling to I-M SAW coupling

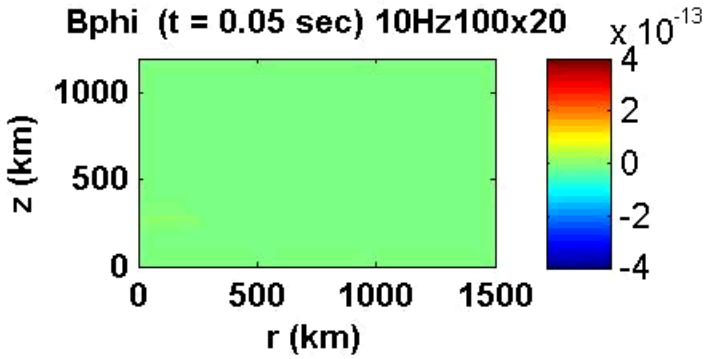
ICD Modeling and PoP HAARP Experiments

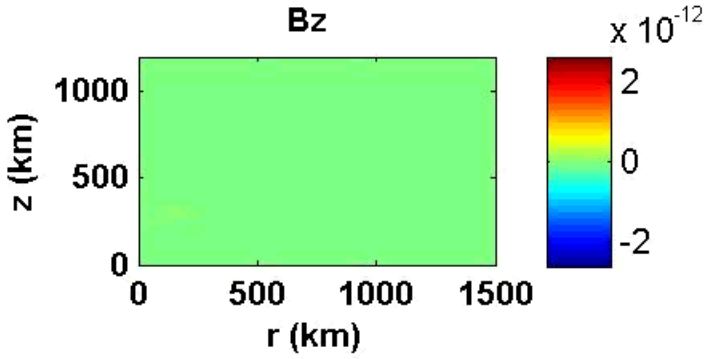


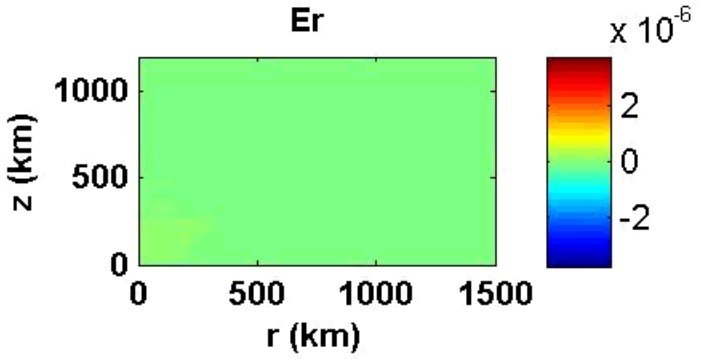
MS Vertical B **SAW**

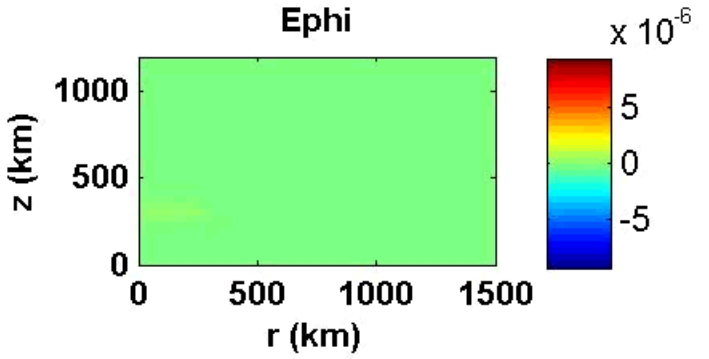
Cylindrical Coordinates

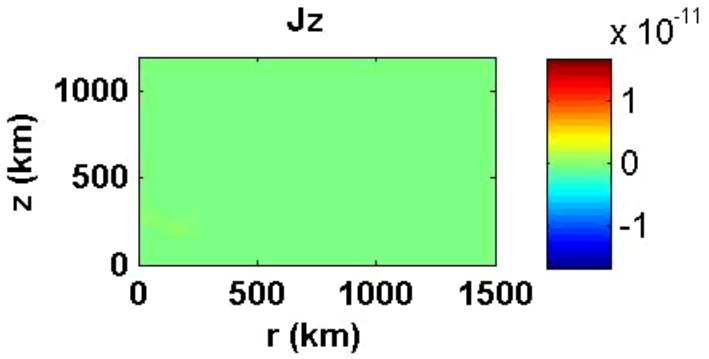

Br (t = 0.05 sec) 10Hz100x20
x 10^-12
1
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)


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
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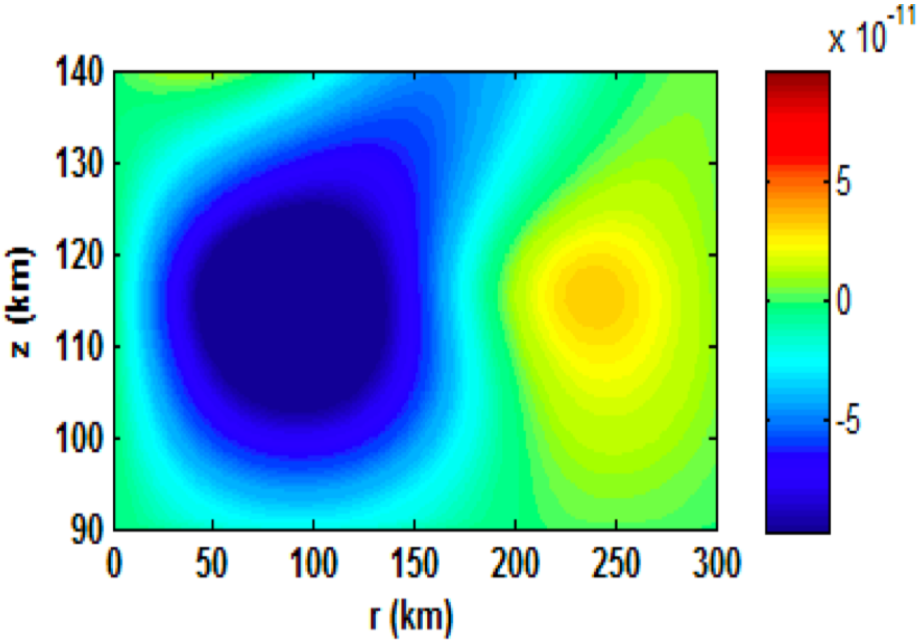
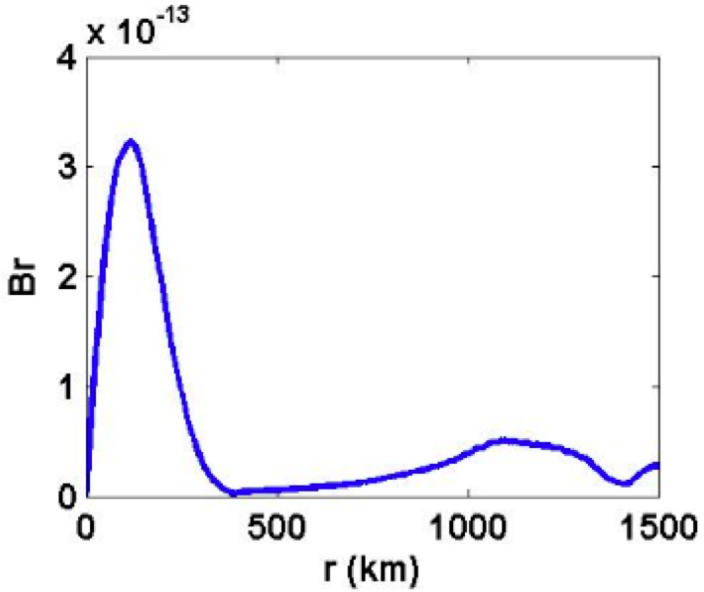
0
-1
1000
500
0
z (km)
0
500
1000
1500
r (km)

