FUNDAMENTAL PHYSICS ISSUES ON RADIATION BELTS AND REMEDIATION

Presentation to Dr. Bobby Junker

DENNIS PAPADOPOULOS
UNIVERSITY OF MARYLAND

August 4, 2009

The Team – Budget - Reviews

- **Leadership**
  - UMCP – Dennis Papadopoulos - Professor of Physics– Overall Direction
  - Stanford University – Umran Inan - Professor of Electrical Engineering –Field tests
  - UCLA – Walter Gekelman – Professor of Physics – Laboratory experiments
  - Va Tech – Wane Scales – Professor, Computer and Electrical Engineering – Particle and hybrid electromagnetic codes (Physics codes) – Support to SPIDER
  - Dartmouth – Anatoly Streltsov – Associate Professor of Engineering – Global numerical models (engineering codes)
- **Ten Post-Docs and Research Scientists**
- **Twelve graduate students**
- **Seven senior visitors**
- **Fifteen undergraduate students**

Budget	FY 07	FY 08	FY 09	FY 10	FY 11
* Actual **Planned	$ 1.5 M*	$ 1.5 M*	$ 1.5 M*	$ 1.5 M**	$ 1.5 M**

Dates and location of Major Reviews/Meetings:

1. Kick-off meeting June 5, 2007 University of Maryland
2. Review March 3, 2008 UCLA Conf. Center, Lake arrowhead Ca
3. Review February 18, 2009 Stanford University

Reviews combined with DSX program review

Overarching Objectives

CONDUCT BASIC RESEARCH THAT WILL PROVIDE THE PHYSICS FOUNDATIONS LEADING TO THE DESIGN OF SYSTEMS THAT PROTECT MILITARY AND COMMERCIAL ASSETS FROM ENERGETIC PARTICLES IN NATURAL OR ARTIFICIALLY ENHANCED INNER RB AND IMPROVE DoD LOW FREQUENCY COMMUNICATIONS CAPABILITIES

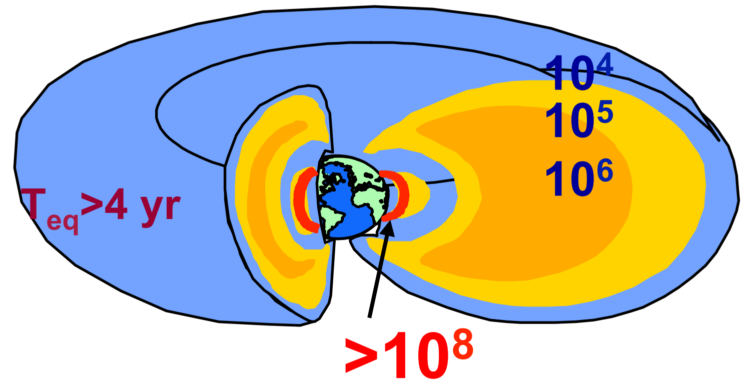
- DEVELOP CROSS DISCIPLINARY CRITICAL MASS WITH EXPERTISE IN THEORY/ MODELING , LAB & FIELD EXPS AND ANALYSIS OF SPACE AND GROUND DATA
- BASIC PHYSICS OF POTENTIAL RBR SYSTEMS
    - HOW TO INJECT EFFICIENTLY AND AMPLIFY ULF/ELF/VLF WAVES FROM SPACE & GROUND TRANSMITTERS AND FROM SPACE INJECTION OF CHEMICALS
    - DEVELOP AND TEST MODELS OF ARTIFICIALLY ENHANCED PRECIPITATION
    - THEORY & LAB EXPERIMENTS OF NOVEL ANTENNA CONCEPTS
- DEVELOP MANPOWER WITH INTERDISCIPLINARY EXPERTISE IN AREAS IMPORTANT TO NATIONAL DEFENSE

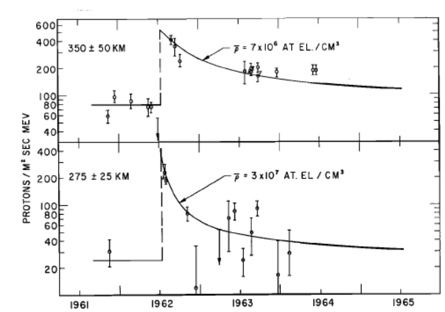
DoD Benefits

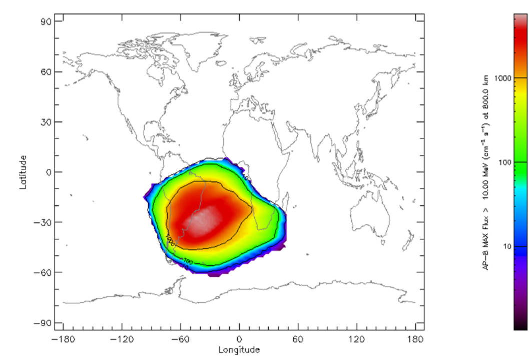
- Prevent loss of Low Earth Orbiting (LEO) satellites in case of deliberate or accidental High Altitude Nuclear Detonation (HAND) [DSX – SPIDER]

