INVITED TALK TO THE 2013 RADIATION BELT WORKSHOP
JUNE 30-JULY 3, 2013
SANTORINI, GREECE

USING IONOSPHERIC HEATERS TO EXPLORE THE PHYSICS OF THE RADIATION BELTS

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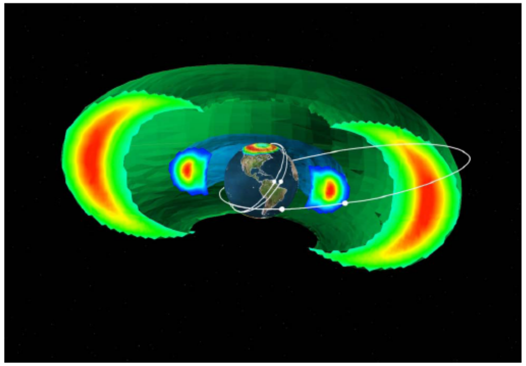
U. INAN STANFORD - MURI
W. GEKELMAN UCLA - MURI

Addressing RB Physics Issues

1. **Conventional System Approach - Passive**

Van Allen Probes



- **Simultaneous multi-point sampling at various spatial scales**
- **High quality satellite data**
- **Ground measurements**
- **Data analysis/ Theory modeling**

GREAT PROGRESS IN RB PHYSICS AND PRDICTIVE MODELS – BUT HINDERED BY

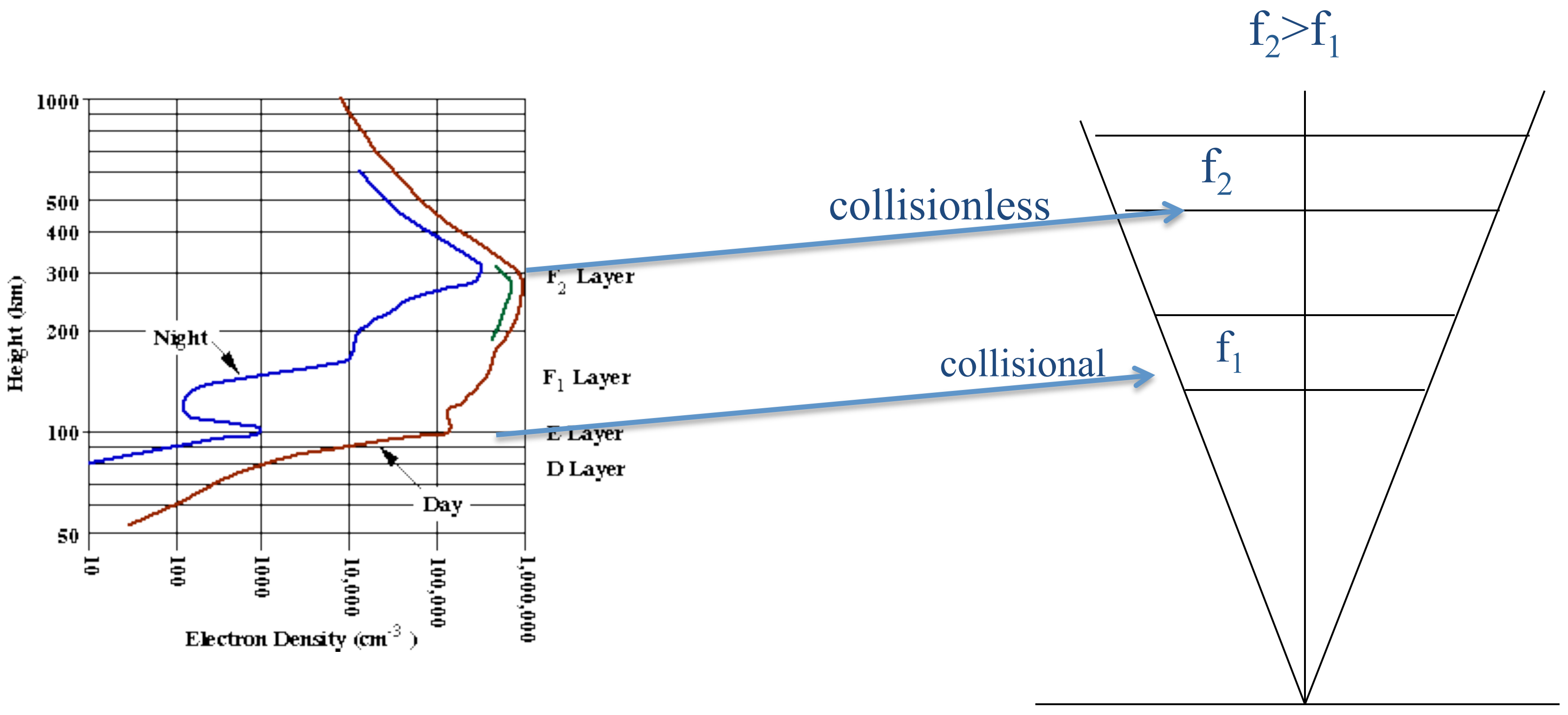
- Scarcity of measurements
- Characterization of wave source

Particles generate waves – waves make particle distribution unstable - **Chicken and Egg Problem**

2. **Complement it with Active -- Cause-and-Effect -- Experimentation and System Component Approach (UMD/ONR MURI Approach; UMD-Stanford-UCLA-Dartmouth – VA Tech)**

- **Active field experiments using ionospheric HF heaters to inject ULF/ELF/VLF waves in the RB and measuring their effects by space-based and ground-based sensors**
- **Well diagnosed laboratory experiments in space chambers-LAPD at UCLA**

Ionospheric Heater – What it is and what it does

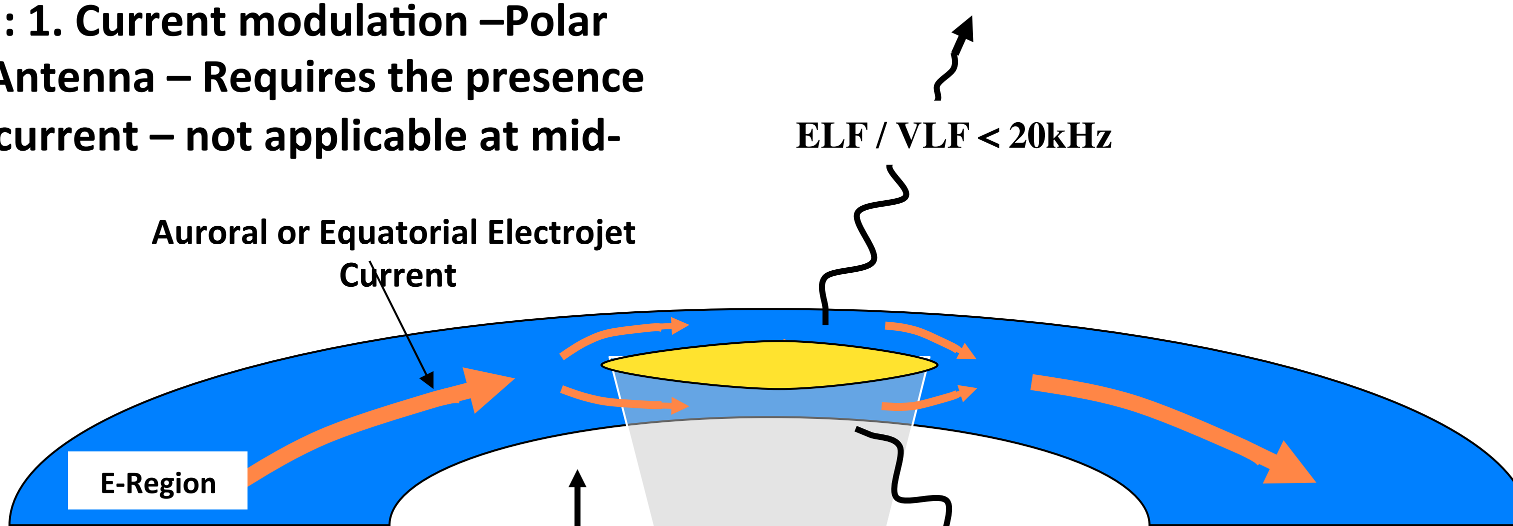


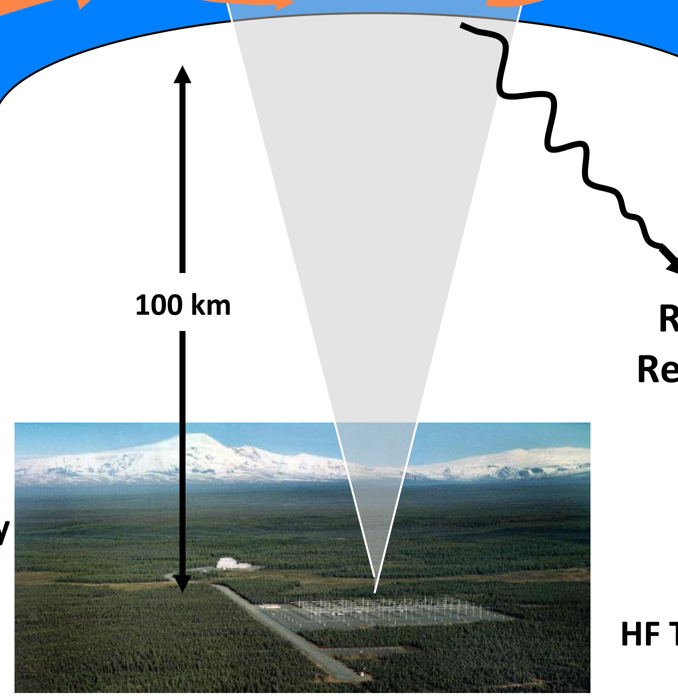
High power RF transmitters between 2.5-10 MHz that deposit energy into the electrons at altitudes 70-100 km (D/E region) or 200-300 km (F-region) in a controlled fashion.

What function of Ionospheric Heaters is relevant to RB Research ?

HF Ionospheric Heaters as “ VIRTUAL” ULF/ELF/VLF Antennae

Two techniques : 1. Current modulation –Polar Electrojet (PEJ) Antenna – Requires the presence of an electrojet current – not applicable at mid-latitude





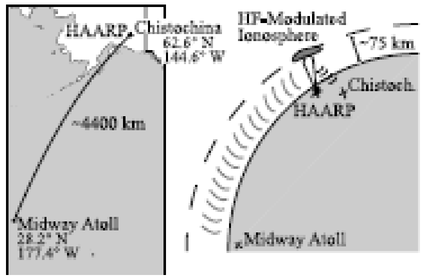
- Natural Currents Flow in the Auroral and Equatorial Ionosphere at 80-100 km
- The HF signal (modulated at ELF/VLF) heats and thereby changes the local conductivity of the ionosphere
- The electrojet current is then caused to vary at the same ELF/VLF rate
- Propagating ELF/VLF signals are radiated by this ‘virtual antenna’

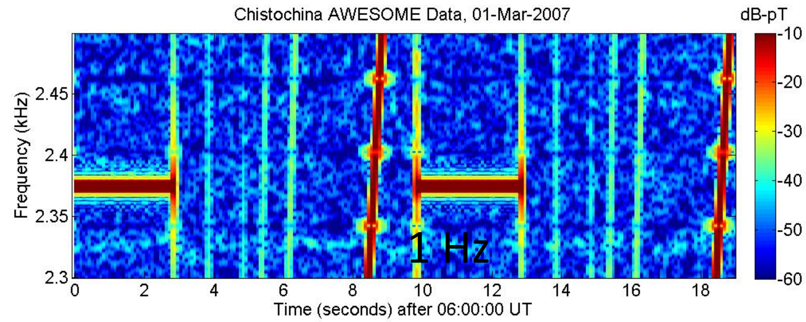
Radiated ELF Signal is Related to the Power of the HF Transmitter

HF Transmitter

PEJ ELF/VLF Ground Detection

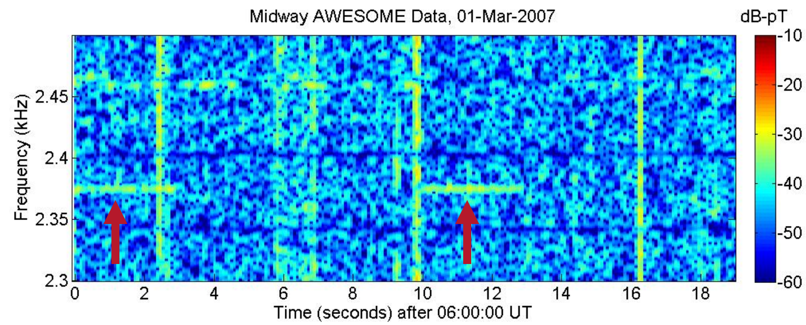
Moore et al.
GRL 2008
Stanford





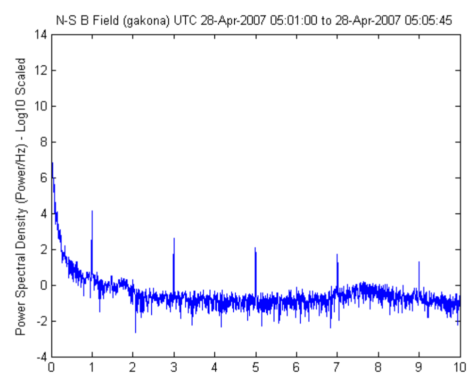
5400
km
away

Midway



Underground sensors 230
km away

Papadopoulos et
al., 2003, 2008
UMD/BAE



PEJ ULF/ELF/VLF Upward Injection HAARP/DEMETER

Frequency .2 Hz

Closest distance 80 km

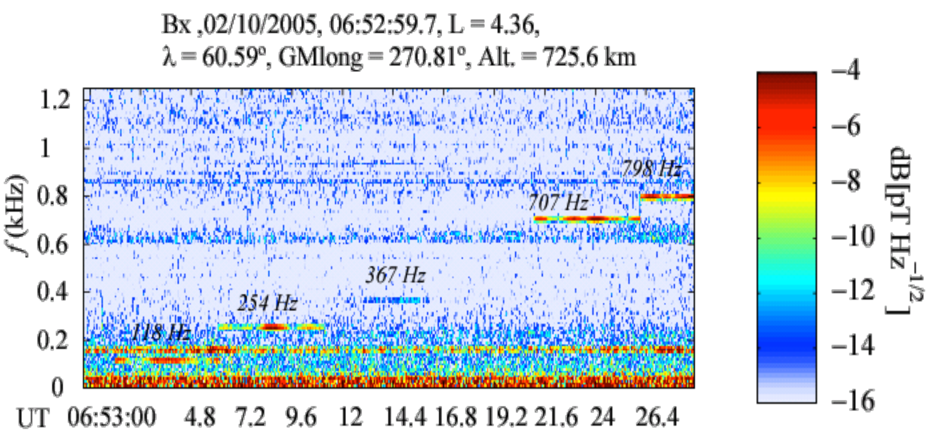
Detection time 25 sec

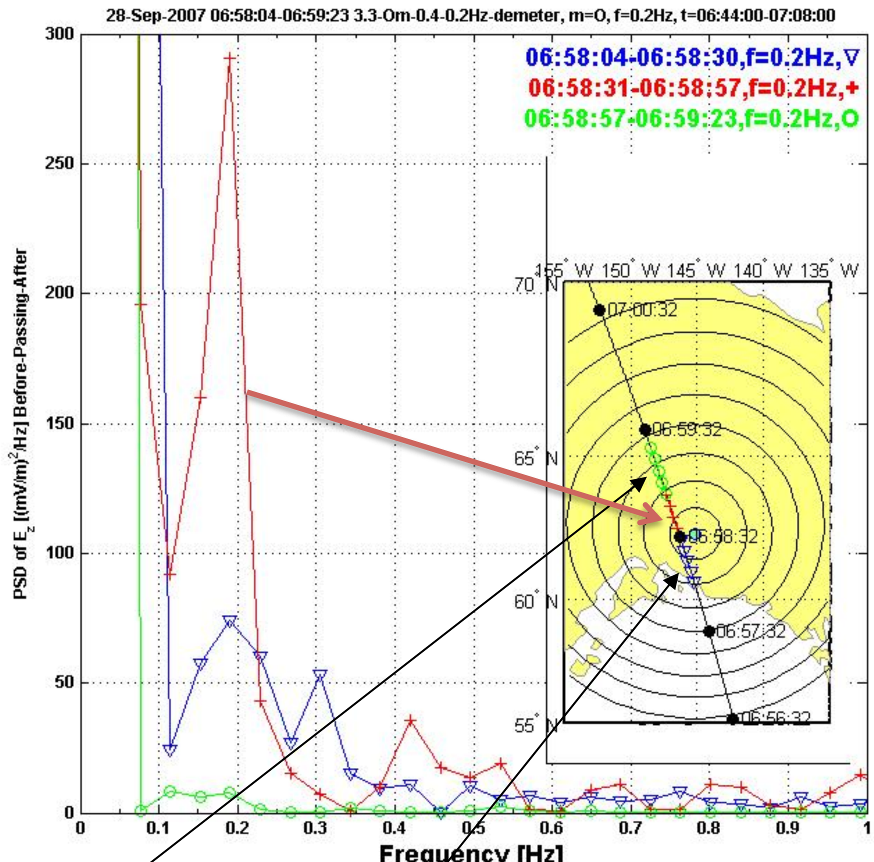
Detection distance 150 km

Maximum E ~10 mV/m

1.5 pT on the ground

DEMETER – 700 km





After

Before

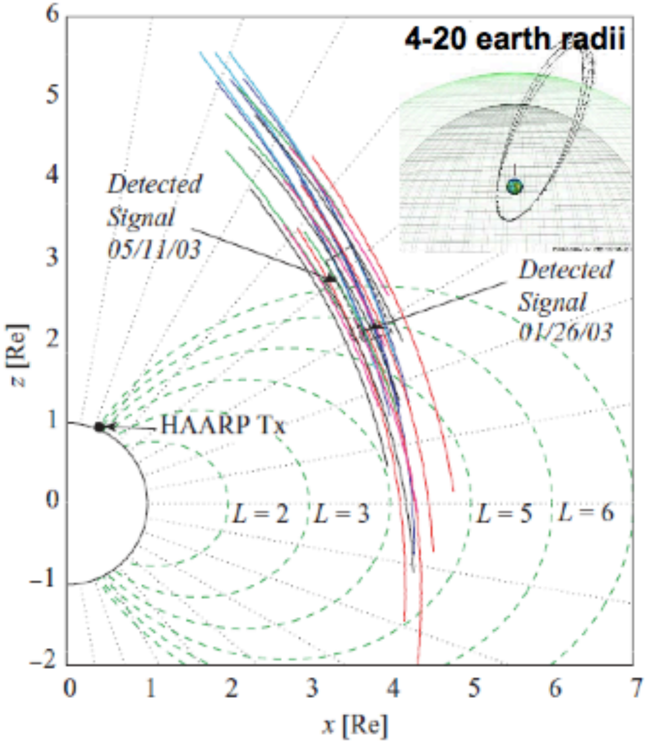
UMD/BAE

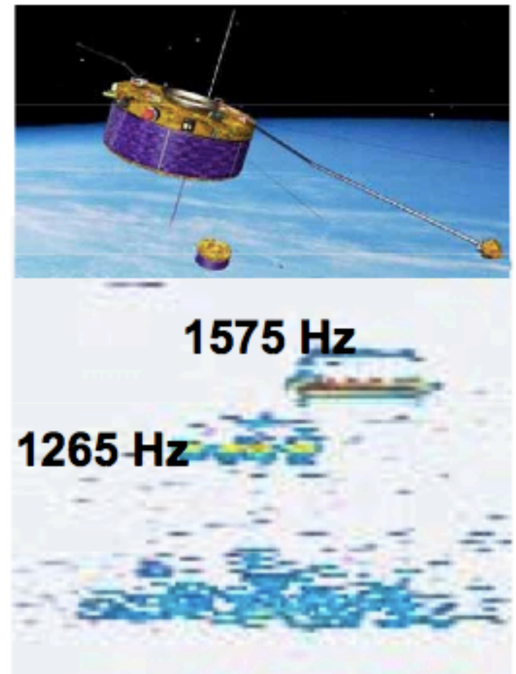
Platino et al., 2006

Stanford

Papadopoulos et al., 2008

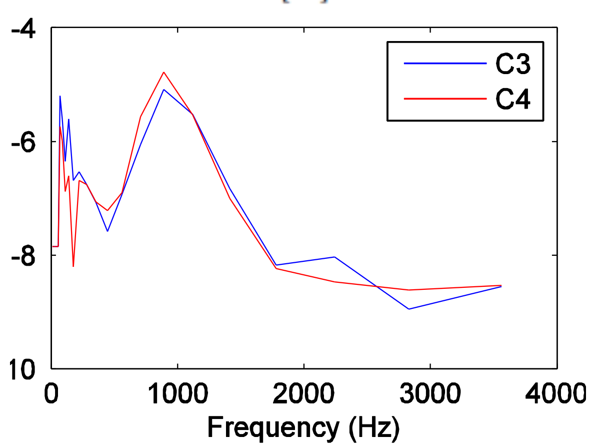
HAARP/CLUSTER





Sideband waves extend several hundred Hz above and below the nominal frequency

Platino et al. 2004



Milikh et al. 2012

F-Region ULF/VLF "Virtual Antenna – Ionospheric Current Drive (ICD)

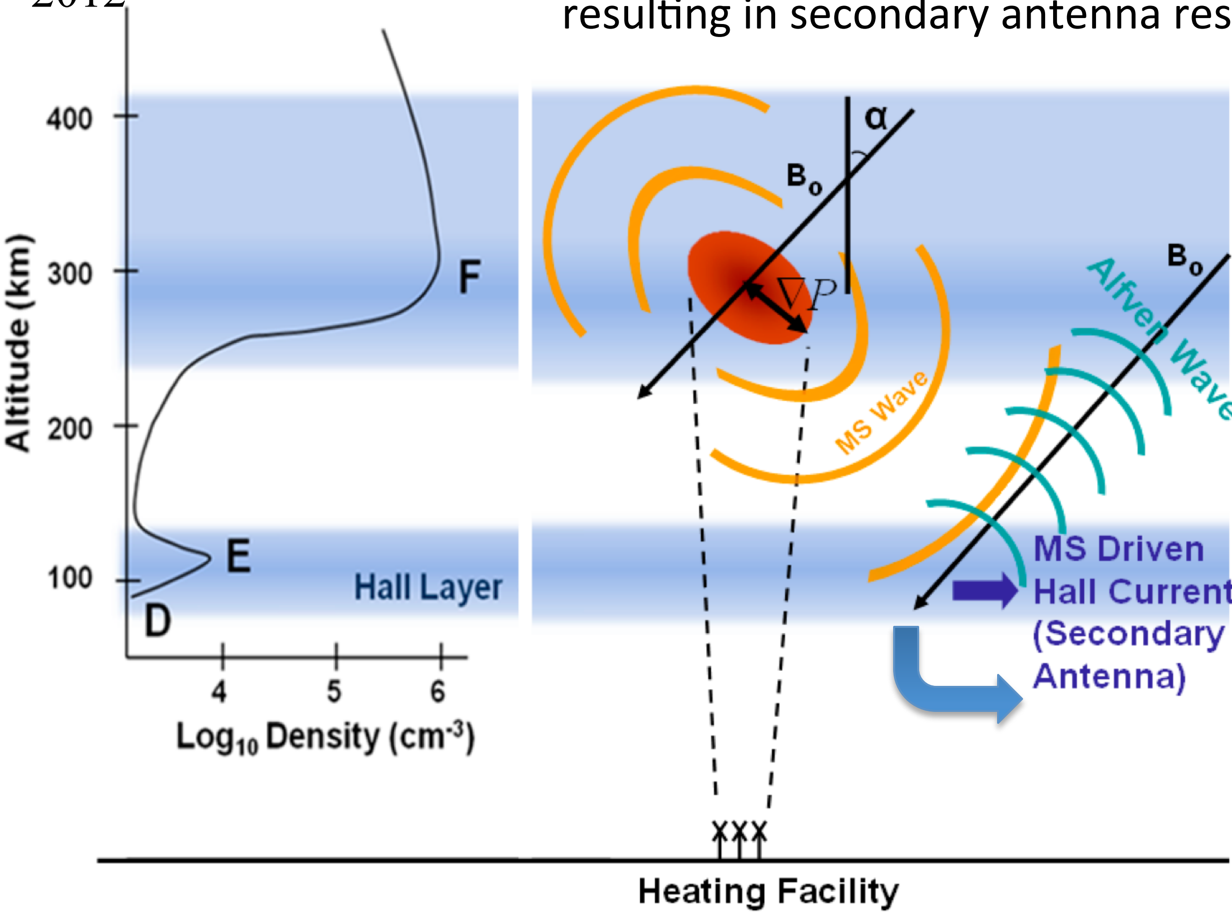
DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