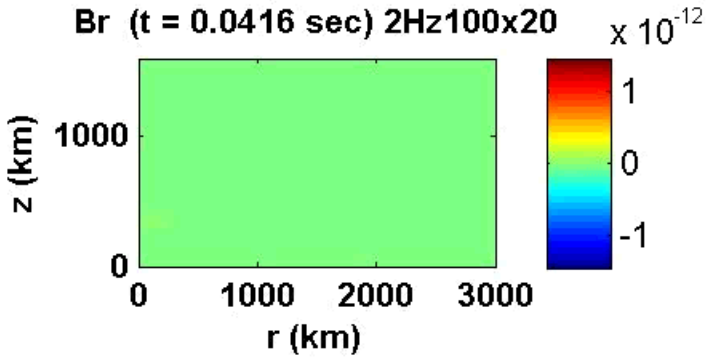
Secondary Antenna Current and Ground Field



J_θ



B_r


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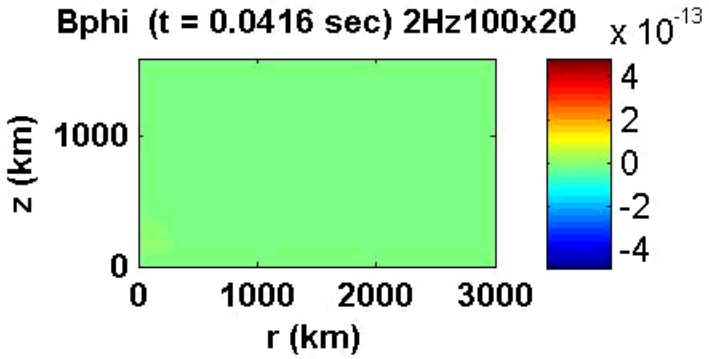
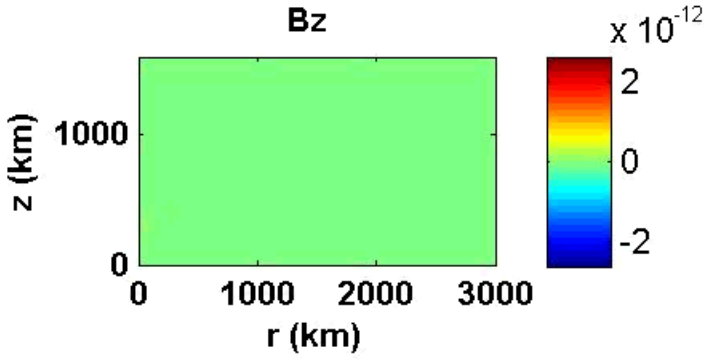
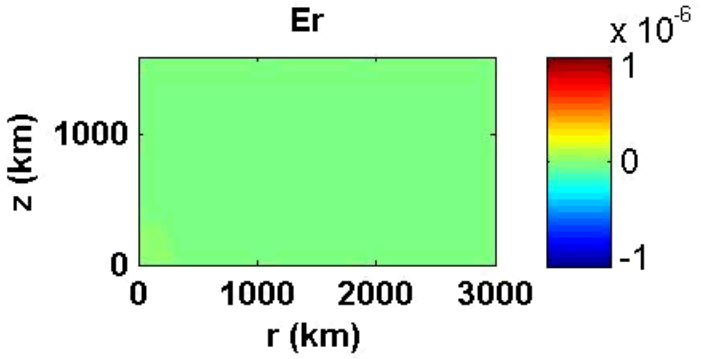
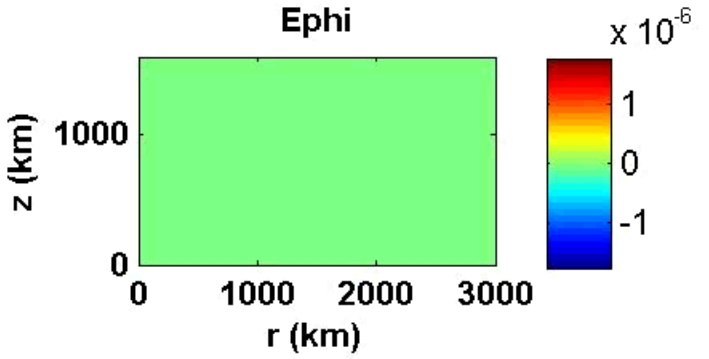
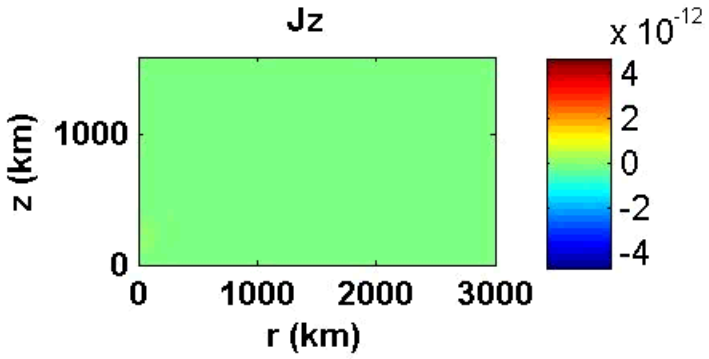
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)


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)

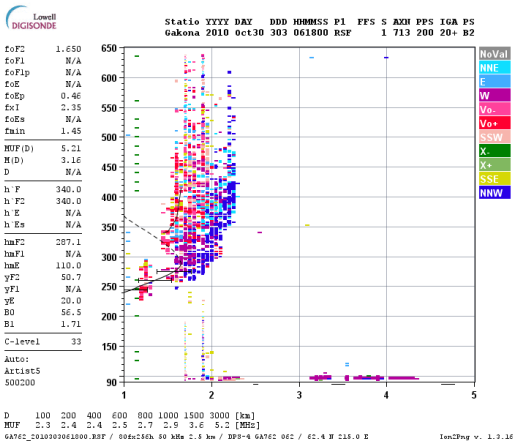

Ephi
x 10^-6
1
0
-1
z (km)
1000
0
0
1000
2000
3000
r (km)

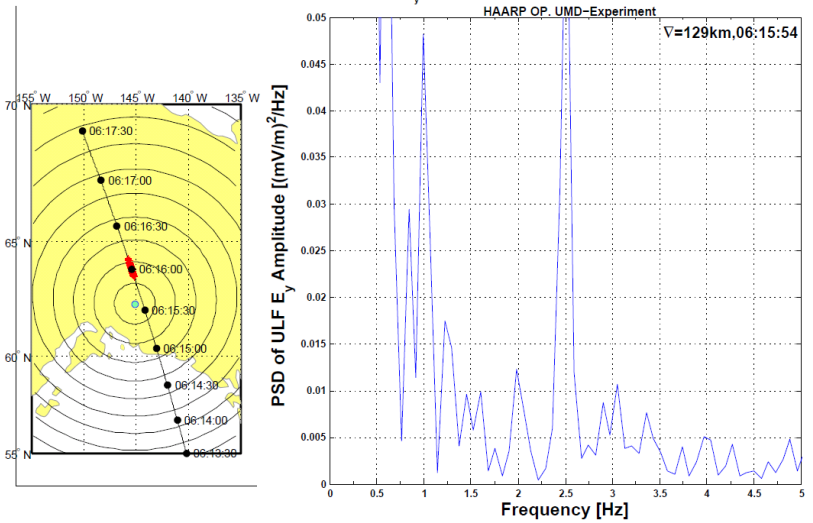

Jz
x 10^-12
4
2
0
-2
-4
z (km)
1000
0
0
1000
2000
3000
r (km)