- Increase lifetime and functionality of satellites by reducing the trapped energetic proton population – SEU major issue due to wide use of submicron Commercial-Off-The-Shelf (COTS) Electronics – (e.g. see Vanderbilt AFOSR MURI)

- Develop broadband, efficient, global ULF/ELF/VLF sources







Physics & Technology Challenges

- **Radiate** - Inject efficiently from space or ground VLF/ELF/ULF waves in the in earth-ionosphere waveguide and the RB
  - Ionospheric Current Drive
  - Performance of electric dipole antennas at VLF in plasmas (DSX - AF)
  - VLF generation in RB by injecting low ionization chemicals (SPIDER - NRL)
  - Innovative Injection Concepts – Rotating Magnetic Field (RMF)
- **Propagate** – Guide waves to regions of enhanced RB
  - Injection to naturally occurring ducts
  - Generation of artificial ducts by ionospheric heaters (HAARP)
- **Amplify** – Use the free energy stored in trapped energetic particles to amplify the VLF wave power
  - The physics of Artificially Stimulated Emissions (ASE)
- **Precipitate** – Physics of particle precipitation with wave particle interactions
  - The physics of slot formation
  - The physics of energetic proton loss

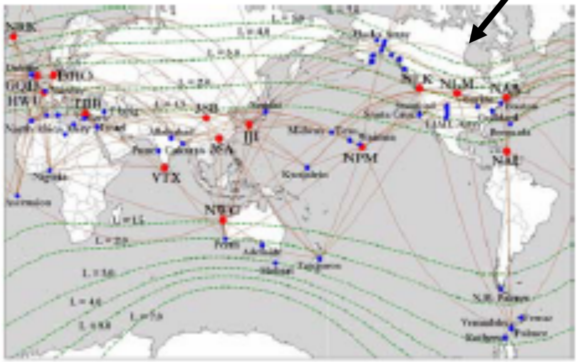
Technical Approach

Combine extensive simulations using newly developed codes and analytic theory, laboratory experiments using the LAPD plasma chamber at UCLA, field experiments using the HAARP facility and ground VLF stations, and satellite and ground based VLF and ULF diagnostics – **MULTI-DISCIPLINARY EFFORT**

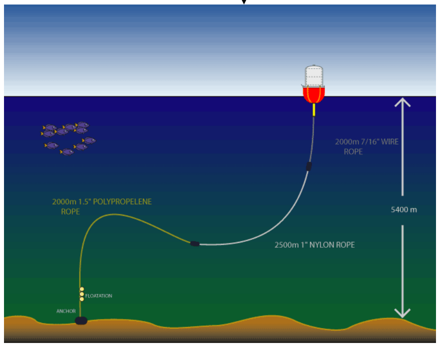
HAARP

DEMETER

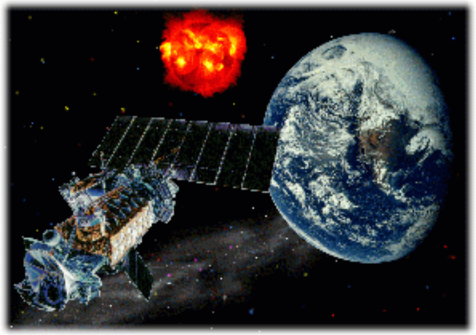
LAPD



Worldwide SU-Deployed VLF Receiver in support of IHY/UNBSS Program



CONJUGATE BUOYS



DMSP

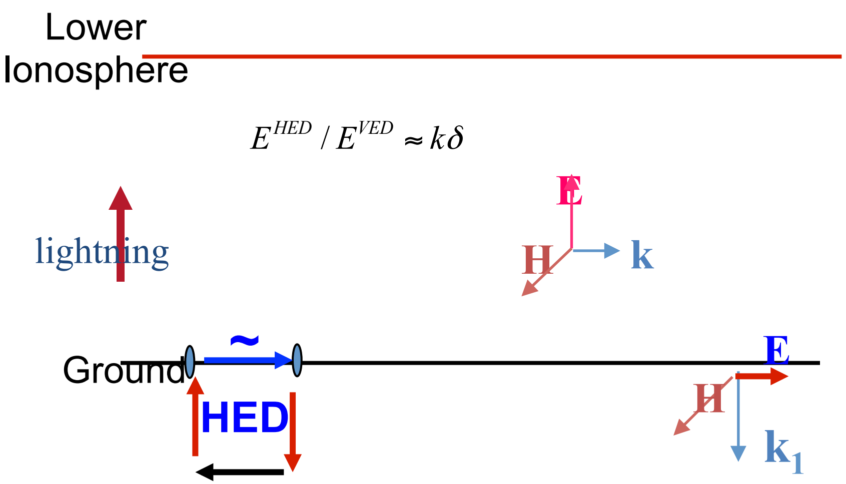
Technical Accomplishments- Transition to DoD Applications

