Invited Presentation
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Ionospheric Current Drive (ICD) at Low Frequencies

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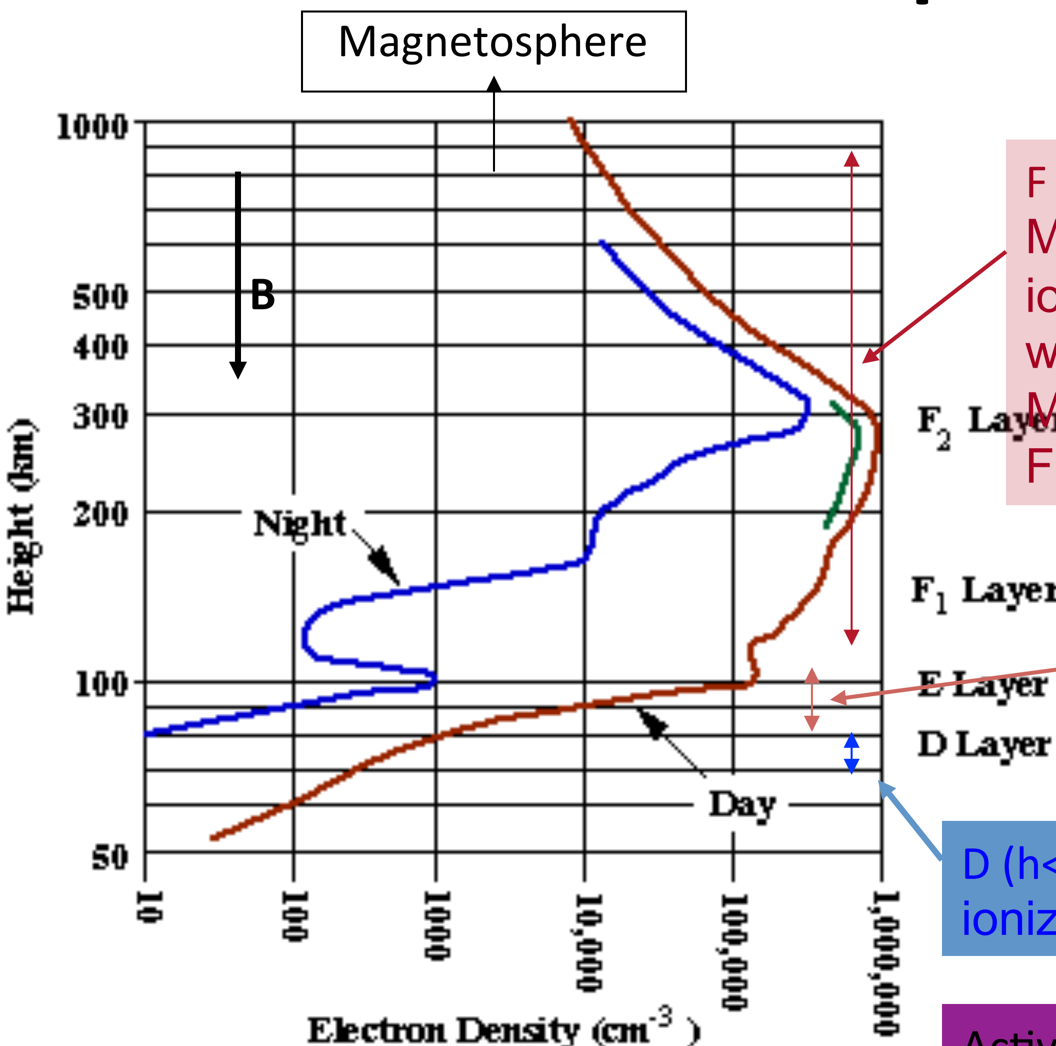
KAW-FEST

PRESENTATION OUTLINE

- THE IONOSPHERE AS A PLASMA – IONOSPHERIC HEATERS - HAARP
- ELF/ULF WHY? GROUND TRANSMITTER ISSUES
- ELF/ULF BY HF MODULATION OF EJET CURRENTS – SUCCESSES - DRAWBACKS
- IONOSPHERIC CURRENT DRIVE (ICD) BY F-REGION HF ANOMALOUS ABSORPTION
  - BASIC PHYSICS MODEL – THEORY/SIMULATIONS
  - PROOF OF PRINCIPLE EXPERIMENTS – CREATION OF SECONDARY VIRTUAL HALL REGION ANTENNA
  - NEAR FIELD EXPERIMENTS
  - FAR FIELD DETECTIONS
- THE FUTURE – TAKING ADVANTAGE OF THE COWLING EFFECT – EQUATORIAL HEATERS

The Polar Ionosphere as Plasma



F (h> 120 km):Collisionless ($\nu << \Omega$), Magnetized plasma – Electron and ion plasma waves, cyclotron waves, whistlers, MHD (Shear-Msonic) waves. Notice min. of V_A at F-peak.

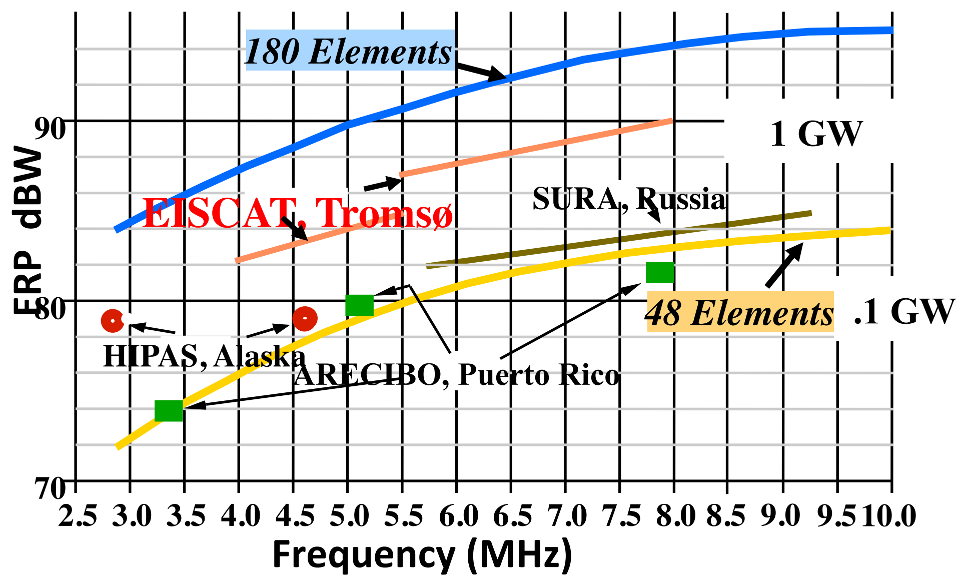
E(70<h<120 km): $\omega_e, \Omega_e > \nu$, $\Omega_i < \nu$ EMHD plasma – Helicon waves – no Alfven or Ion Cyclotron waves

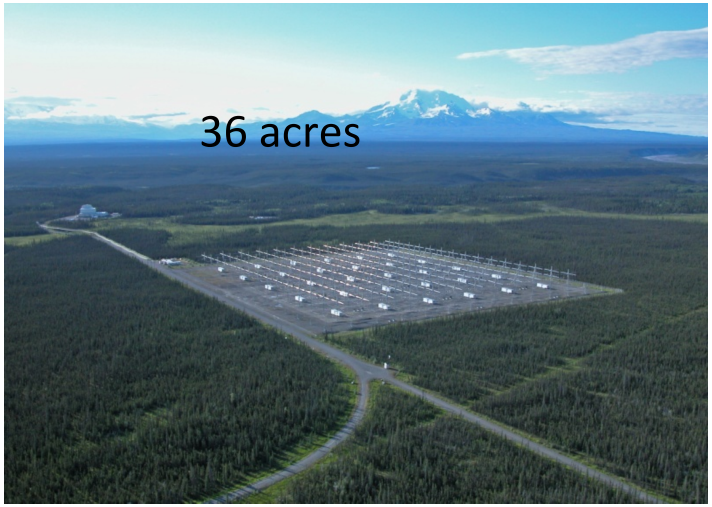
D (h<70 km): $\nu > \Omega_e, \omega_e$ weakly ionized gas – not plasma

Active Regions (Plasmas with Free Energy): E-Electrojets

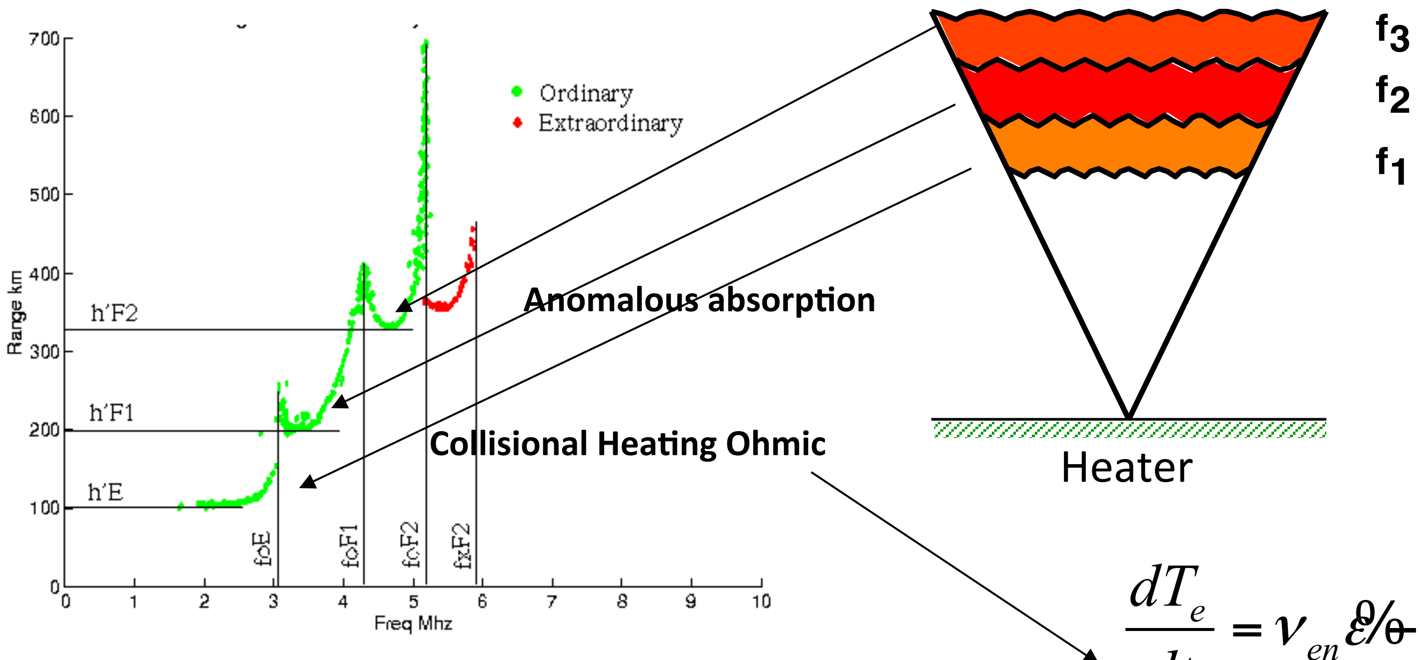
Active Experiments
Inject Energy in Space
Ionospheric Heaters – HAARP

- Ionospheric heater - Powerful HF transmitter (2.8-10 MHz) that induces controlled temporary modification to the electron temperature at desired altitude.
- Use in conjunction with diagnostics to study, in a cause and effect fashion:
  - EM propagation, plasma turbulence and instabilities
  - Creation of artcfiial ionospheric layers
  - Ionospheric ULF/ELF/VLF generation aqd injection in EIW and the RB
  - Induced energetic particle precipitation from RB





How to control location and profile of electron heating



$$\frac{dT_e}{dt} = \nu_{en}\mathcal{E} - losses$$

$$\mathcal{E} = \frac{1}{2} m \left(\frac{eE}{m\omega_{eff}}\right)^2$$

$$\omega_{eff}^2 \approx (\omega \pm \Omega_e)^2 + \nu_{en}^2$$

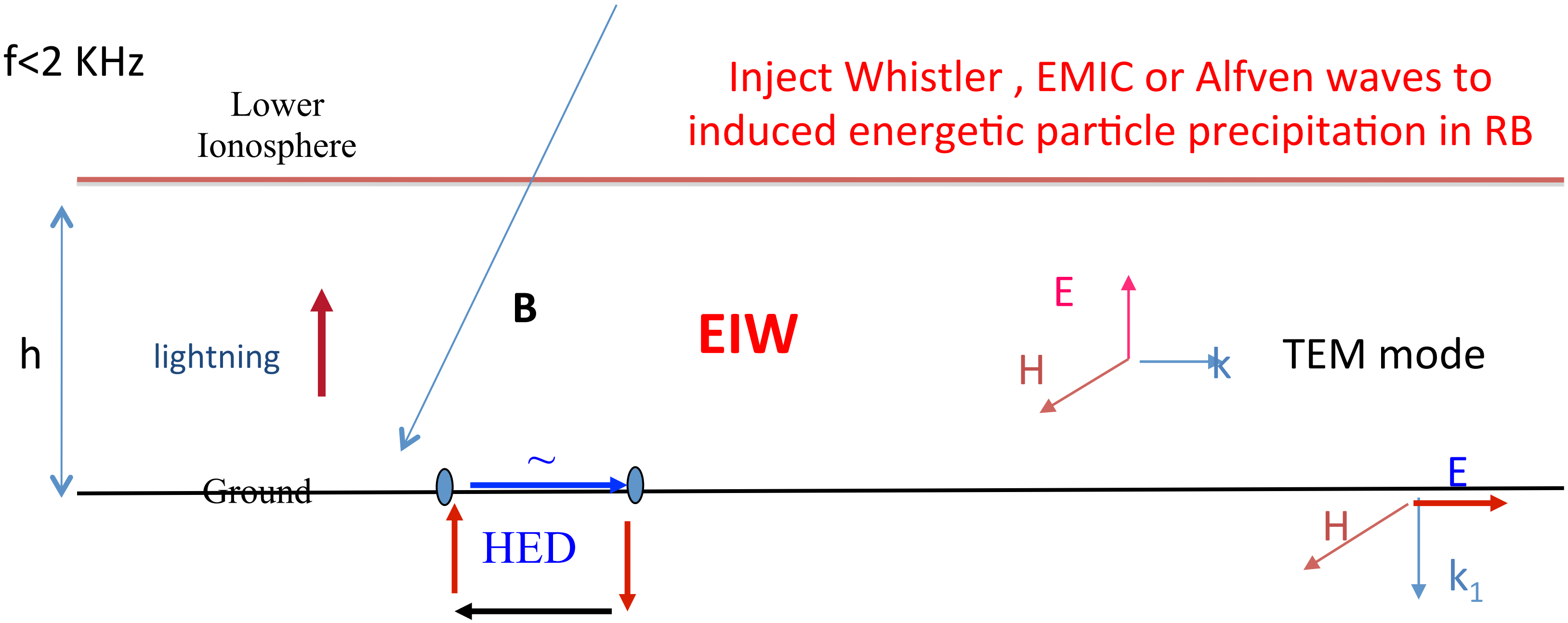
Ionosonde - Radar

$$\omega_{pr} = \omega_e(h) = 5.6x10^4\sqrt{n(h)} \quad \text{O-mode}$$

$$\omega_{pr} = \omega_e(h) + \Omega_e / 2 \quad \text{X-mode}$$

ELF/VLF Generation by Ground HED
Why – Efficiency Showstopper

f<2 KHz

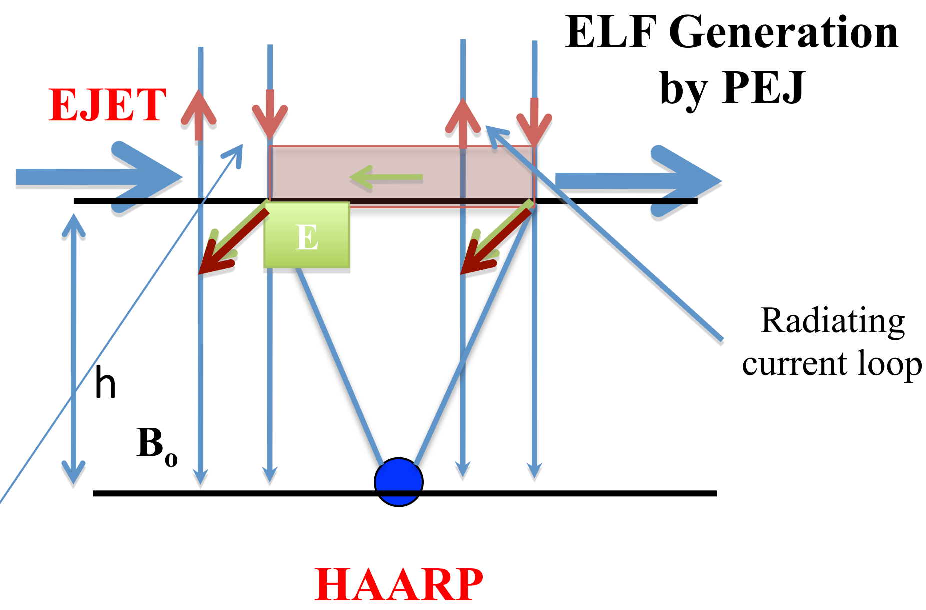


Submarine Communications
Underground Exploration

Ground return reduces coupling efficiency by $(k\delta)=1/\eta_g$.
For example, $1/\eta_g = .004$ at 76 Hz with $\sigma_g \approx 10^{-4}$ S/m.