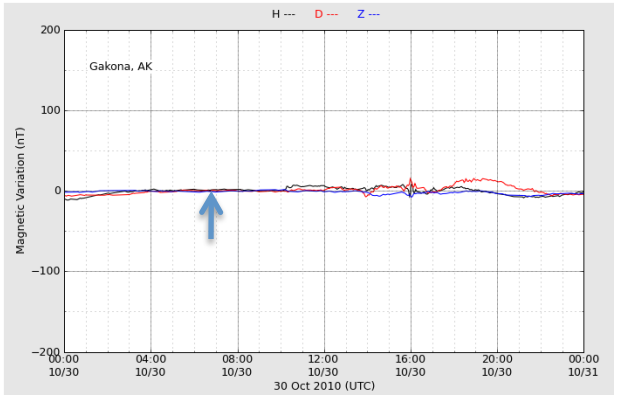
Proof of Concept ICD Experiment – Conducted under DARPA/BRIOCHE

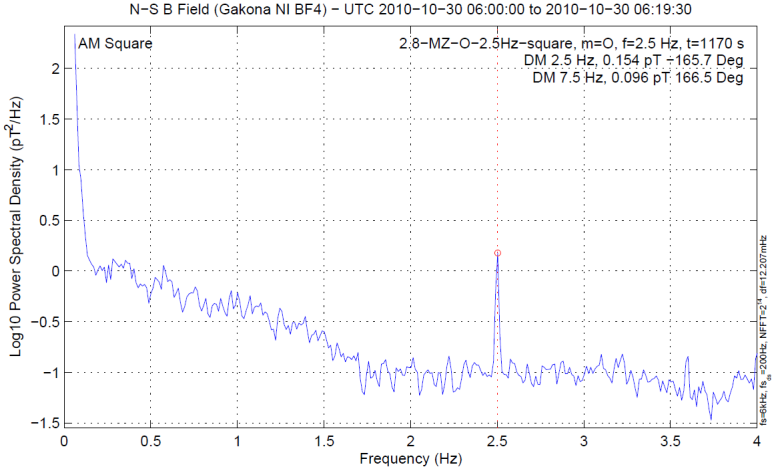
Chang-Lebinsky-Milikh-Papadopoulos

2.8 MHz, O-mode



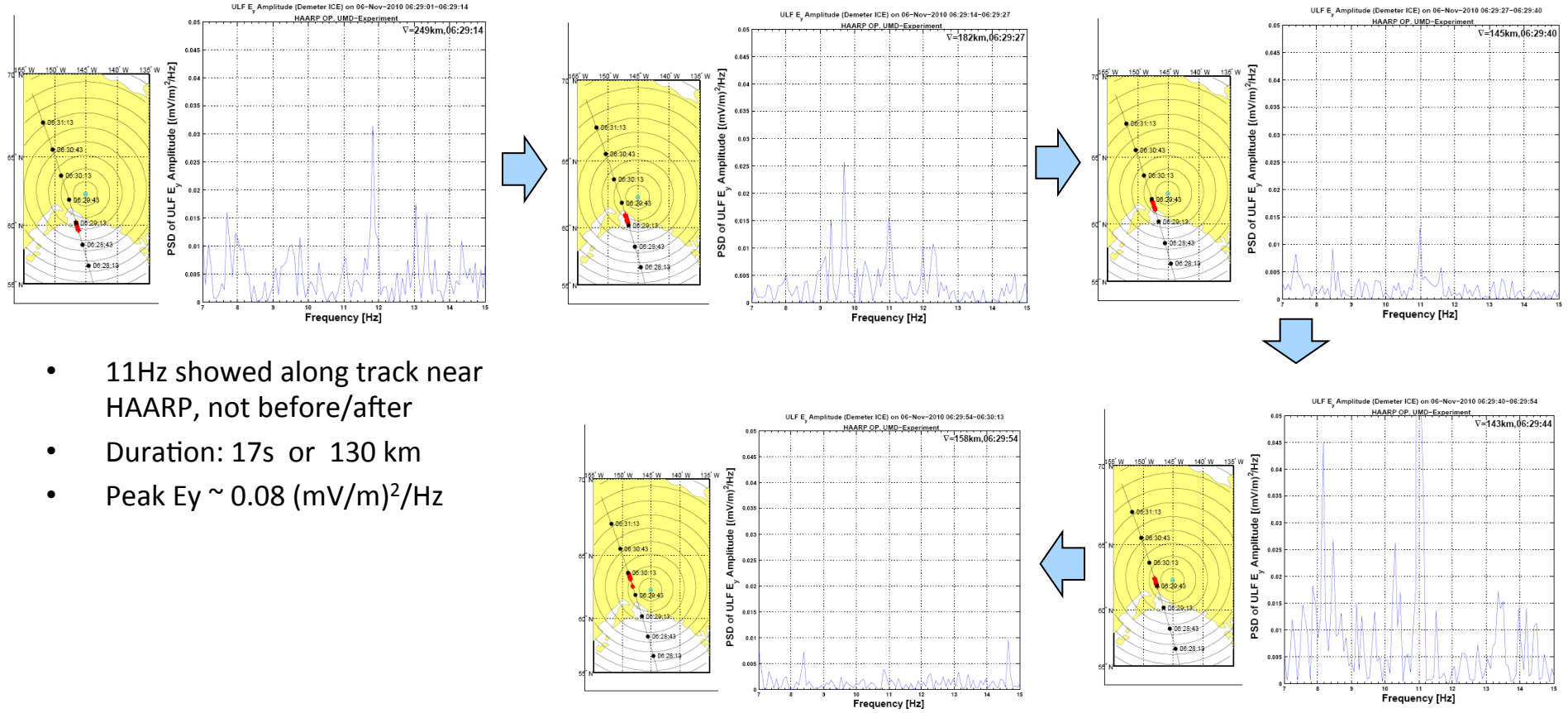






Low ELF Observed by Demeter Satellite

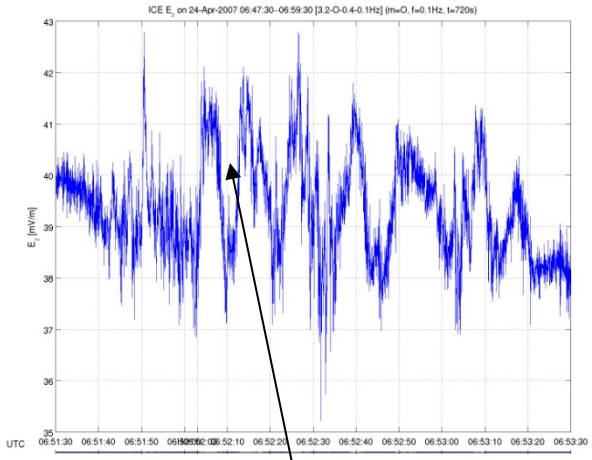
2010-11-06, 06:15:00-06:34:30 ELF 11 Hz modulation (O-MZ)