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

Based on Modulated F-Region Heating

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

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

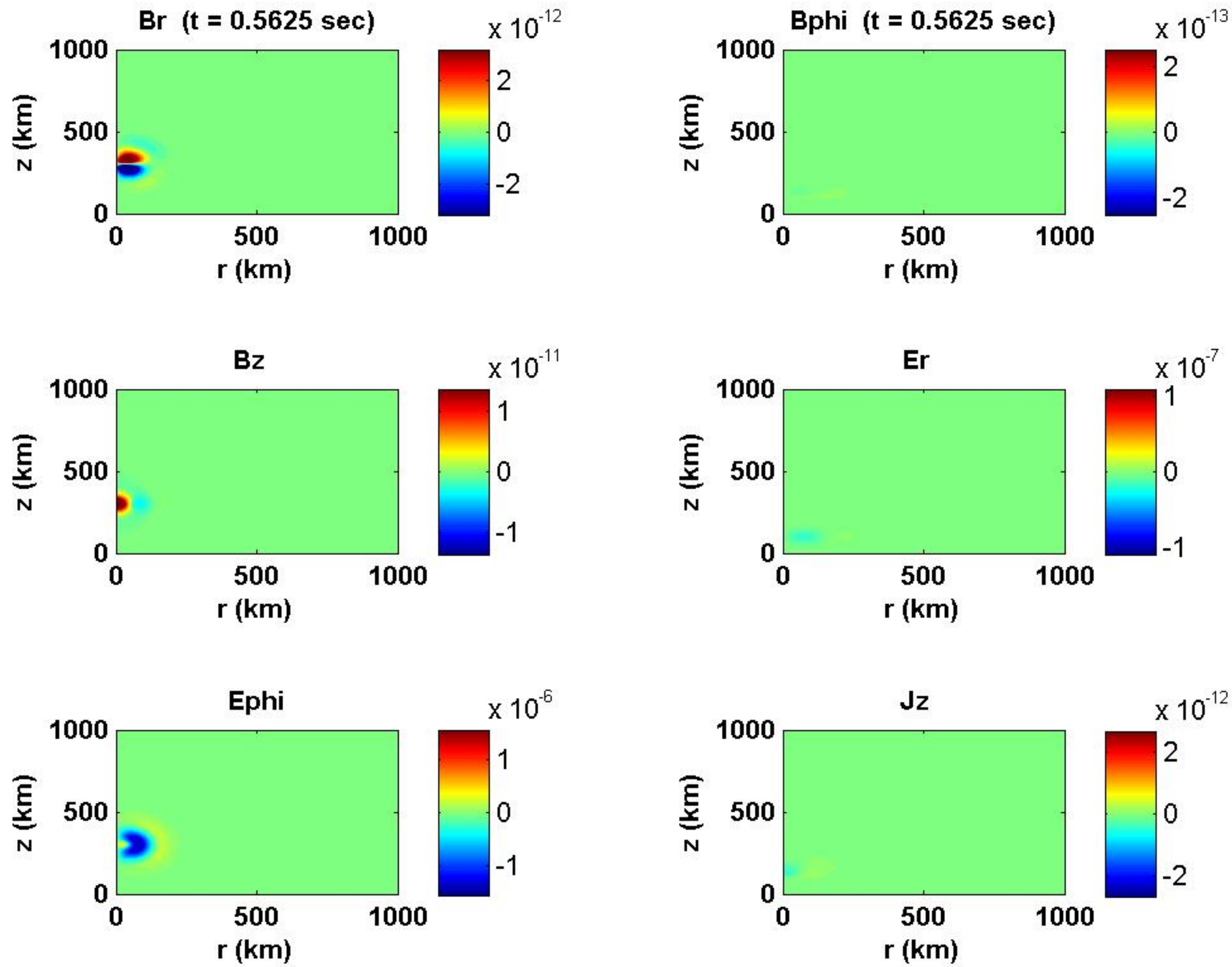


F- region cooling response does not allow frequencies higher than 60-70 Hz

Injects MS & SAW upwards and ELF in the Earth-Ionosphere Waveguide

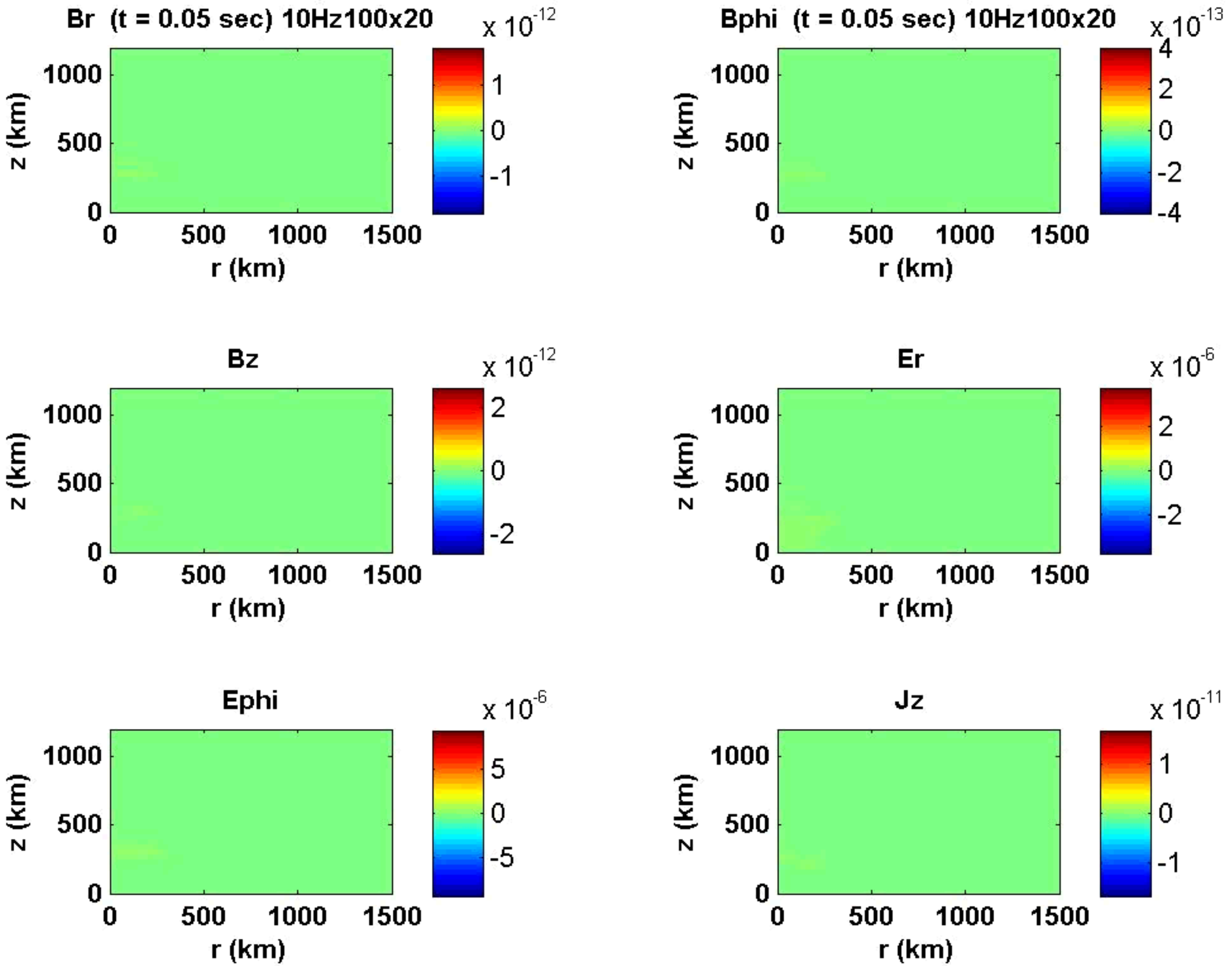
Cylindrical Coordinates

Papadopoulos et al. GRL 2011a



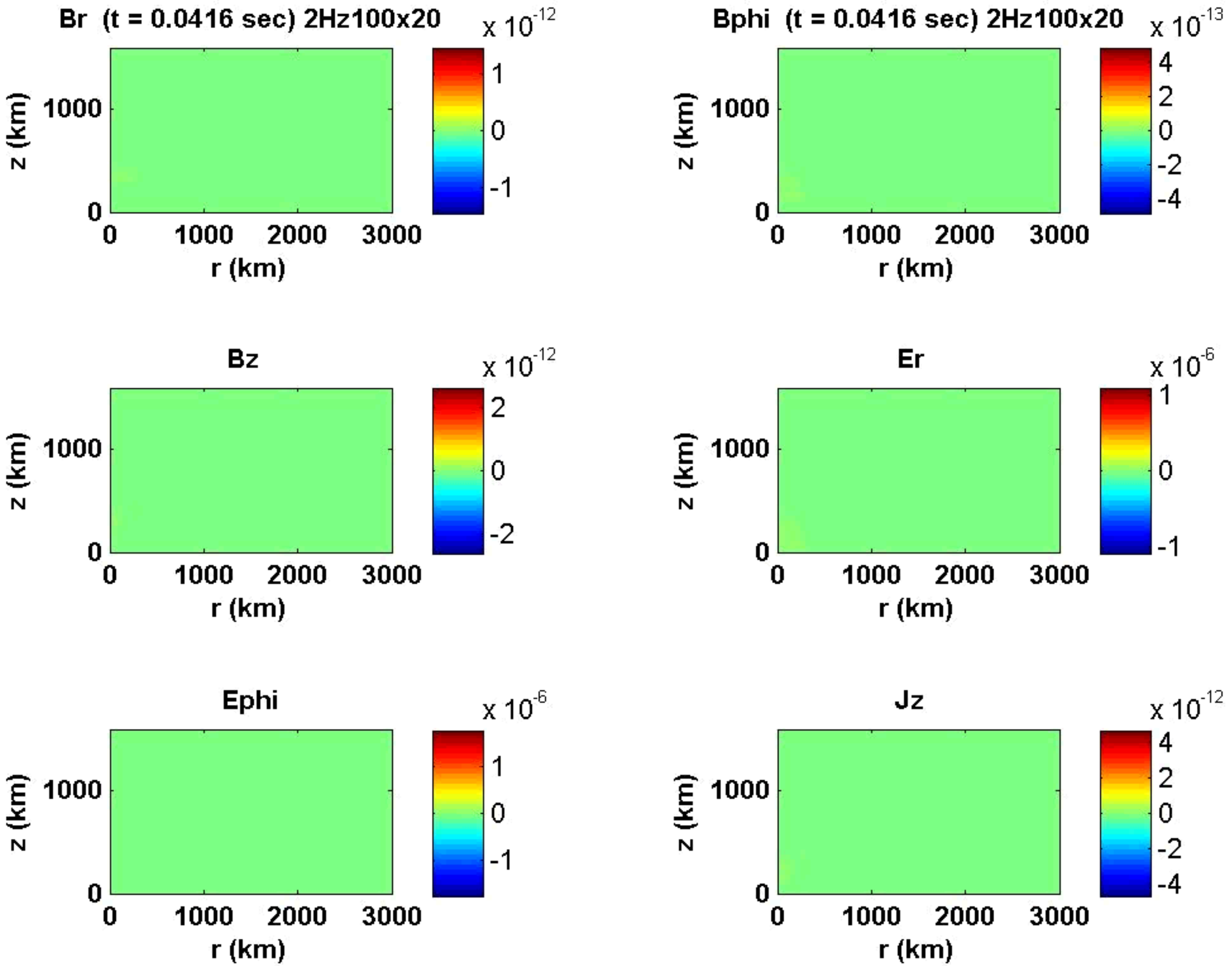
MS

SAW



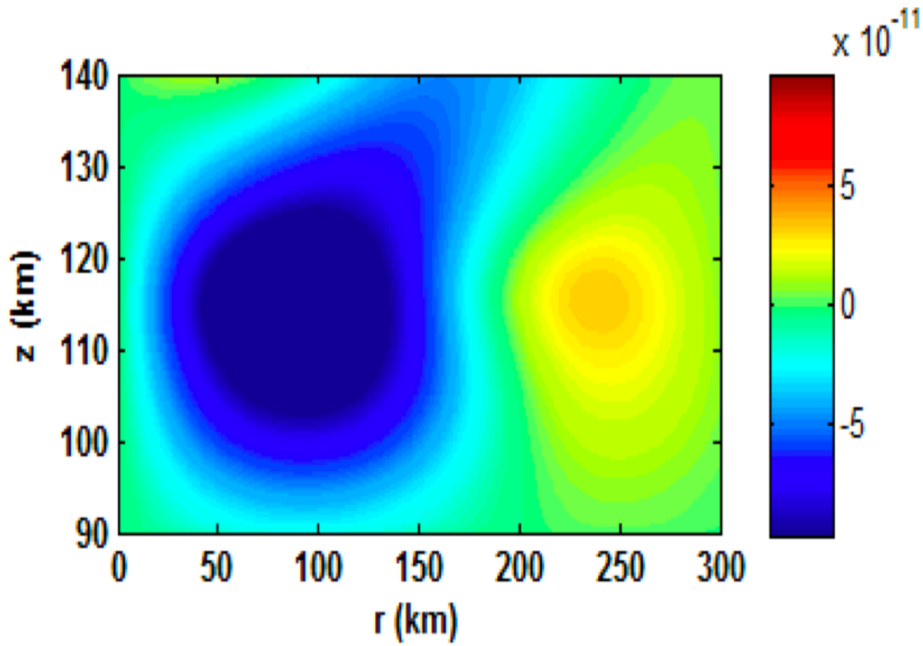
Br (t = 0.05 sec) 10Hz100x20
x 10^-12
z (km)
r (km)
Bphi (t = 0.05 sec) 10Hz100x20
x 10^-13
Bz
x 10^-12
Er
x 10^-6
Ephi
x 10^-6
Jz
x 10^-11

10 Hz



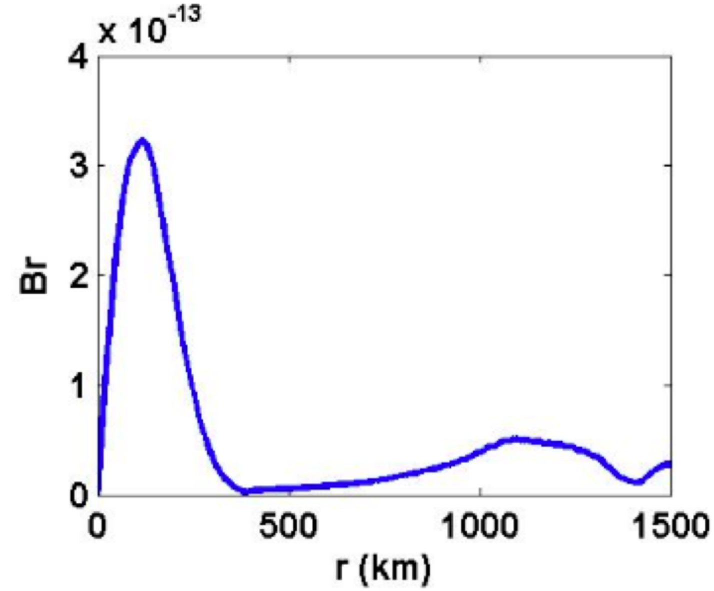
Br (t = 0.0416 sec) 2Hz100x20
x 10^-12
Bphi (t = 0.0416 sec) 2Hz100x20
x 10^-13
Bz
x 10^-12
Er
x 10^-6
Ephi
x 10^-6
Jz
x 10^-12
z (km)
r (km)

Secondary Antenna Current and Ground Field



J_θ

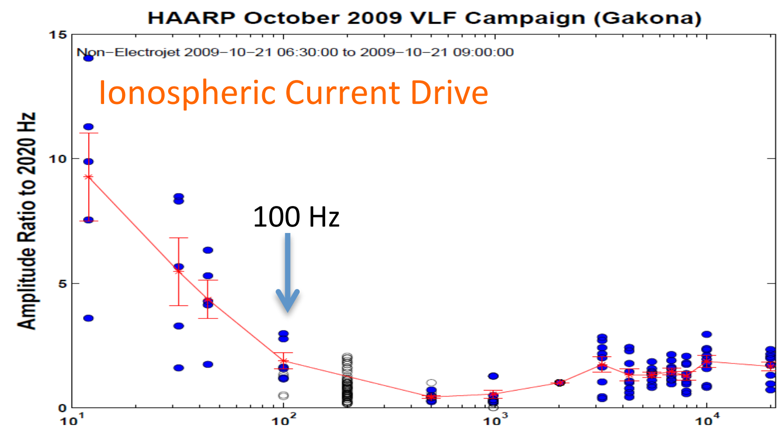
Skip distance

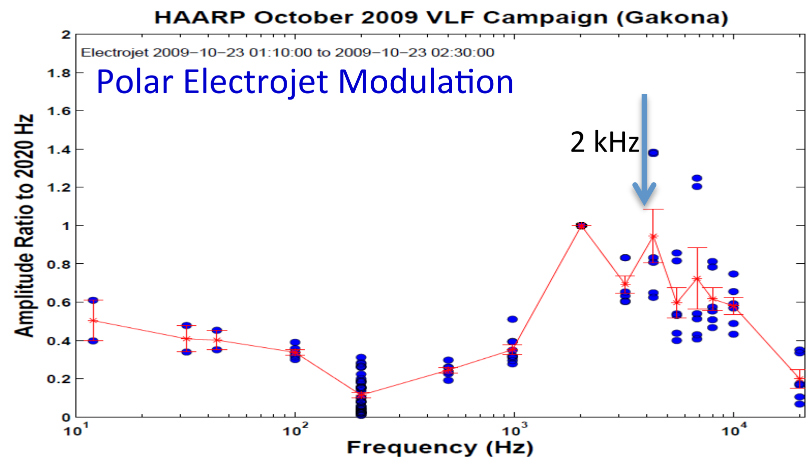


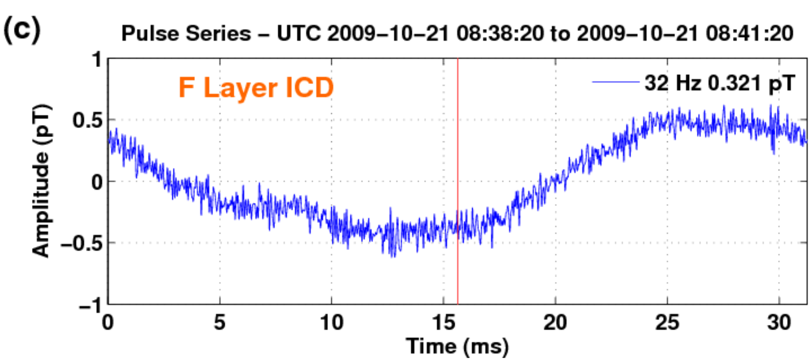
B_r

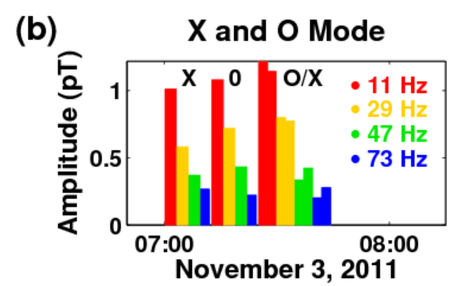
ICD PoP Ground Sensors

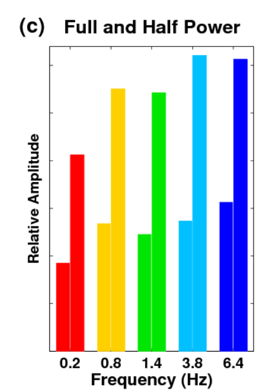
- Ionospheric current drive (*ICD*) produced ULF/ELF waves up to 50-70 Hz
  - F layer mod. - No electrojet
  - < 70 Hz, $1/f^a$ dependence
    - Upper freq. is limited by pressure relaxation time scale of the F layer
    - No O/X effect
- Polar electrojet modulation (***PEJ***) produced ULF/ELF/VLF waves 0.001Hz -20 kHz
  - D/E layers mod. - With electrojet
    - < 1 kHz: plateau
    - 2-8 kHz: peak efficiency
    - > 10 kHz: $1/f^a$ decrease
    - X mode dominant





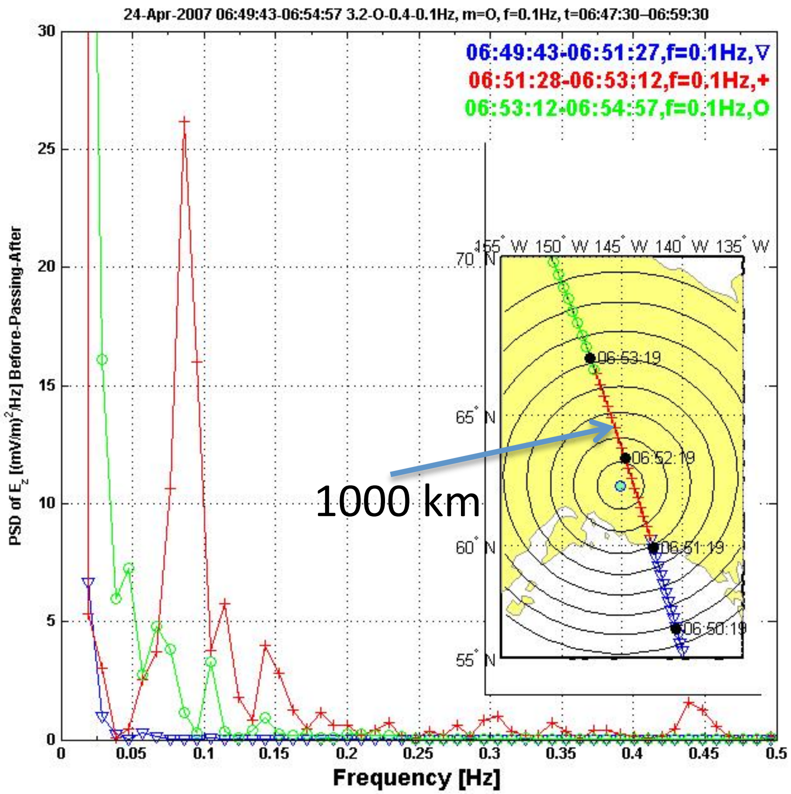


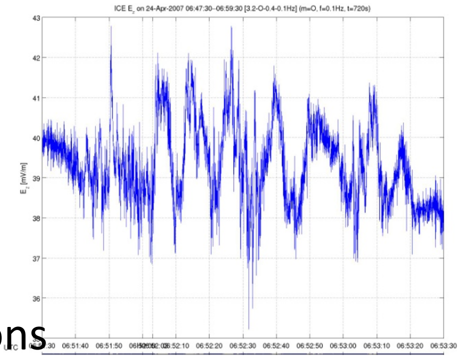




ICD Upward Injection HAARP/DEMETER

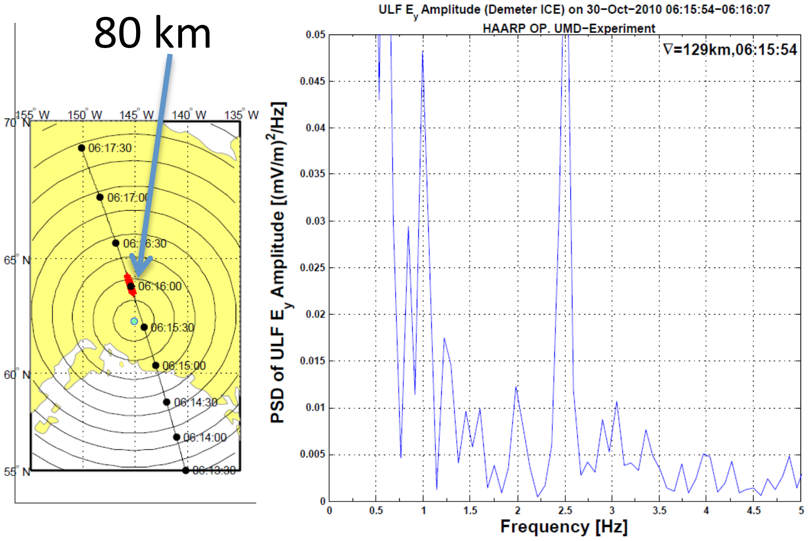
.1 Hz MS

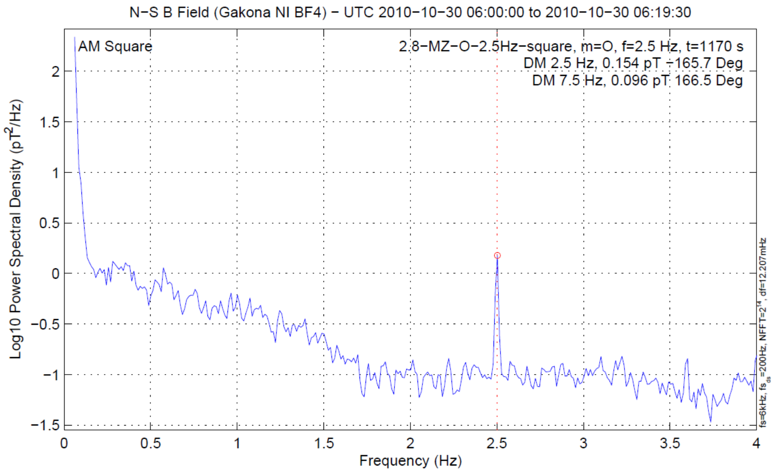




10 sec oscillations

2.5 Hz SAW

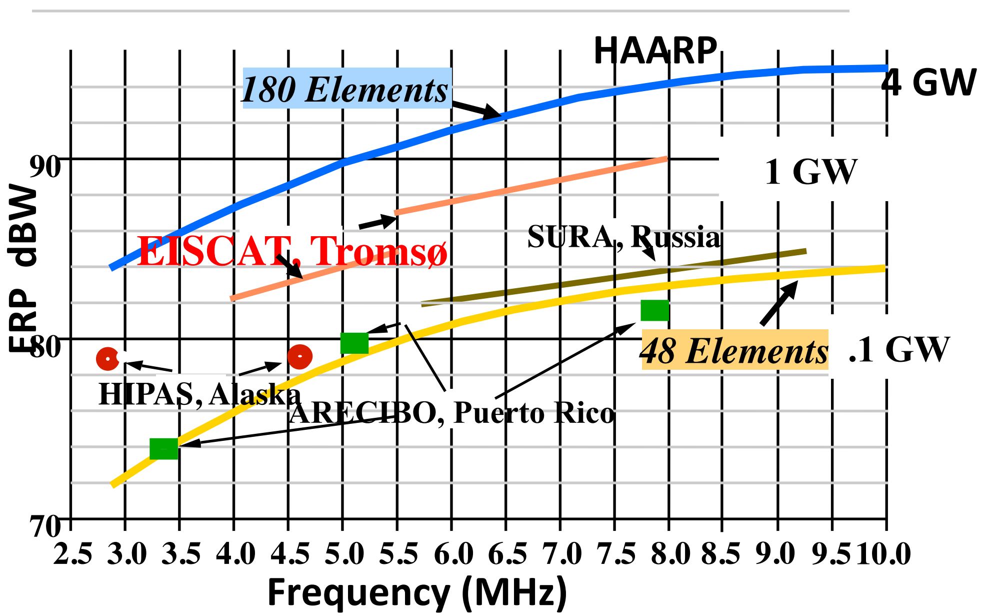




Cause and Effect Studies of the RB Physics

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

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



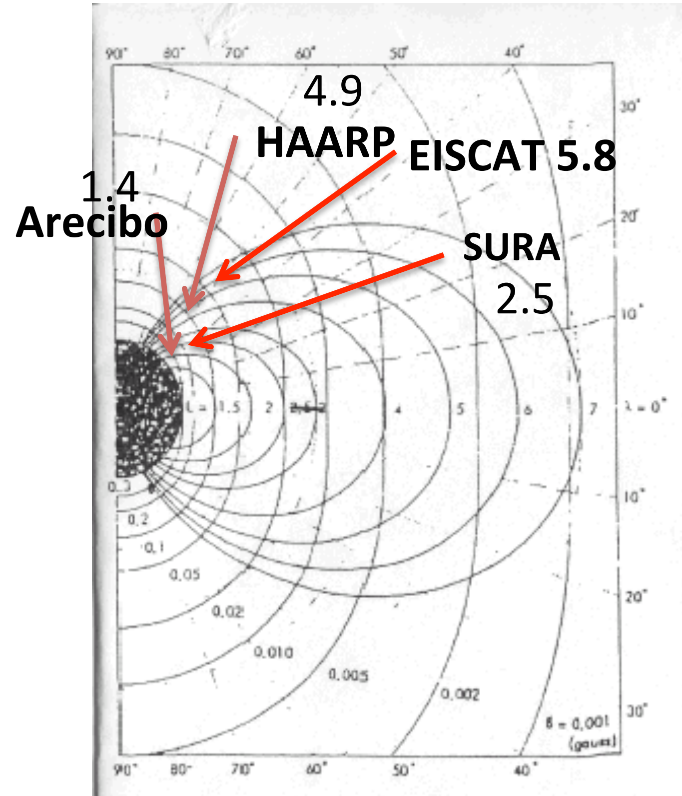
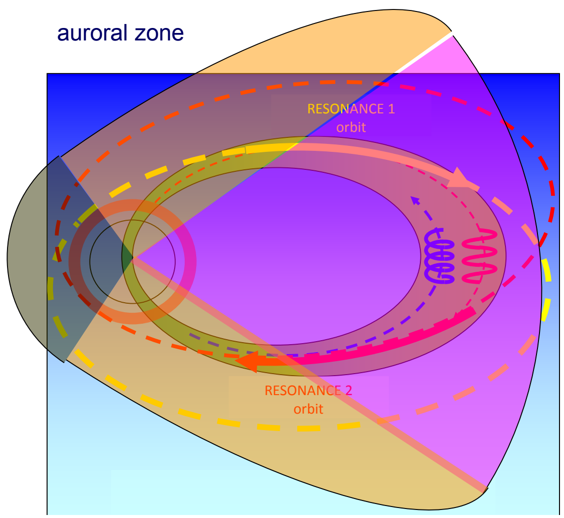


Figure 2-8. Constant-B surfaces in a dipole field.

HAARP

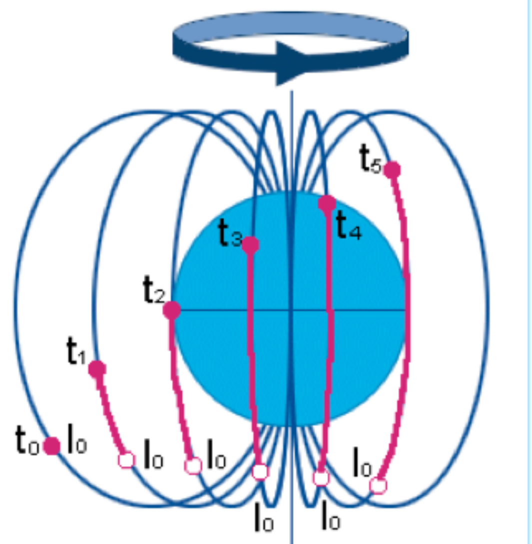
Resonance – Ideal Tool for Active RB Studies

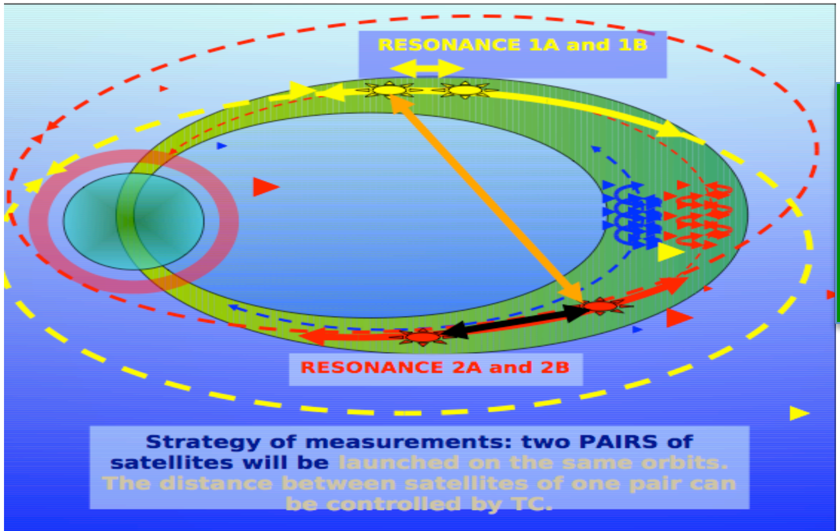
Pair of microsatellites (1A-1B; 2A-2B) in Magneto-synchronous orbit – Stay on same field line for 45-60 minutes. Launch Summer 2014 by IKI.



HAARP Coverage
H_p=500 km, H_a=27300
L=5.08, T= 8 hrs
43 min. within 20 km
3 hrs within 50 km
of HAARP flux tube

Apogee 28000 km, Perigee 500 km, Period 8 hours, Incl. +63.4 and -63.4





~ 1-10 km

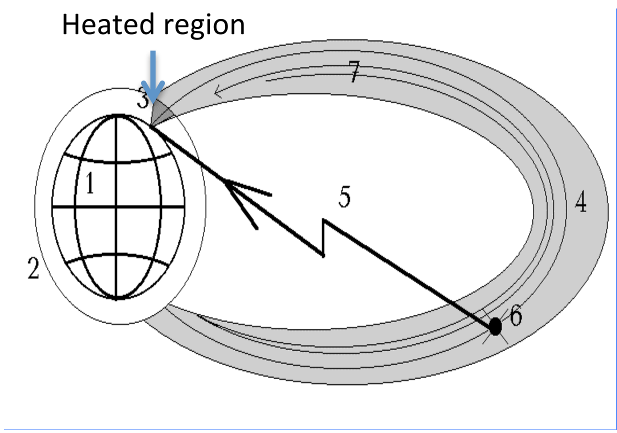
~ 5-15 x10^3 km

Electric and magnetic sensors
Wave analyzer and interferometer
DC – 10 MHz

Plasma sensors
Cold plasma
Suprathermal plasma
Energetic particles
Relativistic electrons

RB Physics Questions to be addressed by Active Probing

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



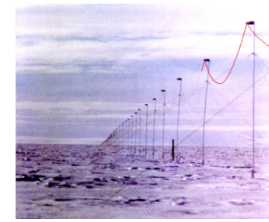
- Diagnose magnetospheric effects(ULF/ELF/VLF waves, energetic particles, plasma flows etc.), of heater operation with high spatiotemporal resolution
- Control heater operation based on transmitted data.
- Exploit dynamic feedback

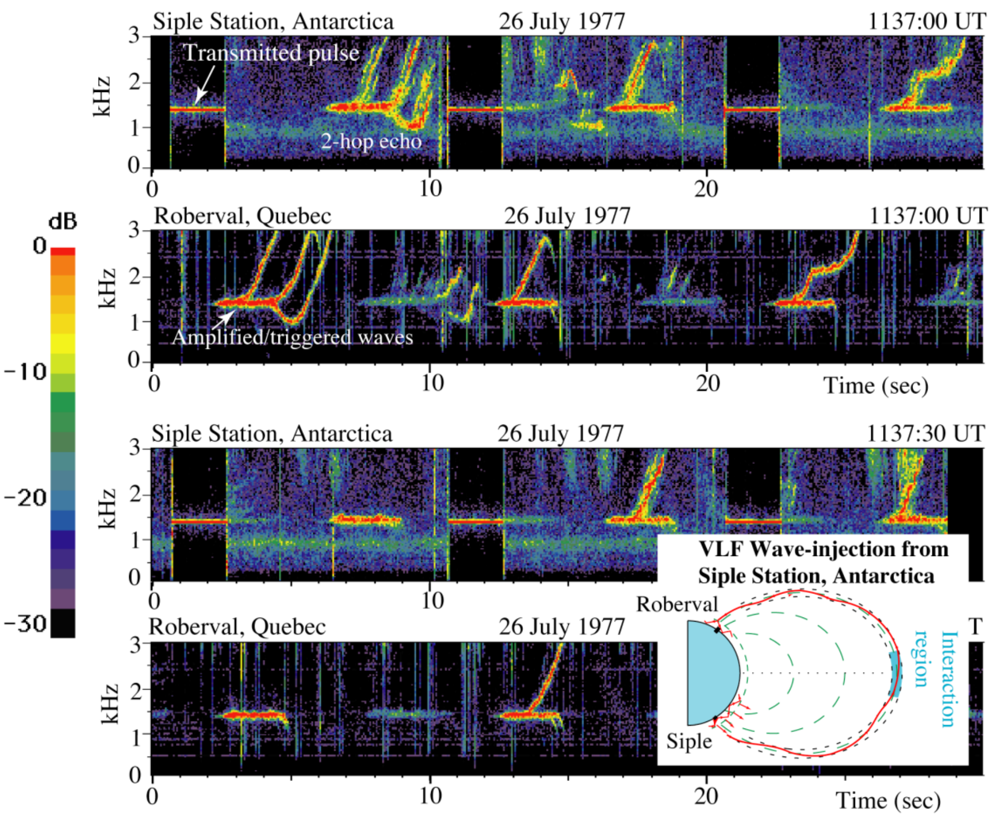
EXAMPLES OF PAST AND CURRENT INVESTIGATIONS AT HIGH LATITUDE

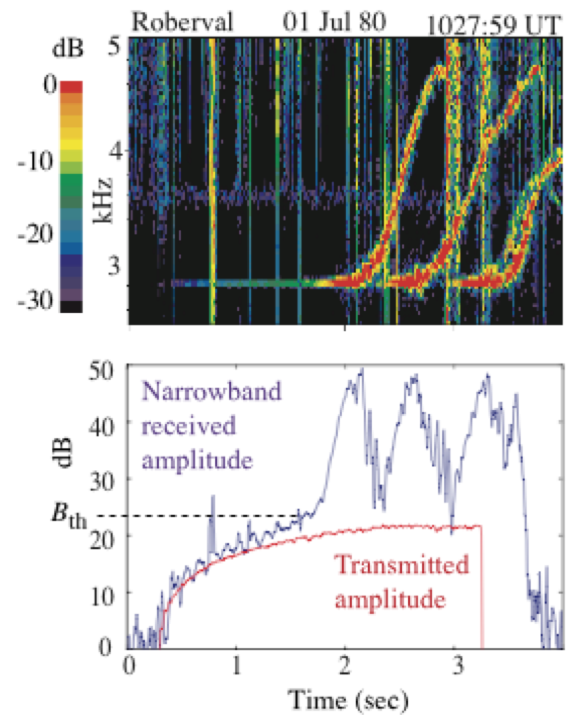
Artificially Stimulated Emissions (ASE)
Key RB Physics Issue – Physics of Chorus

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

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







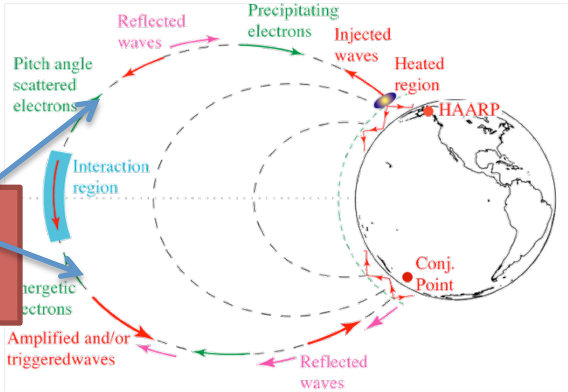
Triggered Emissions

HAARP Artificially Stimulated Emissions
Stanford University

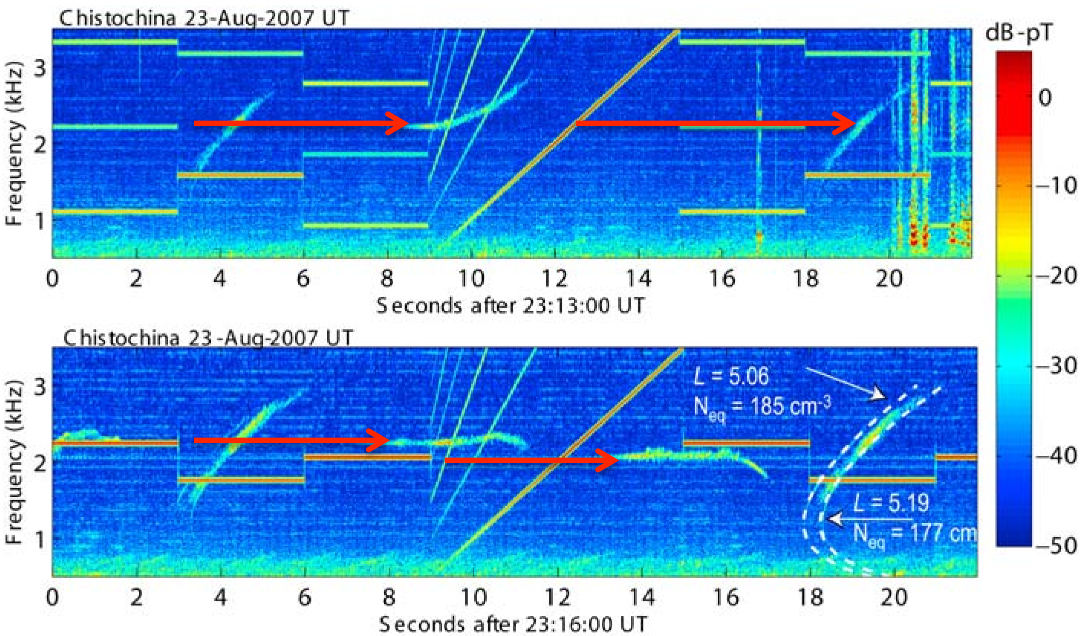
Triggered Emissions -Key non-linear issue in physics of RB (chorus, precipitation, wave-particle amplification, triggered EMIC, etc.) Role of trapped energetic particles.