Lifting the antenna at the top of the waveguide reduces the ground effect by a factor h/δ. More than 30 dB gain

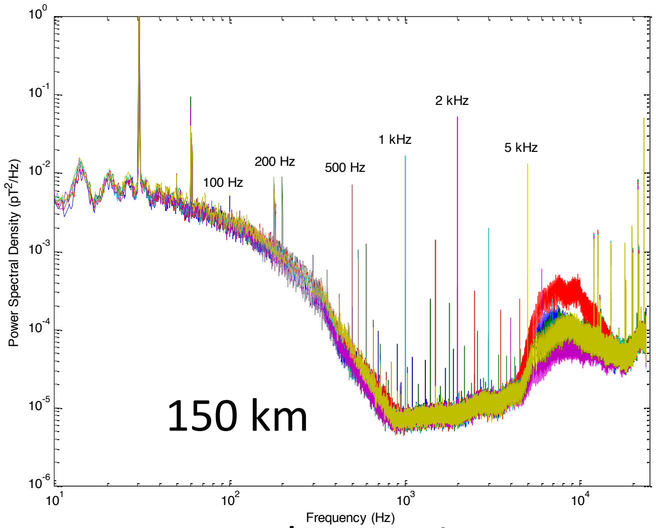
The Polar Electrojet (PEJ) Antenna



How to lift the antenna?
Virtual antenna → PEJ

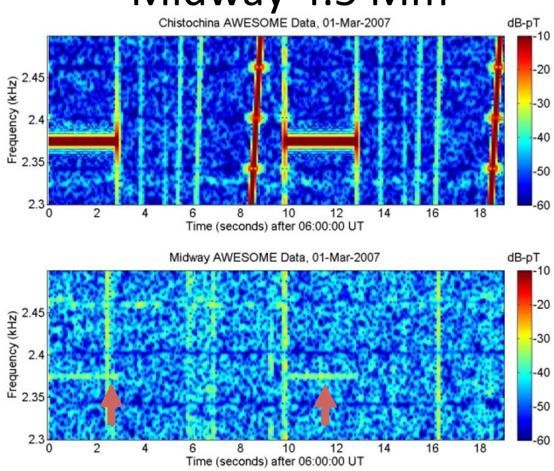
1. **Find a region where natural currents flow in the lower ionosphere – Ejets**
2. **Use an ionospheric heater to modulate the electron temperature and conductivity at the D/E region**
3. **Create an HED at the modulation frequency – current closure by current carried by whistlers or shear Alfven waves in the magnetosphere**

PEJ Performance Examples

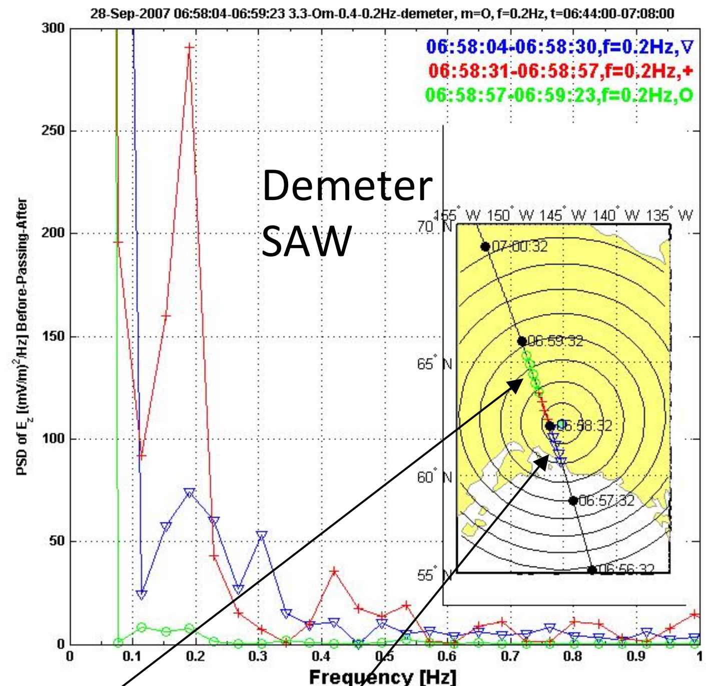


Local Detection

Midway 4.5 Mm

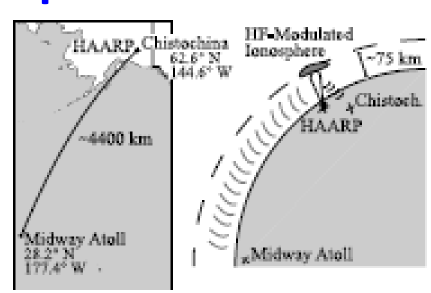


T_{det}< 1 sec



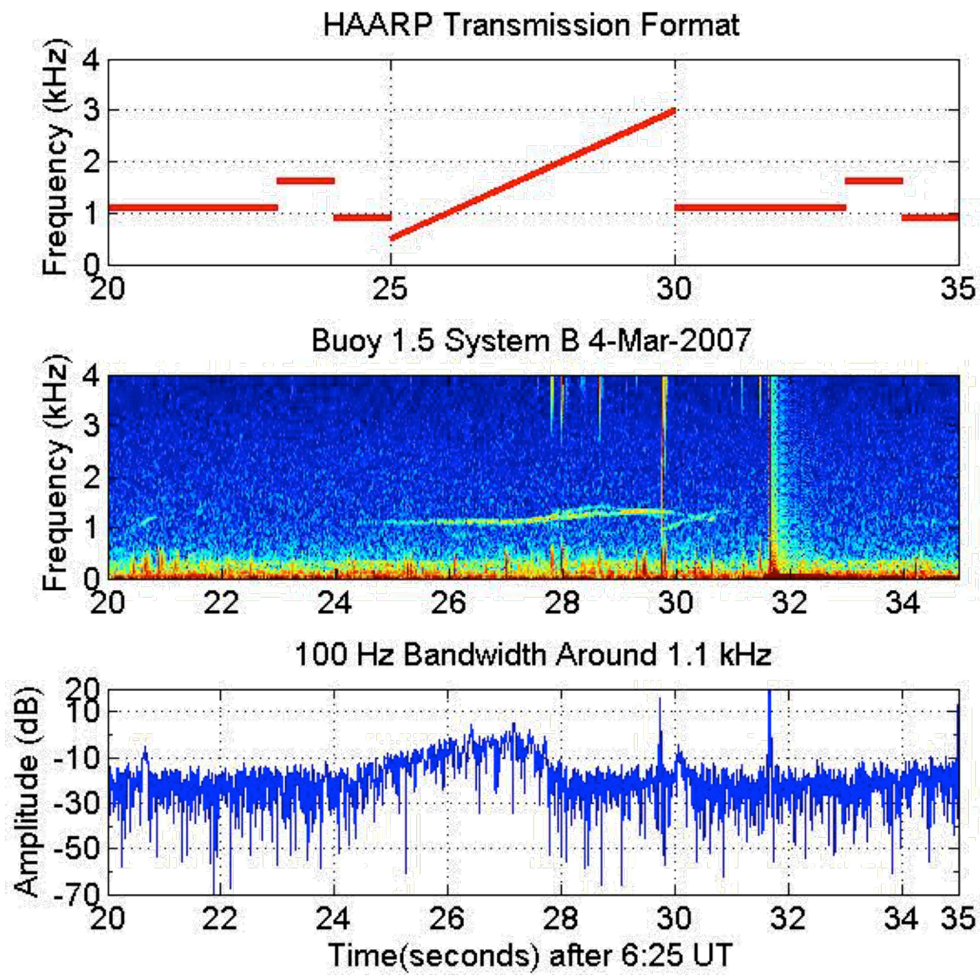
After

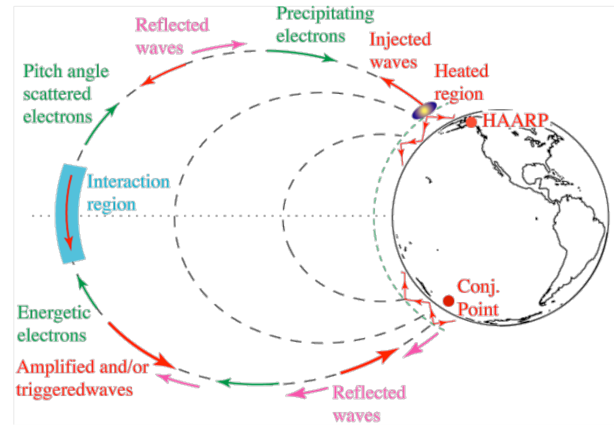
Before



Injection to EIW Stanford

15 dB/s Amplification & Triggered Emissions





Only the pulse at 1100 Hz is amplified

Stanford

PEJ Issues – ICD Desirability

PEJ Issues:

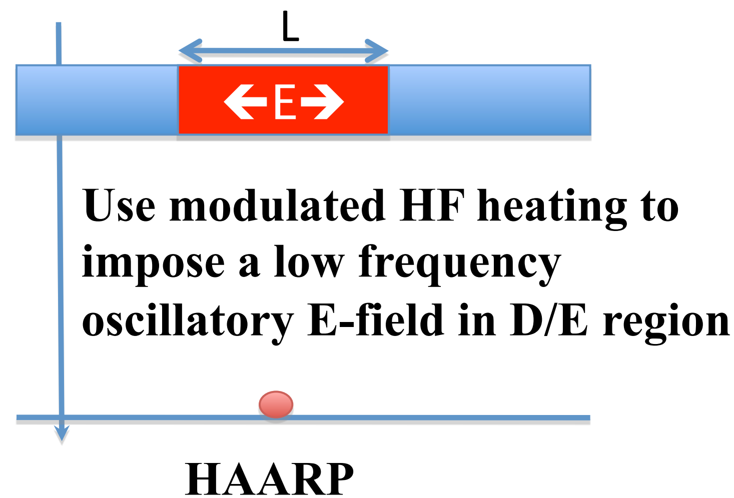
- Availability - EJ Unpredictable and often completely absent
- Location – EJ location far from desirable applications ;Long propagation required even when available

$$\vec{p} = (\overleftrightarrow{\Sigma}\vec{E}L)L$$

$$p_h \approx (\Sigma_h EL)L$$

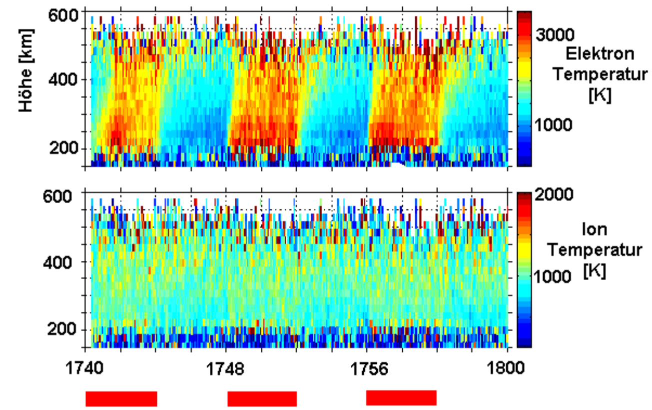
ICD: Use HF to drive oscillatory currents in the Hall (D/E) region. Virtual antenna.

Create your own current. No location and EJ availability constraints

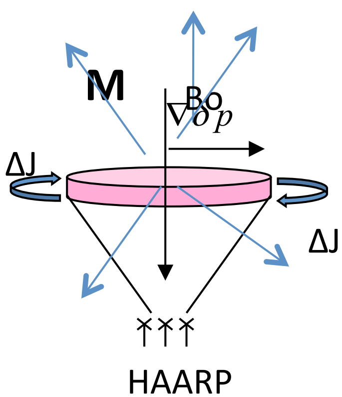


ICD Basics - F-region Heating – Diamagnetic Current

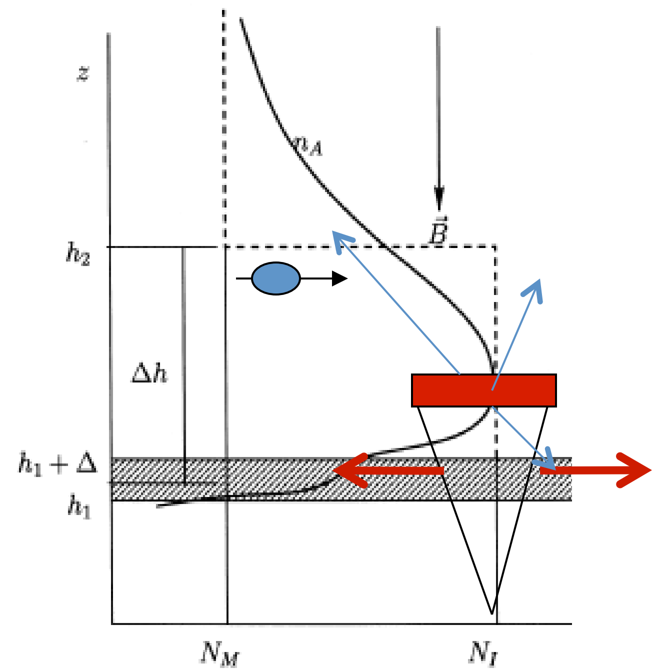
Step 1: Modulated F-region heating creates oscillatory diamagnetic current. Field aligned magnetic moment radiates Msonic waves isotropic in the plasma.