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

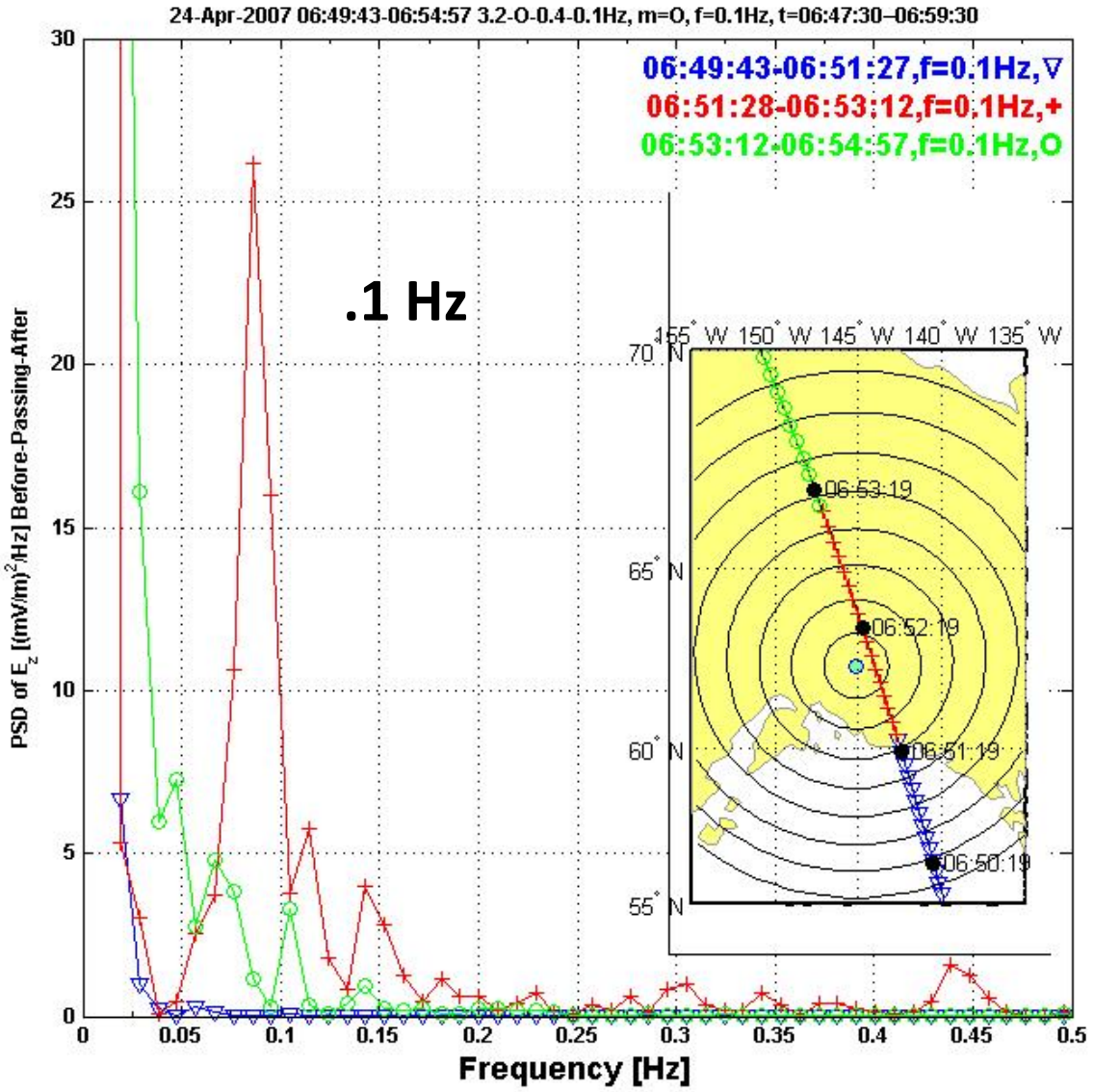
Msonic Wave Injection

DEMETER

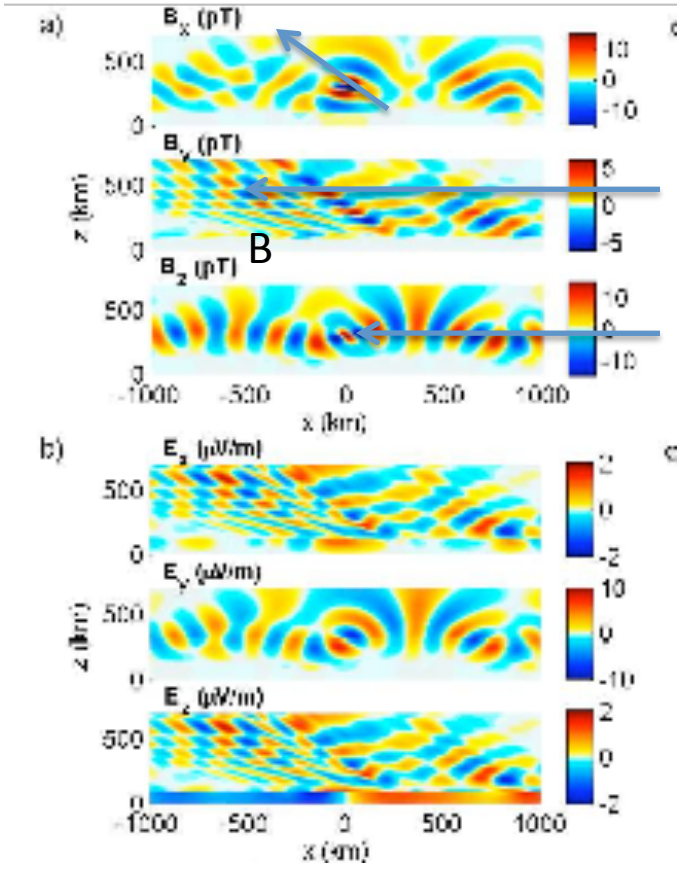


10 sec oscillations

Over 700 km distance

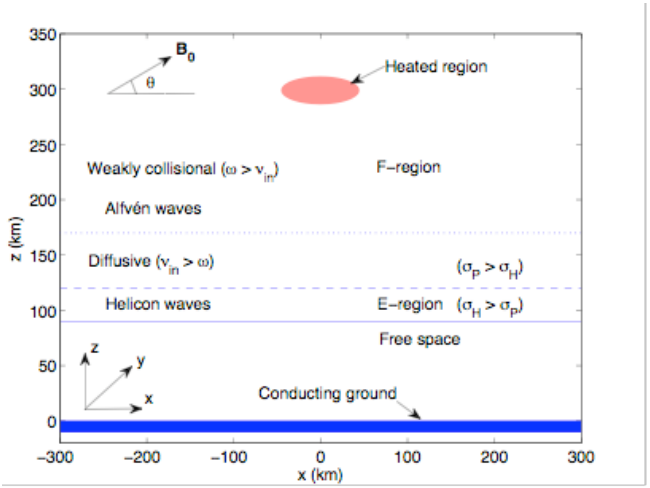


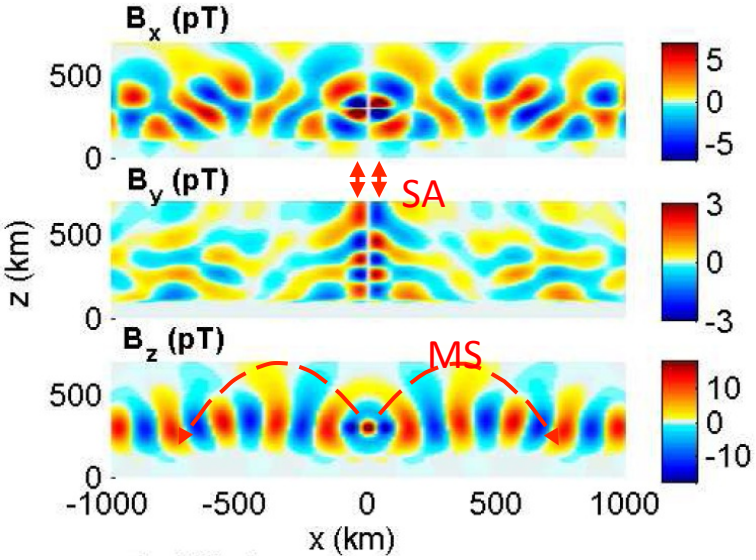