Resonance type diagnostic and feedback

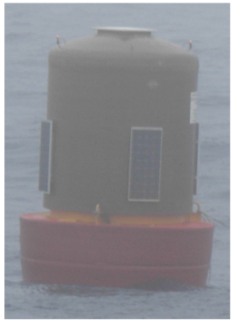
Golkowski et al. JGR 2008, 2010



2-hop echoes



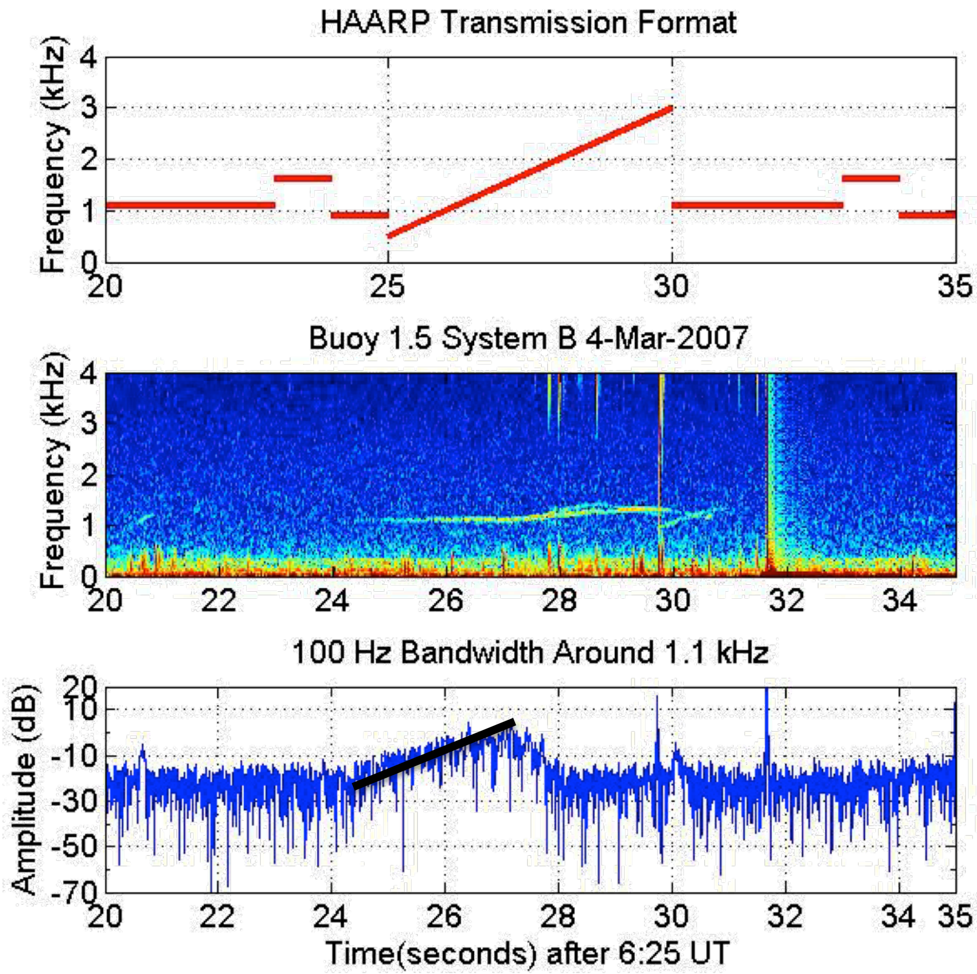
Conjugate



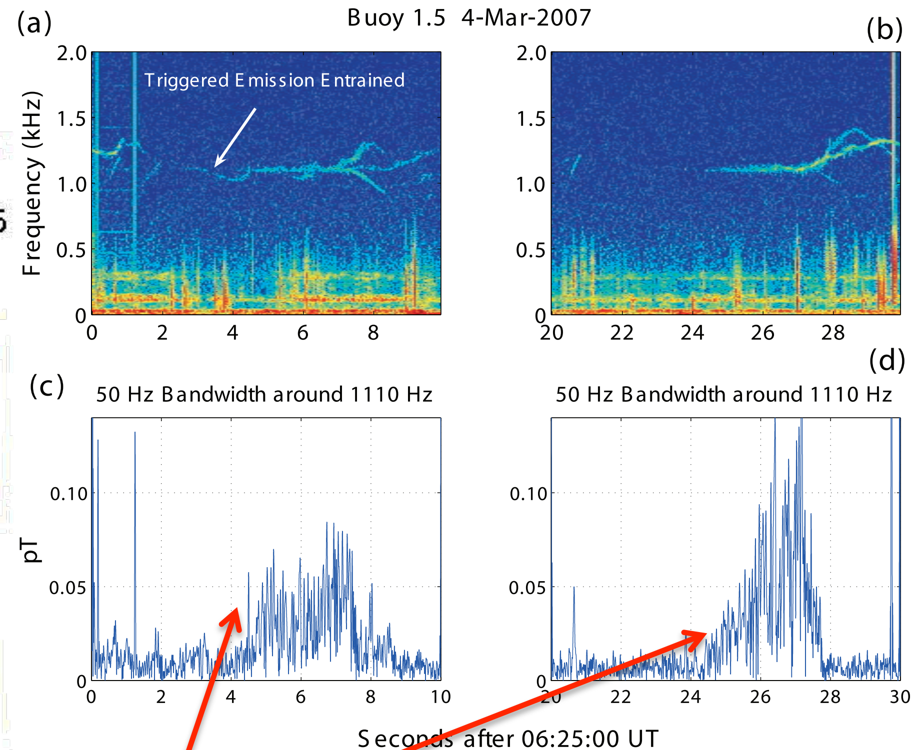
Buoy System

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

15 dB/s Amplification & Triggered Emissions



Golkowski et al., JGR 2008, 2010

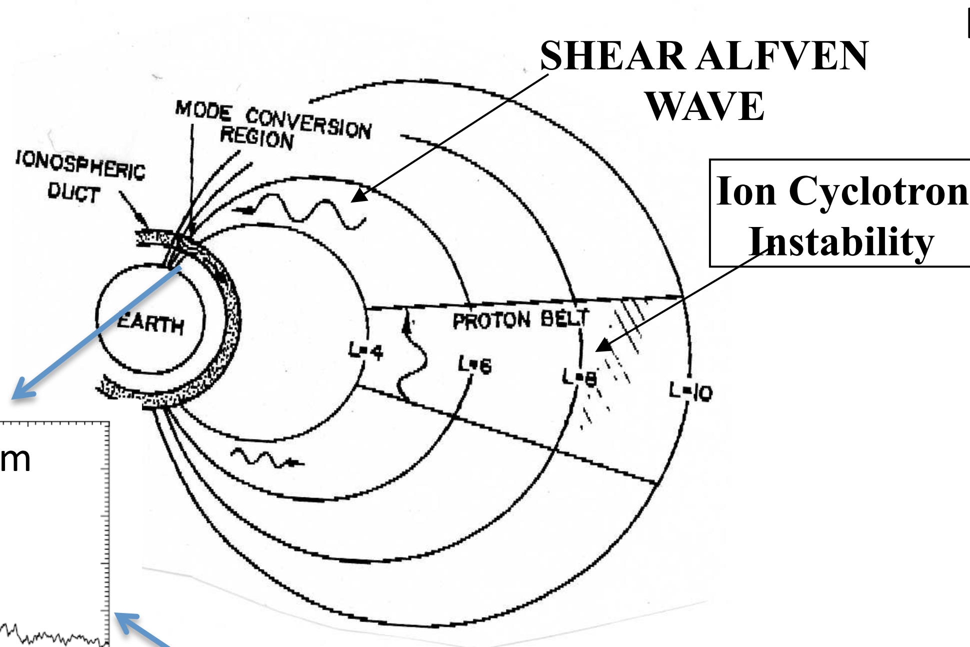


Amplification with and without entrainment. RHS amplification steady below noise floor. LHS initial amplitude above noise due to previous echo (mode locking of coupled oscillators)

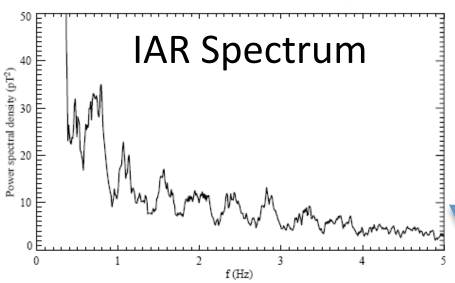
Only the pulse at 1100 Hz is amplified

Definitive resolution of ASE requires long time diagnostics on field tube

MI SEAR ALFVEN WAVE COUPLING

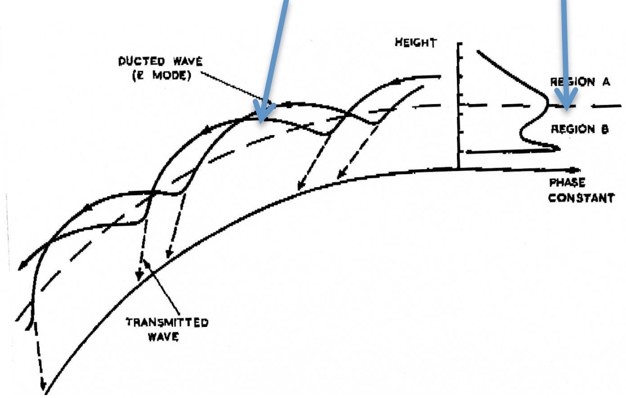


Pc1



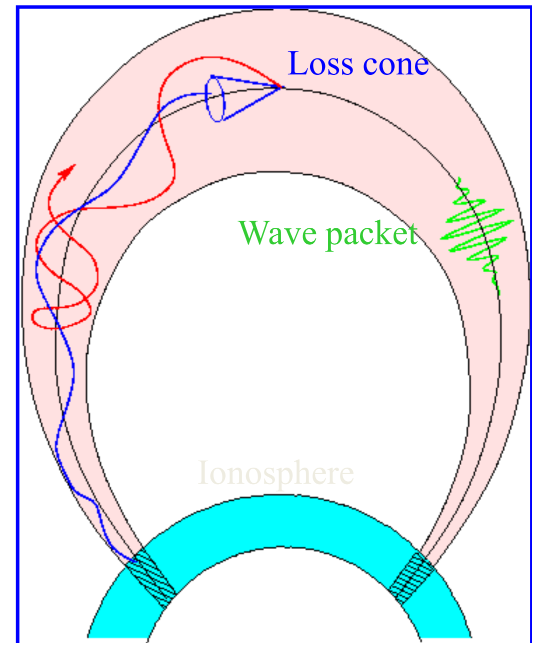
Ionospheric Alfven Resonator (IAR)

MS Duct



ALFVEN MASER

Trakhtengerts-Demekhov etc
Kennel-Petschek, Sagdeev



Active substance: Anisotropic energetic particles
Electro-dynamic system: Magnetic tube with cold plasma & ionosphere as mirrors
Operating modes: Whistlers & SAW

MI SEAR ALFVEN WAVE COUPLING

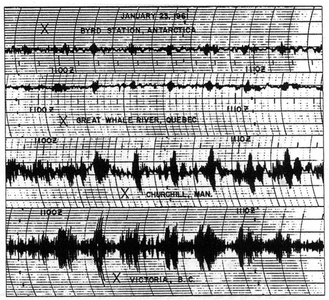
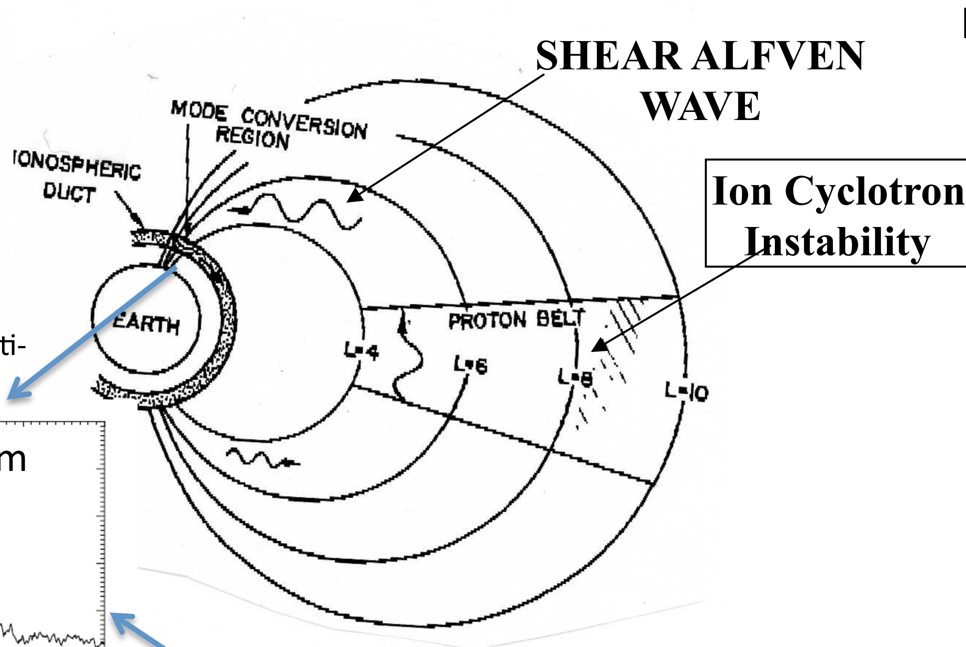
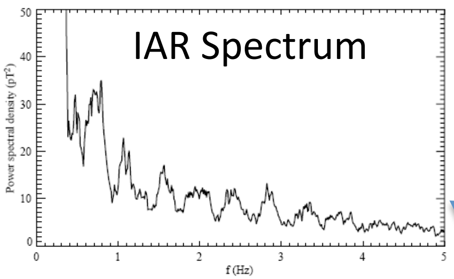


Fig. 2.1. Example of Pc 1's (pearls) recorded at four stations simultaneously. (After J. E. Lokken, J. A. Shand, and C. S. Wright, DREP photograph 2751)

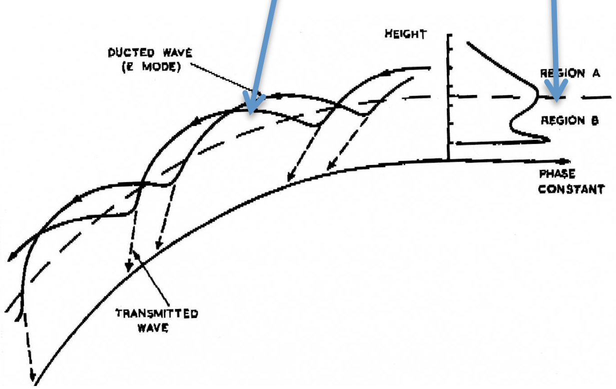
Conjugate stations detect anti-phased pearl wave-packets





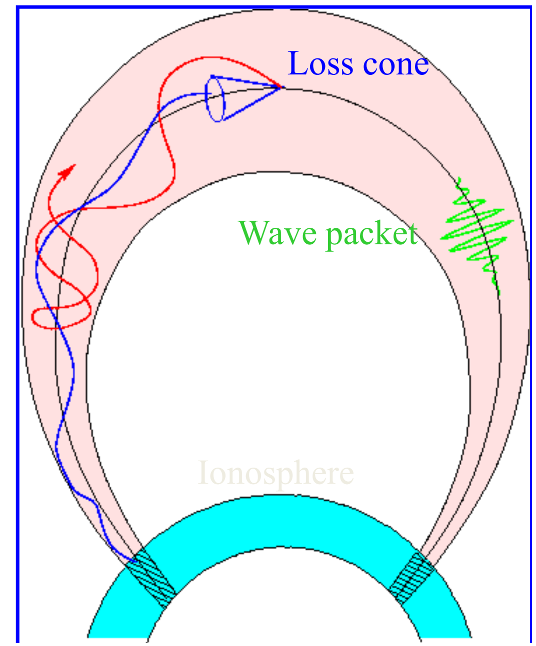
Ionospheric Alfven Resonator (IAR)

MS Duct



ALFVEN MASER

Trakhtengerts-Demekhov etc
Kennel-Petschek, Sagdeev



Active substance: Anisotropic energetic particles

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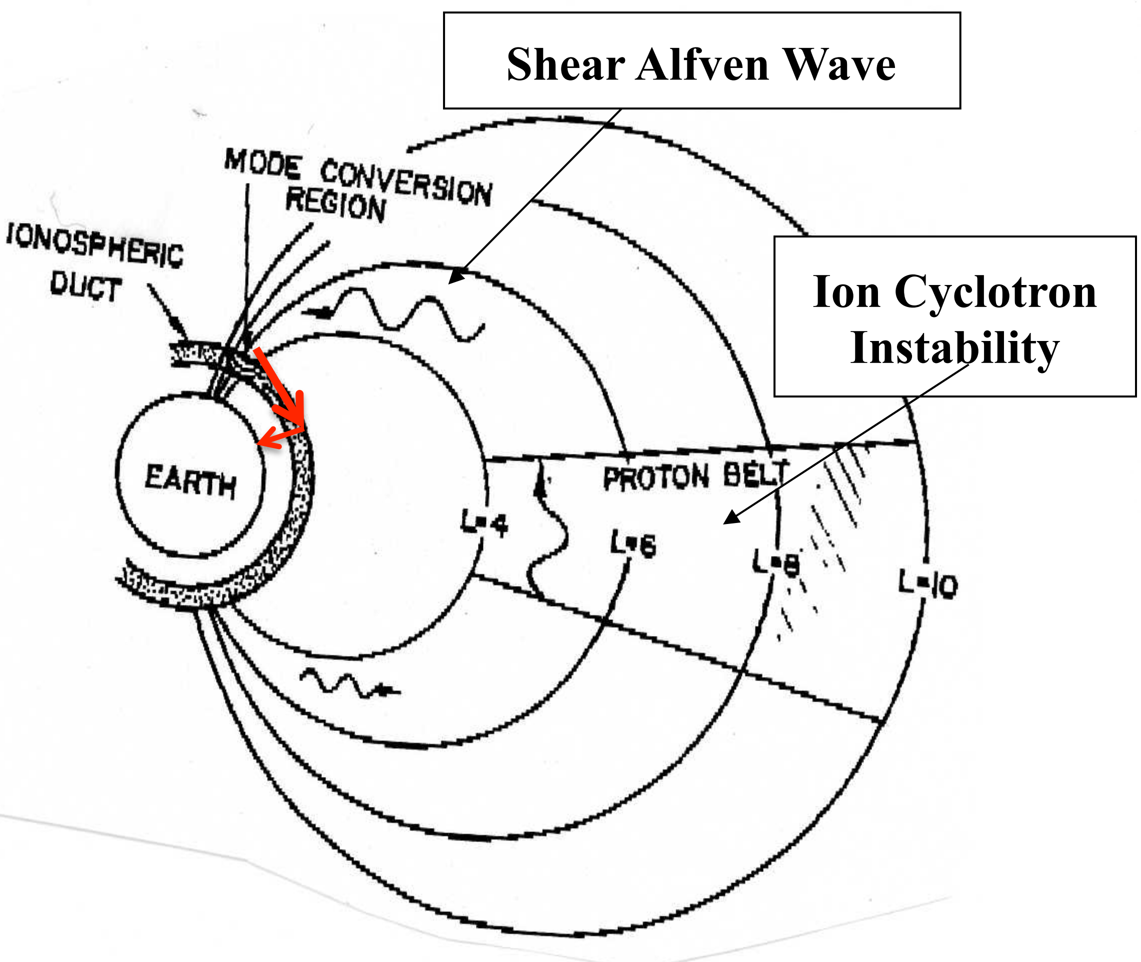
Lateral Propagation of SAW signals as MS Waves

Lysak 1998



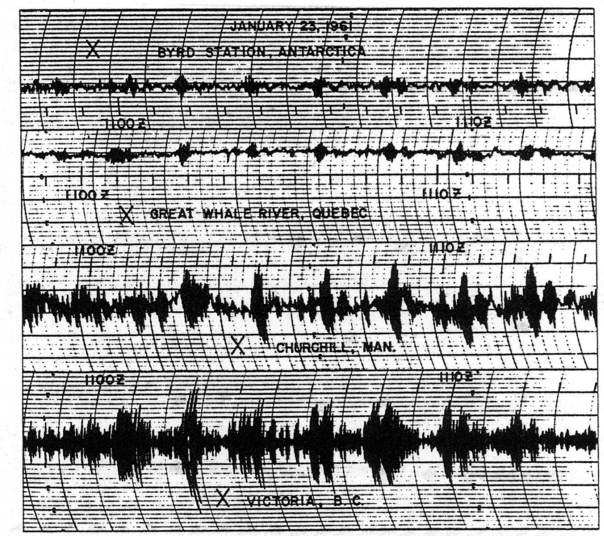
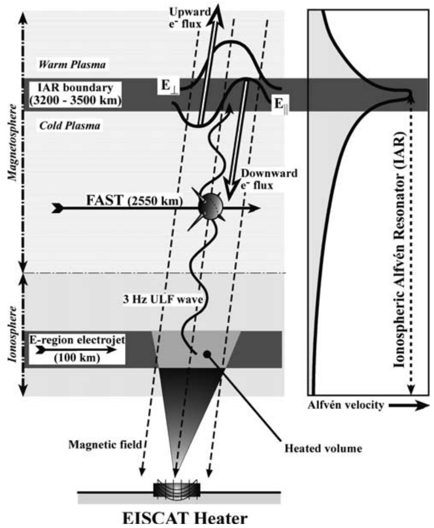


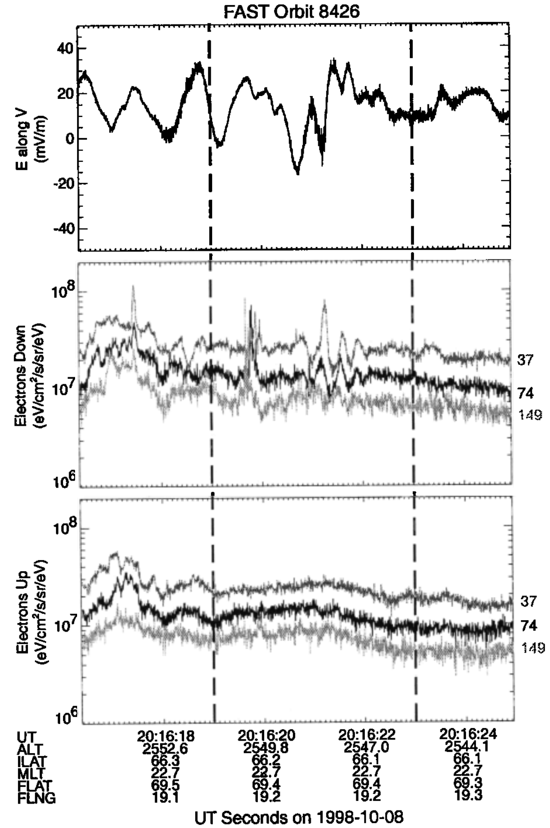
Fig. 2.1. Example of Pc 1's (pearls) recorded at four stations simultaneously. (After J. E. Lokken, J. A. Shand, and C. S. Wright, DREP photograph 2751)

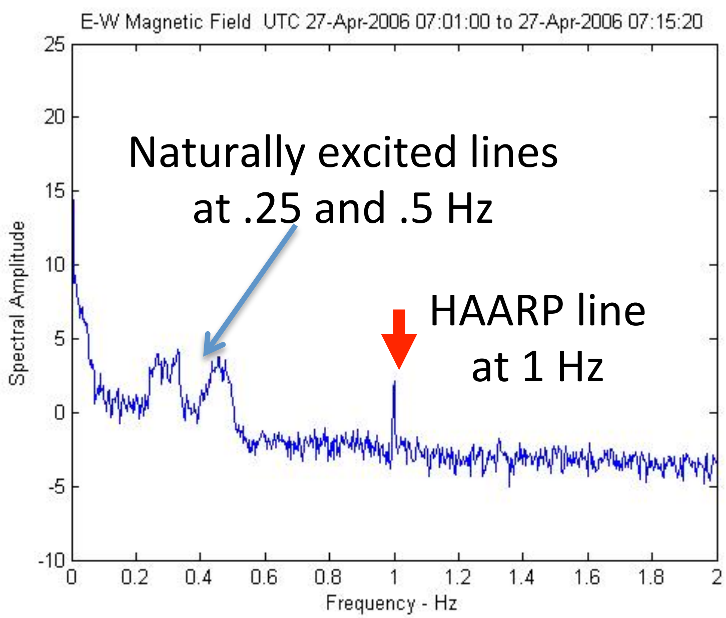
Conjugate stations detect anti-phased pearl wave-packets

IAR Experiments

EISCAT/FAST Robinson et al., 2000

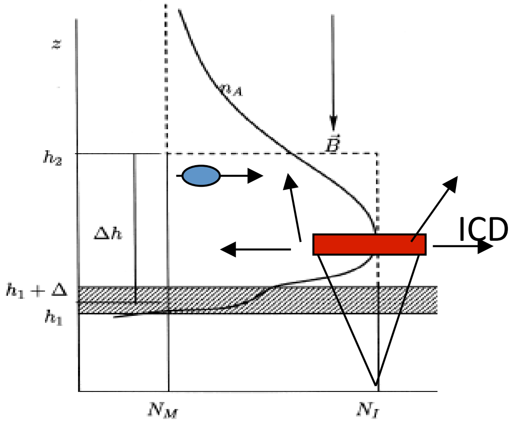




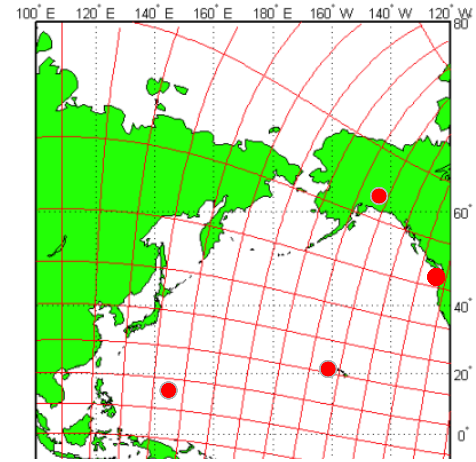


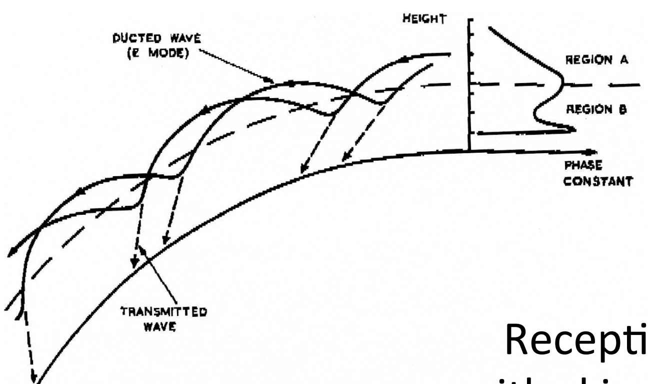
HAARP excitation of IAR
Papadopoulos et al., 2007