$$\Delta J = \frac{B \times \nabla \delta p}{B^2} \exp(i\omega t)$$

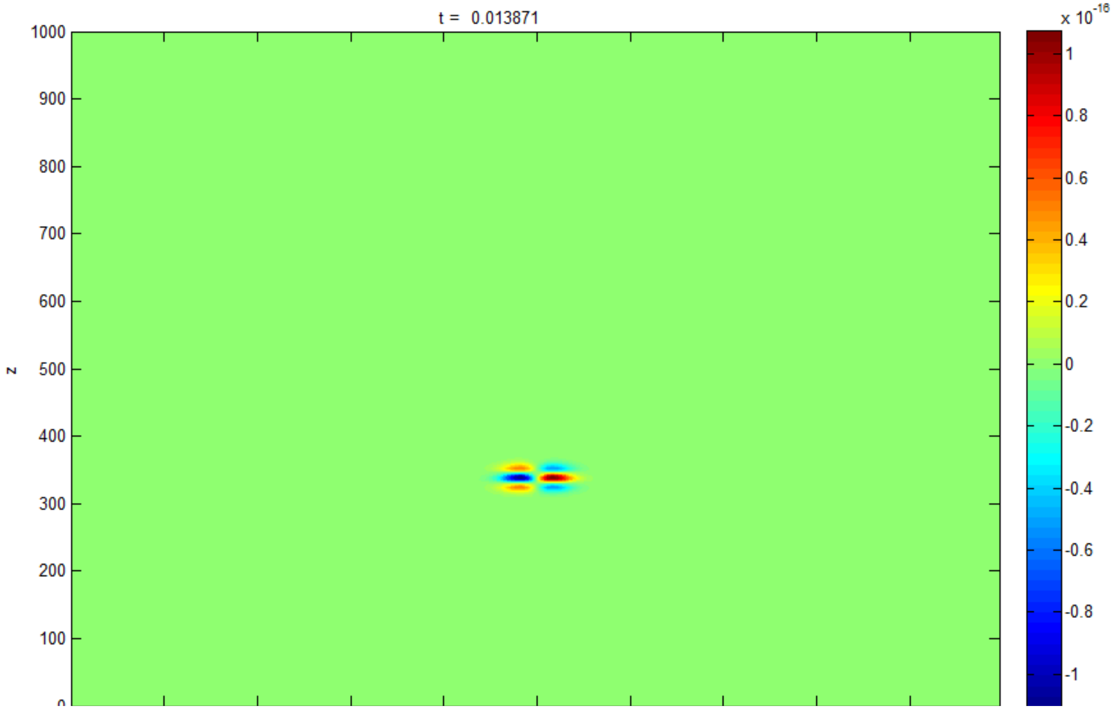


Step 2: E-field of msonic wave drives an oscillatory Hall current in the D/E region creating a virtual antenna. Injects waves in the EIW and SAW in the RB

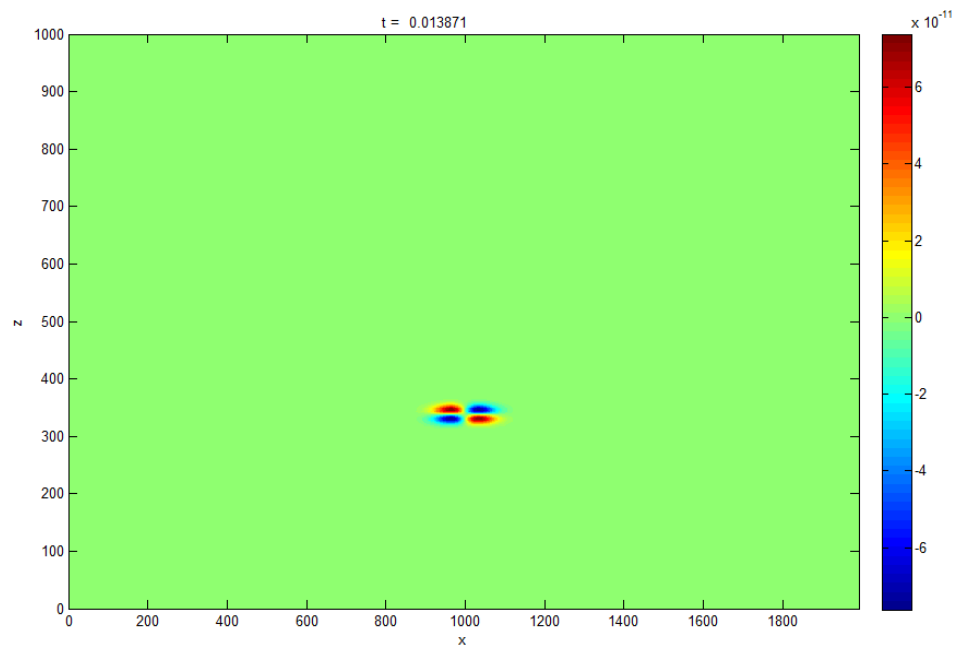


20 Hz ICD

J_{Hall}

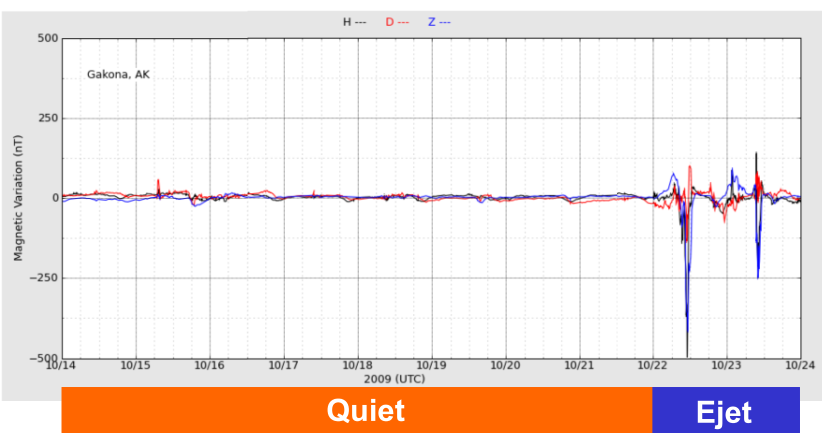


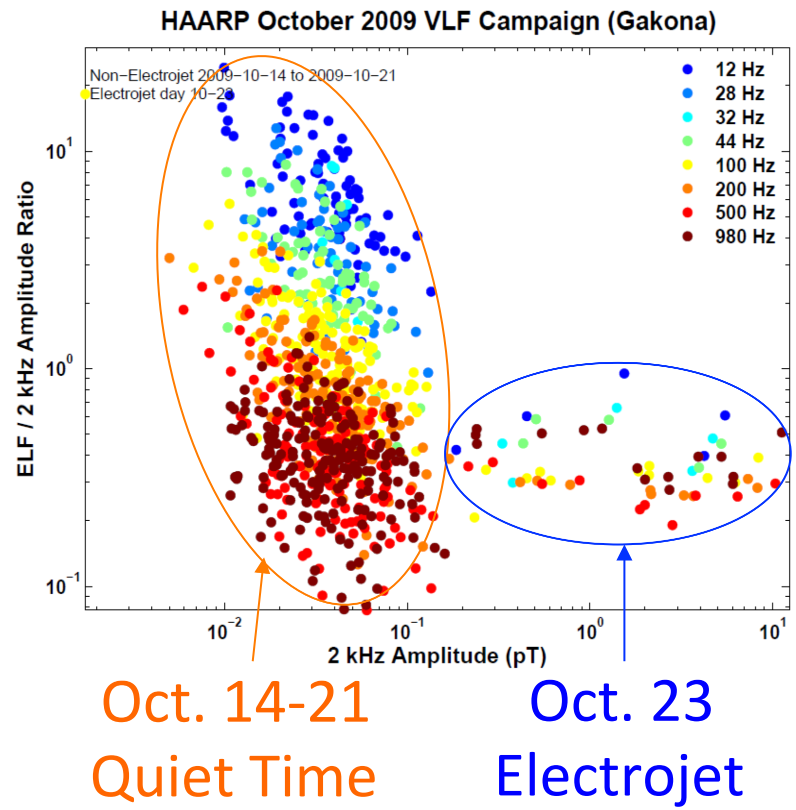
B_y



Overall ELF/VLF Results

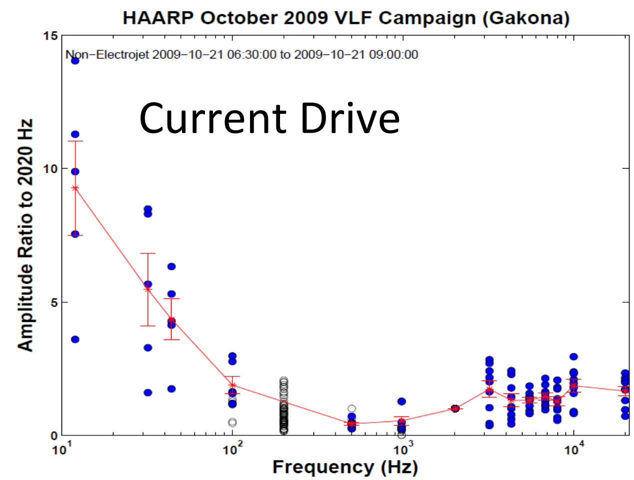
- 10 Hz – 1 kHz Gakona results
  - Normalized to 2 kHz amp.
- Two distinct groups of data
  - Quiet time
  - During Electrojet

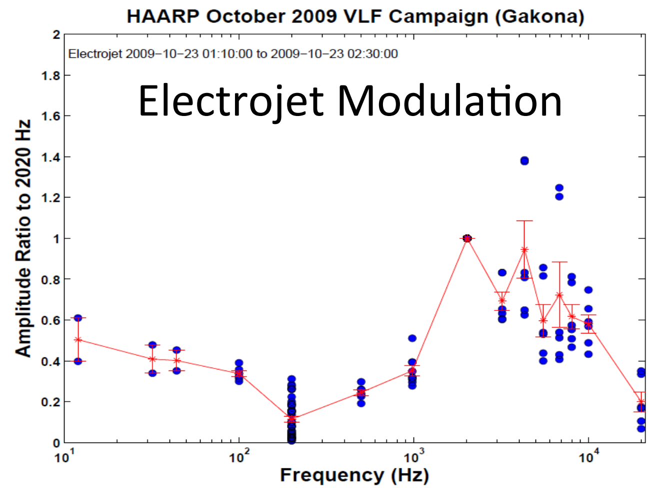




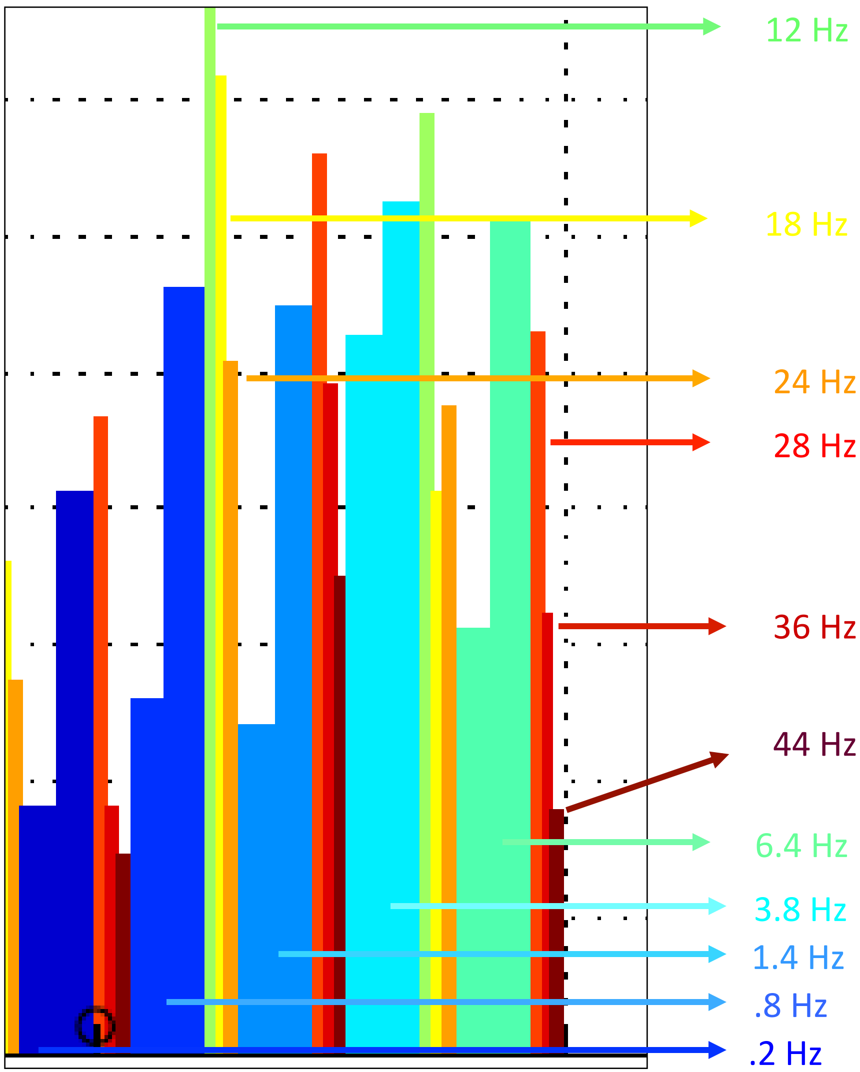
ELF/VLF Generation Efficiency - ICD vs. PE!

- Ionospheric current drive produced ELF waves up to 50 Hz (F layer)
  - < 50 Hz, $1/f^{\alpha}$ dependence
    - Consistent ELF source suitable for mid/low latitude regions
    - Upper freq. is defined by pressure relaxation time scale in the F layer
  - 200-400 Hz under background
  - > 1 kHz, small signals at Gakona
    - Low background
    - Possible ICD in D/E layer?