Implications of ICD to RB and RBR – Potential Arecibo/RBSP Tests

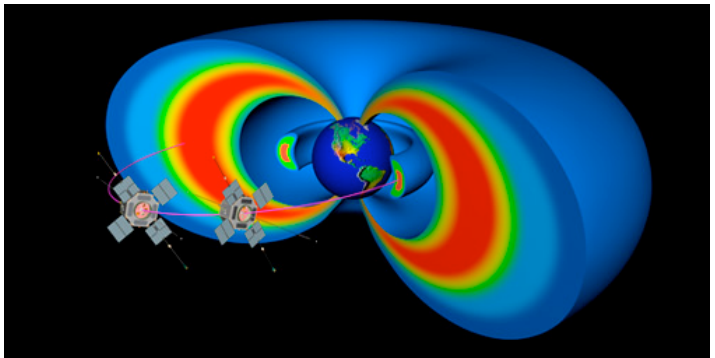


SAW injection

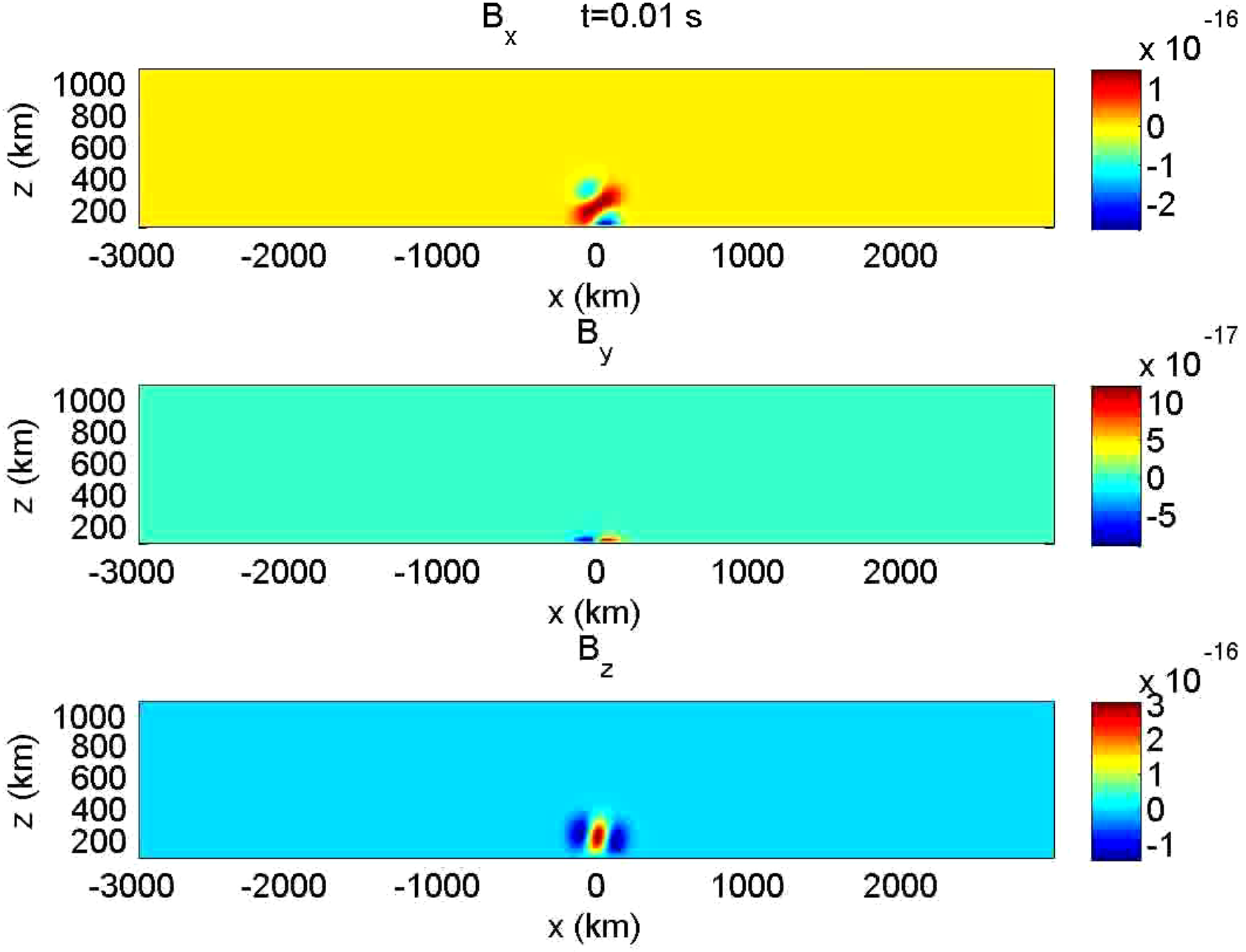
HF heating







RBSP


B x
t=0.01 s
x 10 -16
1
0
-1
-2
1000
800
600
400
200
z (km)
-3000
-2000
-1000
0
1000
2000
x (km)
B y
x 10 -17
10
5
0
-5
z (km)
x (km)
B z
x 10 -16
3
2
1
0
-1
z (km)
x (km)