Physics of Pc-1 MHD Waves Alfvenic Duct

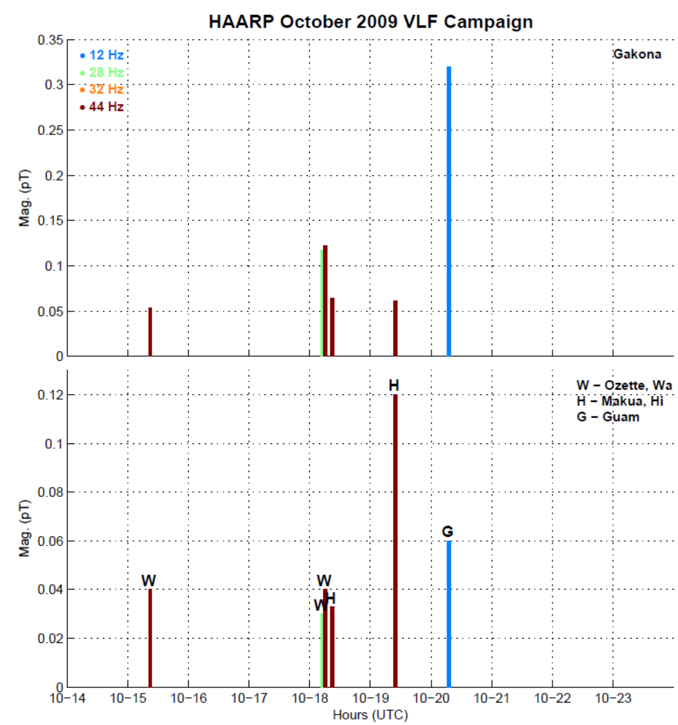


- Distance from Gakona
  - Lake Ozette, WA (W)
    - 1300 mi
  - Hawaii (H)
    - 2900 mi
  - Guam (G)
    - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23



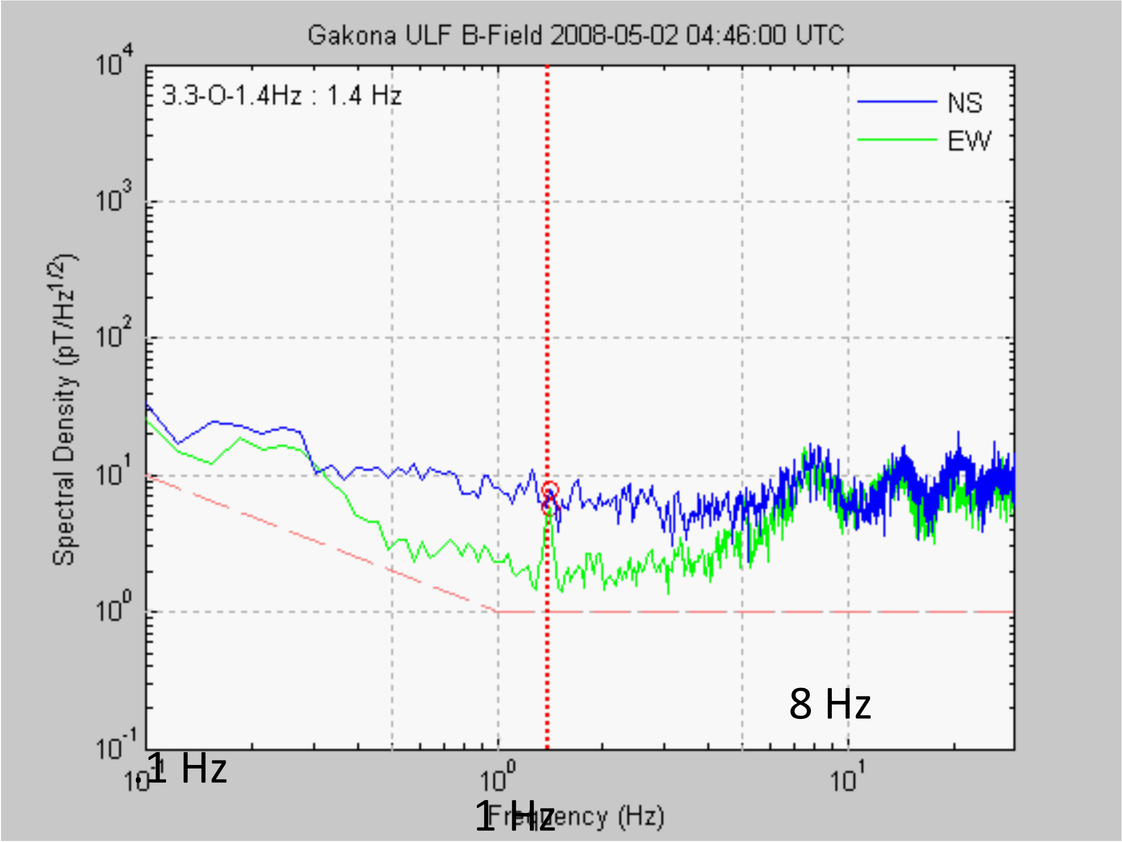


Reception consistent with skip distance effects



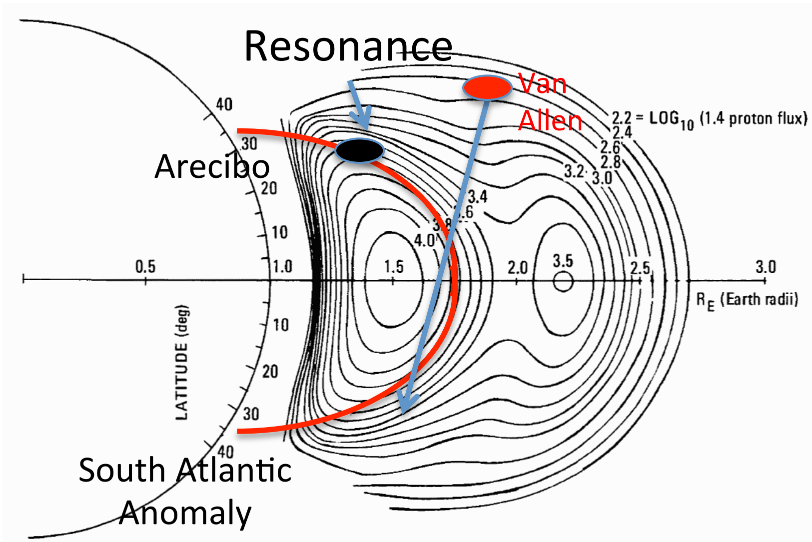
Eliasson, Chang, Papadopoulos, JGR 2012

HAARP –Triggered ULF?



INNER BELT PHYSICS STUDIES

Active SAW Probing of Inner RB Using the Arecibo Heater/Van Allen or Resonance



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

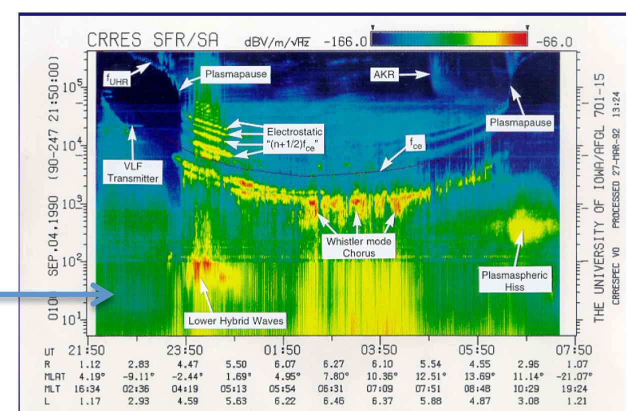
Focus on SAW for protons and EMIC for electrons

Typical inner belt proton lifetimes:

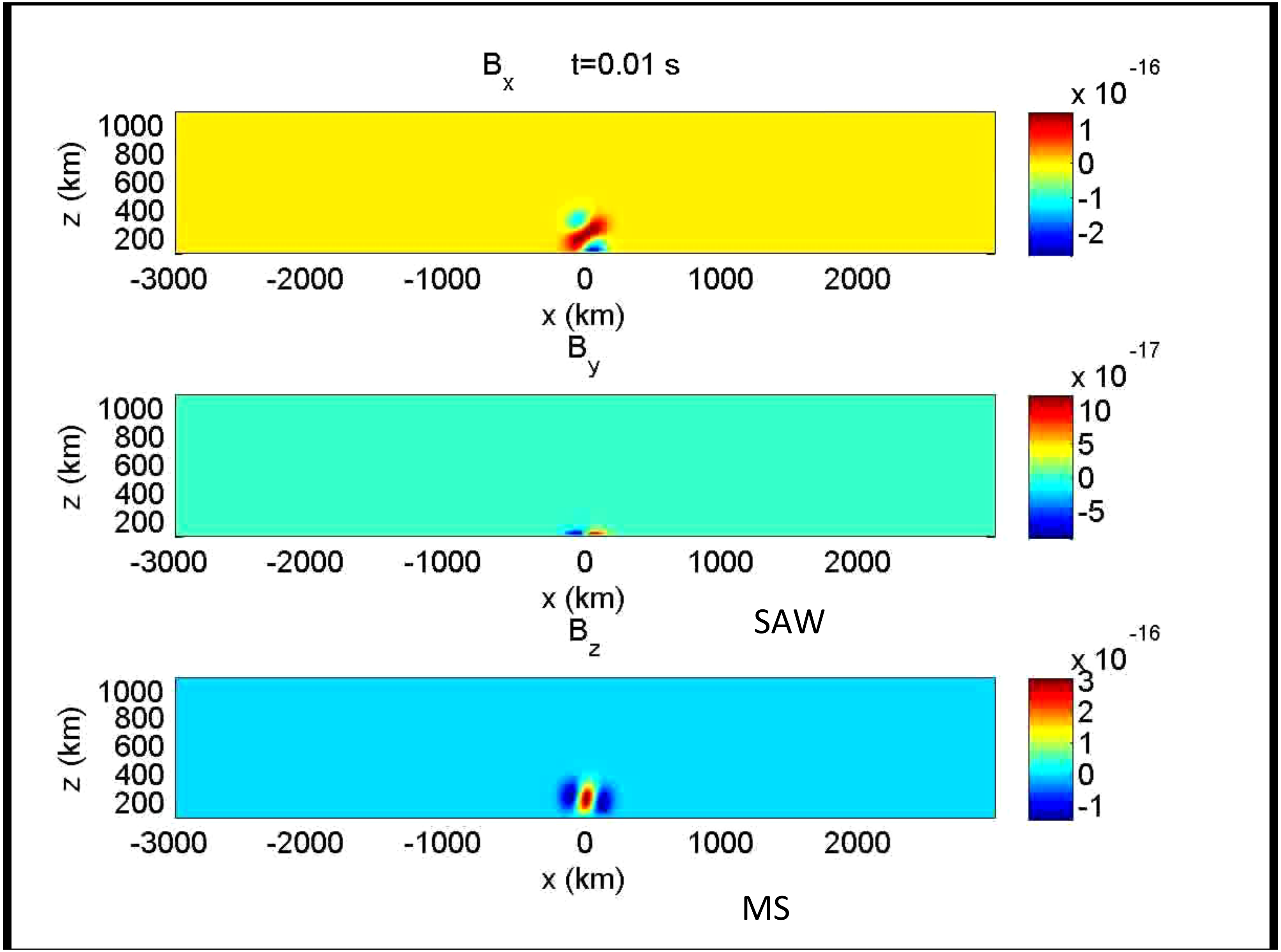
10 MeV – decades

50 MeV – century

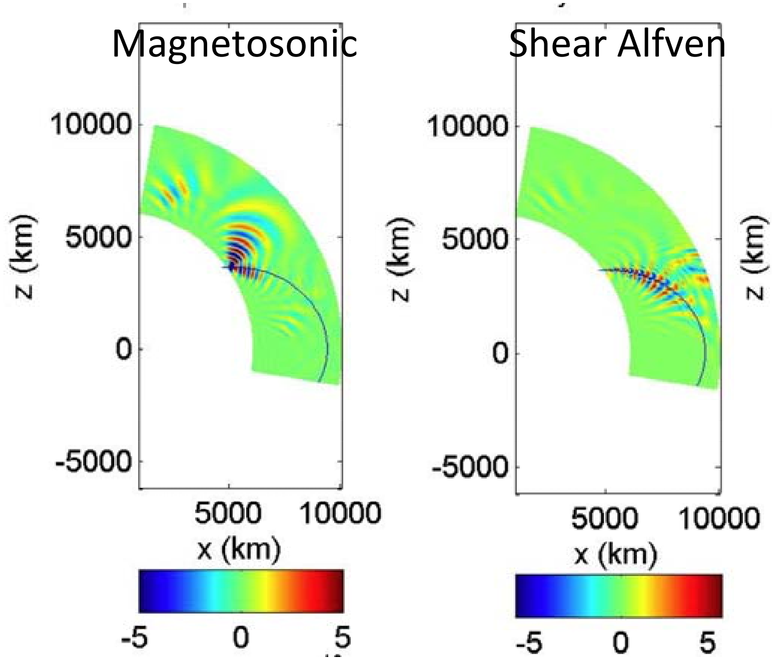
No SAW activity
Stacking



ICD Inner RB Injection - Arecibo



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



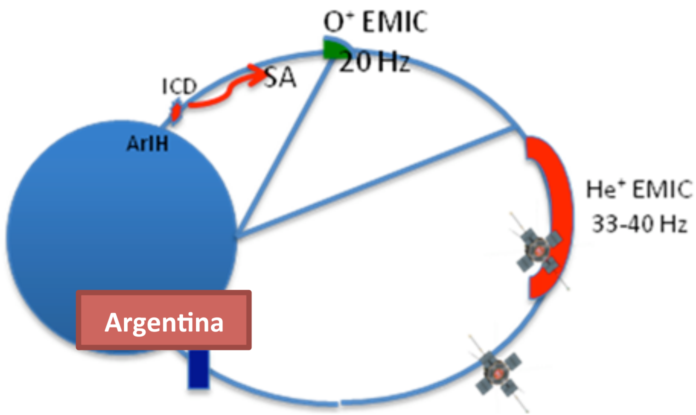
Simulation of MHD Wave injection using the Arecibo Heater

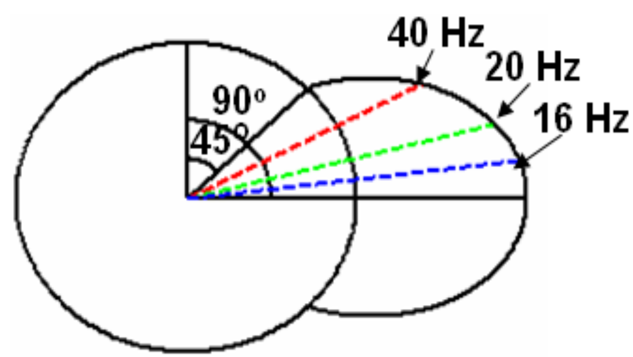
$$-k_z v_z = |\Omega_e| / \gamma$$

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

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

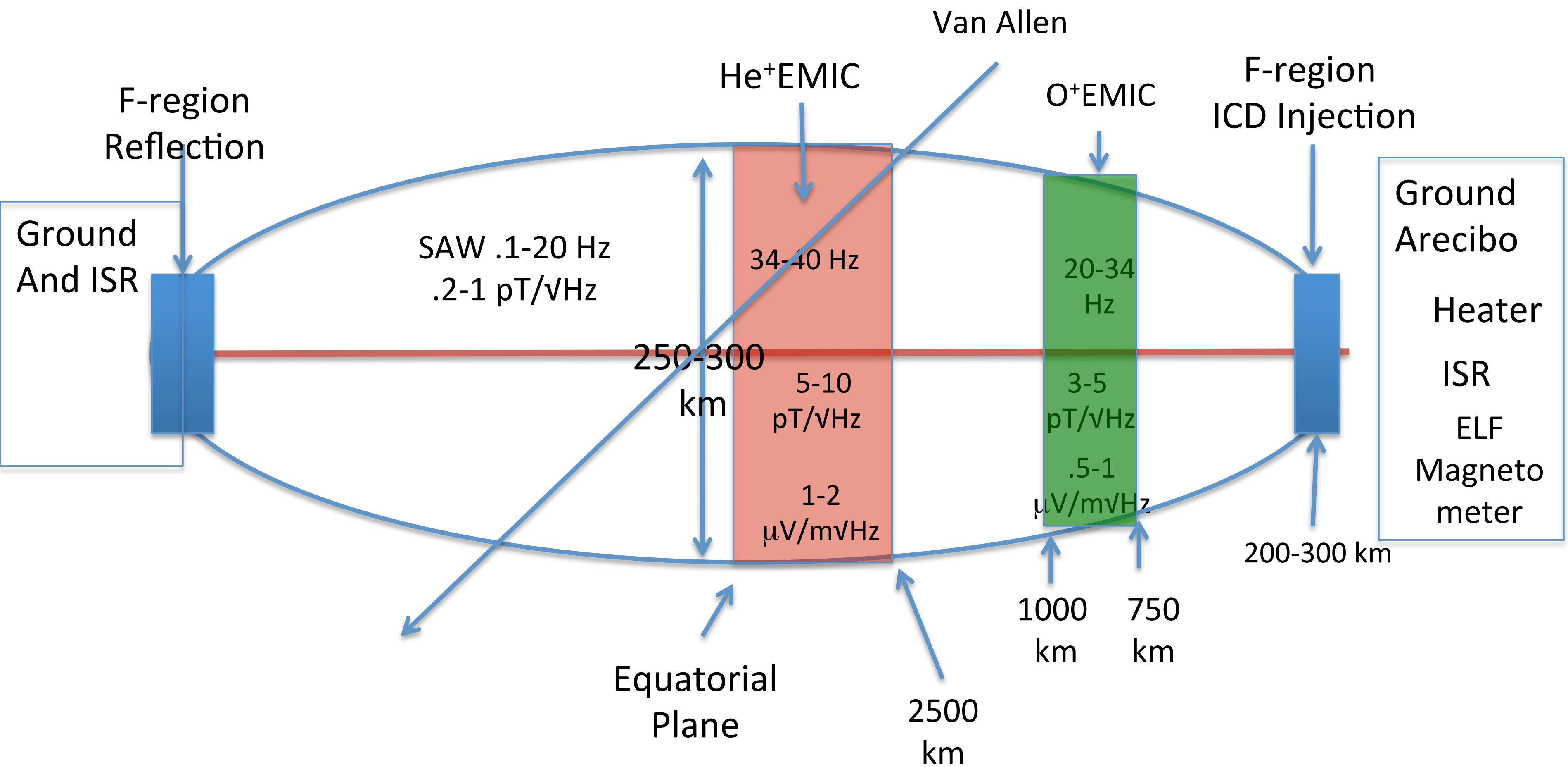
As a result $1/k_z \to |\Omega_e| / \gamma v_z$ before reaching resonance ($1/k_z \to 0$)





Helium Resonances

RBSP measures the waves and the energetic particles before during and after transitioning the L=1.4 flux tube so that we can use change detection and possibly statistical stacking

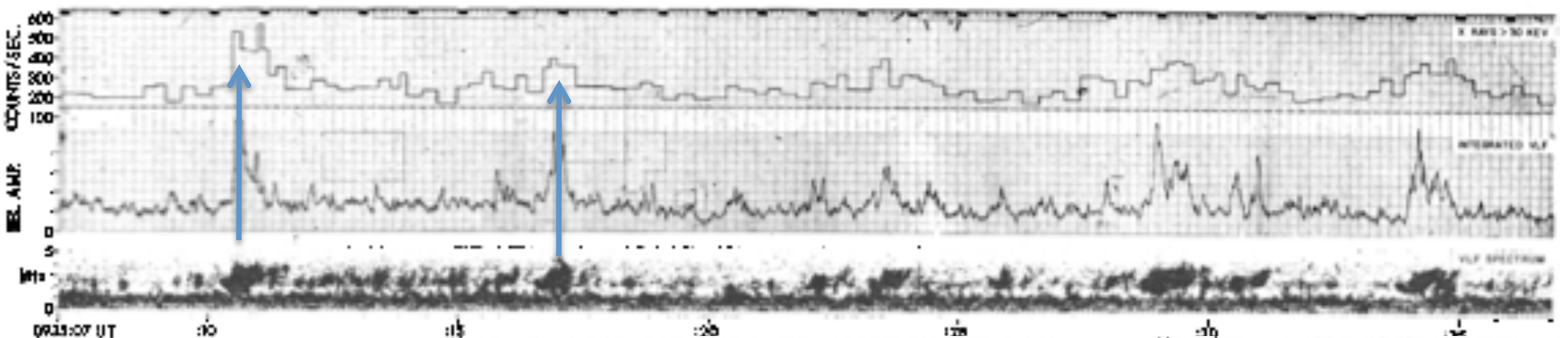


Straw-man of Arecibo Heater ICD/ Van Allen or Resonance type Investigation

QUASI-PERIODIC EMISSIONS

Puzzle: Coupled Whistler-driven Precipitation spikes with ULF (SAW) waves

Rosenberg et al. JGR 76, 8445, 1971; Lanzerotti 6 sec micropulsations



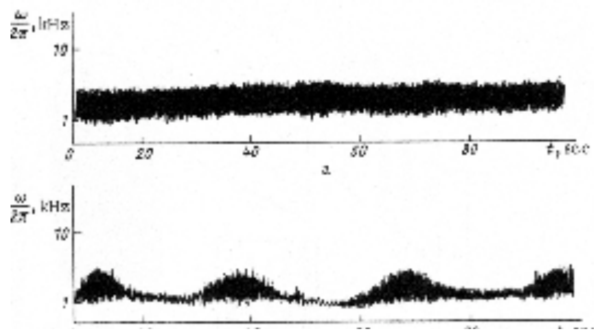
>30 keV

X-rays

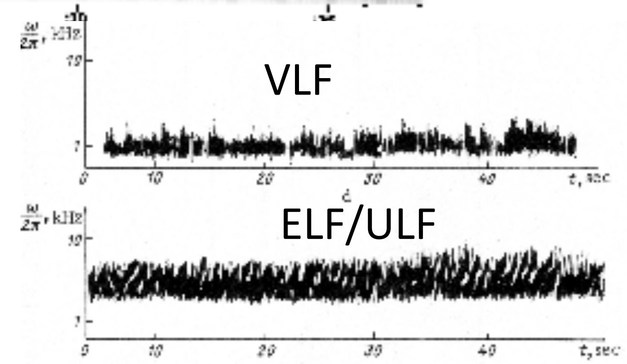
.5-5 kHz

6 sec mod

Ground



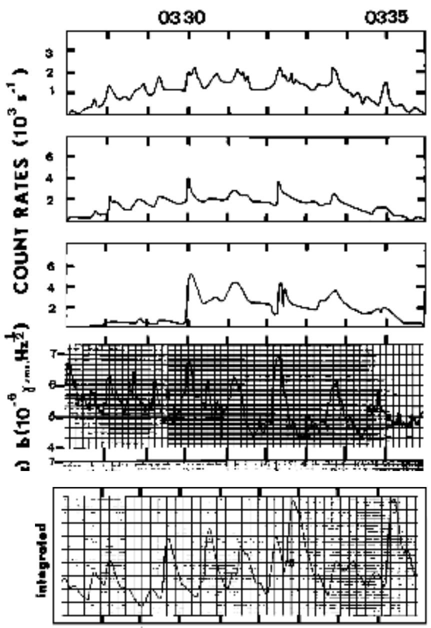
Hiss and q-periodic hiss



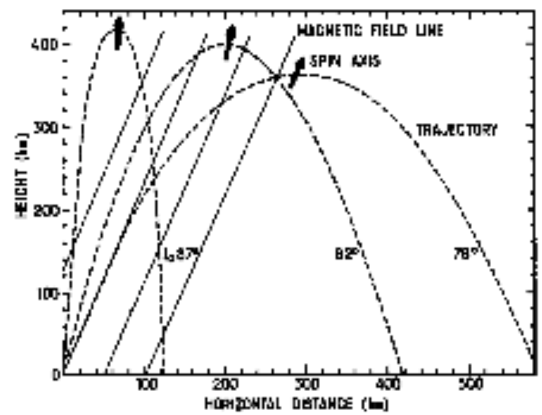
Chorus – Coherent hiss

Increase whistler energy density ->increase precipitation –RBR-> Inject whistlers (Helliwell 70's; DSX-Inan et al., 2002) Alternative: Is it possible to inject SAW and use them to amplify whistlers or convert them to EMIC?

Speculation: SAW can lead to amplified whistler spikes



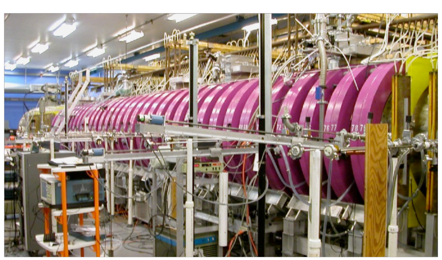
Gedrin et al. JGR, 1970



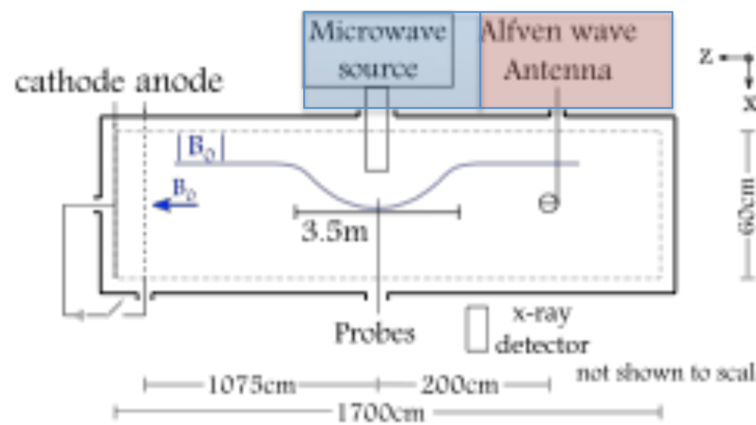
Periodic & quasi-periodic emissions: 100's of papers: Bespalov & Trakhtengerts Rev. Plasma Physics Vol. 10, 1986

CAN SAW CAUSE
MeV Electron Precipitation

Lab experiment UCLA Wang et al. PRL, April 2012



17 m,
10 sections control B
450 diagnostic ports

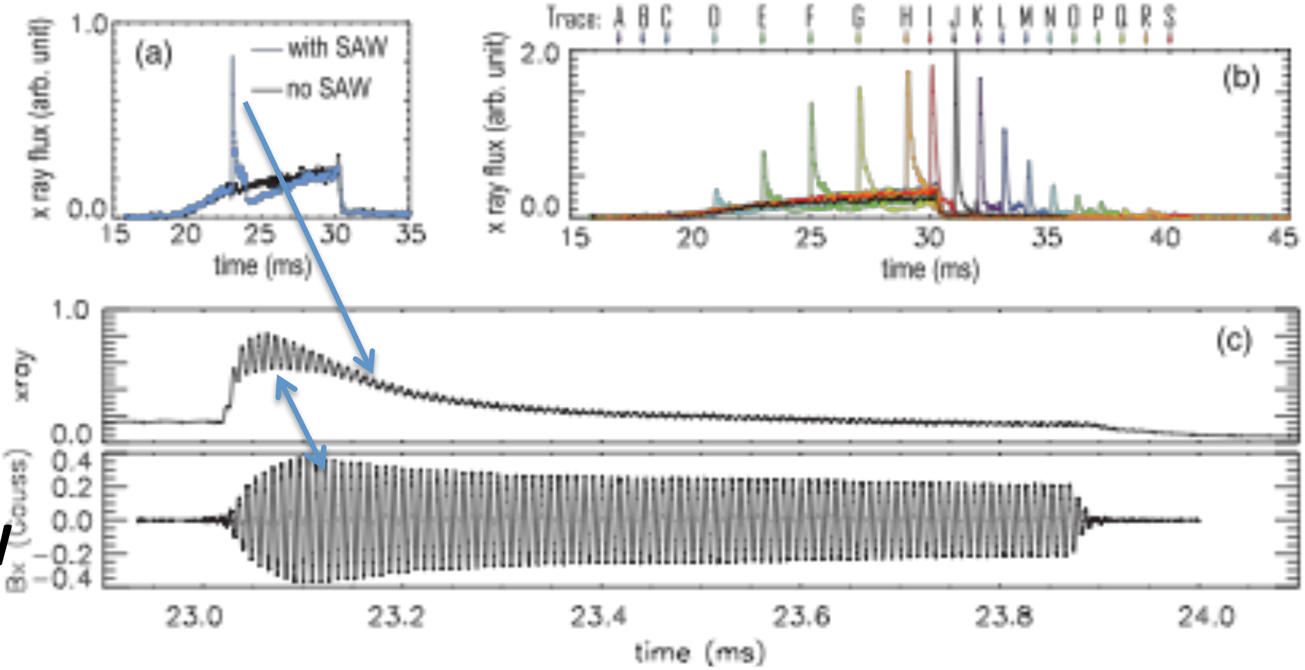


LAPD Experiment

SAW cannot break μ

Single pulse X-rays

Injected SAW 100 cycles



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

$$\frac{dN}{dt} = -\alpha\varepsilon_w N + J(t)$$

$$\frac{d\varepsilon_w}{dt} = \beta N\varepsilon_w - \nu\varepsilon_w + G_w(t) + \eta\varepsilon_w G_{SAW}$$

$$\nu \equiv \frac{2}{\tau_g}\left|\ln R\right|$$

$$\varepsilon_w = (\beta/\alpha\nu)J$$

$$N = \nu/\beta$$

Analogy with Maser. First noted by Trakhtengerts

THANK YOU

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

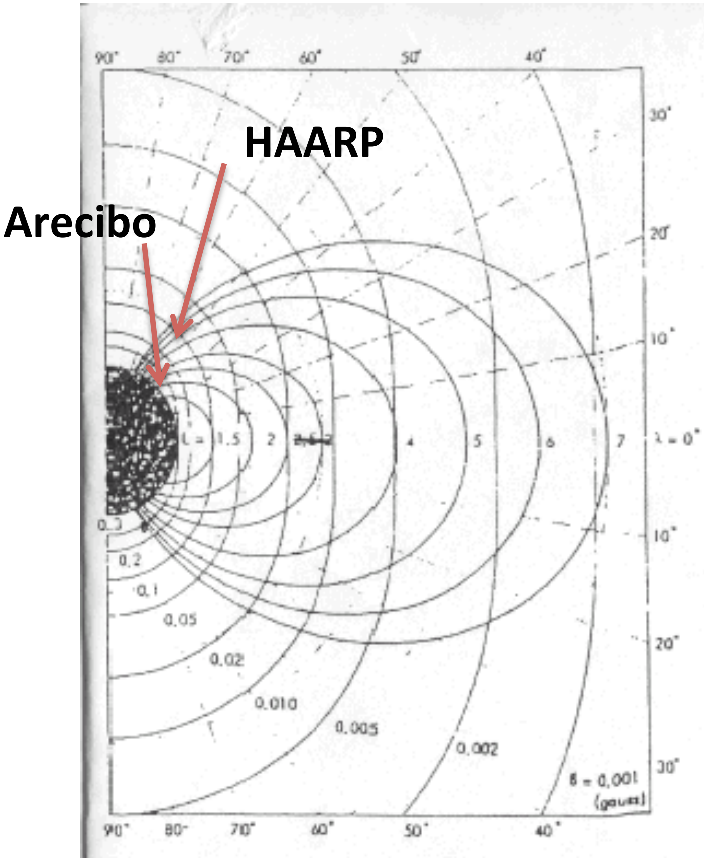
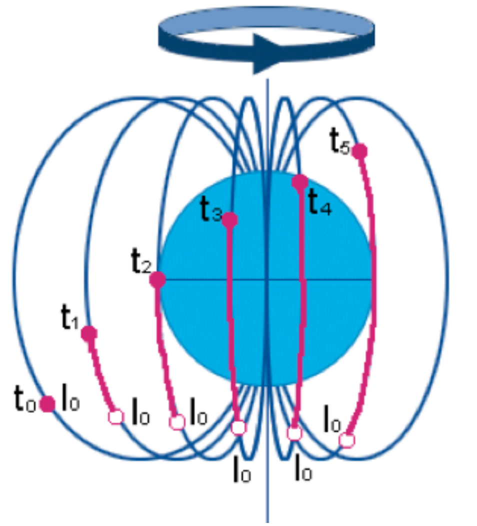
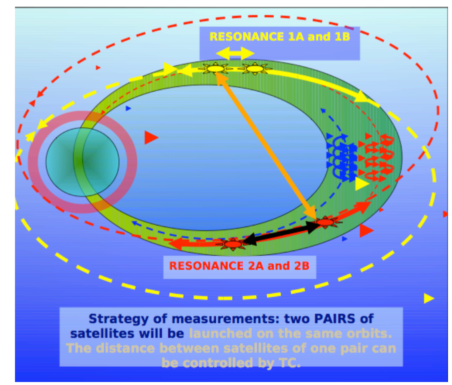


Figure 2-8. Constant-B surfaces in a dipole field.