ICD Scaling with HF Power and ELF Frequency



$$B \sim (pressure)Volume \approx \mathrm{E}_{absorbed}$$

$$\frac{dE_a}{dt} = \alpha P_{HF} - \frac{E_a}{\tau}$$

$$E_a = \alpha P_{HF} \tau (1 - e^{-t/\tau})$$

$$f \sim 1/2t, f_o = 1/2\tau$$

$$B \sim (\alpha P_{HF} / f_o)[1 - e^{-(f_o/f)}]$$

$$f >> f_o, B \sim 1/f$$

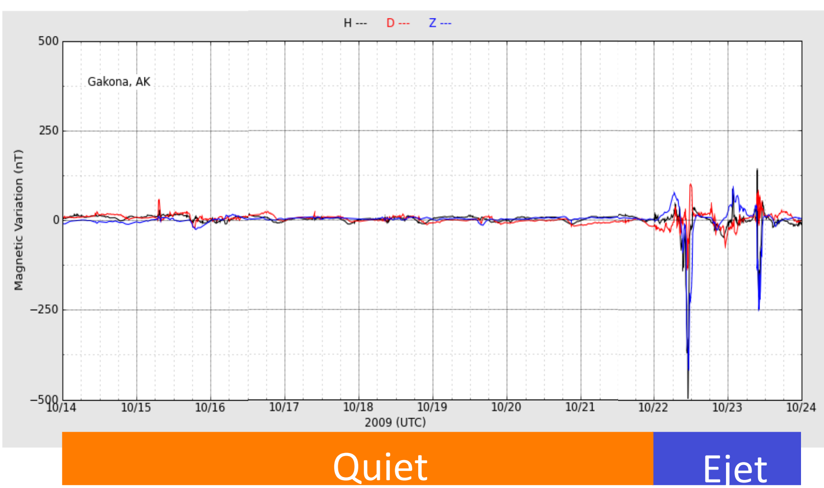
$$P_{ULF} \sim P_{HF}^2$$

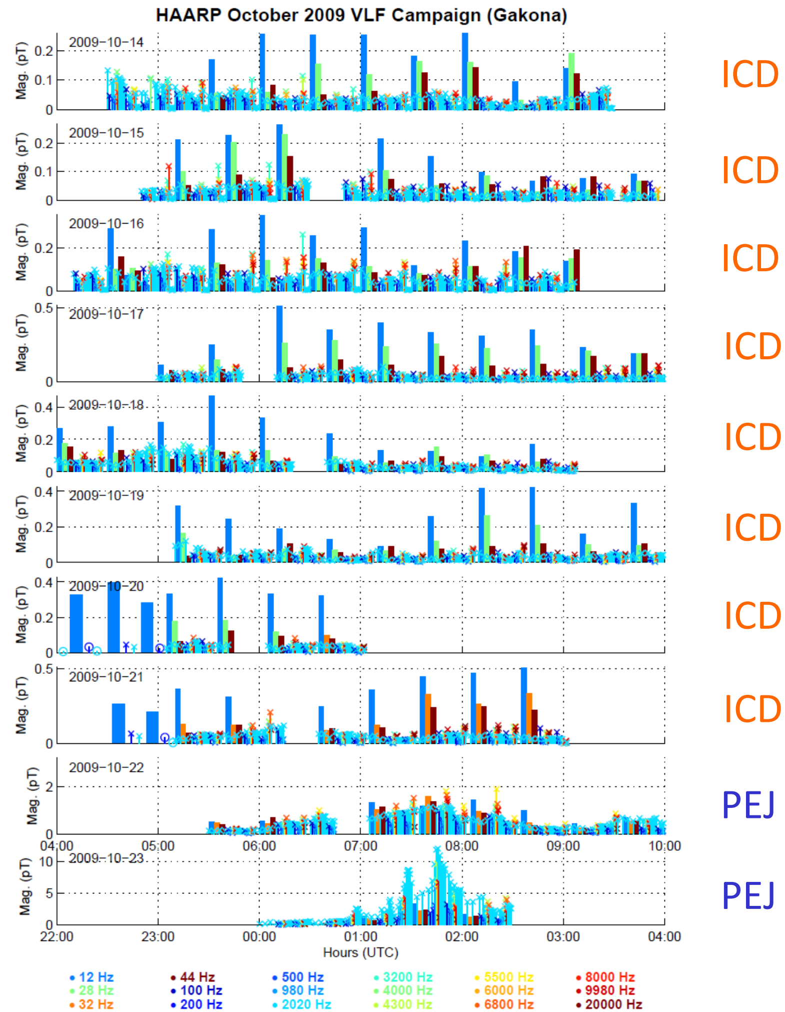
τ≈.1 sec , f_o≈ 4-6 Hz,

α≈.2-.3(X), α≈.1-.2 (O)

ELF/VLF Generation - ICD vs. PEJ

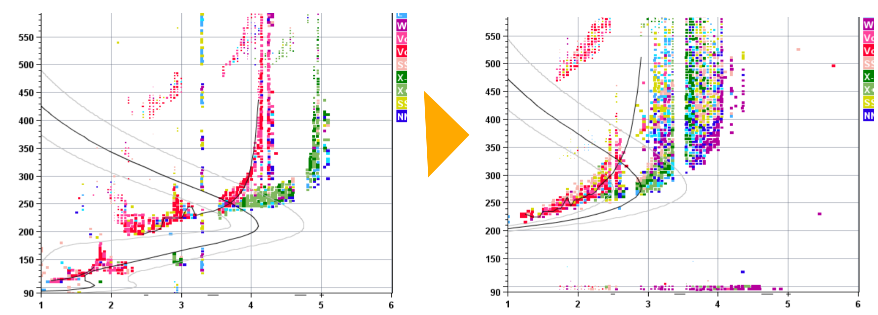
- **Oct.14-21, *ICD* was the source**
  - No electrojet, quiet ionosphere
  - Consistent daily ELF production, < 0.5 pT
- **Oct. 22-23, *PEJ* was the source**
  - Active electrojet
  - Spur of ELF/VLF production

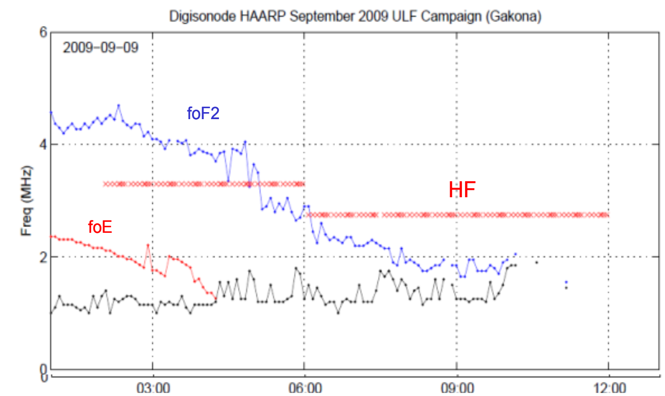


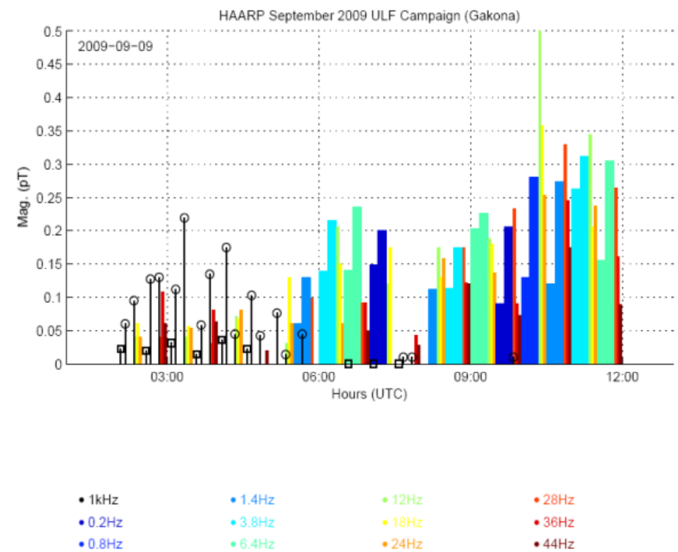


ELF Generation by F layer Modulation

- September HAARP campaign
  - ULF: 0.2-6.4 Hz
  - ELF: 12-44 Hz & 1 kHz
- The ULF-ELF signals at Gakona:
  - Emerge on Sep. 9 after F is exposed
  - Generated up to 50 Hz
- The 1 kHz amp. is only significant when D/E layers were present

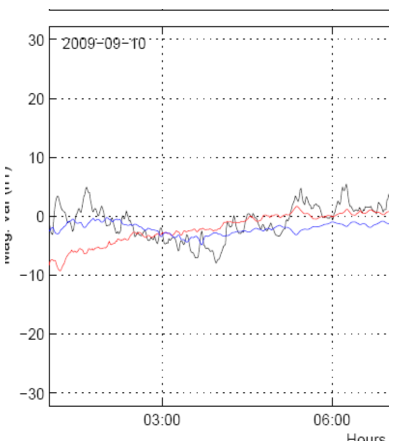


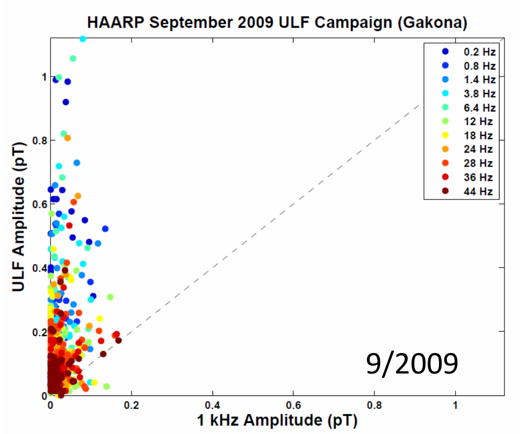


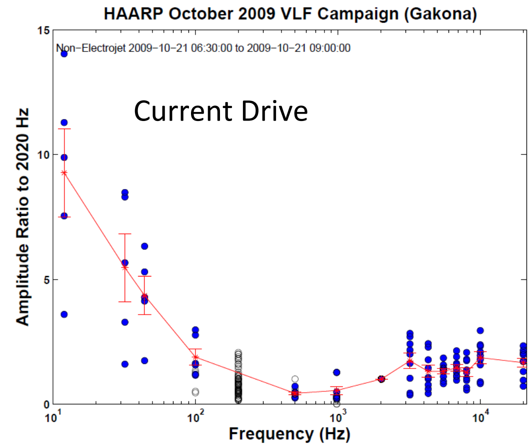


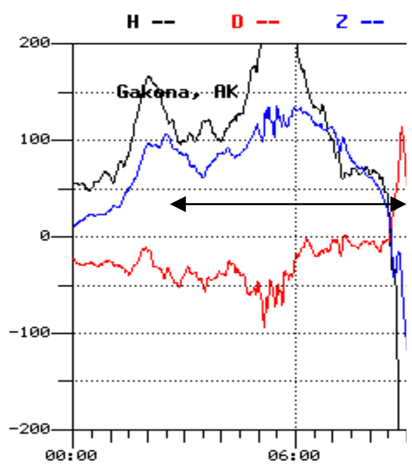
ICD Further PoP Tests

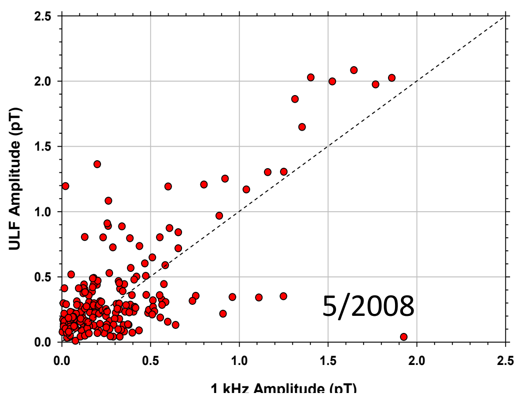
Ejet Current Strength

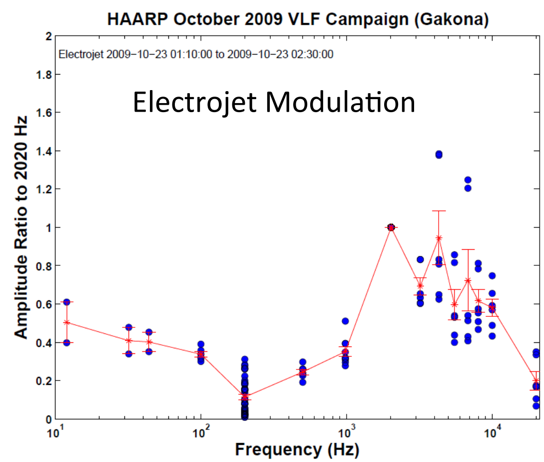








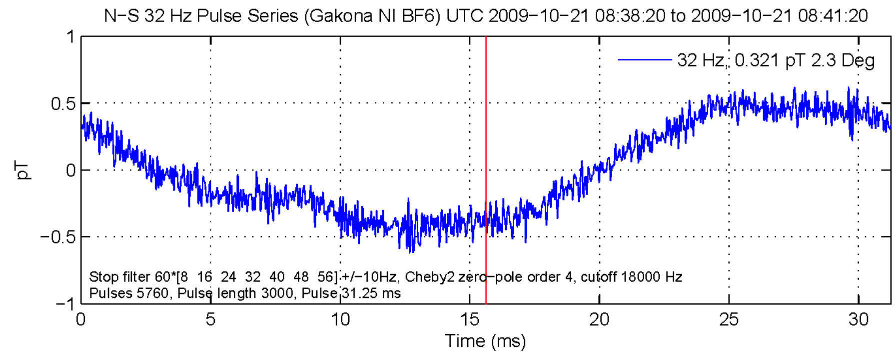


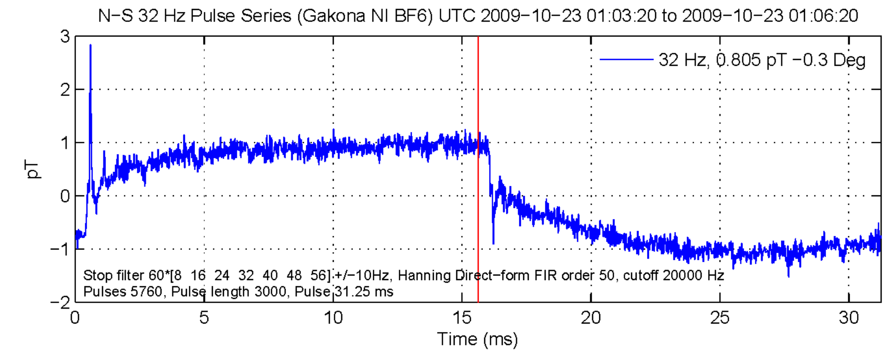


ELF Temporal Waveform – ICD vs. PEJ

- Use 32 Hz as an example
- ICD in the F layer does not have sharp peaks – time scale for pressure relax. Is long
- PEJ in D/E layers has initial sharp peak at ON and OFF due to current surge – time scale for HF heating is short ~ 0.1 ms. It also has other peaks due to wave bounce between ionosphere & ground