ICD provides explanation for puzzling Arecibo experiment

Ganguly-Gordon-Papadopoulos PRL 1985

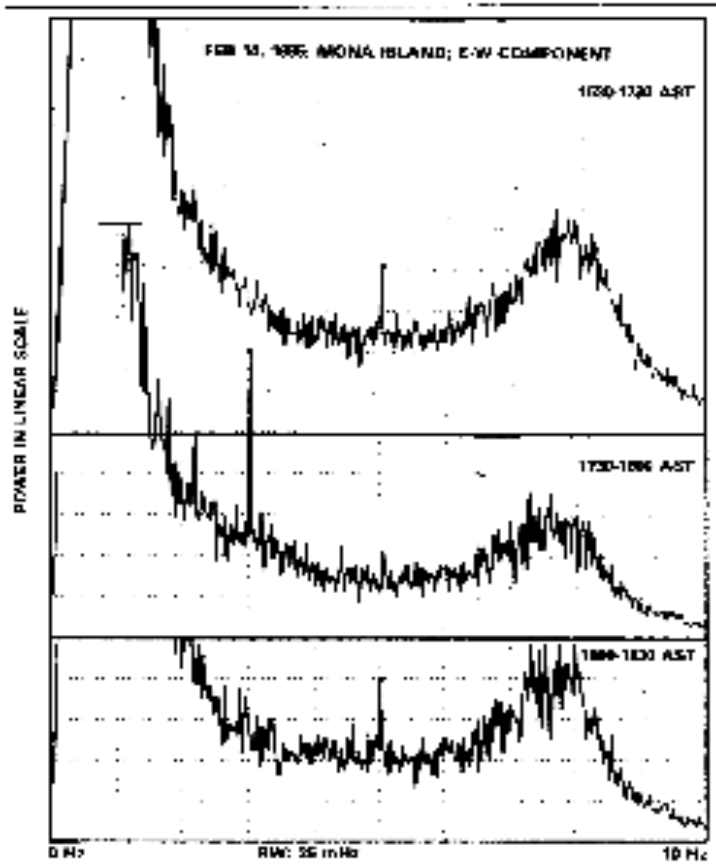
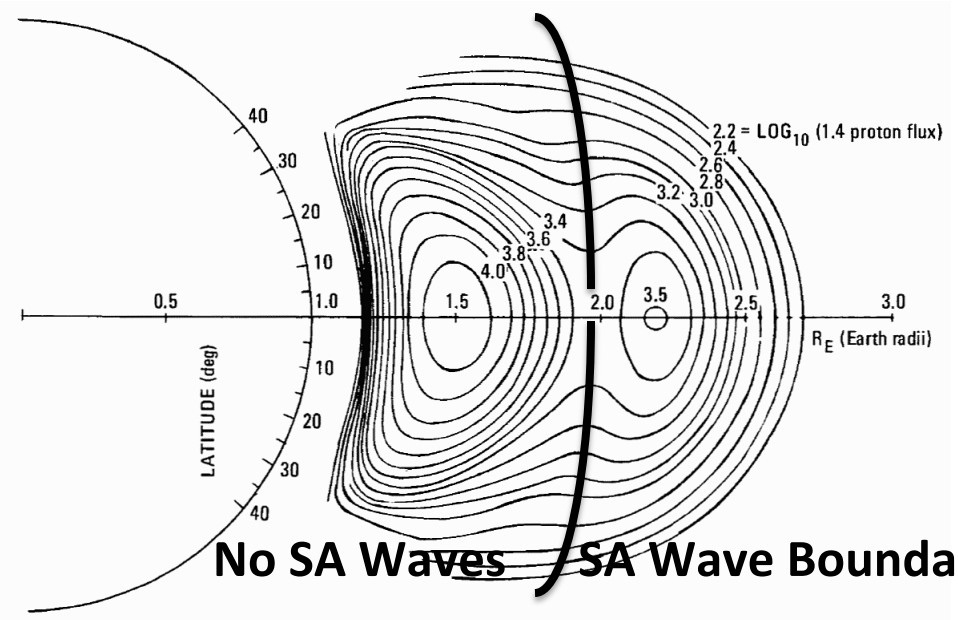
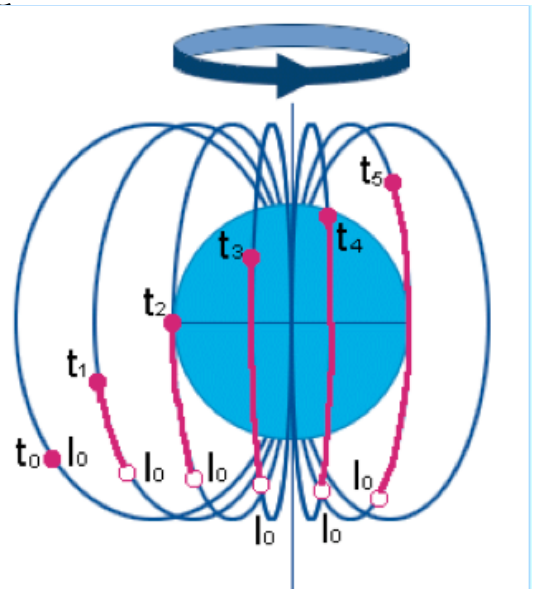


FIG. 1. Spectra of the received signal in the 0–10-Hz band (14 February 1985). Receiver was located at Mona Island. Data cover the period 16:30–18:30 AST. The HF transmitters were operated at 5.1 MHz and with a difference frequency Δf of 5 Hz during 16:30–17:30 AST, which was changed to 3 Hz during 17:30–18:00 AST and changed back to 5.0 Hz during 18:00–18:30 AST. The magnitude of the 5.0-Hz signal is about 160 $\mu\gamma$ $Hz^{-1/2}$ and that of the 3.0-Hz signal is about 340 $\mu\gamma$ $Hz^{-1/2}$.

COMPLEMENTARY SLIDES

Inner Proton Belt

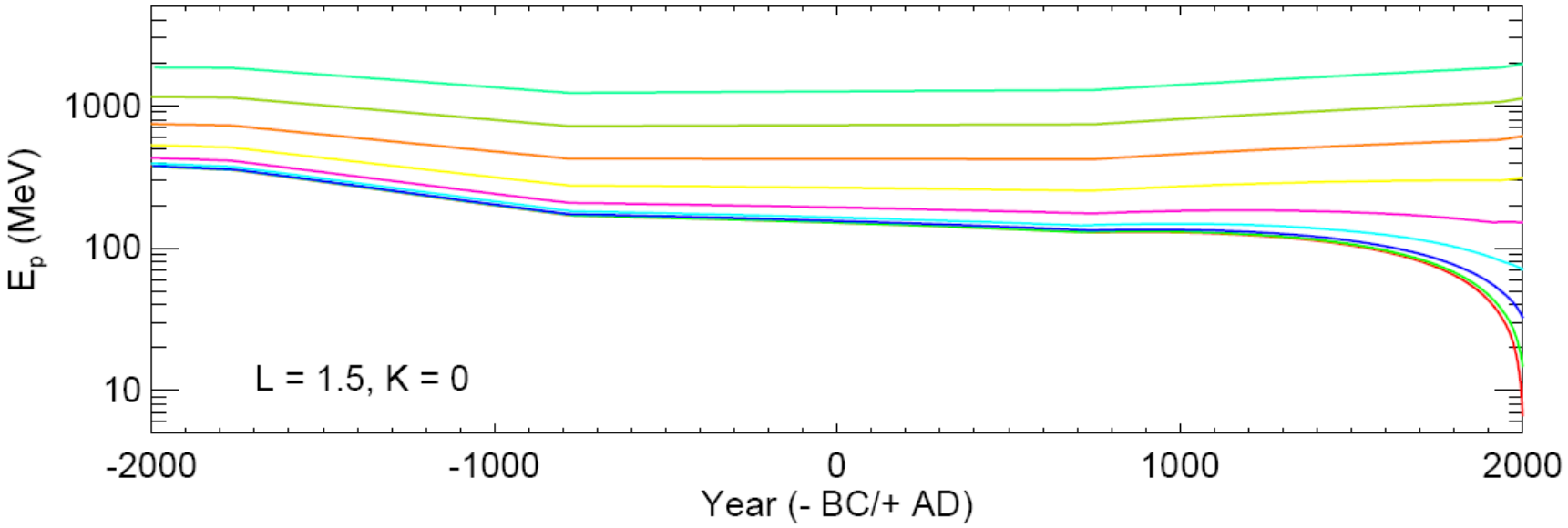




Typical inner belt proton lifetimes:

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

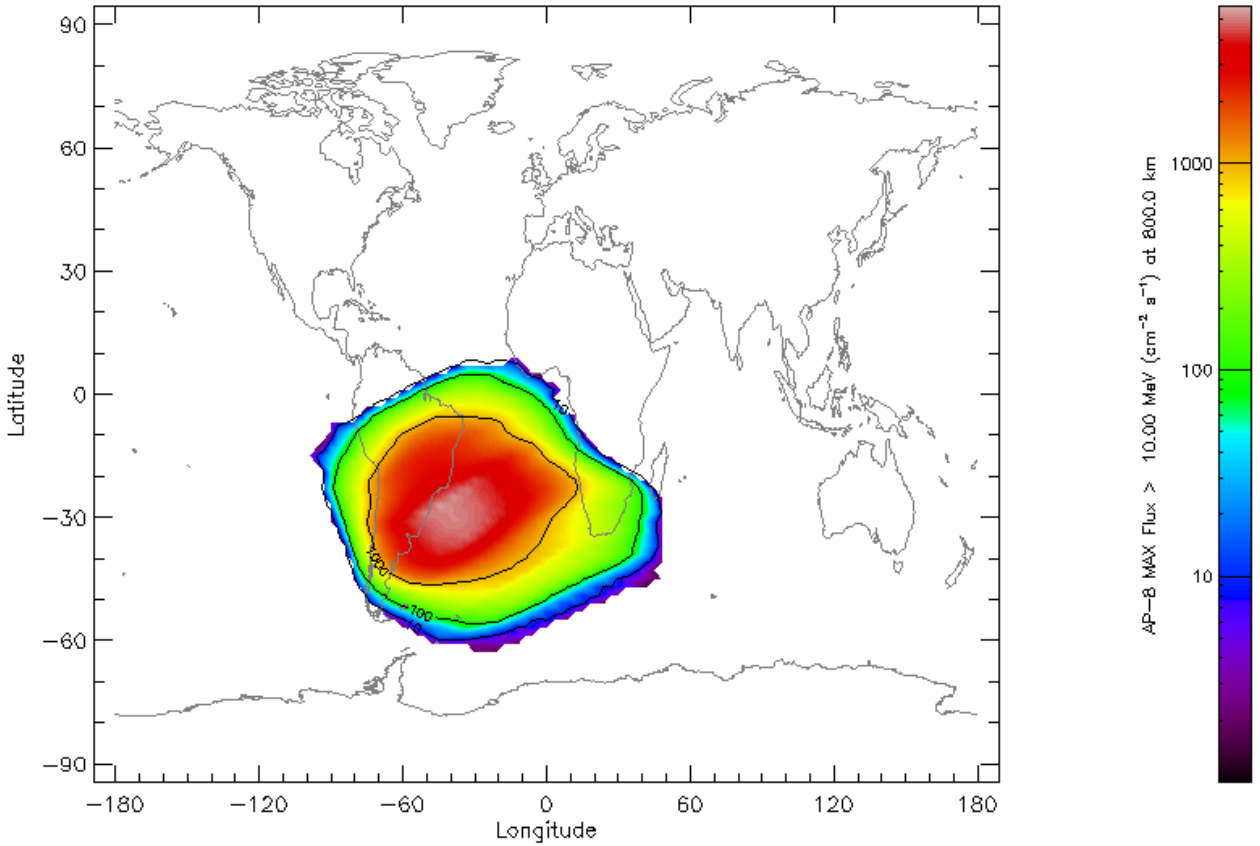
Proton Lifetimes in the Inner Belt are Long



Typical inner belt proton lifetimes:

- 10 MeV – decades
- 100 MeV – centuries
- 1000 MeV – millennia

South Atlantic Anomaly

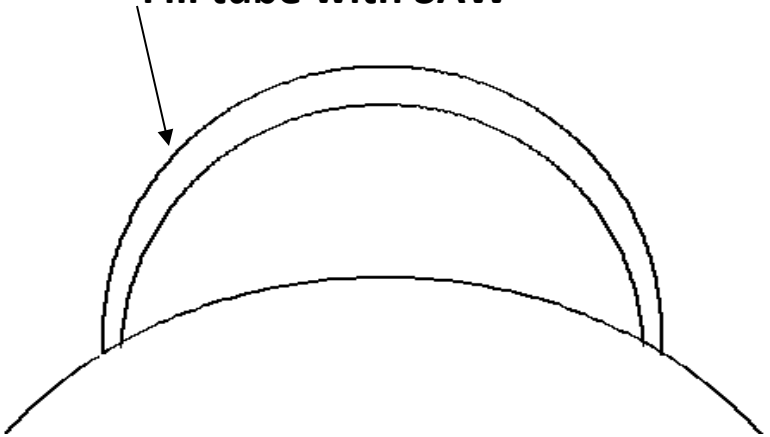


Over the south Atlantic, the inner proton belt is closest to the surface
Protons in this region are the largest radiation source for LEO satellites

Frequency Selection for Protons

Example for L=1.5

Fill tube with SAW

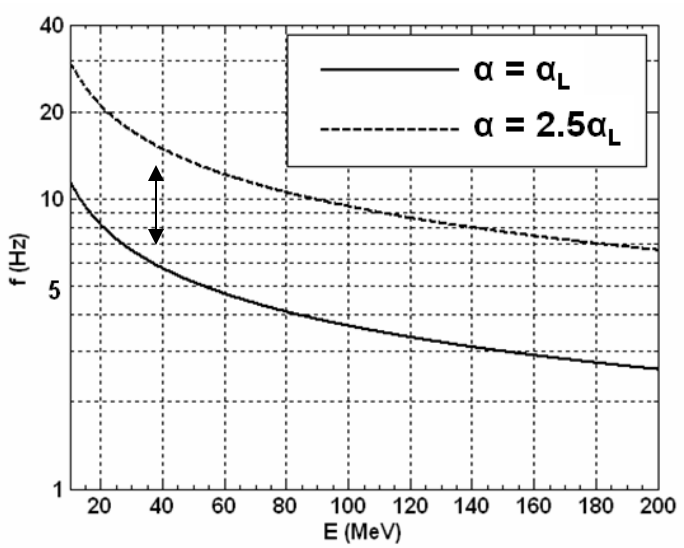


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

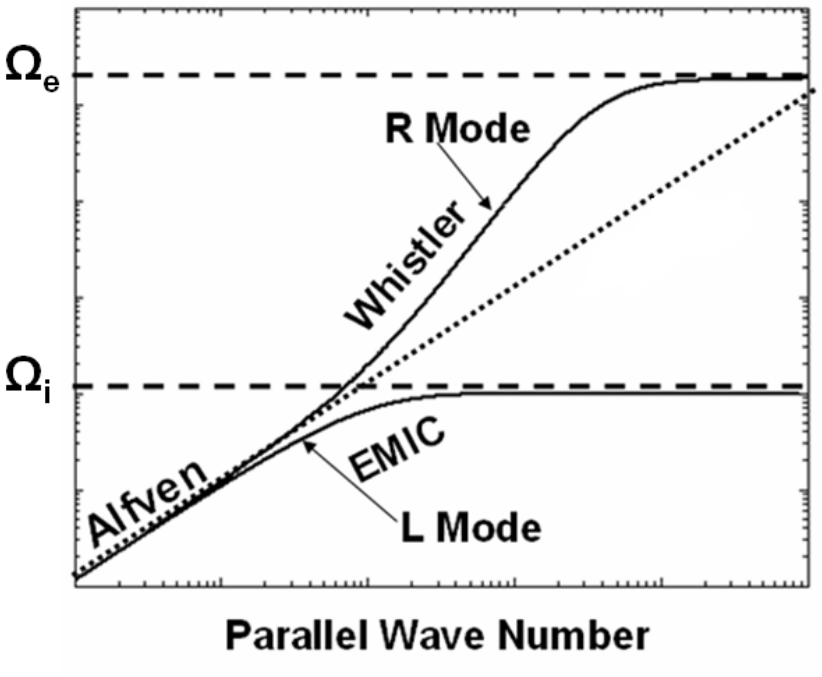
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$