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

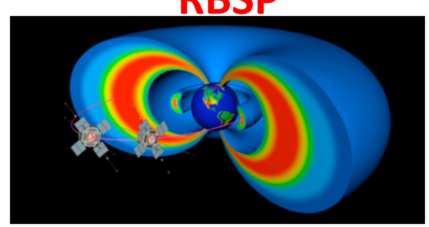
Magneto-synchronous





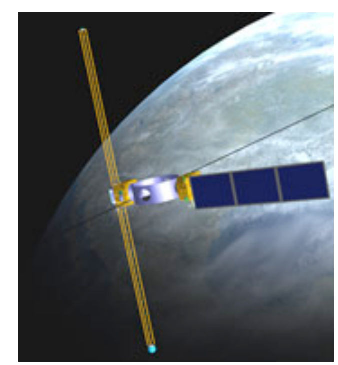
RESONANCE (Russia)
Launch ~2012-14, 4-spacecraft
Orbit:1800x30,000km, ~63° incl.

RBSP

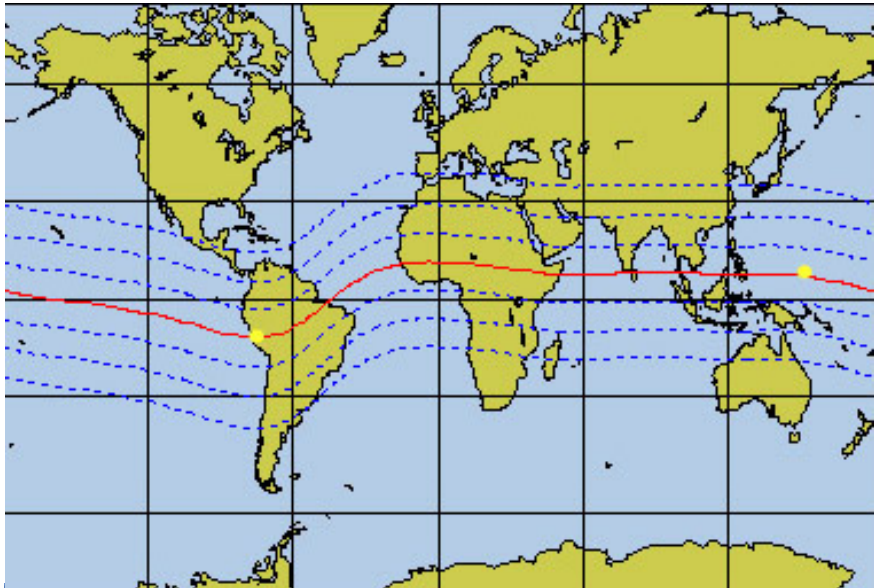


Launch May 18, 2012
2 probes, <1500 kg for both
10° inclination, 9 hr orbits
~500 km x 30,600 km

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



An Equatorial Location May Be Optimal for Operational Use.

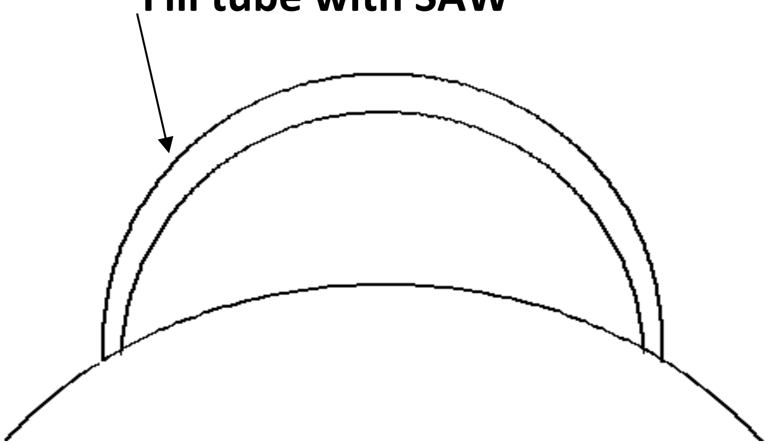


- **Equatorial Electrojet is More Reliable than the Auroral.**
- **Magnetic Geometry and Electron Density Profiles Suggest Much Higher Conversion Efficiency Than Auroral.**
- **Operational Facility Would Be Single Purpose and Much Simpler than HAARP.**
- **Land-based Facility Could be Sited on Kwajalein Atoll. Alternatively, a Re-Locatable Sea-Based Facility Could be Sited as Needed.**

Frequency Selection for Protons

Example for L=1.5

Fill tube with SAW

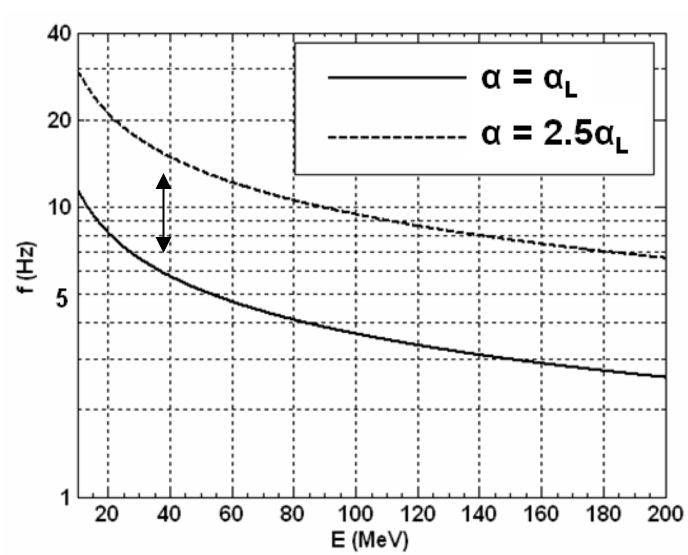


Frequency Selection for Resonance of Protons with SAW

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

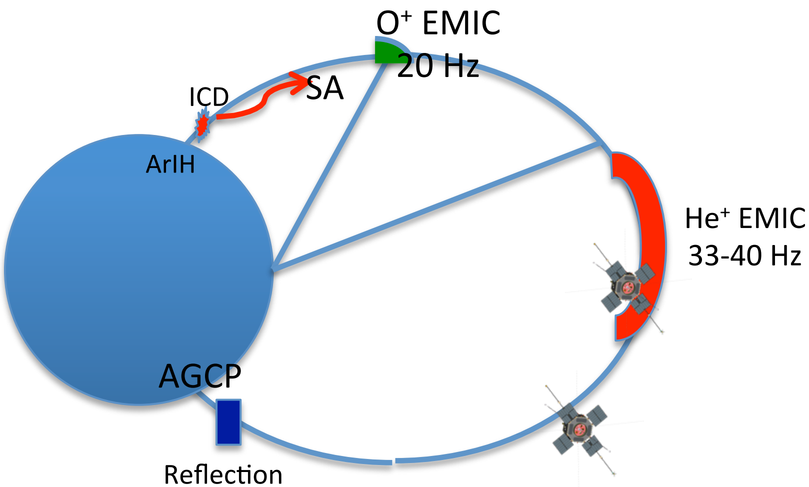
$$\omega(E,\alpha) \approx \frac{\Omega}{\cos\alpha}\sqrt{\frac{MV_A^2}{2E}}$$

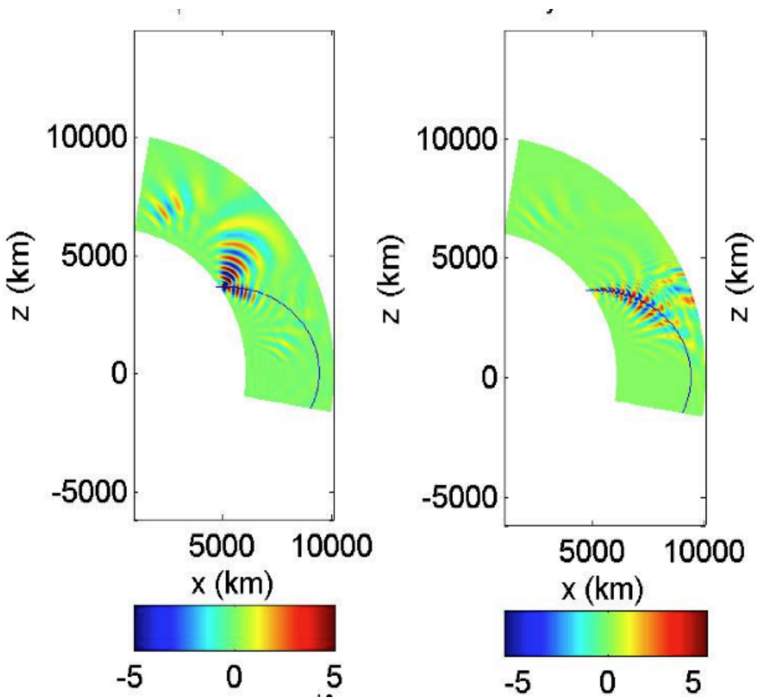


Frequency requirement for equatorial resonance with SAW at L=1.5

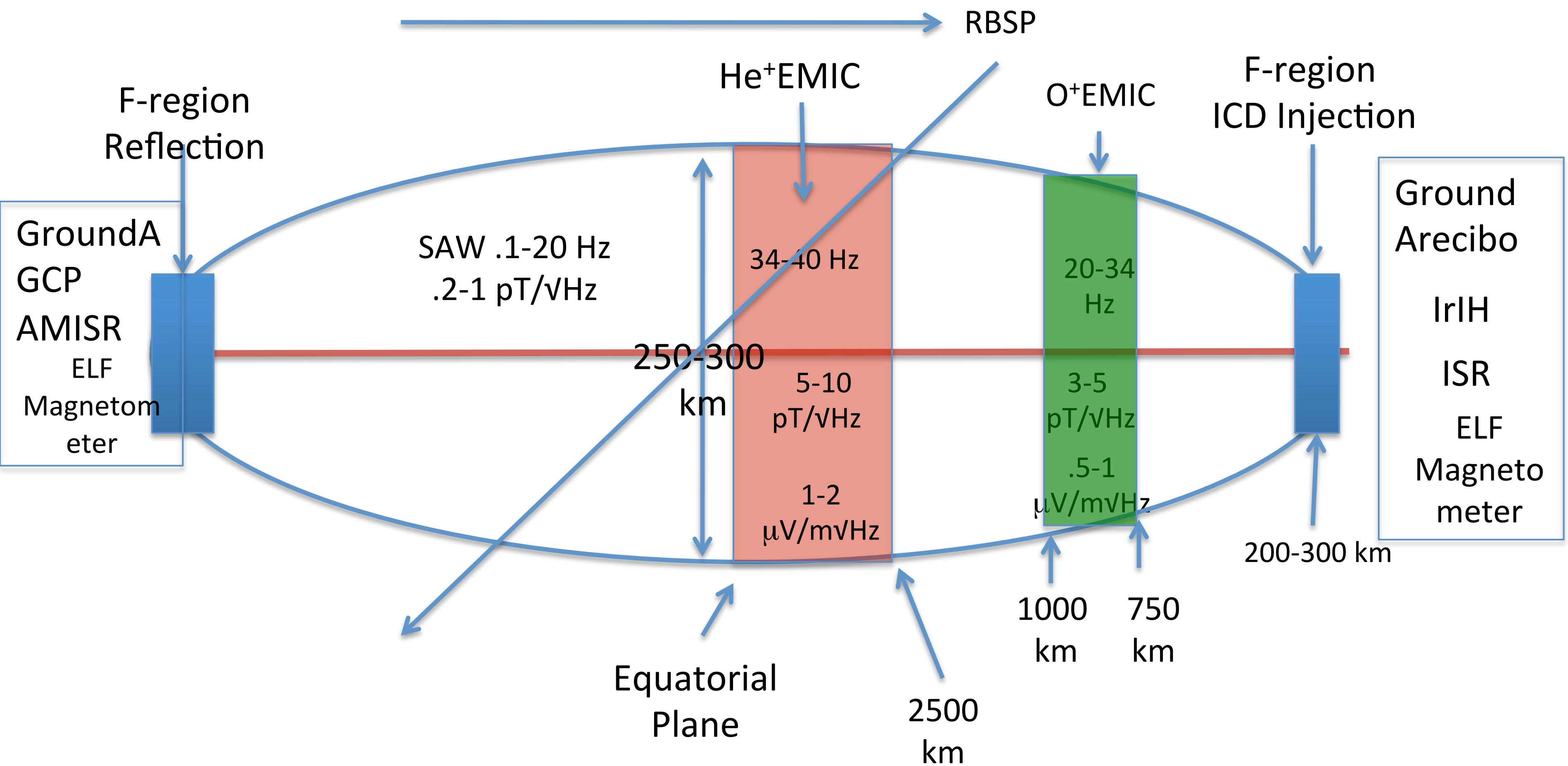
Frequency range 5-30 Hz

Arecibo Heater Experiments





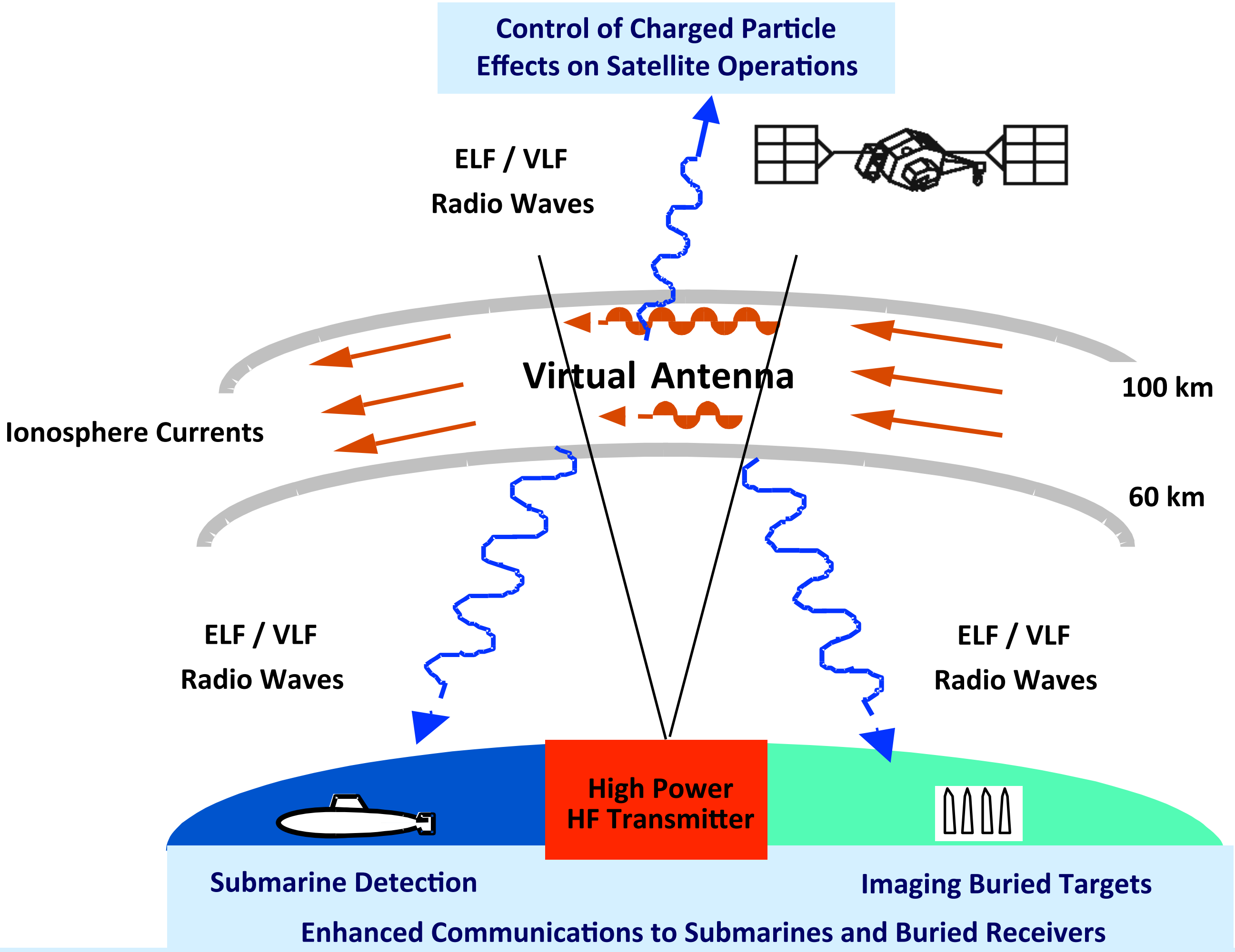
RBSP measures the waves and the energetic particles before during and after transitioning the L=1.4 flux tube so that we can use change detection and possibly statistical stacking



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)

Present Research Emphasis

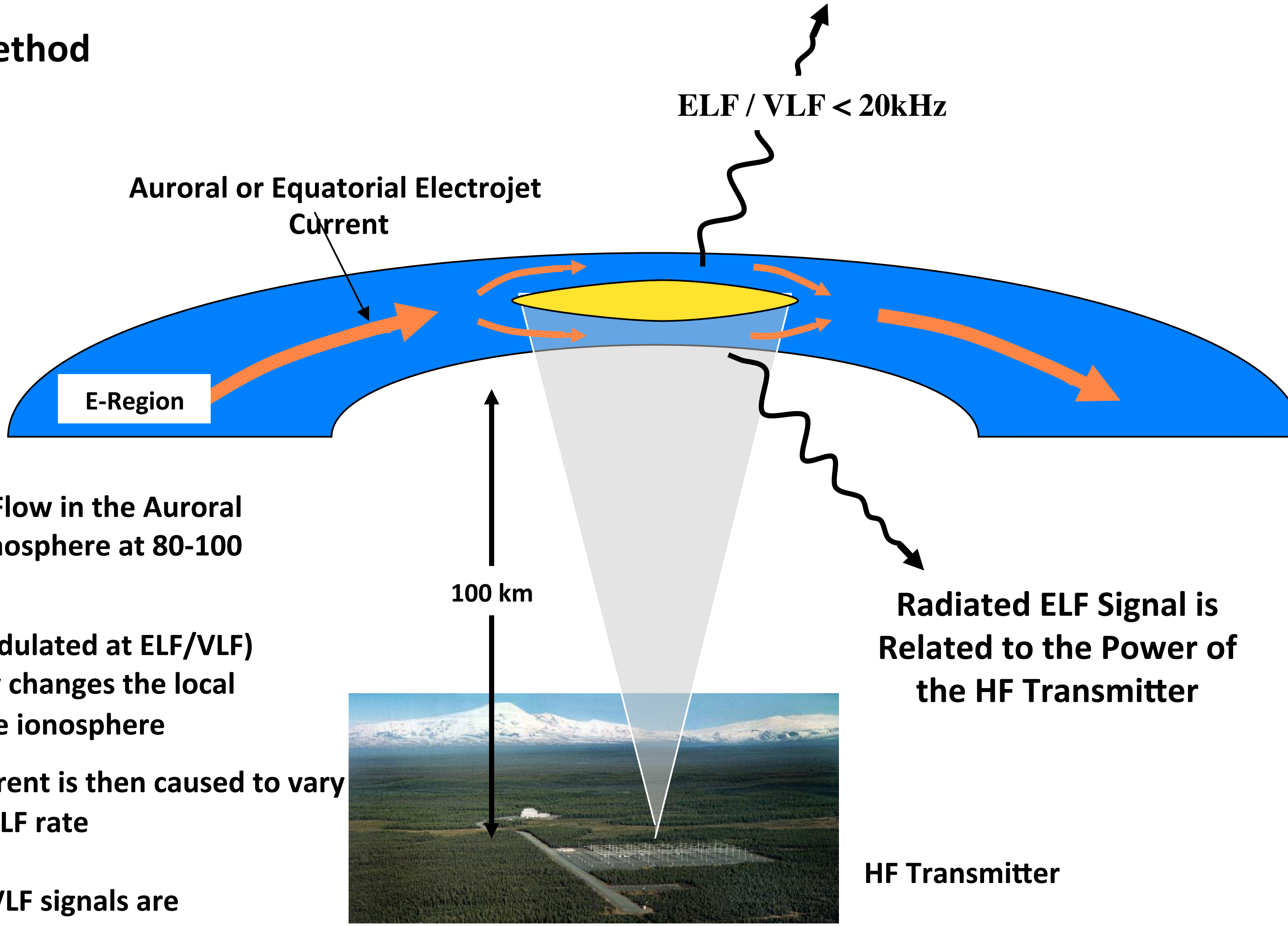
ULF/ELF/VLF



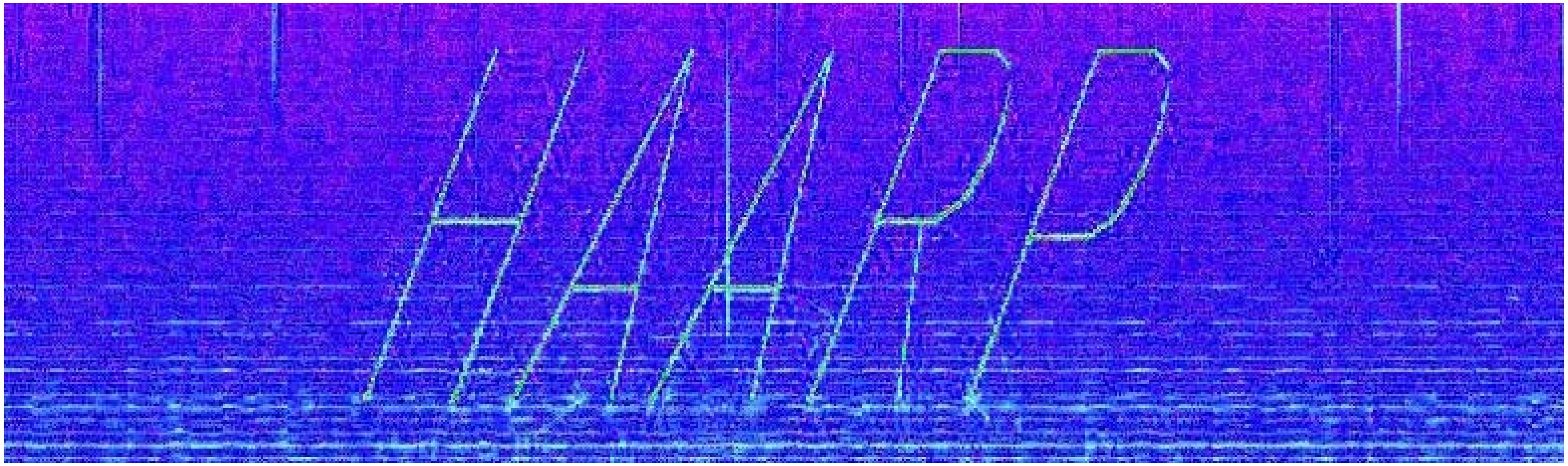
Applications Related Research and Technology Demonstrations

ELF / VLF Wave Generation Through Ionosphere Interactions

“Traditional” Method



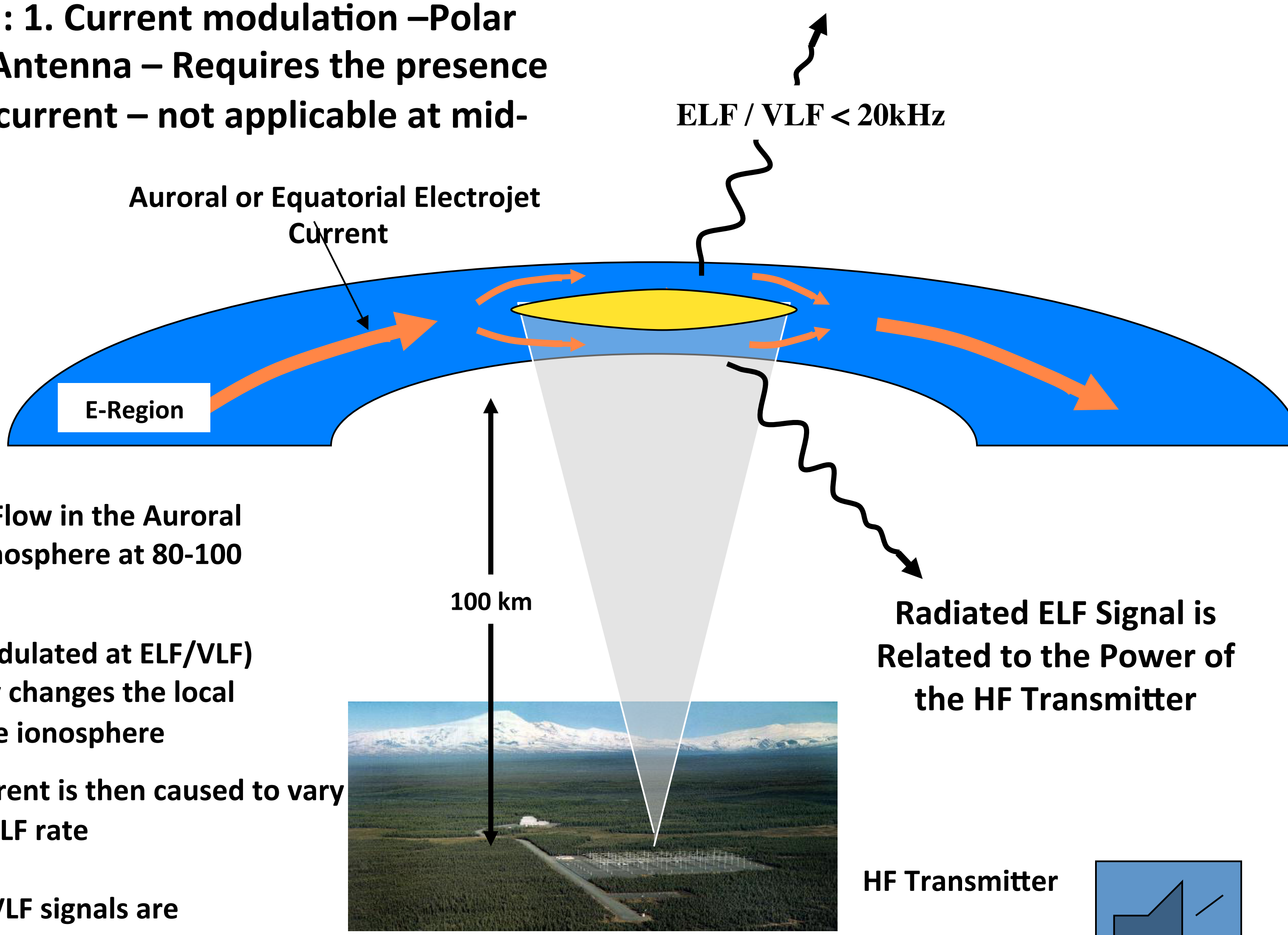
- Natural Currents Flow in the Auroral and Equatorial Ionosphere at 80-100 km
- The HF signal (modulated at ELF/VLF) heats and thereby changes the local conductivity of the ionosphere
- The electrojet current is then caused to vary at the same ELF/VLF rate
- Propagating ELF/VLF signals are radiated by this ‘virtual antenna’



Message Received on the Ground from a Virtual ELF Antenna in Space Generated by HAARP Modulations of Currents in the Ionosphere

HF Ionospheric Heaters as " VIRTUAL" ULF/ELF/VLF Antennae

Two techniques : 1. Current modulation –Polar Electrojet (PEJ) Antenna – Requires the presence of an electrojet current – not applicable at mid-latitude heaters



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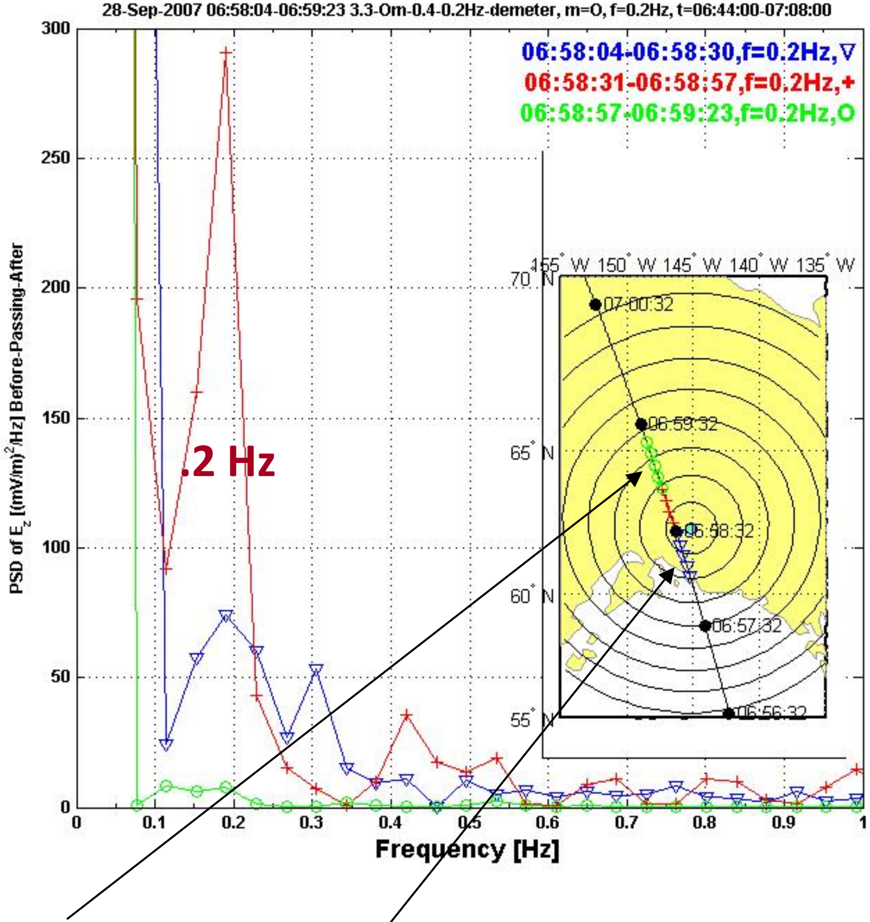
SAW DEMETER Detection