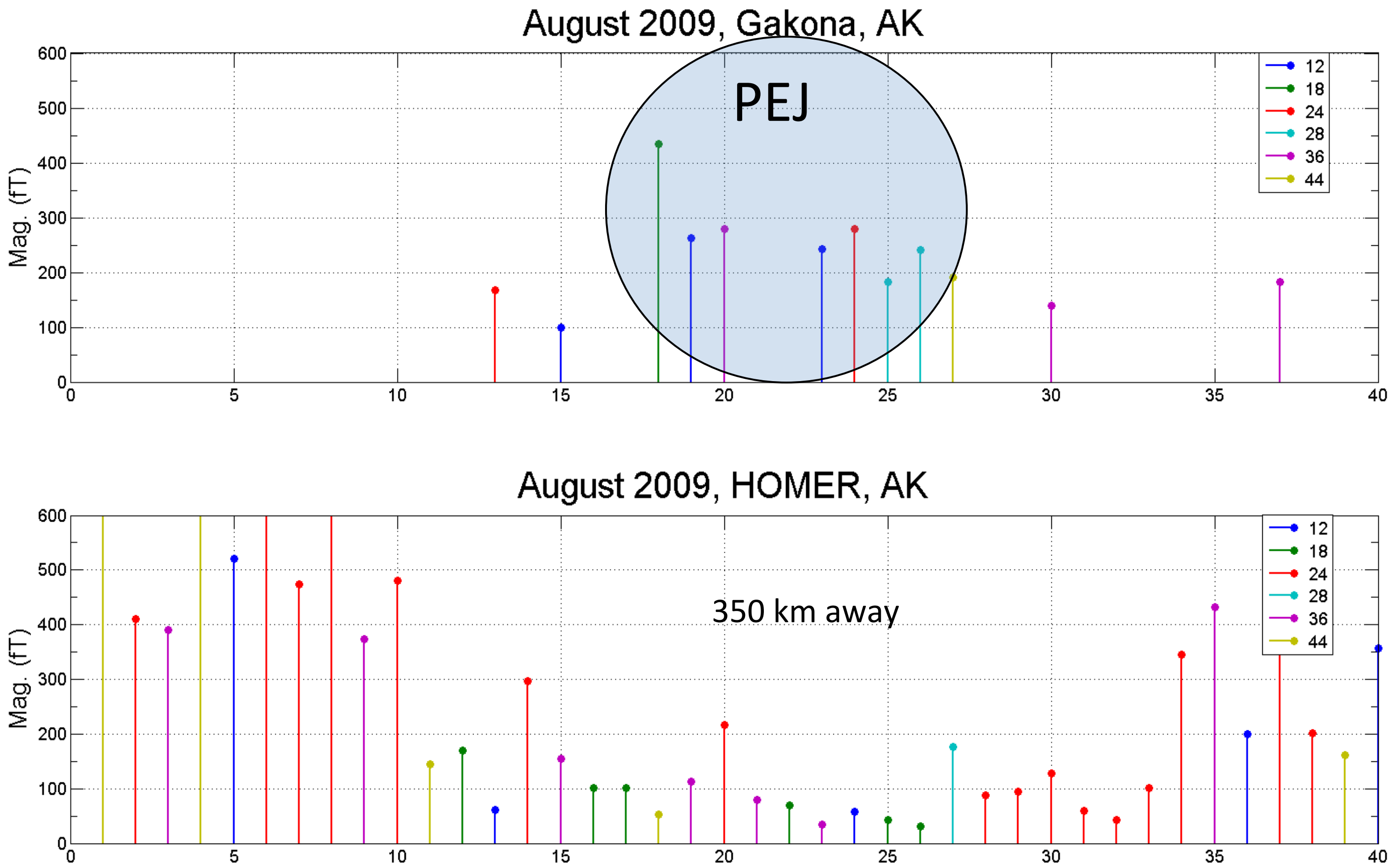
F Layer ICD



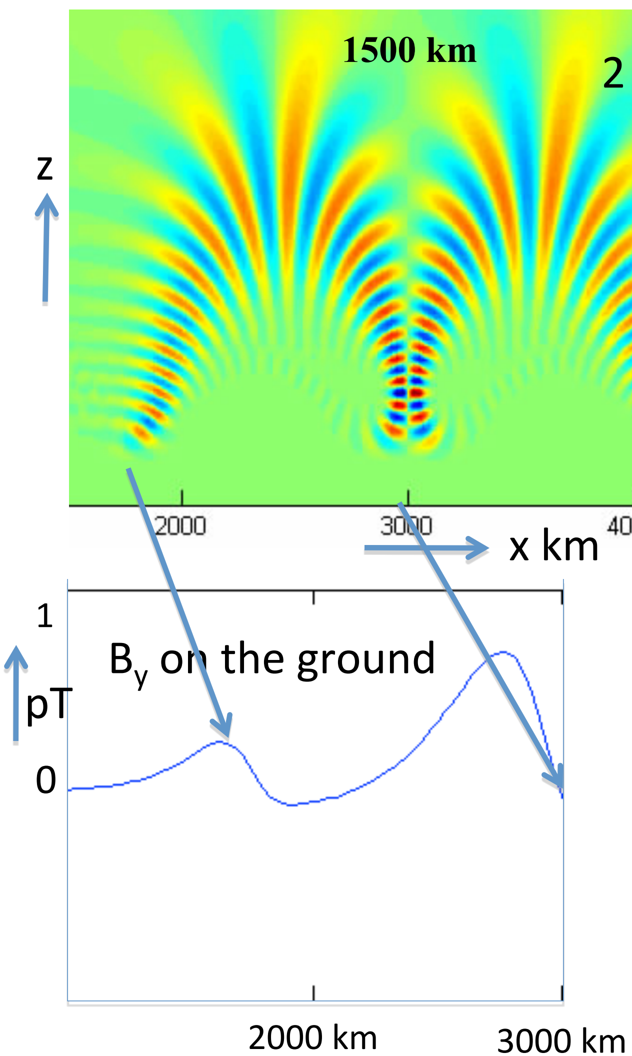


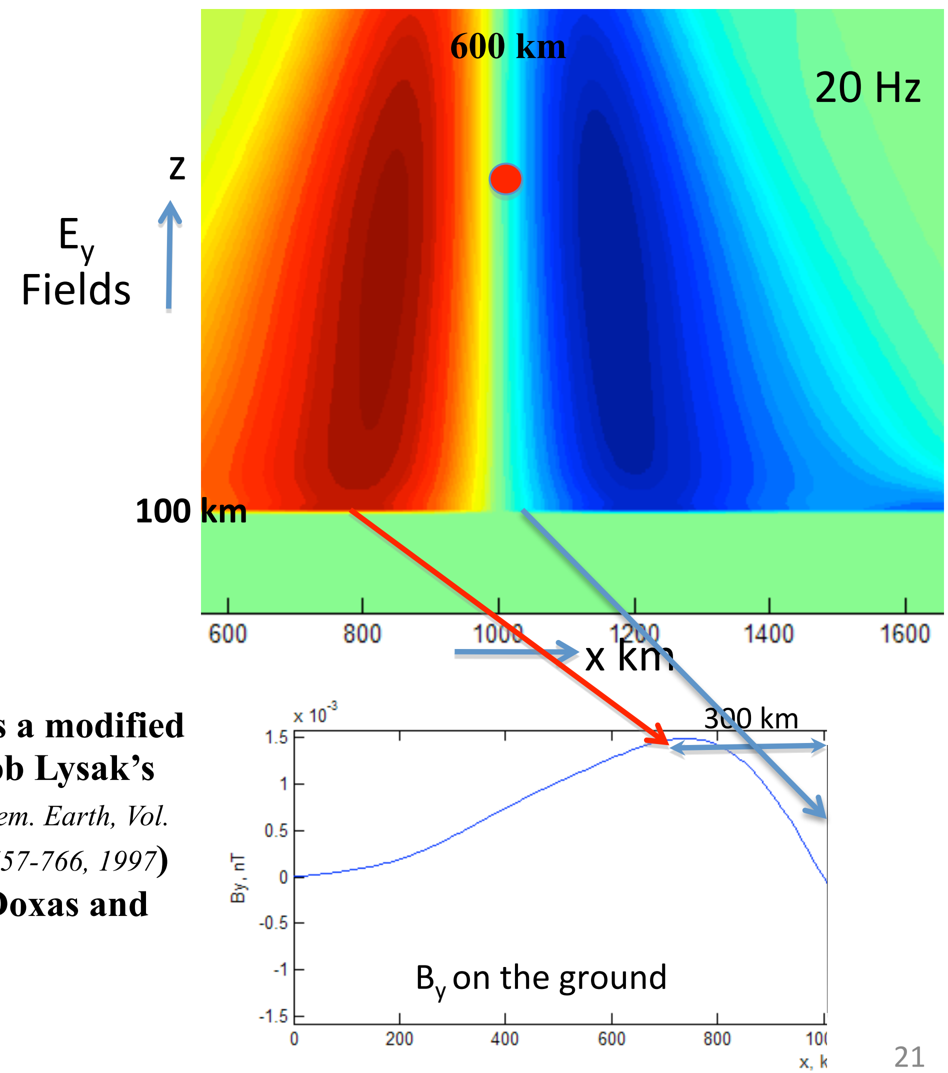
D/E Layer PEJ

Two site measurements - ICD vs. PEJ – The puzzle



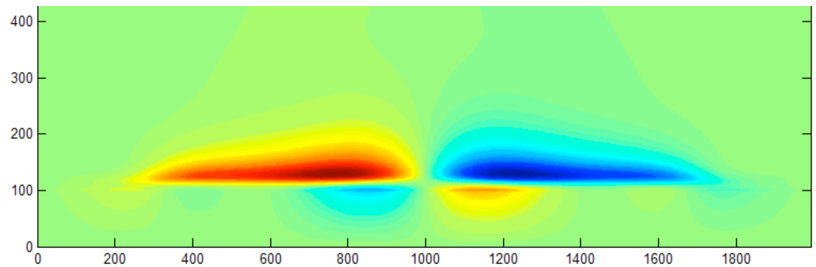
ICD Numerical Predictions





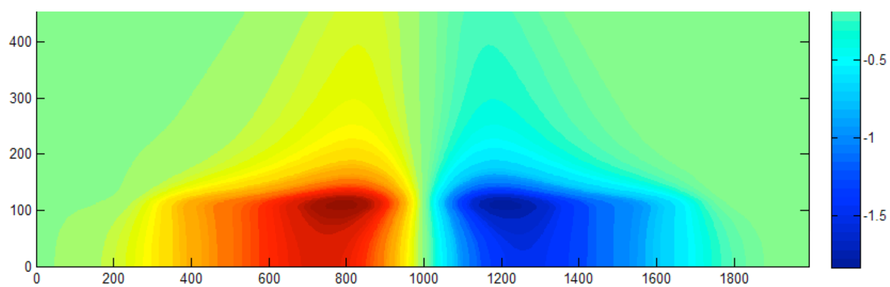
- **Code used is a modified version of Bob Lysak's code (***Phys. Chem. Earth, Vol. 22, No. 7-8, pp. 757-766, 1997***)**
- **Runs by I. Doxas and N. Gomarov**

ICD Secondary Antenna – Resolution of the puzzle



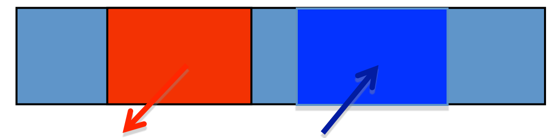
Hall Current

20 Hz



B_y

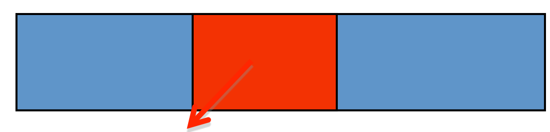
ICD



EIW

Min. below, Max 300 km away

PEJ

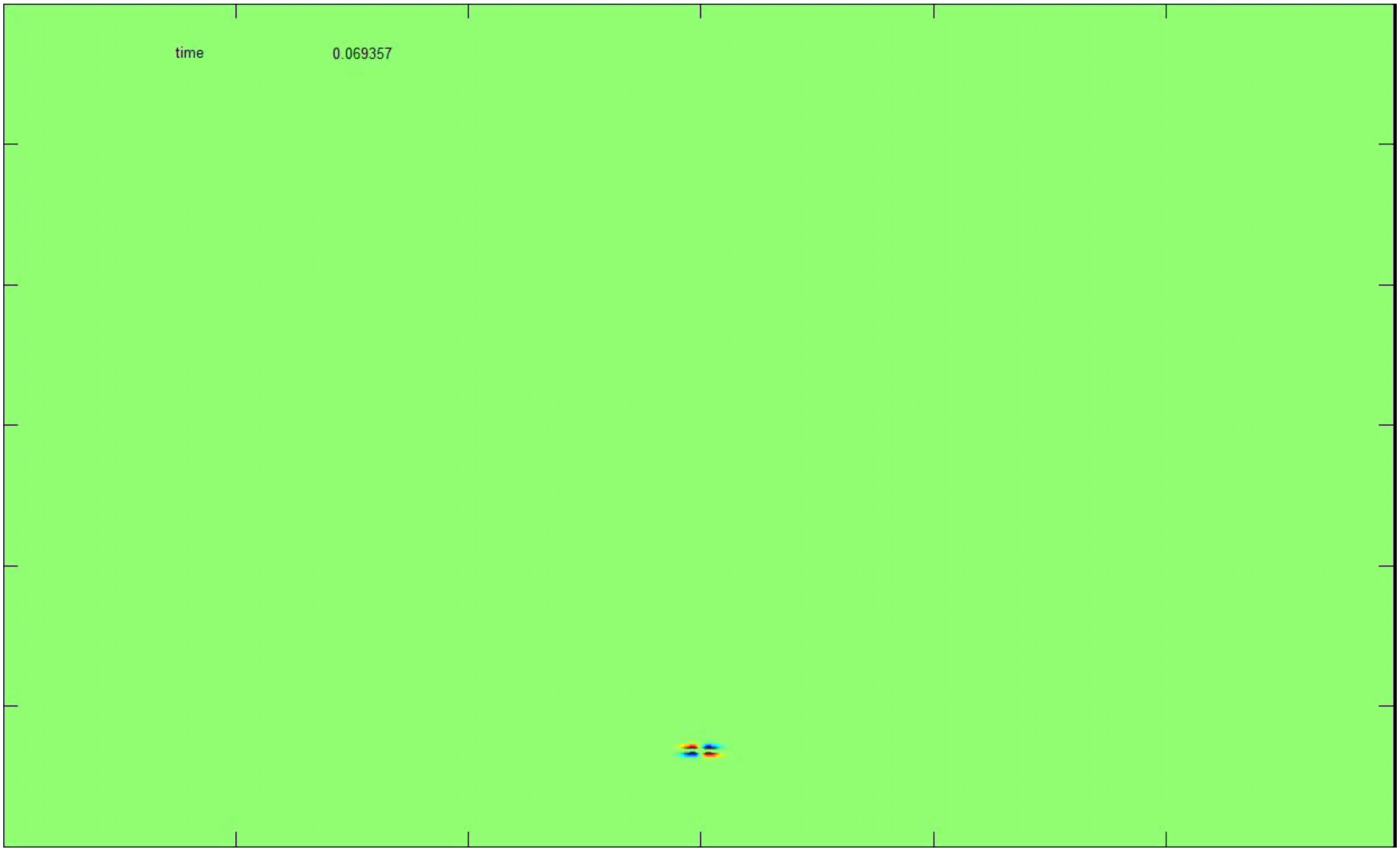


EIW

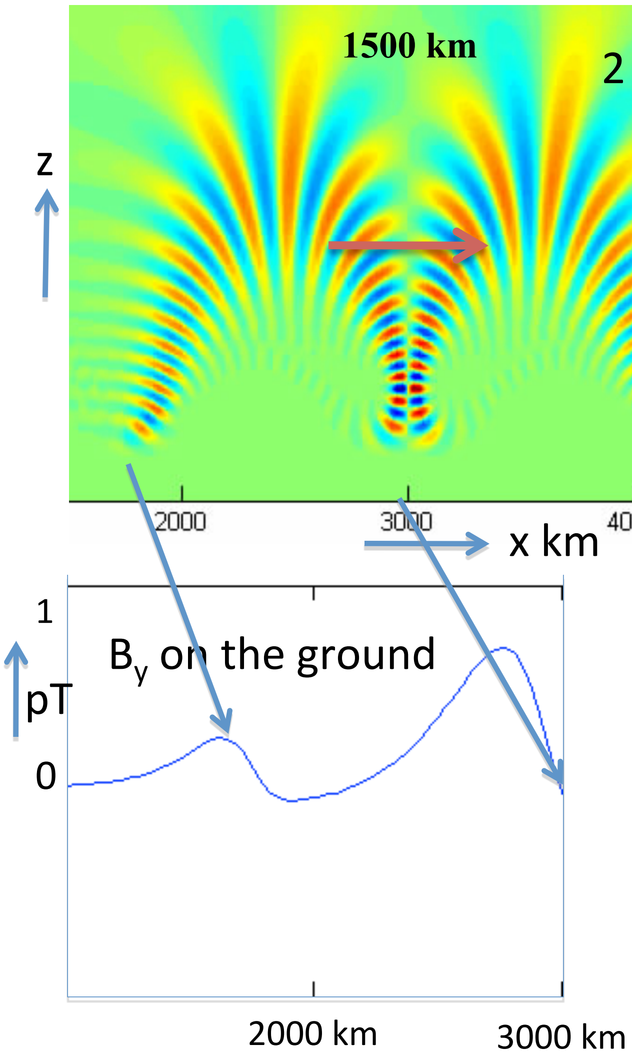
Max below

Monotonically decreasing away

Msonic 2 Hz Far Propagation in the Alfvenic Duct



ICD Far Field Guided Propagation

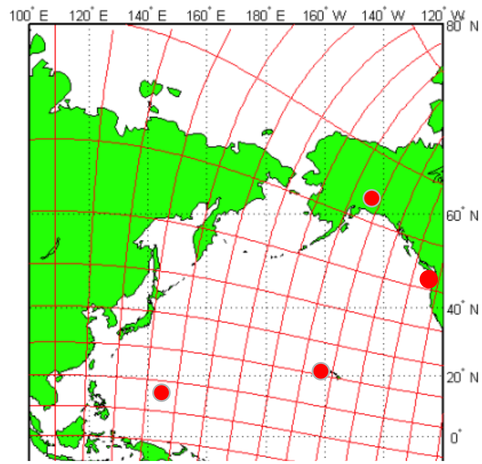


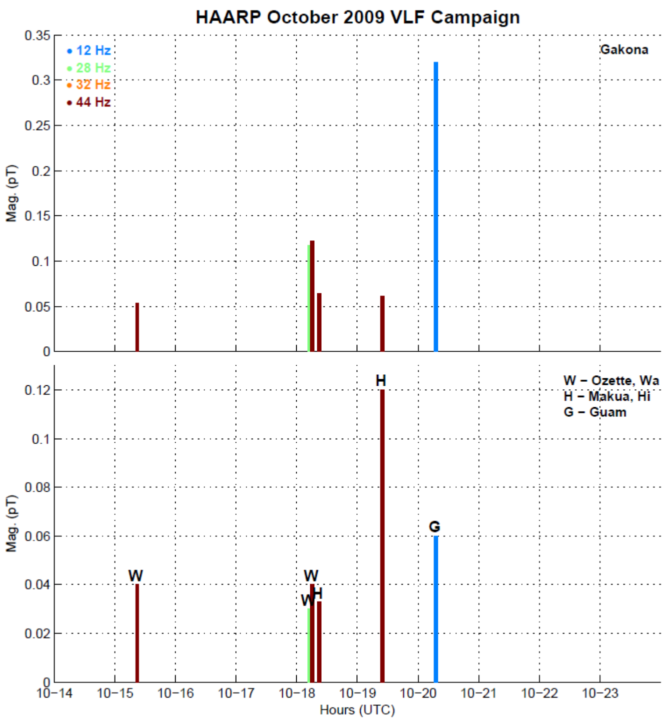
Skip Distance 2000 km

•Code used is a modified version of Bob Lysak's code (*Phys. Chem. Earth, Vol. 22, No. 7-8, pp. 757-766, 1997***)**
•Runs by I. Doxas and N. Gomarov