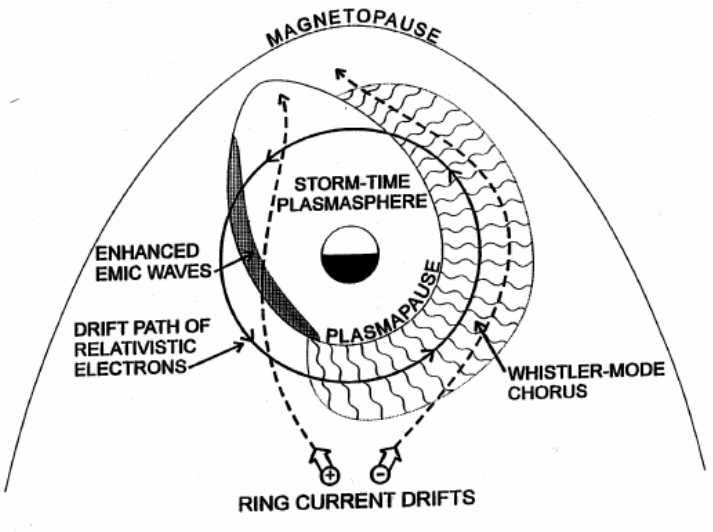
Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz

Frequency Selection for Electrons EMIC

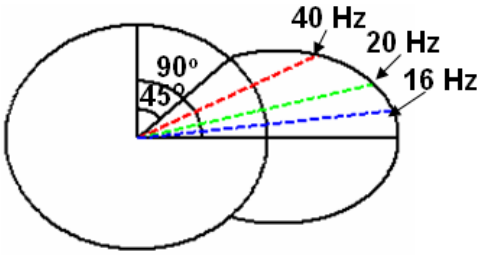


Outer Belts



Summers et al., 1998, 2000, 2003

Helium branch

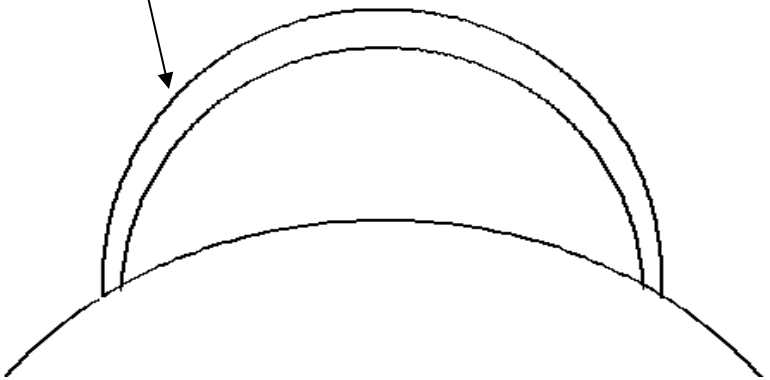


For midlatitude MeV electrons

Frequency Selection for Protons

Example for L=1.5

SAW Injection

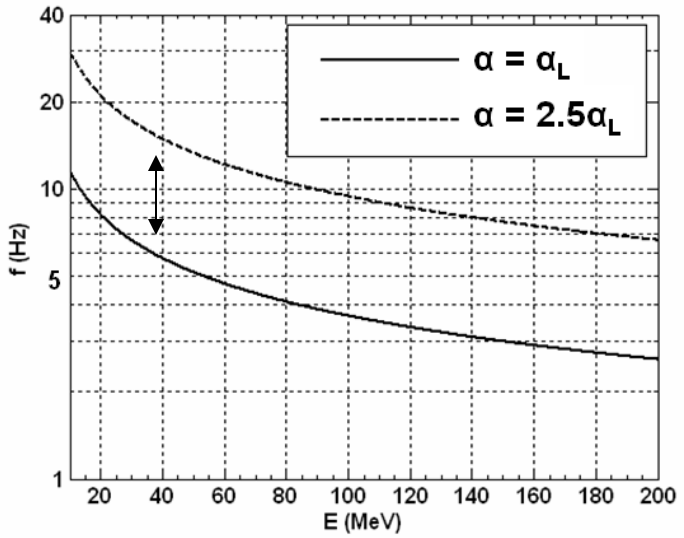


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

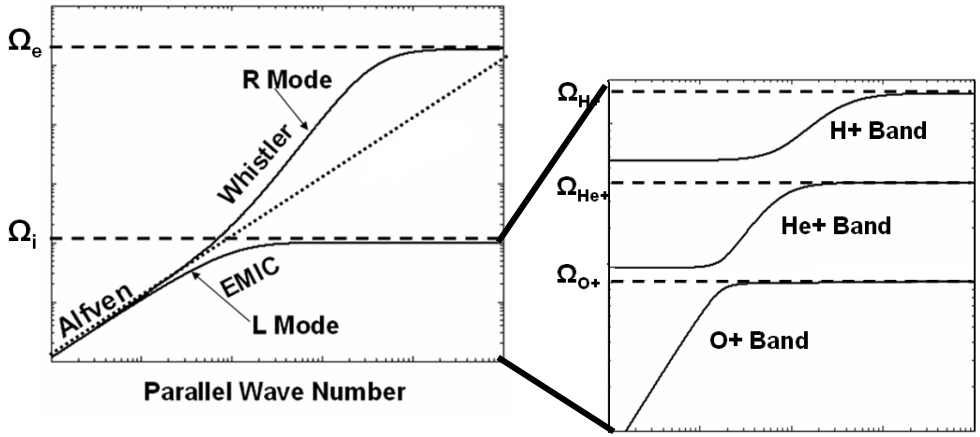
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$



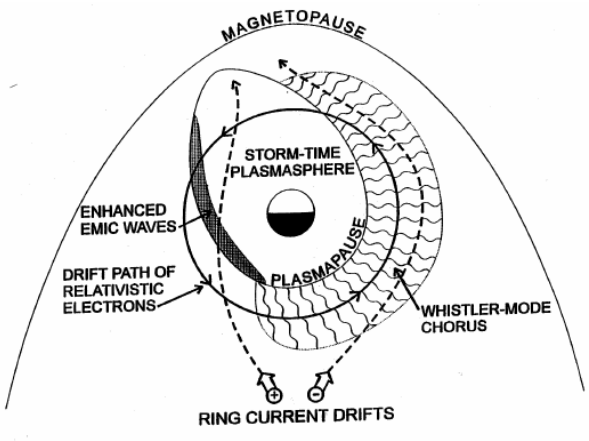
Frequency requirement for equatorial resonance with SAW at L=1.5

Frequency range 5-30 Hz

ENERGETIC ELECTRON WP INTERACTIONS DUE TO EMIC WAVES



Outer Belts



Summers et al., 1998, 2000, 2003

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

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

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

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

HELIUM BRANCH