UMD - BAE



After **Before**

Frequency .2 Hz

Closest distance 80 km

Detection time 25 sec

Detection distance 150 km

Maximum E ≈ 10 mV/m

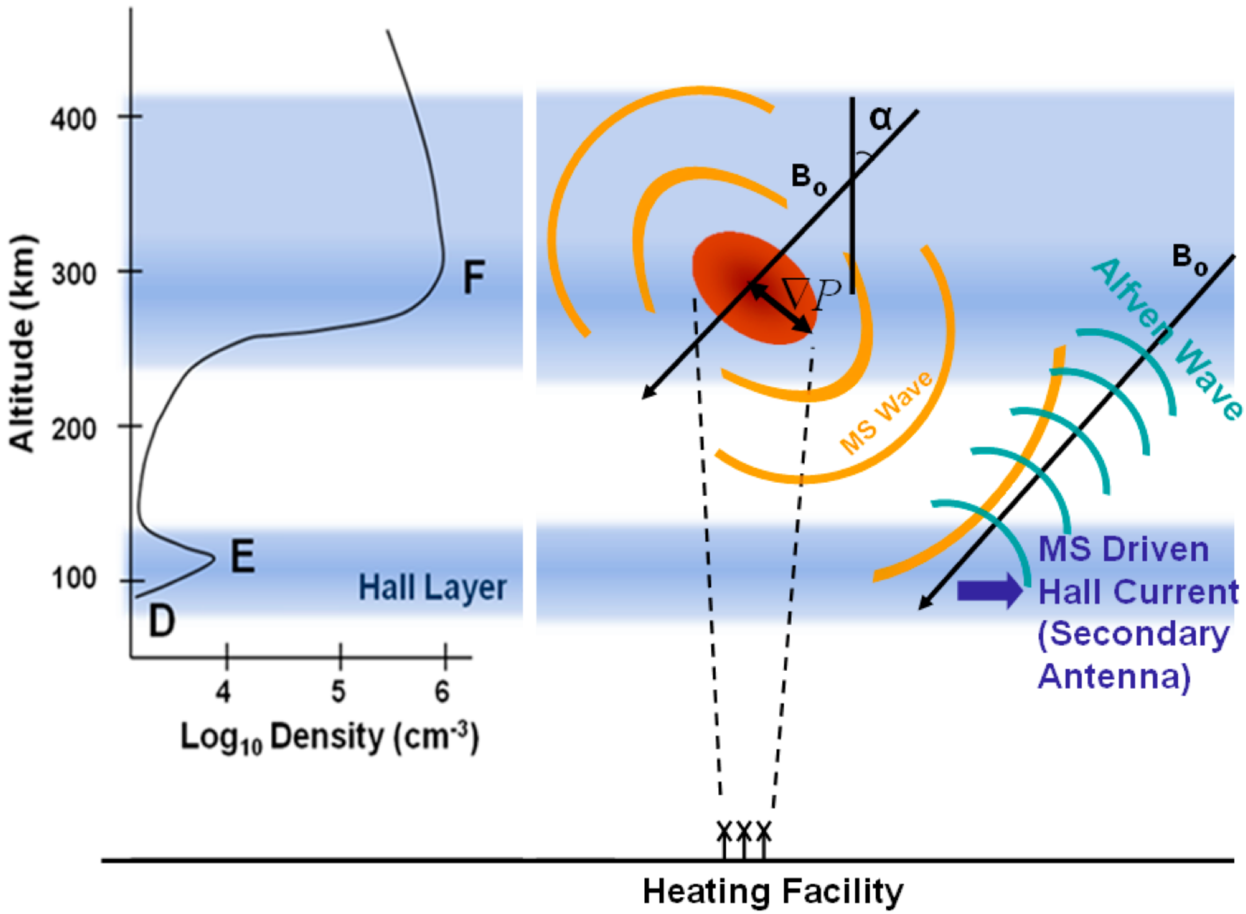
1.5 pT on the ground

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



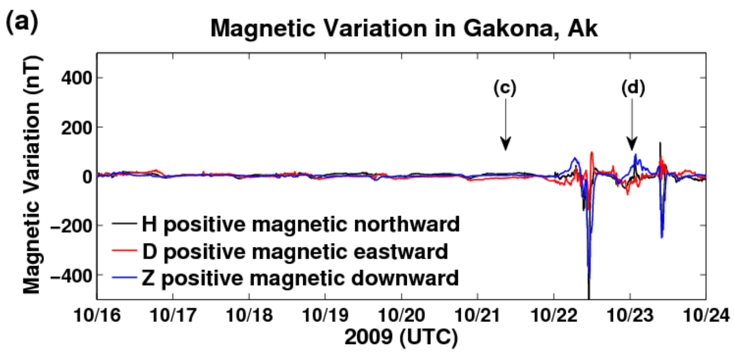
F- region cooling response does not allow frequencies higher than 60-70 Hz

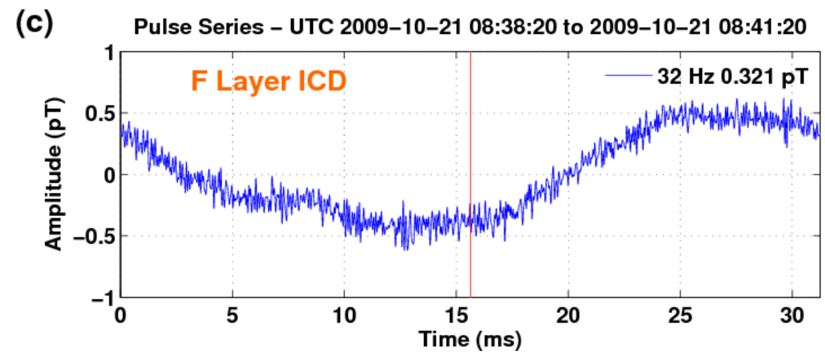
Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

DOES NOT REQUIRE EJET – CAN BE IMPLEMENTED ANYWHERE AND ANYTIME

ICD PoP Experiments

Papadopoulos et al GRL 2011b

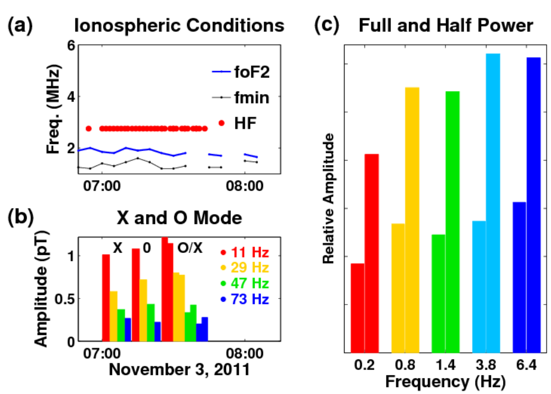




- 10/14-10/21 Magnetometer below 10 nT
- 10/14-10/23 55 hours of VLF/ELF/ULF tests
- 6 hours of VLF ground measurements

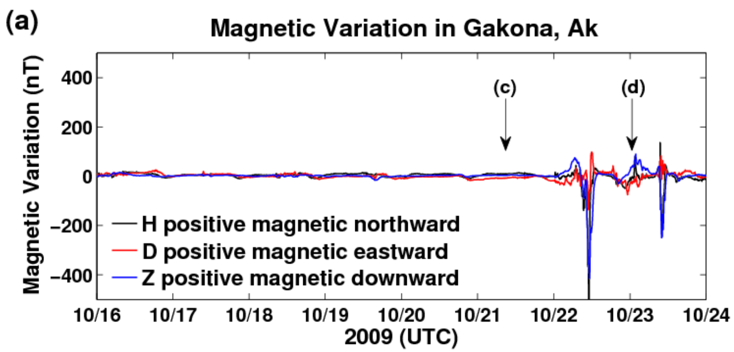
–PEJ operational

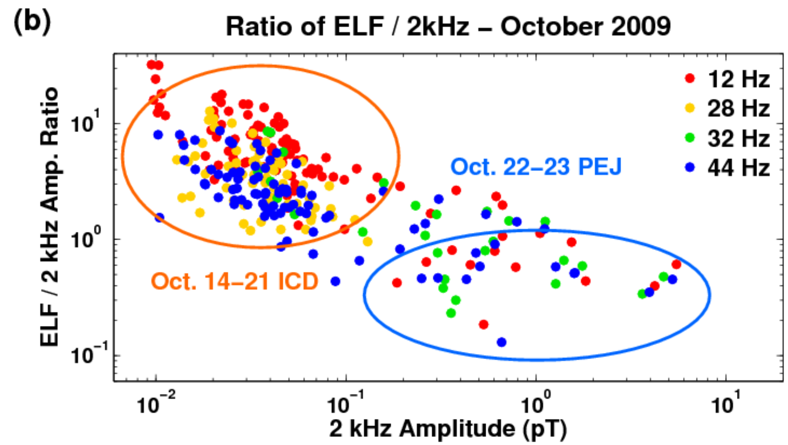
- 51 hours of low ELF/ULF (12-44 Hz) ground measurements



ICD PoP Experiments

Papadopoulos et al GRL 2011b





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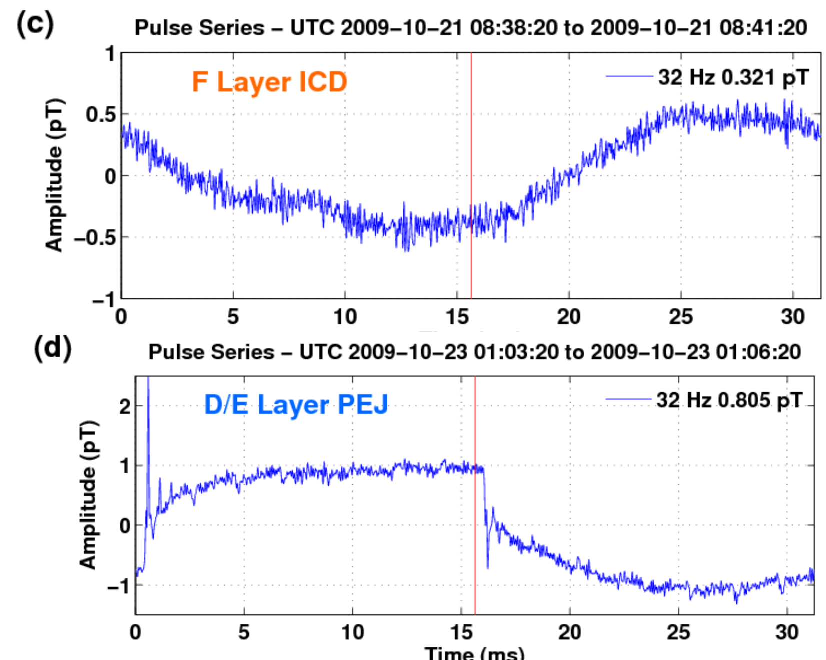
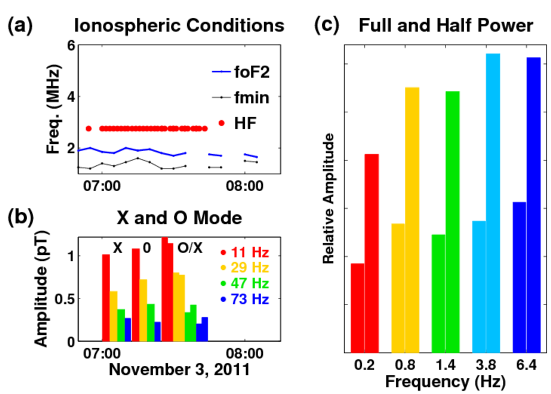
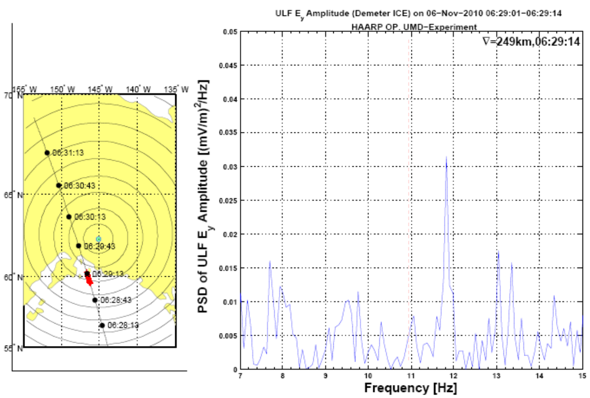
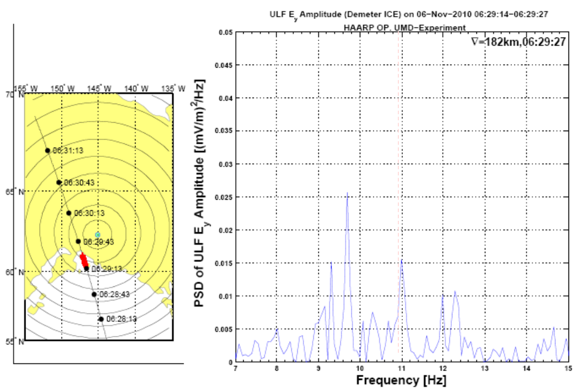


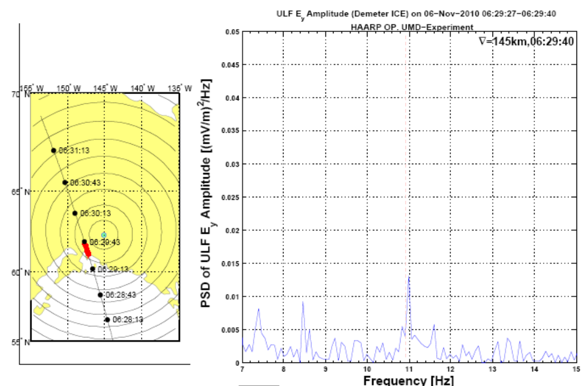


Low ELF Observed by Demeter Satellite

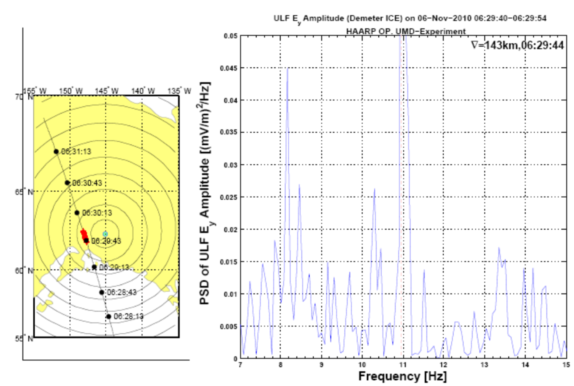
2010-11-06, 06:15:00-06:34:30 ELF 11 Hz modulation (O-MZ)

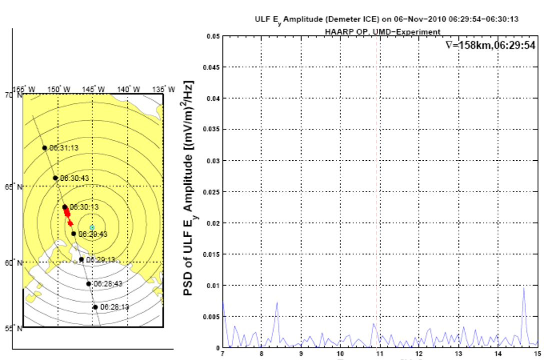






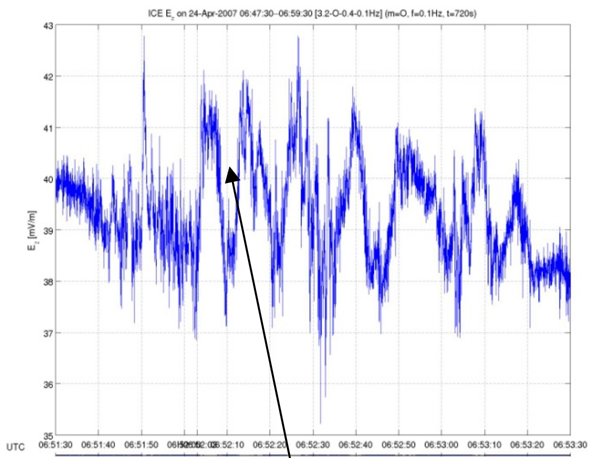
- 11Hz showed along track near HAARP, not before/after
- Duration: 17s or 130 km
- Peak Ey ~ 0.08 $(mV/m)^2/Hz$

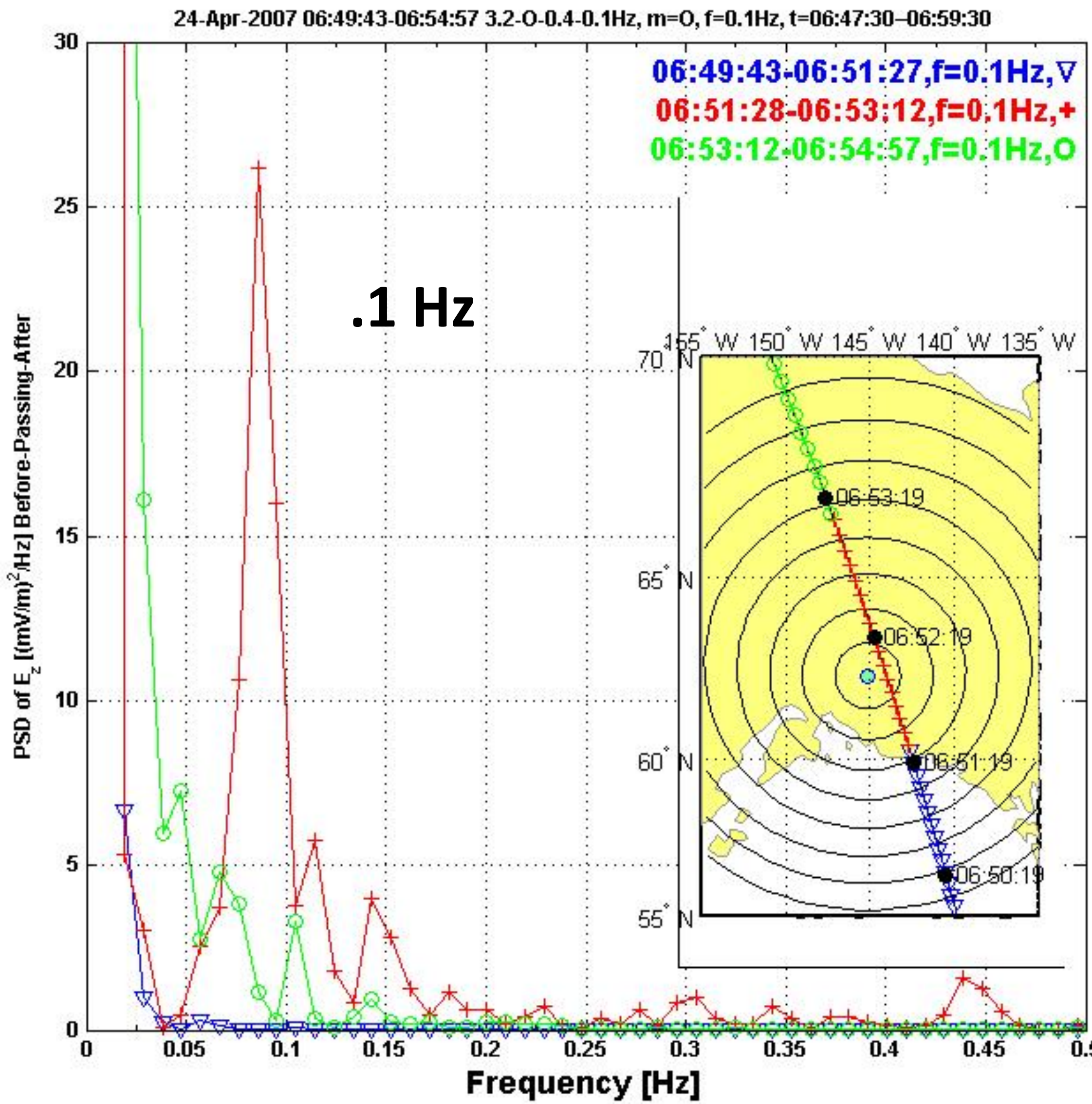




Msonic Wave Injection

DEMETER





.1 Hz

10 sec oscillations

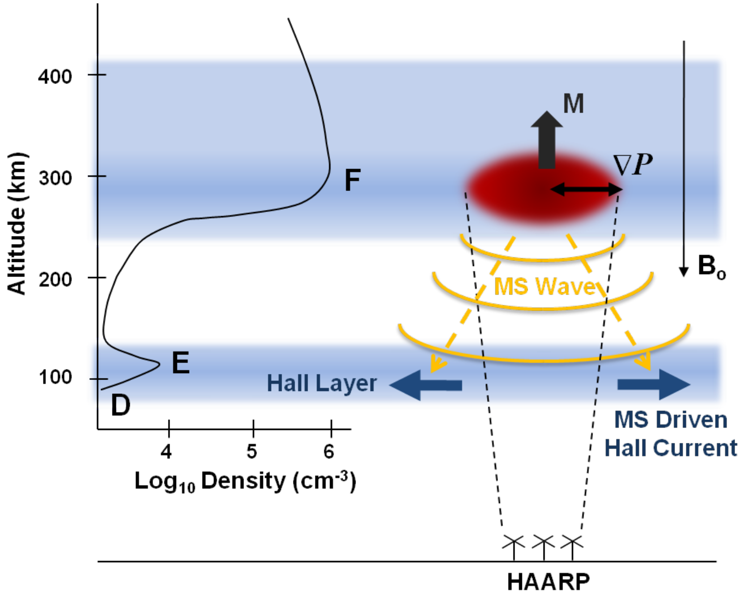
Over 700 km distance

What's New - Ionospheric ELF Source Without Electrojet

- ELF produced by HAARP with ***No Electrojet*** – A Major Breakthrough based on discoveries in recent HAARP campaigns
  - Predictable and repeatable ELF generation up to 50 Hz on daily basis
  - Meff ≈ 5×10^9 A-m^2
  - Validated technique: plasma currents driven by HF heating in the F/E layers
  - Technology transferable to low latitude regions with robust F & no E'Jet

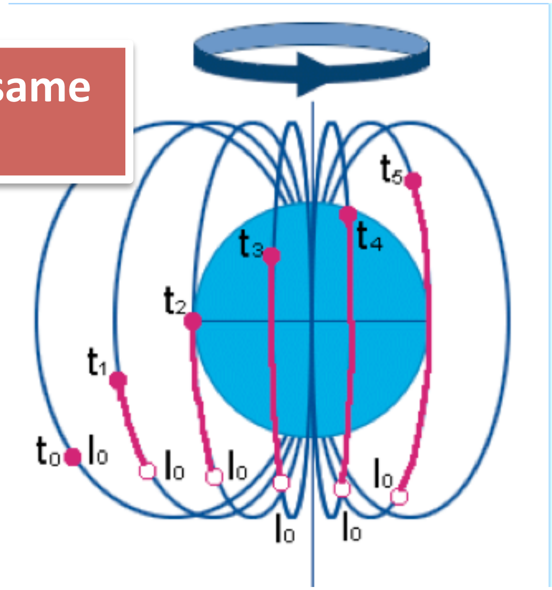
- Ionospheric ELF source provides
  - Higher source strength
    - Closer to region of interest
    - Data rate >> FELF system
      - Greatly increased bandwidth
      - Higher SNR in near field

Papadopoulos et al.
GRL 2011

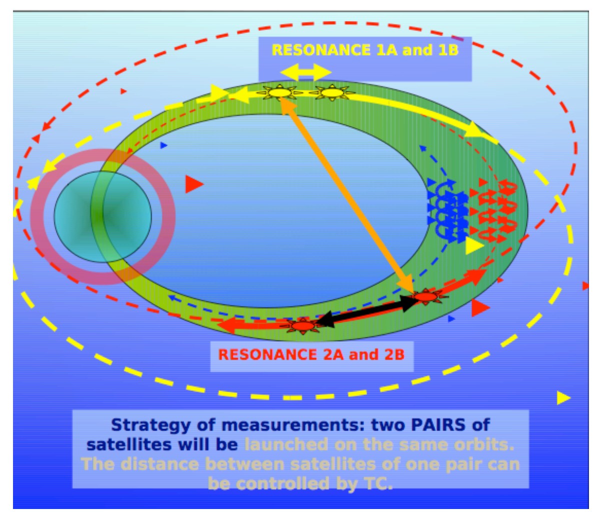


Resonance – The ideal Partner of HAARP

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



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



Mission to be launched by IKI/Russia Summer 2014

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

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

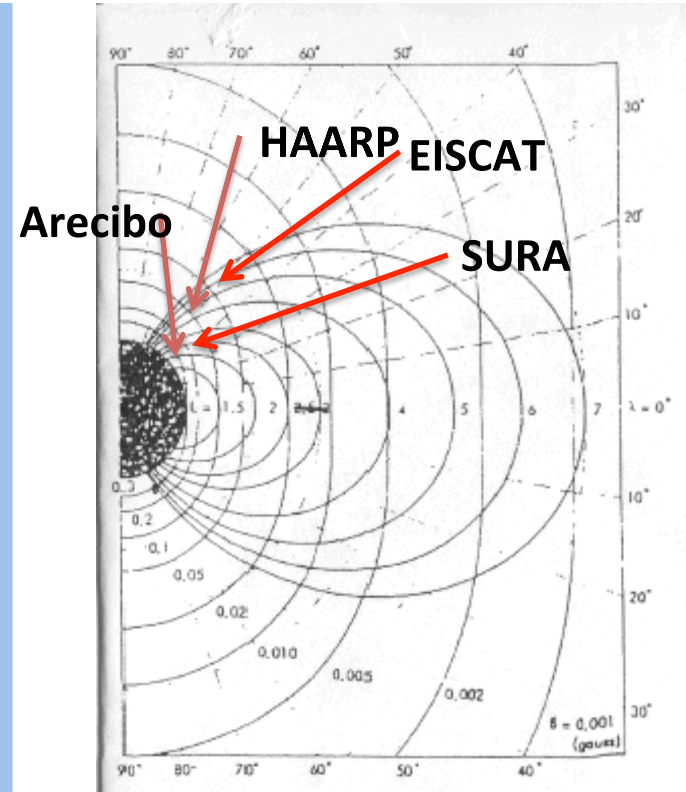
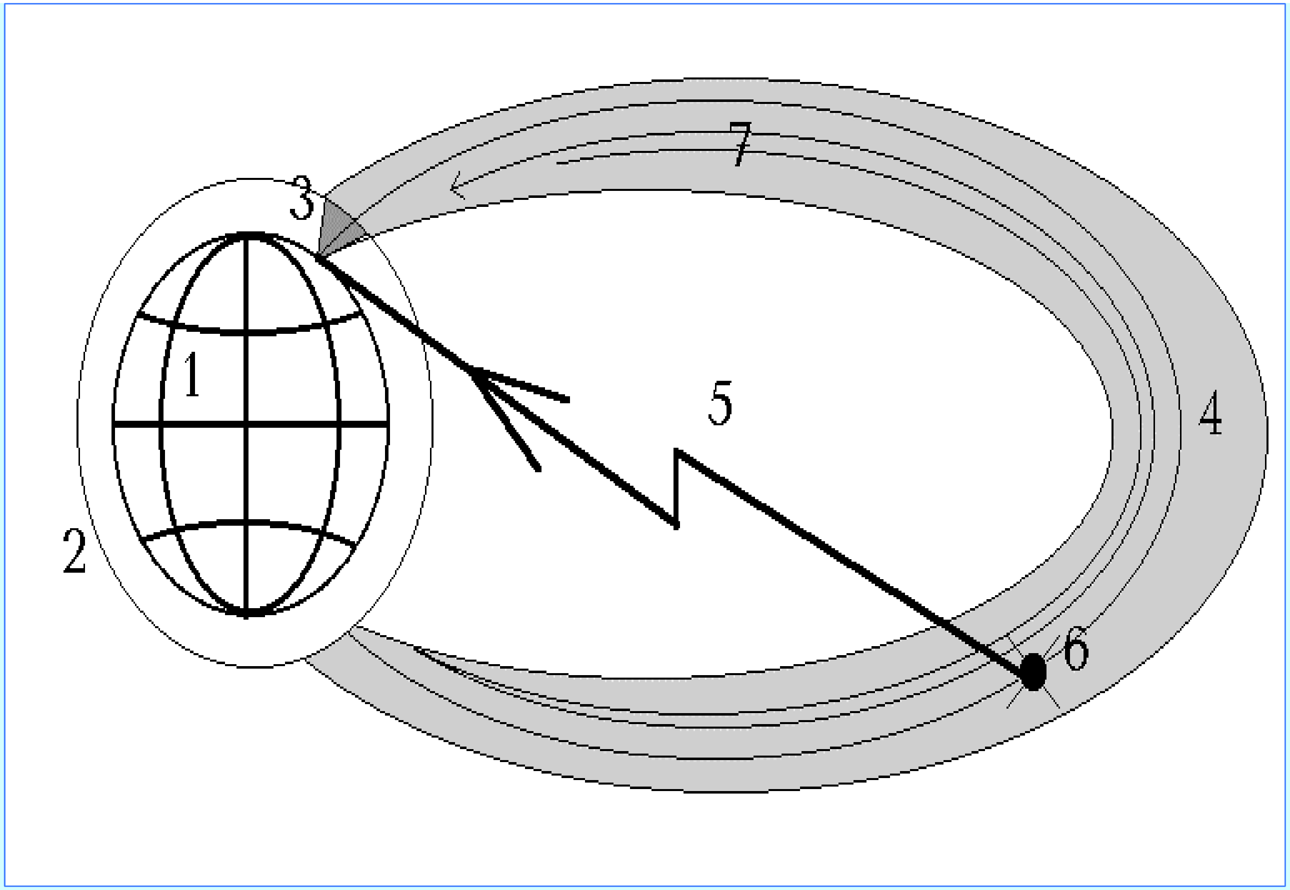


Figure 2-8. Constant-B surfaces in a dipole field.