ELF detection at Distant Sites

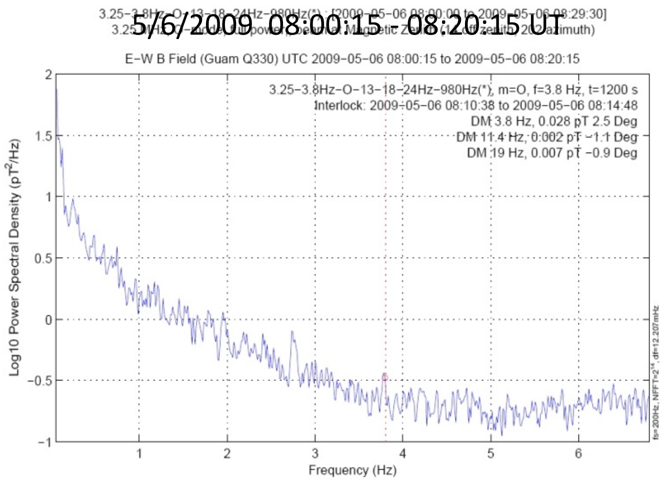
- Distance to Gakona
  - Lake Ozette, WA (W)
    - 1300 mi
  - Hawaii (H)
    - 2900 mi
  - Guam (G)
    - 4800 mi
- Detection under quiet Gakona cond.
- No detection during electrojet days Oct. 22-23
- Need close-in sites (~ 200 mi) to study near-field effects and ELF entrance to the waveguide