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

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

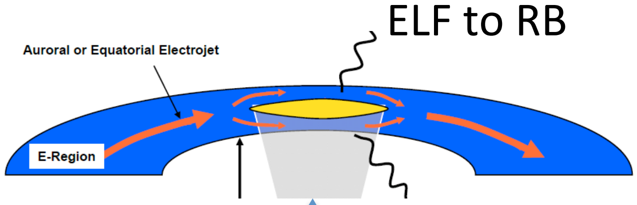
FROM RESONANCE PLAN DOCUMENT



Scheme of a joint experiment with a ground-based heater

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

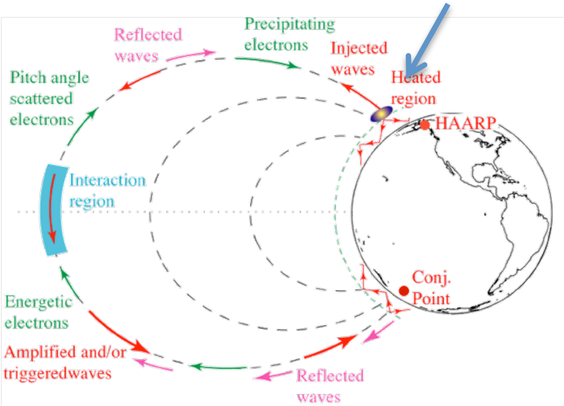
HAARP Artificially Stimulated Emissions
Stanford University



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

Diagnostics ?

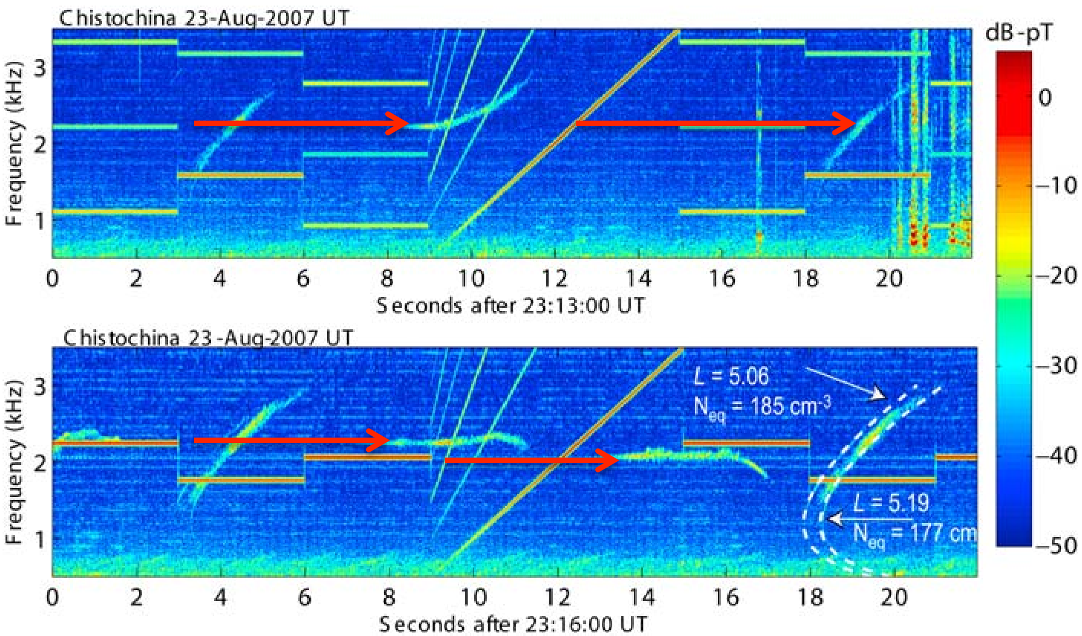
Chistochina

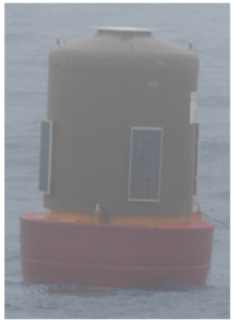


Conjugate

Golkowski et al. JGR 2008, 2010

2-hop echoes

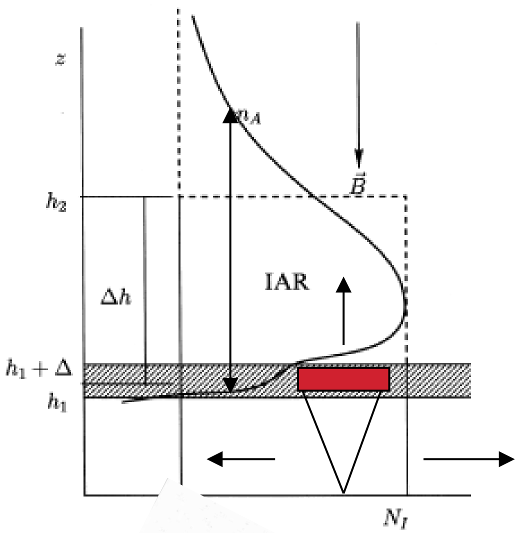


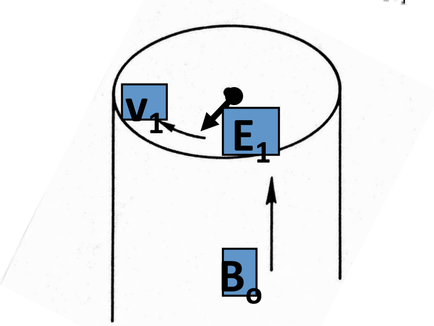


Buoy System

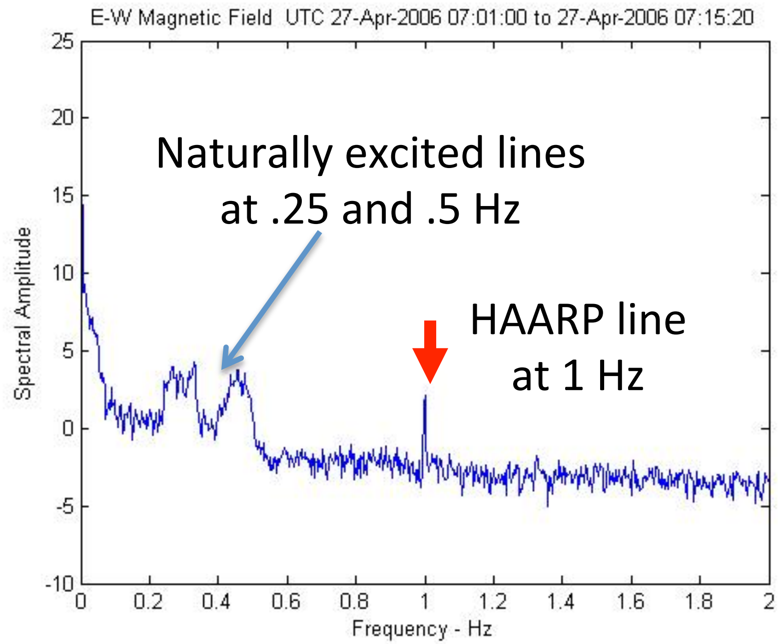
Pulses above 2 kHz have 2-hop echoes with triggered emissions
Pulses below 2 kHz and above 2.8 do not; ramps most often have echoes

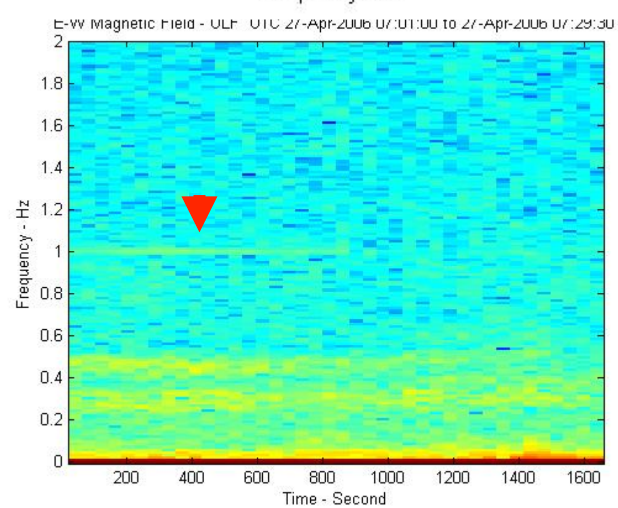
Physics of Pc-1 MHD Waves
Ionospheric Alfven Resonator (IAR)



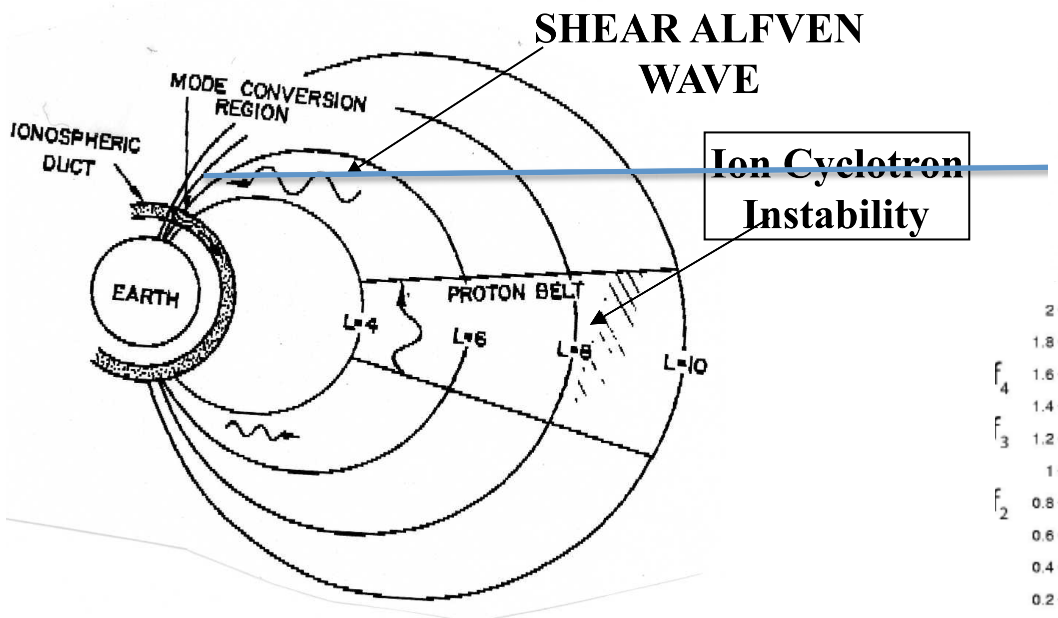


Shear Alfven Wave –Field Guided



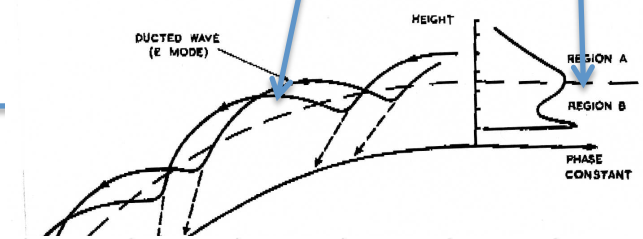


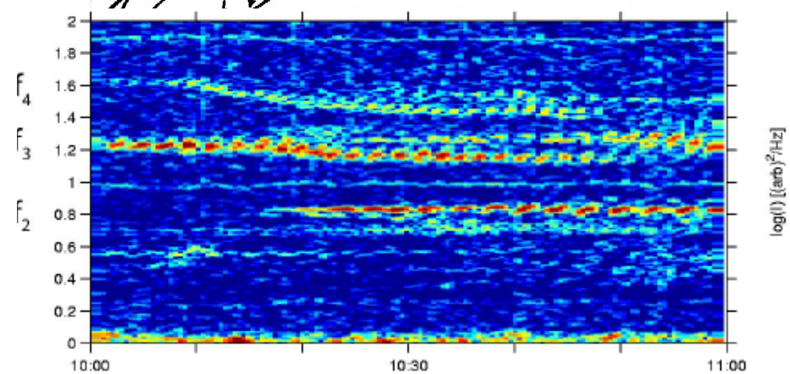
M-I SAW Coupling Studies



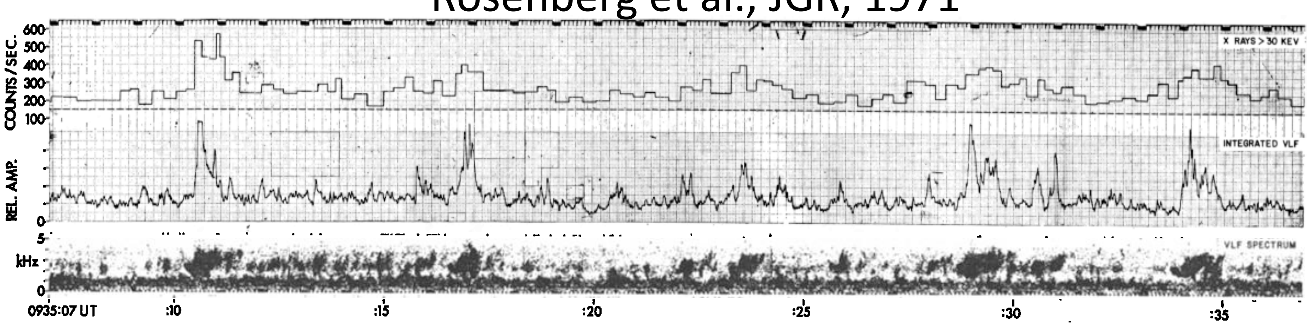
Ionospheric Alfven Resonator

Alfvenic Duct





Rosenberg et al., JGR, 1971



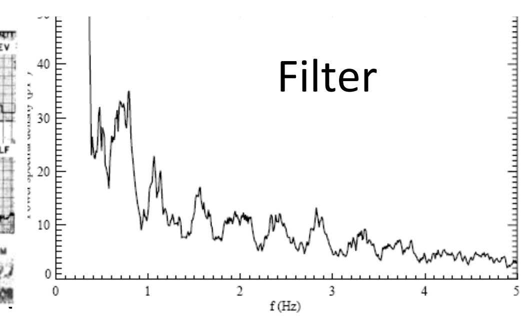
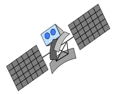


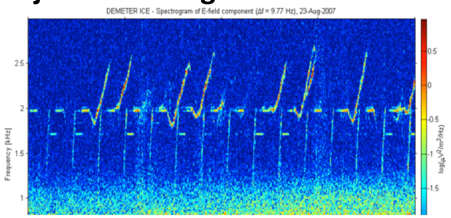
Fig. 1. A 30-sec segment of simultaneous recordings of X-ray count rate for $E > 30$ kev (top), integrated VLF amplitude from 0.6 to 5 kHz (middle), and VLF spectrum from 0 to 5 kHz (bottom), at Siple station, Antarctica, on January 2, 1971. The dashed line in the top portion of the figure refers to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

Quasi-periodic ULF/VLF and electron precipitation

HAARP / RBR
Research Activities

- **Satellite Observations of Injected VLF Signals**

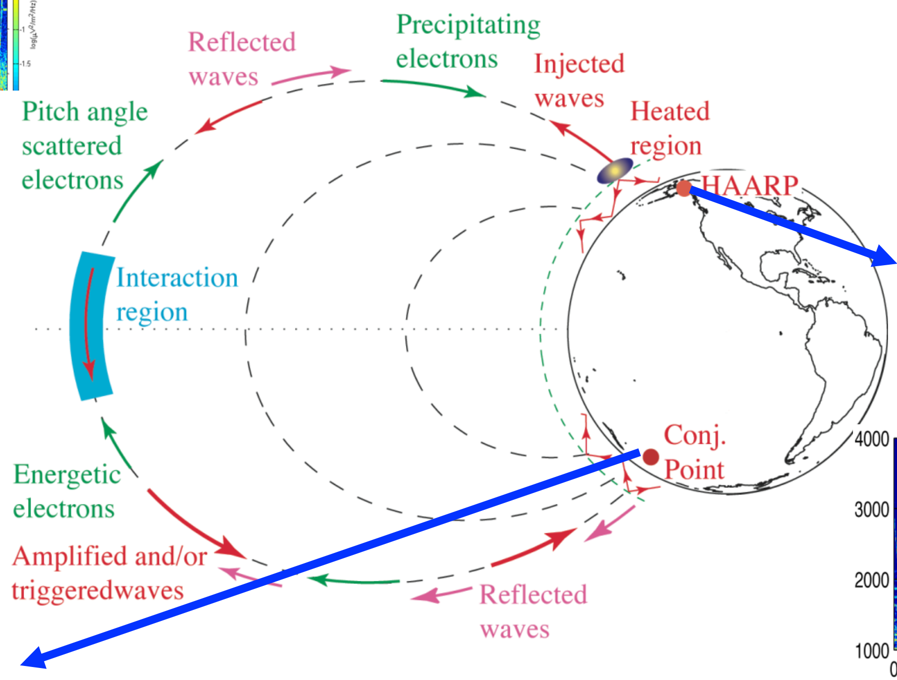


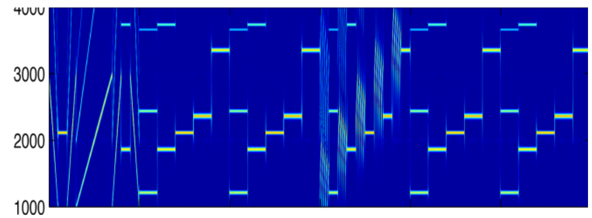


DEMETER

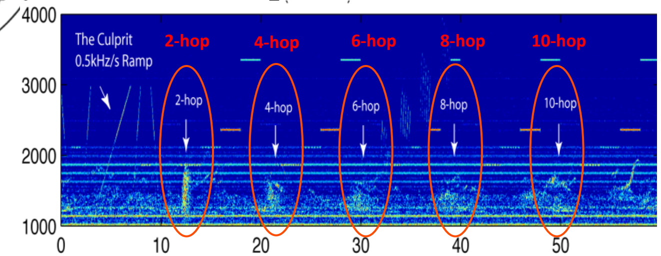
- **VLF Wave Generation and Injection in Alaska**
- **Ground Measurements of Multiple-Hop Signals in Alaska**
- **Observations of Triggered Particle Precipitation Events**

HAARP Facility, Alaska

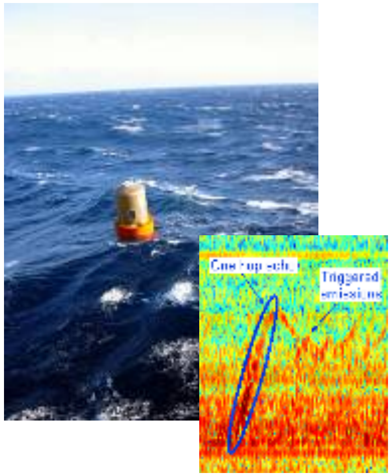




VLF Signals Generated with HAARP



Measurements of Multiple-hop VLF Signals Generated at HAARP and Propagated in the Magnetosphere its Conjugate Point off New Zealand and Then Received Back in Alaska



- **Measurements of 1-Hop Signals Generated at HAARP and Received at its Conjugate Point off New Zealand**

Planned Experiments to Understand VLF Injection, Propagation, and Amplification in the Magnetosphere– A Key Enabler for an Operational Mitigation System

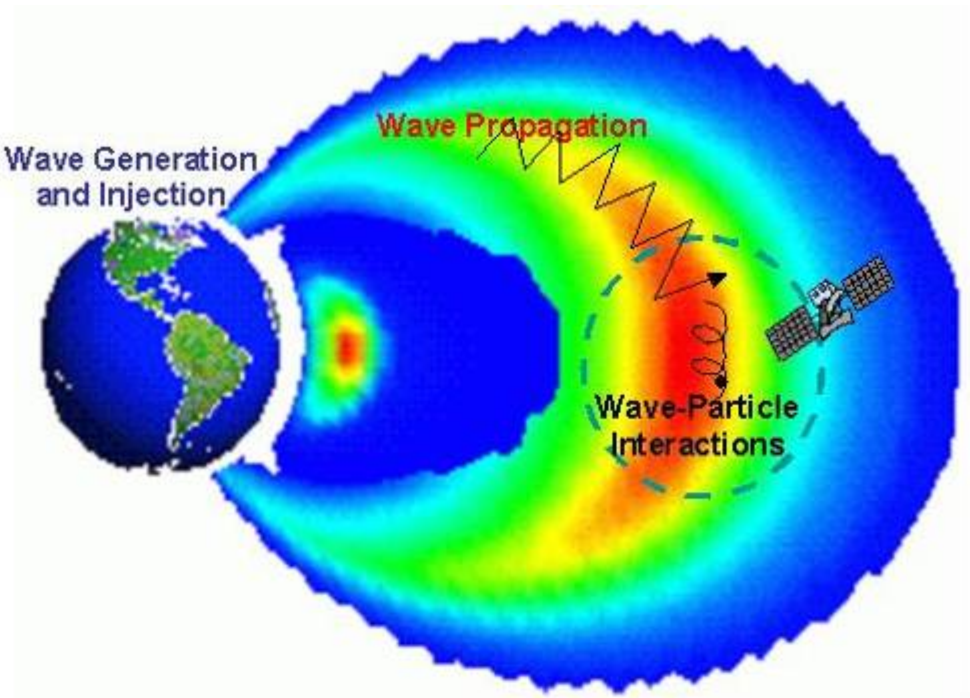
Near-Term Research Focus

Radiation Belt Remediation (RBR) Issues

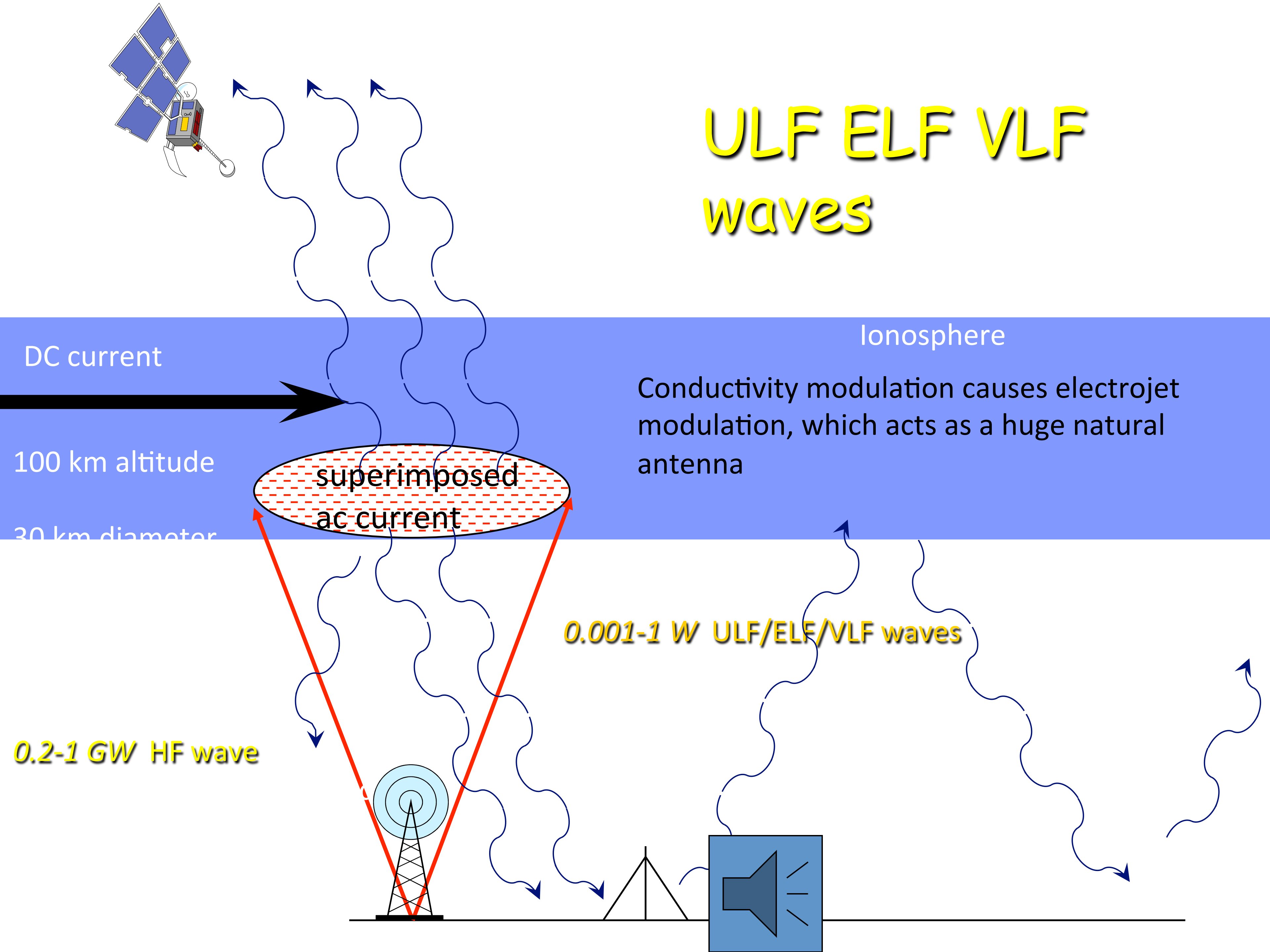
ELF/VLF Waves Known to Control Lifetimes of Radiation Belt Particles

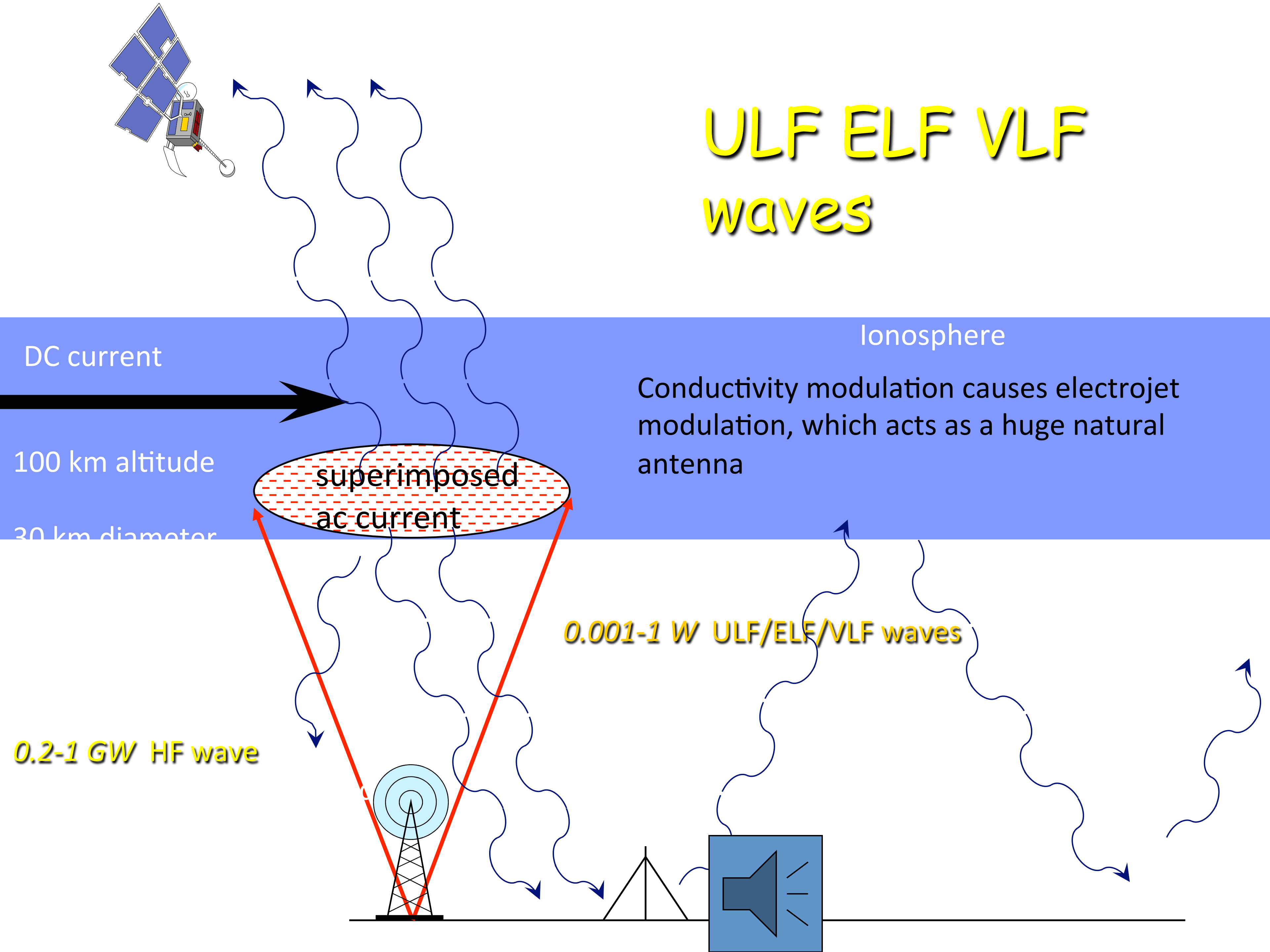
Scientific Unknowns

- **Wave Generation/Injection Efficiencies**
  - Dependence on Frequency, Waveforms
  - Dependence on Geophysical Conditions
- **Wave Propagation Characteristics**
  - Ducting Conditions
  - Wave Amplification Processes
  - Dependence on Frequency, Waveforms
  - Dependence on Geophysical Conditions
- **Wave-Particle Interactions**
  - Effects of Waves on Particle Motion /Scattering
  - Efficiency of Precipitating Particles out of the Belts
  - Dependence on Geophysical Conditions



Research to Help Specify the Nature, Number, and Orbits of VLF Satellite Transmitters Required for Timely Radiation Belt Remediation


ULF ELF VLF
waves
Ionosphere
DC current
100 km altitude
30 km diameter
superimposed
ac current
Conductivity modulation causes electrojet modulation, which acts as a huge natural antenna
0.001-1 W ULF/ELF/VLF waves
0.2-1 GW HF wave


ULF ELF VLF
waves
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Conductivity modulation causes electrojet modulation, which acts as a huge natural antenna
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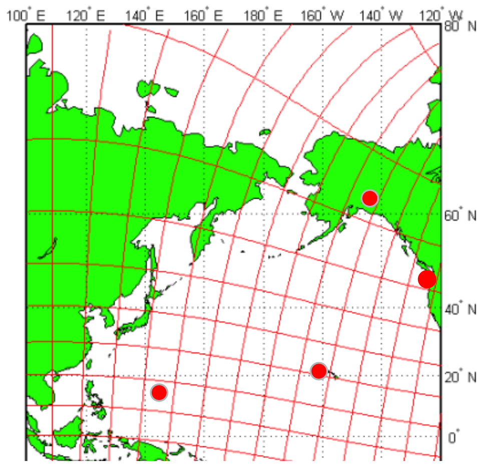
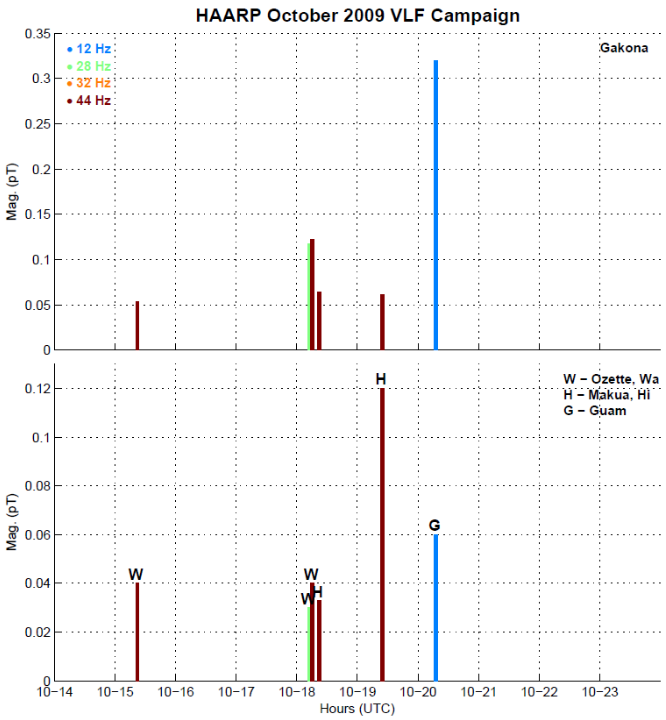
0.2-1 GW HF wave