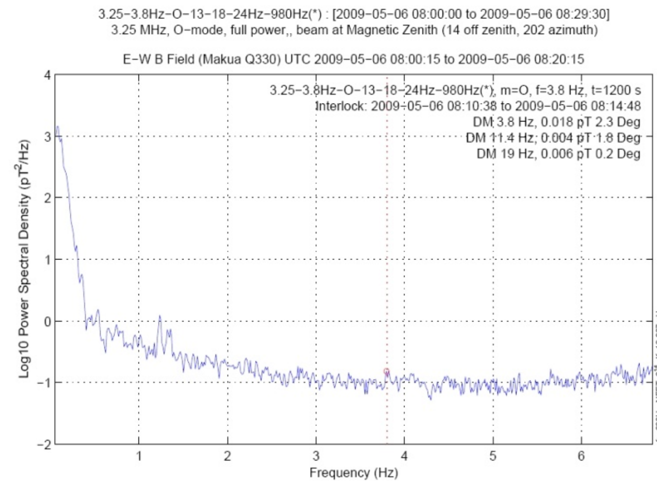


May 6, 2009 Grand Slam Results – 3.8 Hz

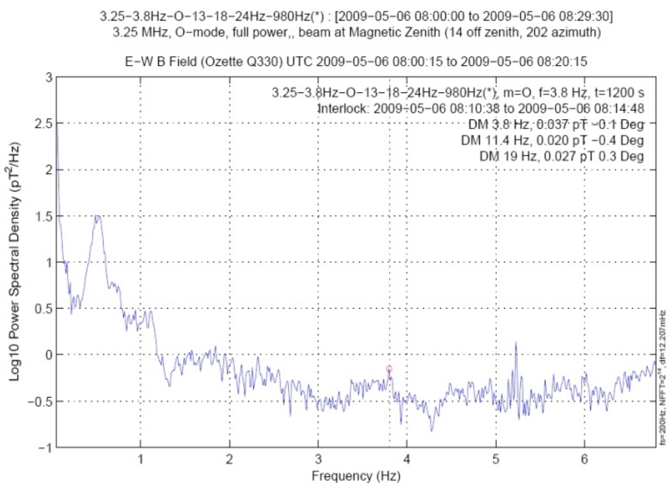
5/6/2009 08:00:15 - 08:20:15 UT



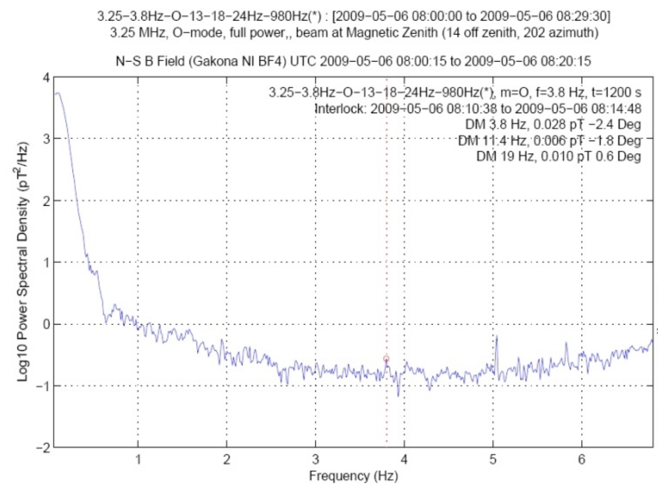
Guam



Makua Valley



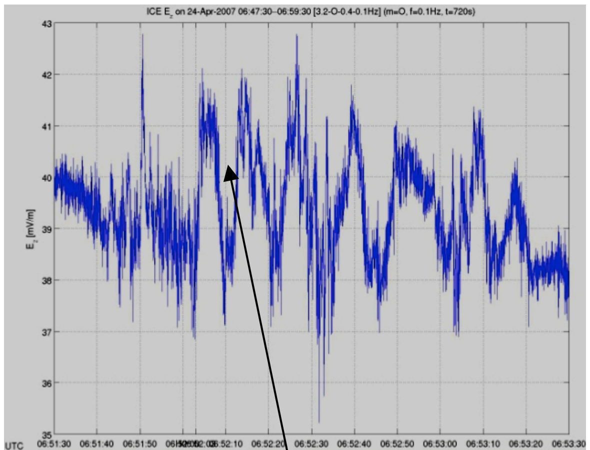
Lake Ozette



Gakona

Msonic Wave Injection

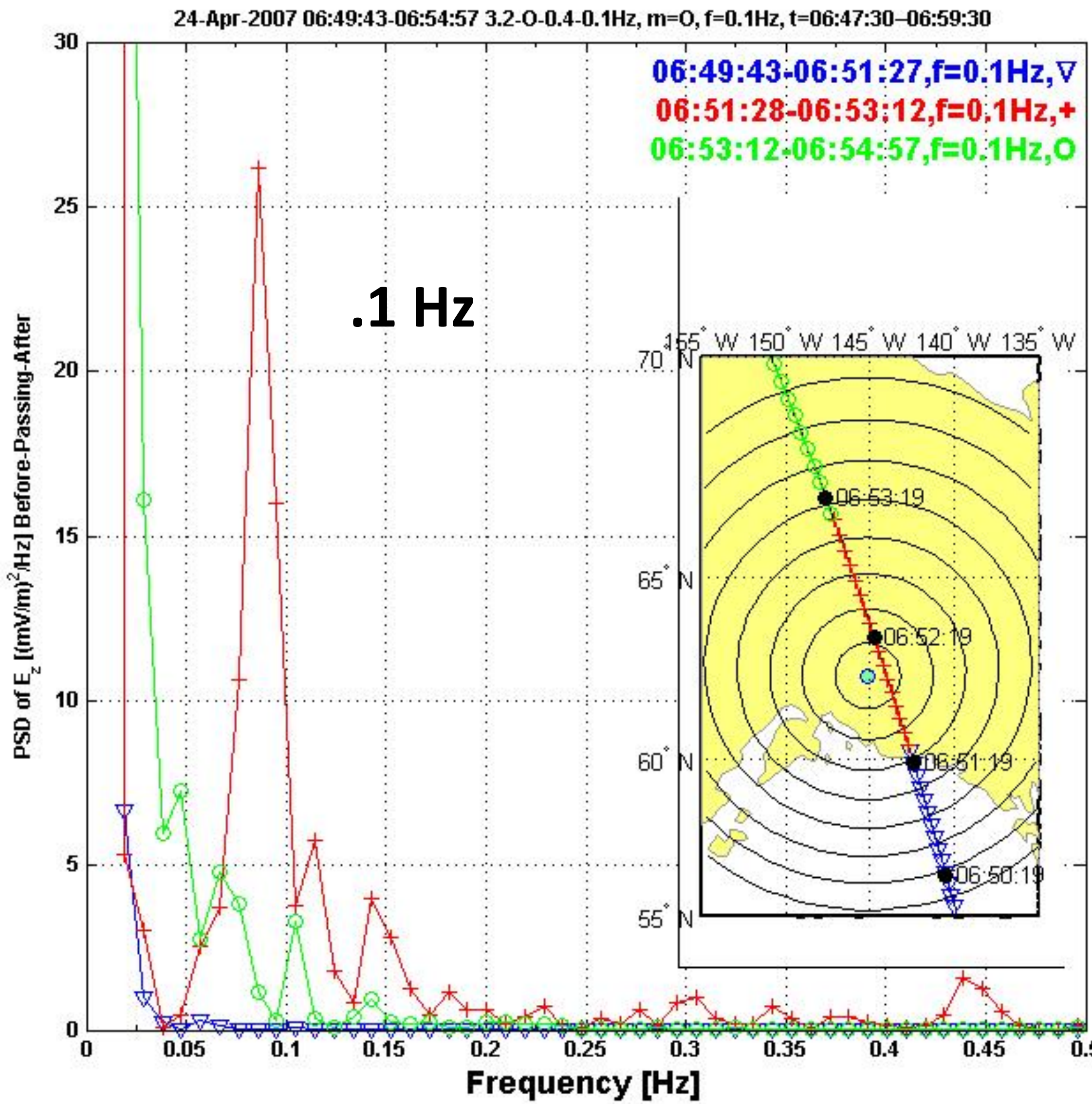
DEMETER



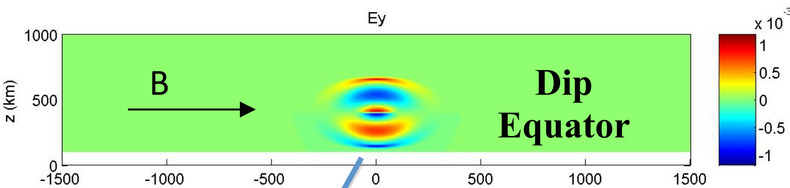
10 sec oscillations

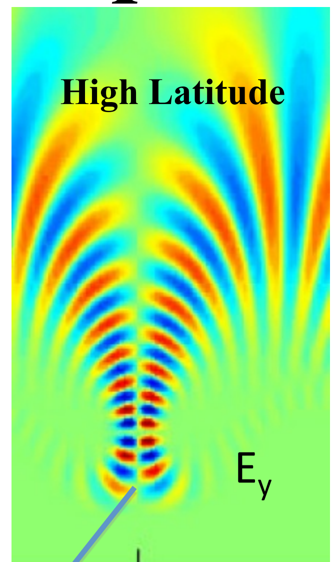
kW power

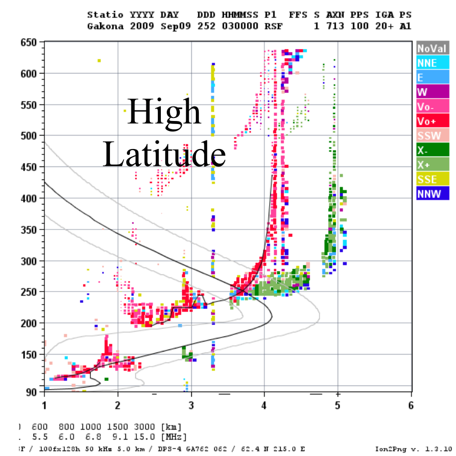
Demeter data – Inan and Piddyachiyi

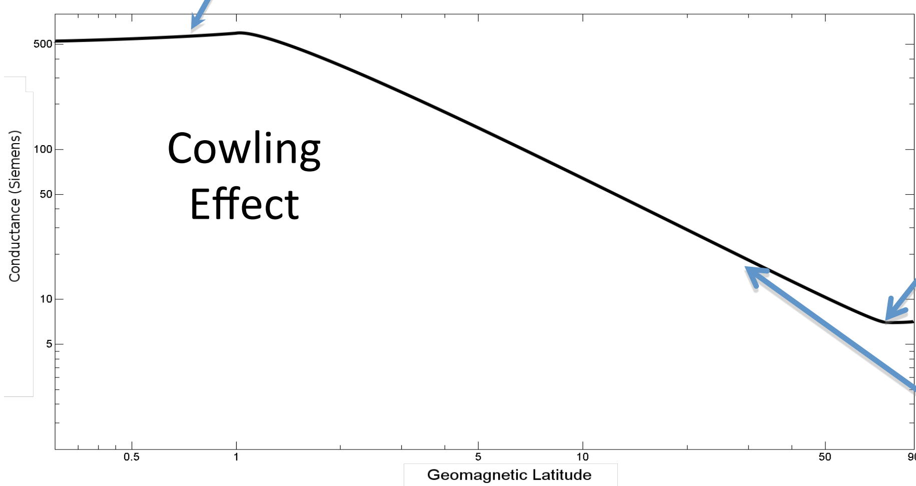


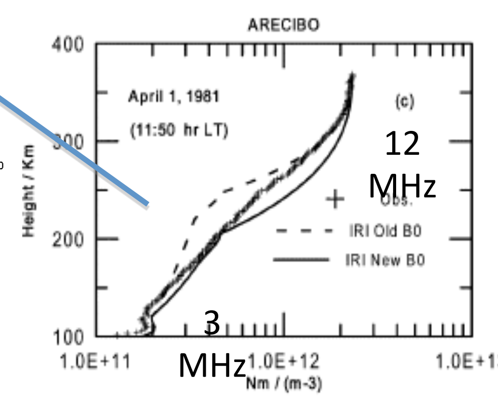
ICD Latitude Dependence

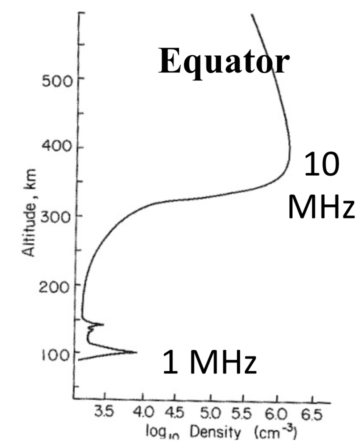










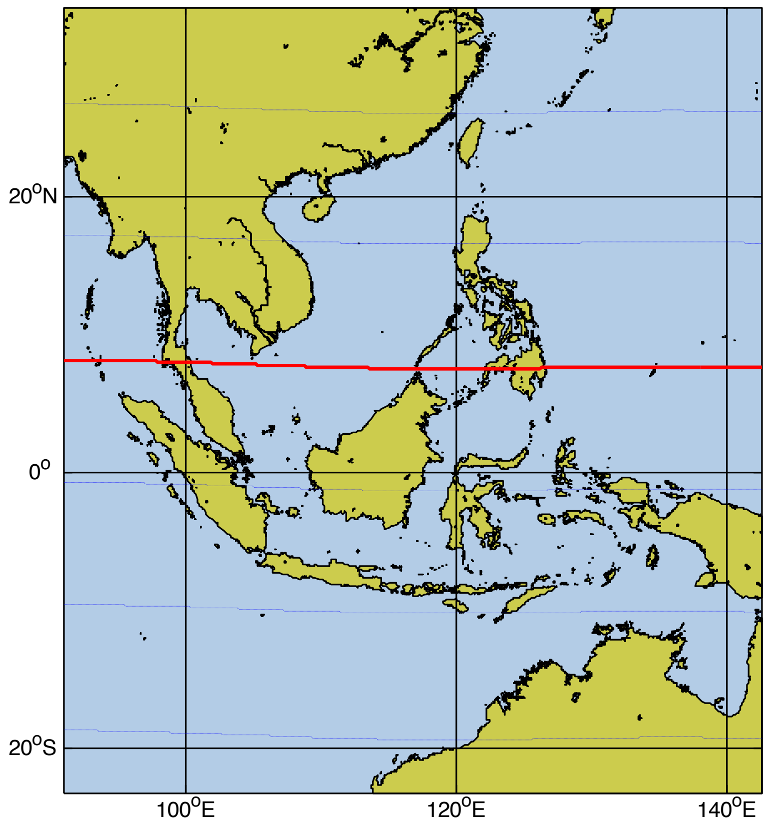


1. Conduction 100 times better
2. Msonic E field at Hall region unidirectional
3. Weak D/E region self absorption self absorption

Summary of equatorial location advantages

- **Equatorial ionosphere much more reliable than auroral**
- **Equatorial electron density profiles better suited to heating at high altitudes (improving heating efficiency and reducing absorption)**
- **Cowling current provides a factor of 400 more power than aurora for similar VMD moment**
- **Equatorial heating creates significant vertical electric dipole moment providing isotropic coverage**
- **Equatorial and sea based facilities can provide global ULF/ELF coverage for all frequencies up to 50 Hz**
- **Required HF frequency 6-10 MHz. Facility smaller and relatively inexpensive**

Potential sites



Potential land sites:
- Jicamarca, Peru
- Thumba, India
- Koror, Palau
- Phuket Area, Thailand
- Mindanao, Philippines

Sea basing offers additional flexibility

Self-propelled drilling platforms have the deck area and electrical power necessary for an ionospheric heater the size of the current HAARP IRI

SUPPLEMENTARY SLIDES

ELF/VLF Summary

- Generation with Electrojet
  - 12 Hz – 20 kHz
  - Amplitude as high as 10 pT has been observed
- Generation without Electrojet – major breakthrough
  - Up to 50 Hz
  - Ionospheric current drive in F layer
  - Predictable and repeatable signal generation on daily basis
  - Viable technique in low latitude regions with robust F

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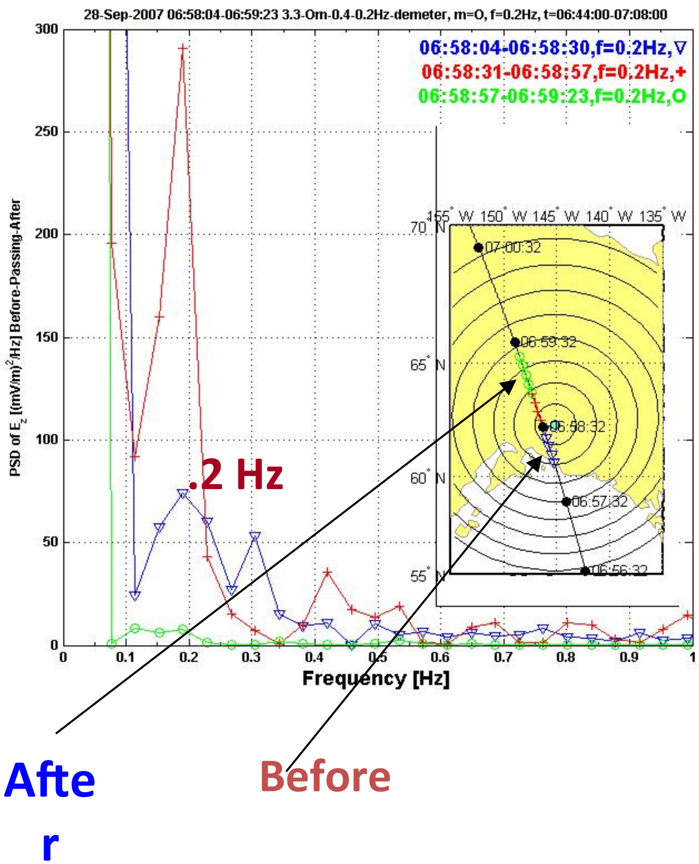
SAW DEMETER Detection



Frequency .2 Hz

Closest distance 80 km

Detection time 25 sec

Detection distance 150 km

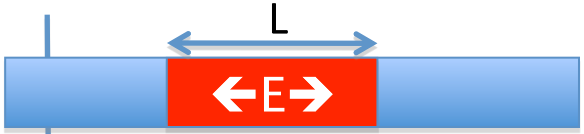
Maximum E 10 mV/m

Estimated power ~ kW

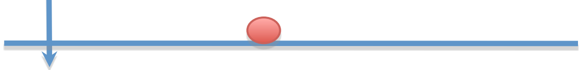
1.5 pT on the ground

SEPTEMBER 28, 2008

The Physics of ICD



Use modulated HF heating to impose a low frequency oscillatory currents in D/E region



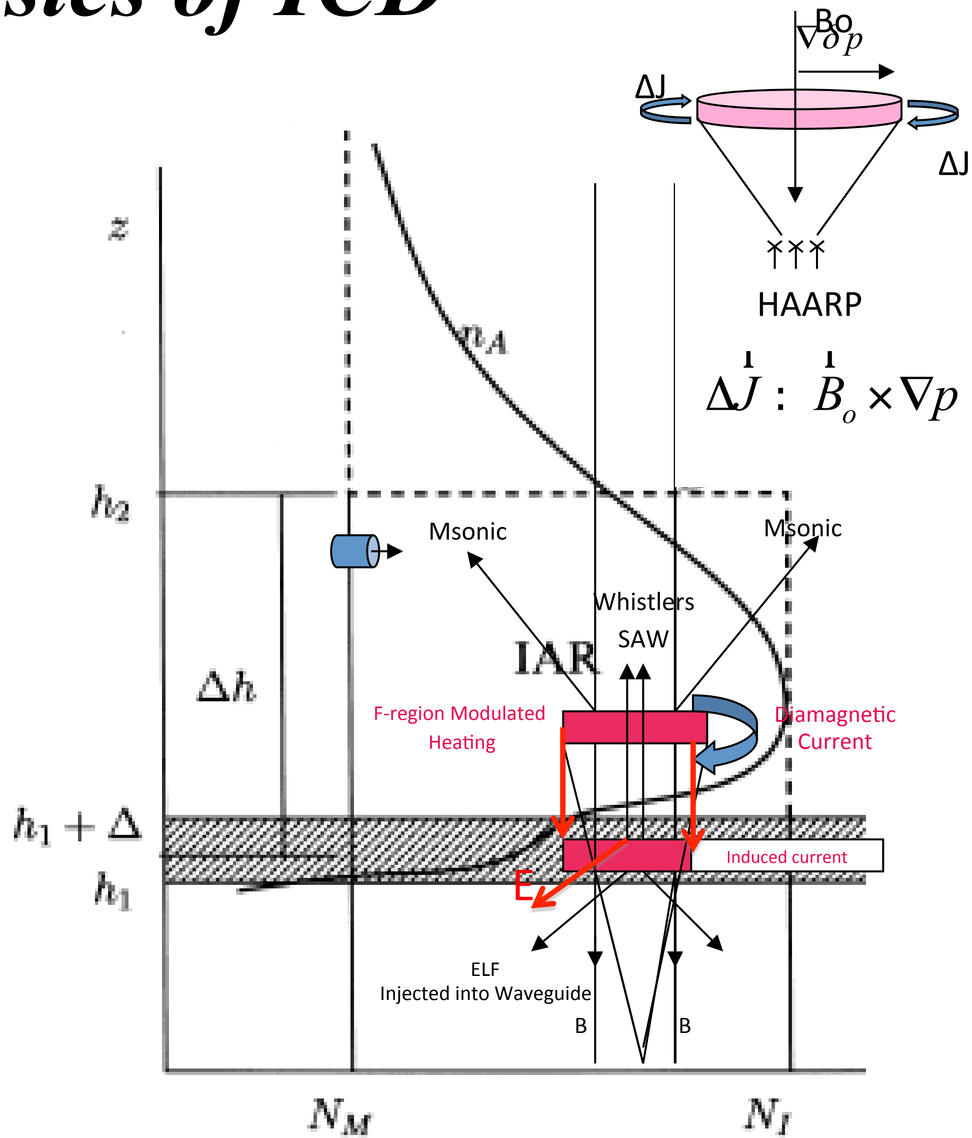
HAARP

$$\vec{p} = (\overleftrightarrow{\Sigma}\vec{E}L)L$$

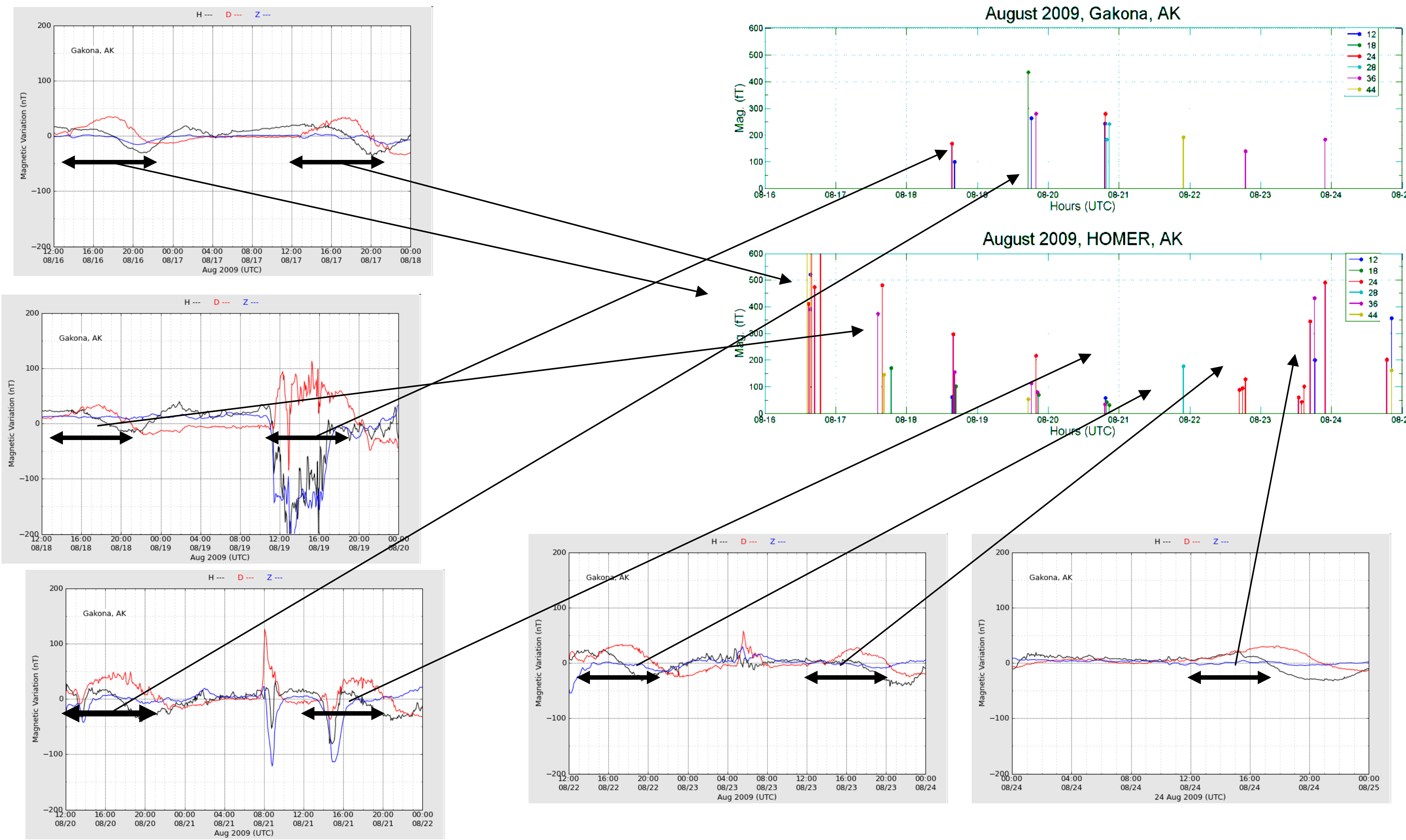
$$p_h \approx (\Sigma_h EL)L$$

Nuances of MS Waves and Alfvenic Duct:

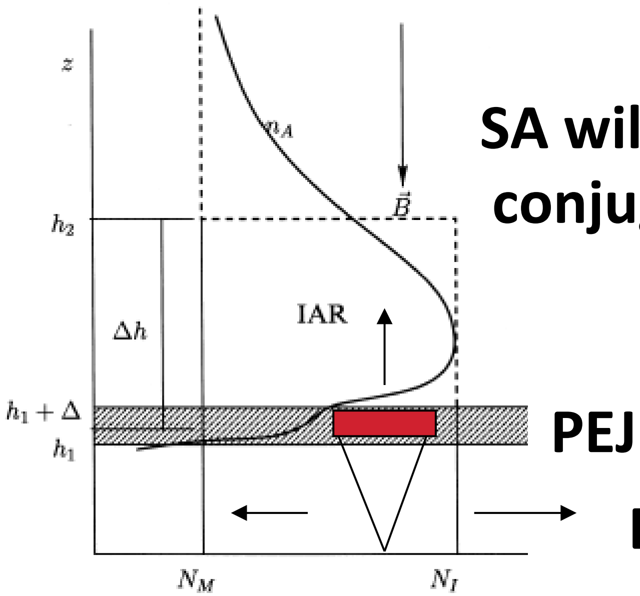
- **Duct propagation window .2-6 Hz**
- **Only MS waves propagate**
- **Hall region couples them to Shear and allows ground detection**