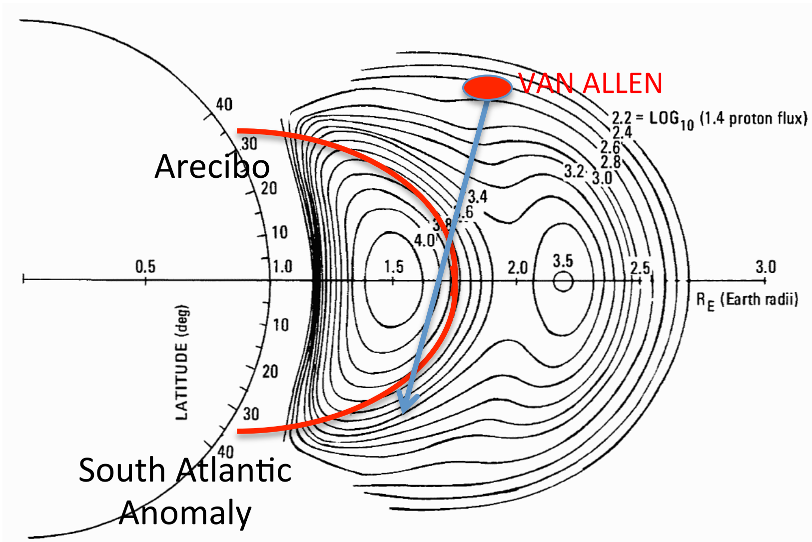
ICD ELF detection at Distant Sites





- 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

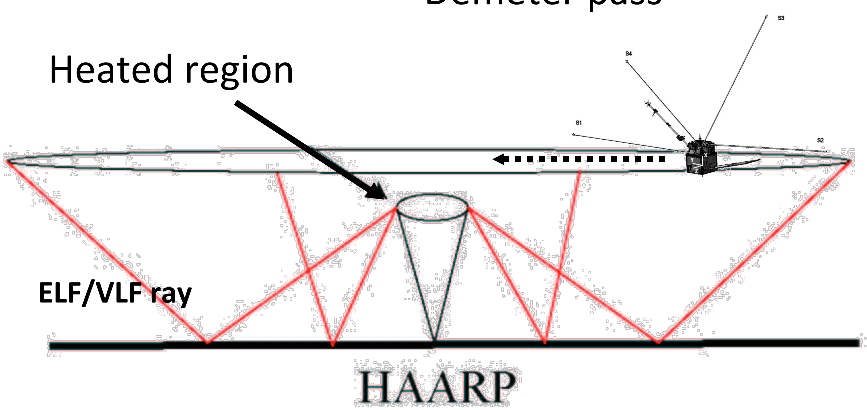
Active Probing of Inner RB Using the Arecibo Heater Using ICD

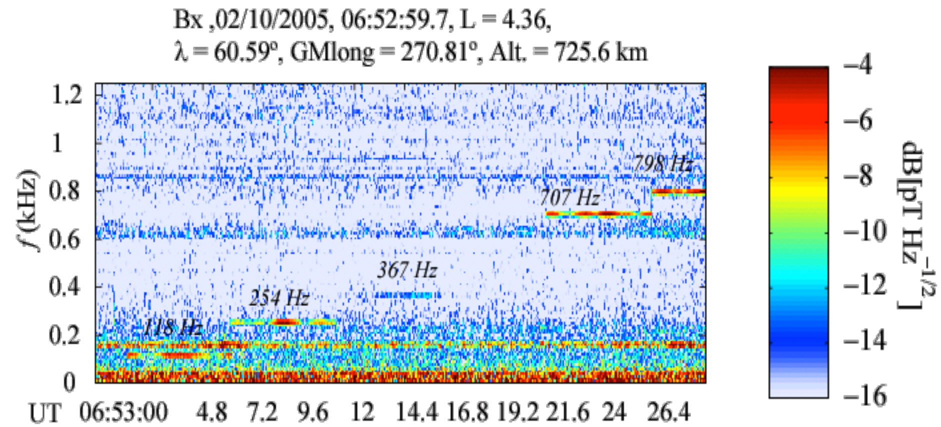


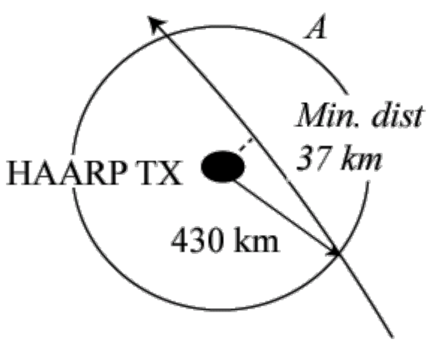
Focus on SAW for protons and EMIC for electrons

WPI critical aspect of RB physics. Van Allen Probes will study interactions in the natural environment, A wave injection facility at Arecibo at frequencies that resonate with energetic protons and electrons offers cause and effect understanding of the induced transport processes with RBSP and other satellite diagnostics. Also study of mid-latitude IAR and SAW and EMIC propagation

HAARP-DEMETER VLF INJECTION



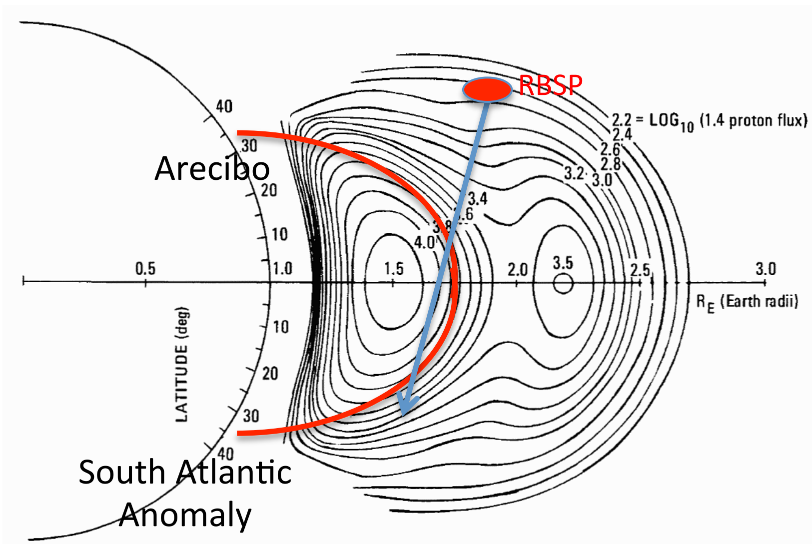


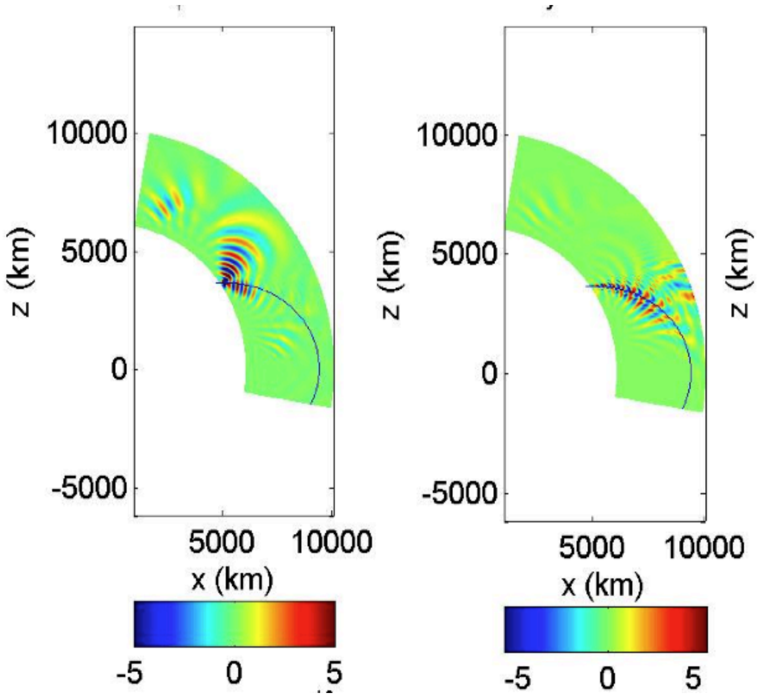


- **ELF/VLF signals observed in LEO (~700 km) at lateral distances of >400-km from HAARP**
- **Simultaneous measurement of all six components (3*E*, 3*B*) allows estimation of the Poynting vector**
- **Total ELF/VLF radiated power estimated to be ~10 to 30 Watts in the range ~100 Hz to 800 Hz.**

COURTESY STANFORD UNIVERSITY

New Opportinuty - Active SAW Probing of Inner RB Using the Arecibo Heater/Van Allen





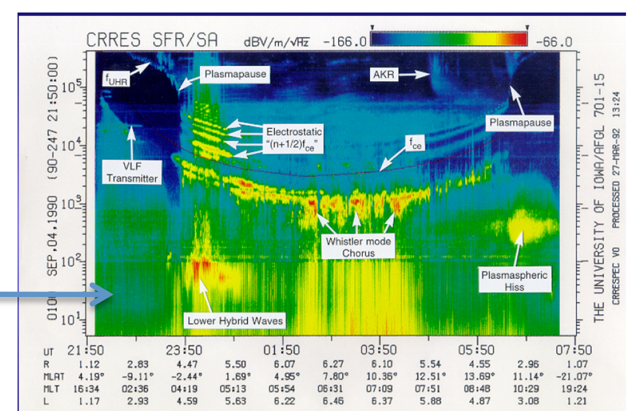
Focus on SAW for protons and EMIC for electrons

Typical inner belt proton lifetimes:

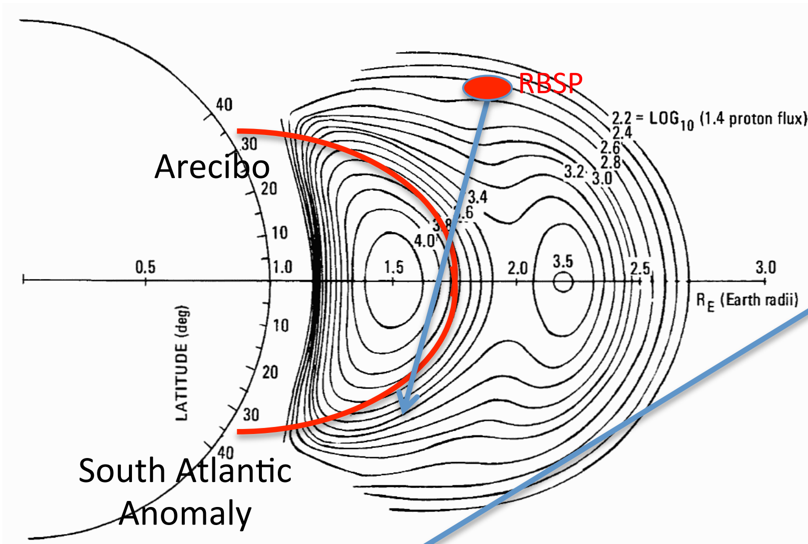
10 MeV – decades

50 MeV – century

No SAW activity
Stacking



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



Focus on SAW for protons and EMIC for electrons

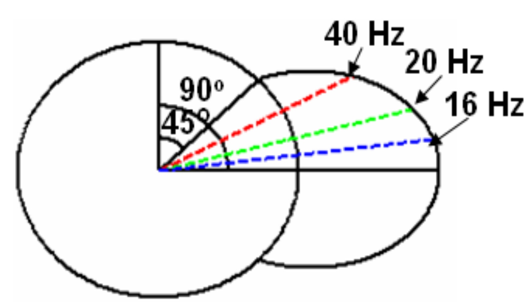
Proton Energy	Resonance Frequencies
30 MeV	6-16 Hz
50 MeV	5-15 Hz
100 MeV	3.5-9.5Hz

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

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

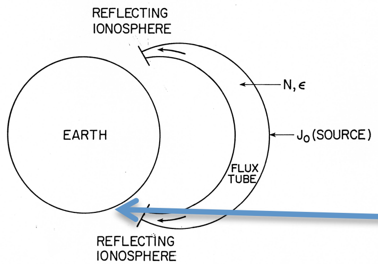
$$\frac{k^2c^2}{\omega^2} \rightarrow \infty \quad \text{for } \omega \rightarrow \Omega_j$$

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



HELIUM BRANCH Resonances

RB SAW Injection Tests

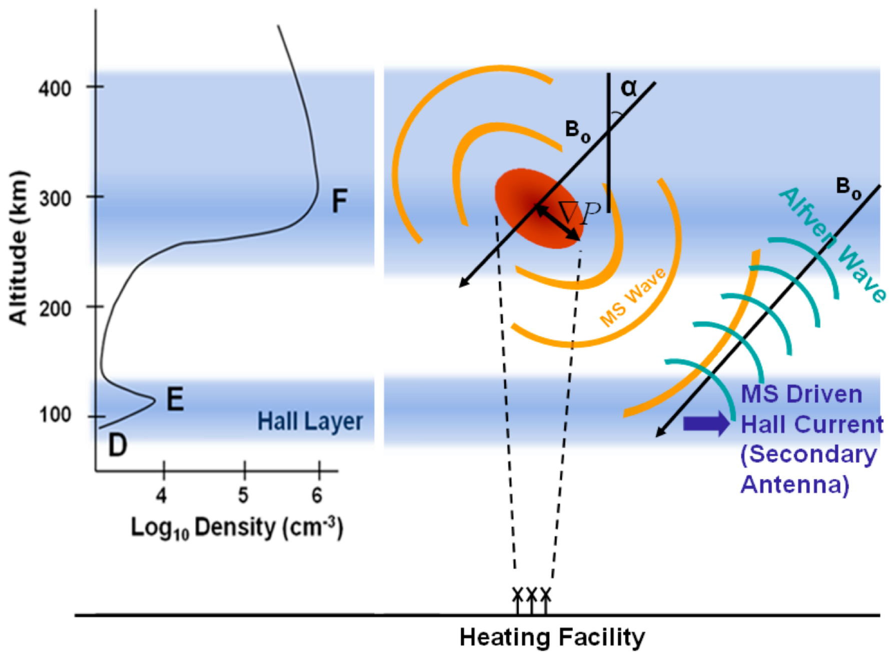


Need Source that can inject SAW into RB Ionospheric Heater

Ionospheric Current Drive (ICD)

Step 1: $\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$ Diamagnetic current -> MS wave

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



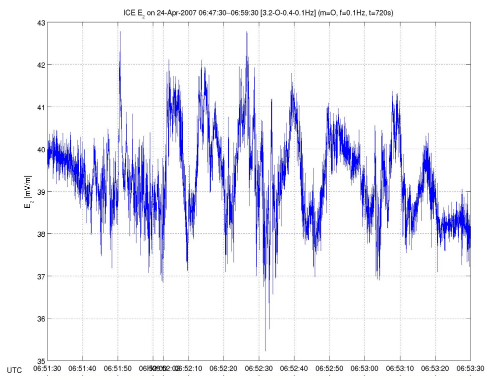
Injects SAW upwards and ELF in the Earth-Ionosphere Waveguide

Proof of Concept ICD Injection Experiment HAARP/DEMETER

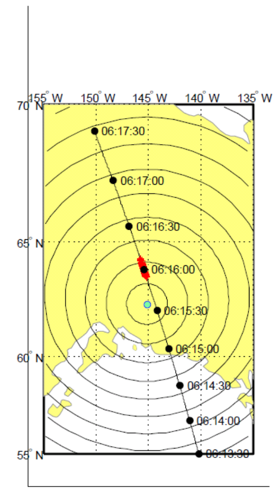
Chang-Lebinsky-Milikh-Papadopoulos

2.8 MHz, O-mode

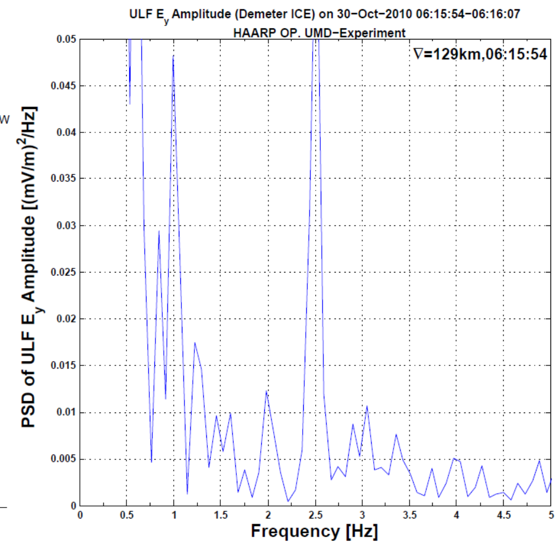
MS

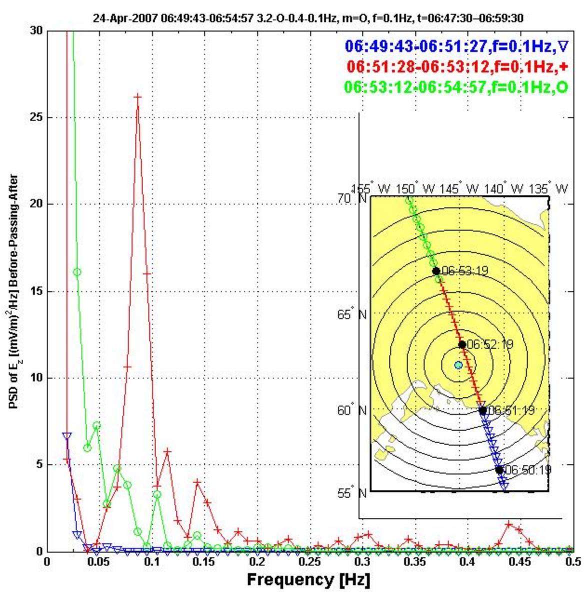


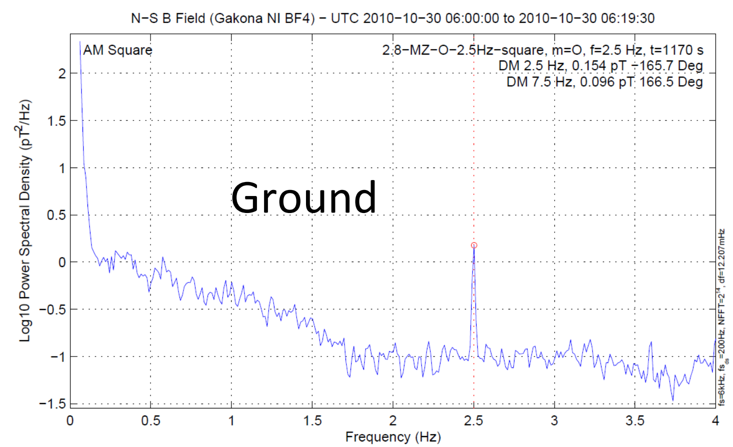
BRIOCHE



SAW

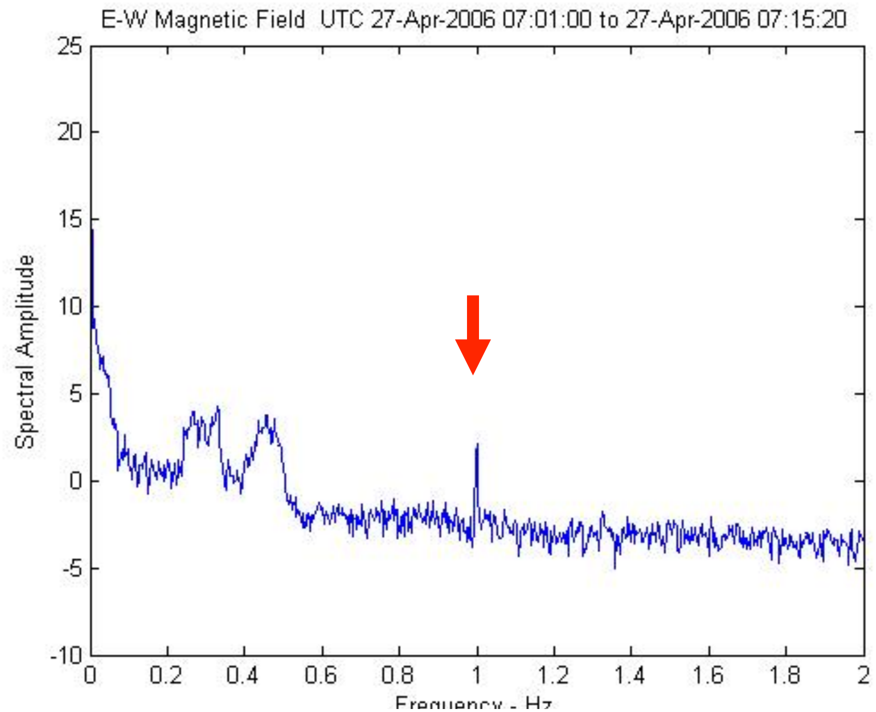


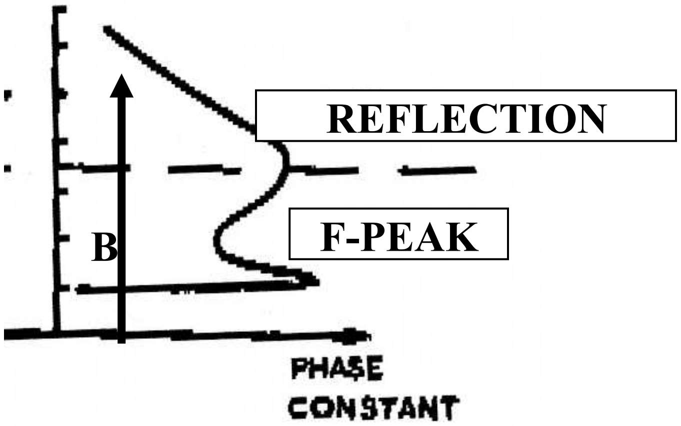


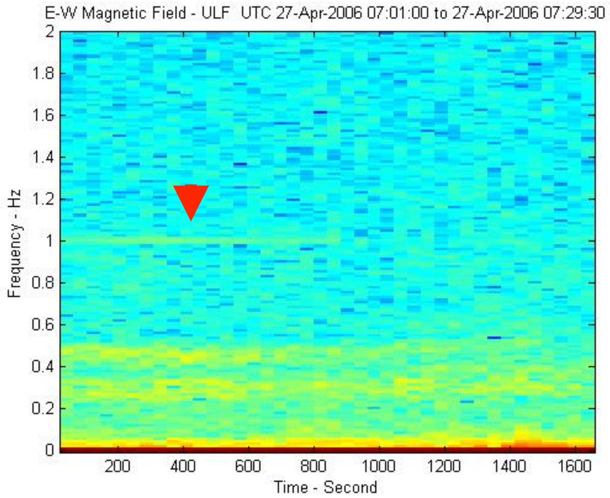


Papadopoulos et al.
GRL 2011a,b

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.

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

Focus on SAW for protons and EMIC for electrons

$$\omega \approx k_z V_p$$

$$\omega = k_z V_A$$

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

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

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

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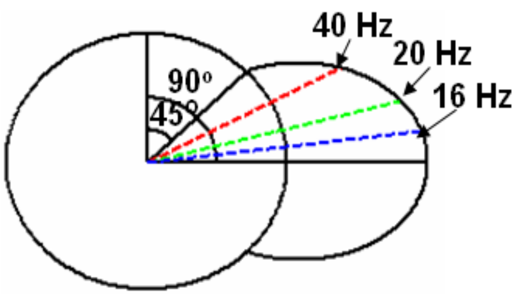
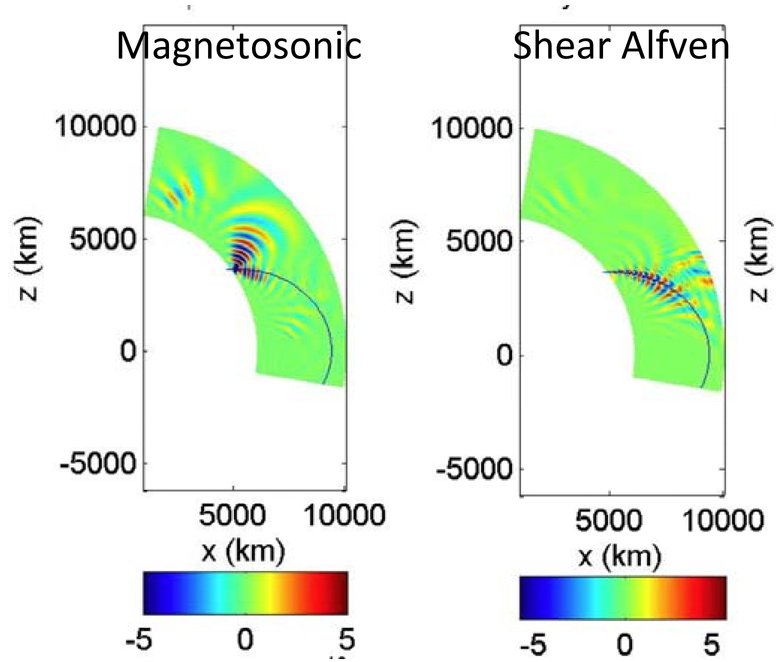


HELIUM BRANCH Resonances

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



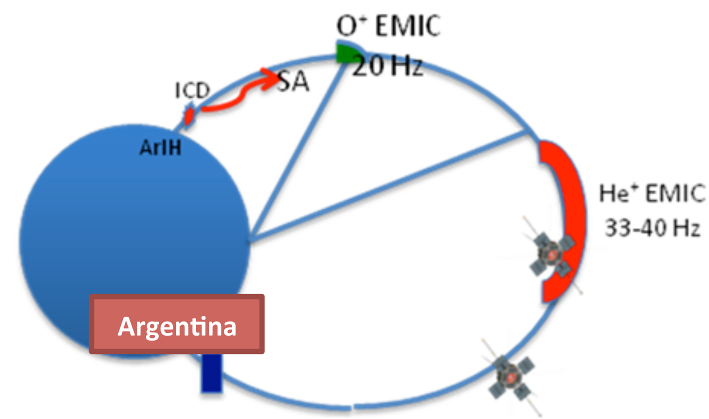
Simulation of MHD Wave injection using the Arecibo Heater

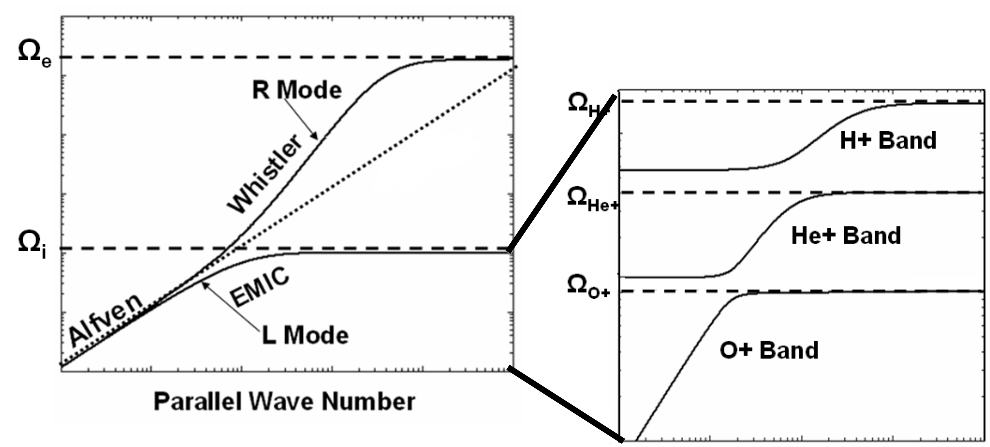
$$-k_z v_z = |\Omega_e| / \gamma$$

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

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

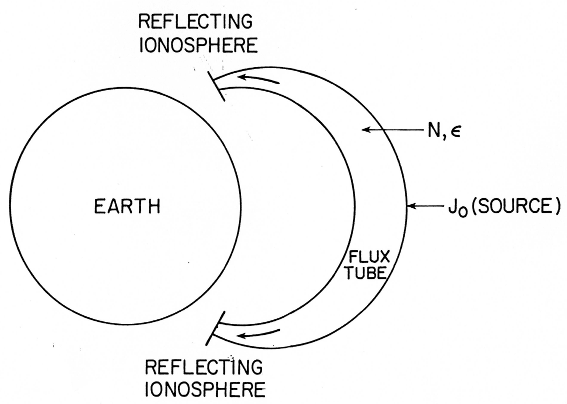
As a result $1/k_z \rightarrow |\Omega_e|/\gamma v_z$ before reaching resonance ($1/k_z \rightarrow 0$)



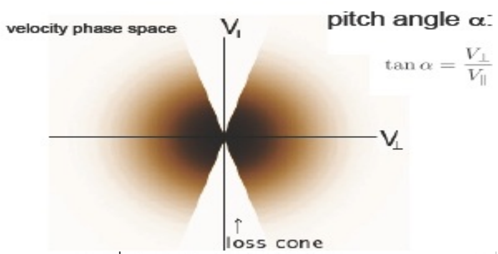


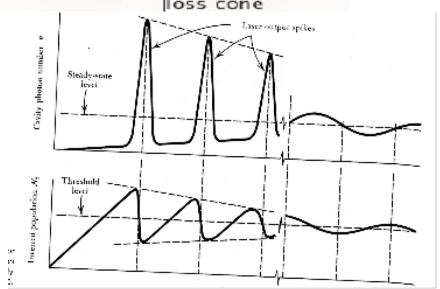
RB as a Maser WHY ?

Take a flux tube



Loss Cone Distribution





1. Fundamental modes Whistler and Alfven Waves.
2. Magnetic field tube with low density magneto-plasma corresponds to a quasi-optical resonator.
3. High density and conduction ionospheric regions correspond to the mirrors with reflection and transmission coefficients.
4. The active medium is the energetic particle loss cone distribution intrinsically maintained in the geometry – Population inversion
5. Pumping can be provided by sources of energetic particles or waves externally injected or external control of the cavity Q.

$$\frac{dn_p}{dt} = Kn_pN_2 + KN_2 - \frac{n_p}{\tau}$$

$$\frac{dN_2}{dt} = -Kn_pN_2 - \frac{N_2}{\tau_2} + R_p(t)$$

Exhibits relaxation oscillations, spiking, Q switching controlled by the pumping rate R(t)