ELF – Ejet Correlation



MHD Wave Generation by the PEJ



SA will be guided by the magnetic field to the conjugates – No lateral propagation through the plasma

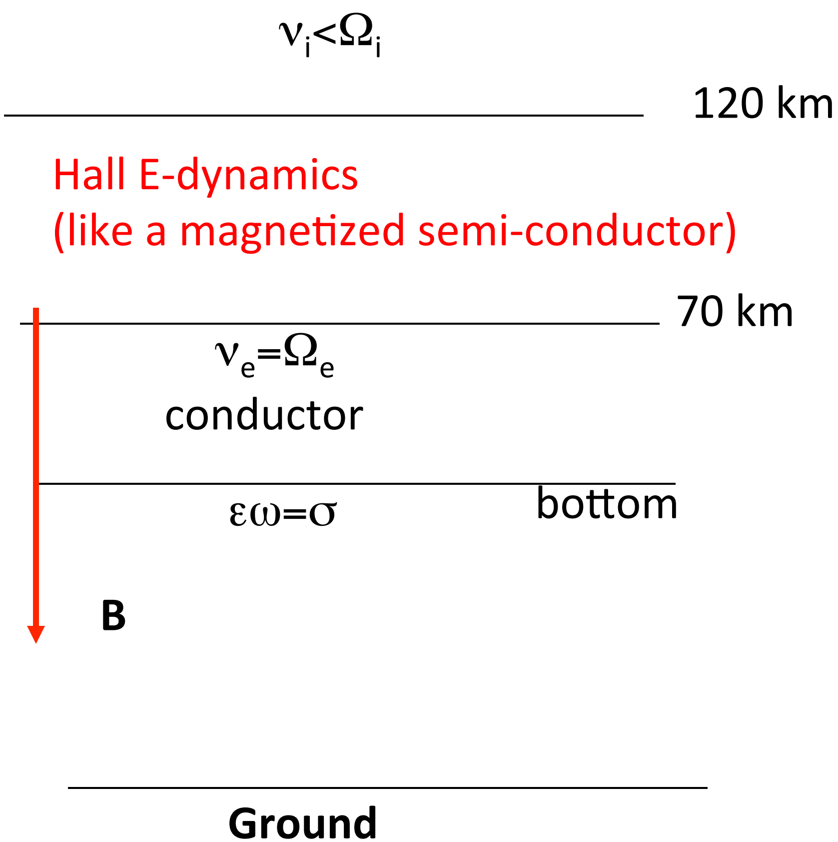
$$f \approx c / 2\pi R_E \approx 8Hz$$ **Schumann**

Evanescent in EI Waveguide if f<8Hz

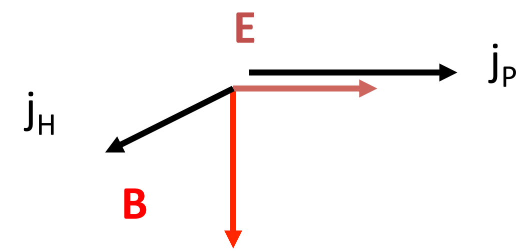
- **SA waves can be detected: (a) In the near zone below the heated spot and (b) By satellites over-flying the heated spot but confined to the magnetic flux tube that spans the heated spot (c) Through the EI waveguide for f>8 Hz (Schumann Resonance)**

THE LOWER IONOSPHERE AS A PLASMA

- **Lower ionosphere 65 – 120 km altitude, D and E region**



Hall and Pedersen conductivities



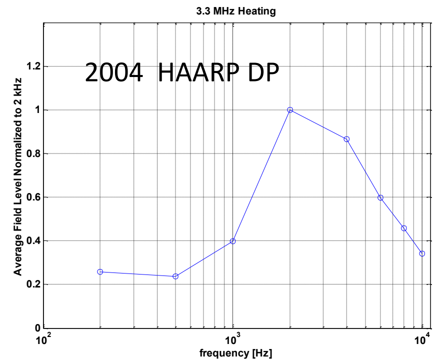
$$\vec{j} = \overleftrightarrow{\sigma}\vec{E}$$

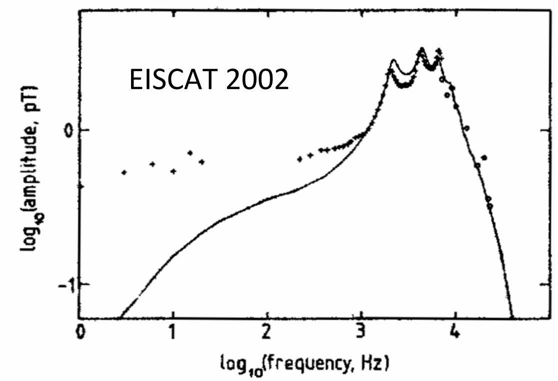
$$\overleftrightarrow{\sigma} = \begin{pmatrix} \sigma_P & \sigma_H \\ -\sigma_H & \sigma_p \end{pmatrix}$$

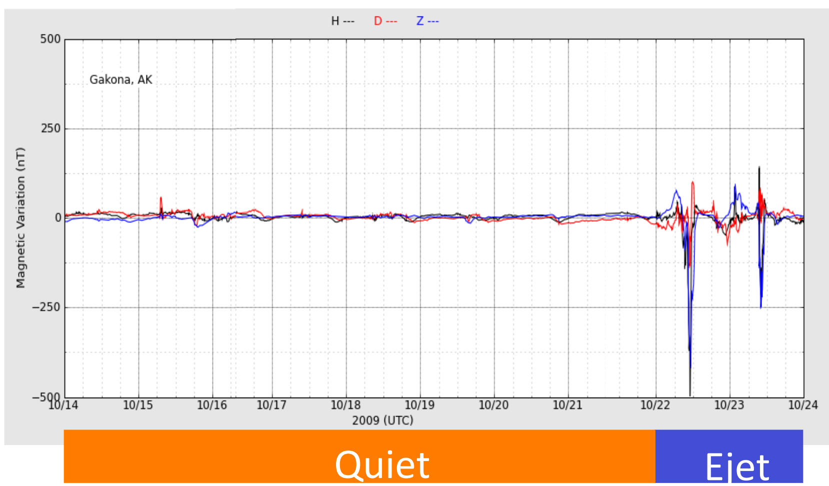
ICD vs. PEJ Gakona Measurements

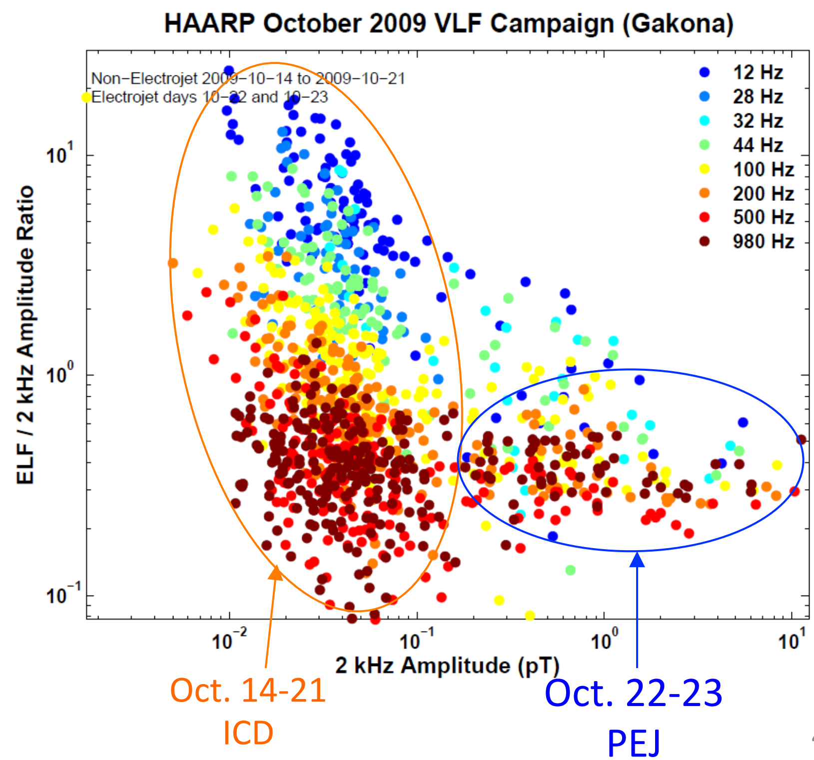
Oct.14-23 , Campaign

- **Oct. 14-21**
  - No electrojet, quiet ionosphere
- **Oct. 22-23,**
  - Active electrojet

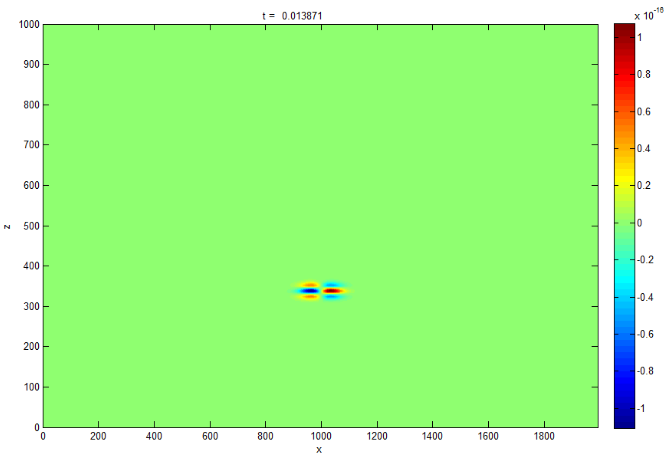




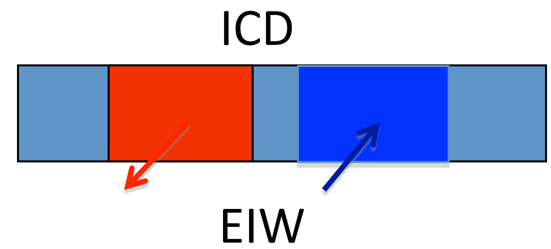




ICD Secondary Antenna – Resolution of the puzzle

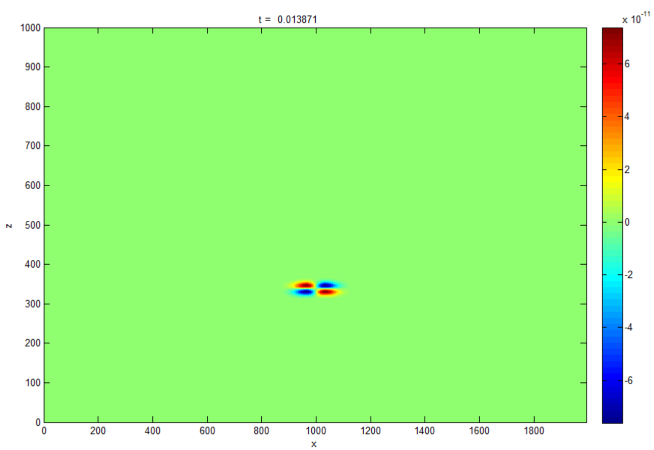


Hall Current

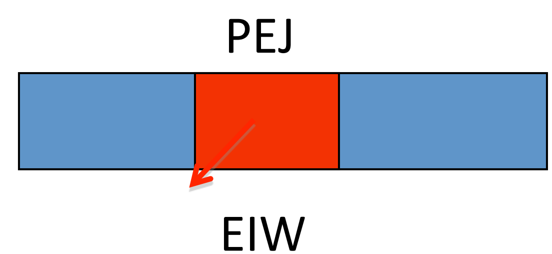


Min. below, Max 300 km away

20 Hz



B_y



Max below
Monotonically decreasing away

Scaling with Power and Frequency

External Control of Ion Waves in a Plasma by High-Frequency Fields,
Phys. Fluids 14, p.792 (1971).

$$B : \ (pressure)Volume \approx \mathrm{E}_{absorbed}$$

$$\frac{dE_a}{dt} = \alpha P_{HF} - \frac{E_a}{\tau}$$

$$E_a = \alpha P_{HF}\tau(1 - e^{-t/\tau})$$

$$f \ ; \ 1/2t, f_o = 1/2\tau$$

$$B : \ (\alpha P_{HF} / f_o)[1 - e^{-(f_o/f)}]$$

$$f >> f_o, B : \ 1/f$$

$$P_{ULF} : \ P_{HF}^2$$

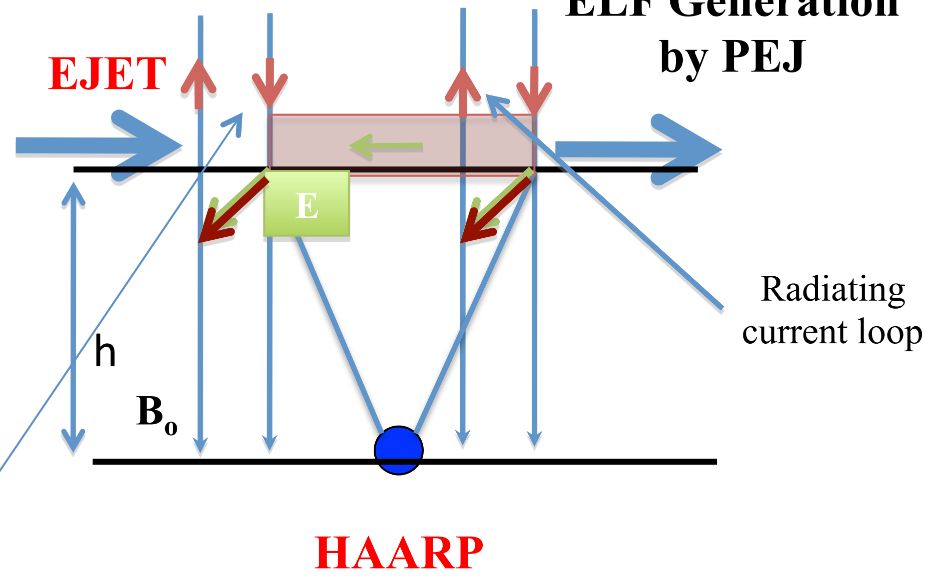
Gamma Ray Flashes by Plasma effects in the middle Atmosphere,
Phys. Plasmas 8, p.4954 (2001).

The Polar Electrojet (PEJ) Antenna

How to lift the antenna?
Virtual antenna → PEJ

1. **Find a region where natural currents flow in the lower ionosphere – Ejets**
2. **Use an ionospheric heater to modulate the electron temperature and conductivity at the D/E region**
3. **Create an HED at the modulation frequency – current closure by current carried by whistlers or shear Alfven waves in the magnetosphere**

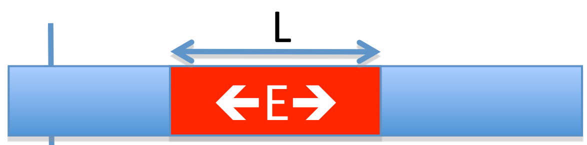
ELF Generation by PEJ



Advantages:
1.Reduces ground effect from (kδ) to (kh): gain h/δ
2. Small size and tunability
Disadvantages:
1. Weak IL moment and often no availability
2. Ejet site too far from many applications

ICD->Use HF to drive currents in E-region
All the advantages of PEJ without the availability and location issue

The Physics of ICD



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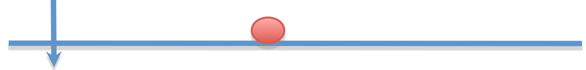

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