- **First models of enhanced RB proton precipitation**
  - **Design of a ground based Proton RBR system – DARPA conducted environmental impact study in anticipation of new start**
- **First demonstration of ionospheric generation of ELF/ULF waves without relying on electrojet currents (HF to ELF/ULF conversion)**
  - **Simultaneous detection in Alaska-Seattle-Hawai-Guam (~ 8Mm)**
  - **Injection in the magnetosphere of more than 5 kW ULF power**
  - **Spin-off – PACE-New concept for HED current drive – 30-50 dB more efficient than traditional ELF/ULF radiators – First test (DARPA seedling) in August, 2009**
- **First laboratory demonstration of high efficiency antenna radiation in plasma using Rotating Magnetic Fields (RMF)**
- **Laboratory resolution of controversy of electric dipole antenna radiation efficiency – AF DSX mission antenna design support**
- **New 2-D off plane code provided guidance to NRL's SPIDER test**
- **Global effects of VLF transmitters – VLF mode conversion to LHW**

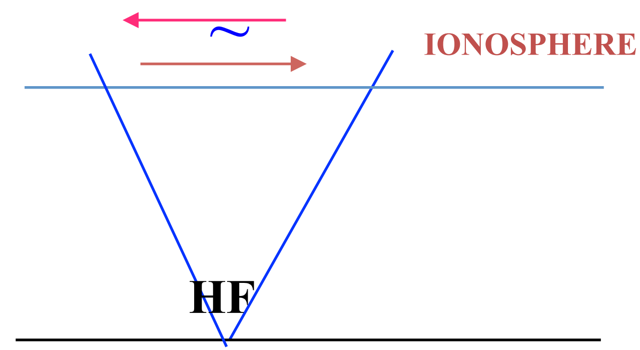
Technical Accomplishments (cont.)

- Amplification – Artificially Stimulated Emissions (ASE)
  - Empirical ASE model using the Stanford Sipple facility digitized data
  - MURI-DARPA joint ASE tests using HAARP/Conjugate buoy system (> 20 dB amplification)
  - Joint NRL-MURI modeling optimizes probability of ASE gain
  - New ASE targeted experiments using Alpha (Russian) VLF transmitter (inner RB)
  - Generation of artificial propagation ducts using HAARP with Demeter detection
- Light- Induced Electron Precipitation(LEP)
  - New Demeter measurements reveal it as key to slot maintenance
  - New global detection of LEP via VLF paths
  - Global effects of VLF transmitters – Irregularity triggering -VLF mode conversion to Lower Hybrid Waves – Possible proton precipitation
- Development of new efficient numerical simulation codes
  - Three dimensional MHD, EMHD, whistler and hybrid codes simulating VLF/ELF/ULF generation and injection and modeling precipitation
  - Many of the codes implemented on new GPU processors (game platforms) accelerating their performance by factors between 20-50

Ionospheric Current Drive (ICD)
A little history

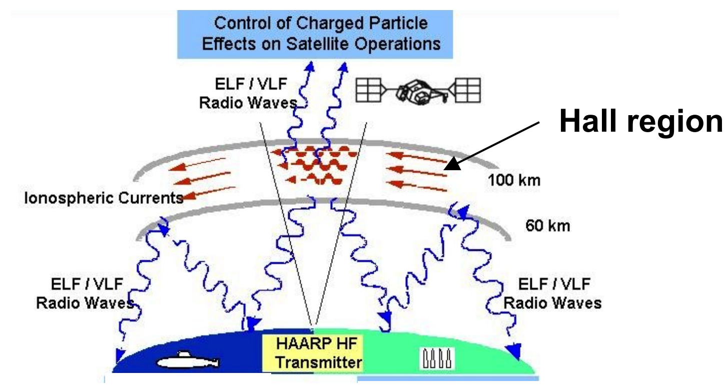


Circa 1973



PONDEROMOTIVE FORCE CURRENT DRIVE THRESHOLD - EITHER VERY OBLIQUE HEATERS OR TOO MUCH POWER

ALTERNATIVE (1974): MODULATE EJET CONDUCTIVITY – PEJ.
DEMOSTRATED IN TROMSO, HAARP, HIPAS



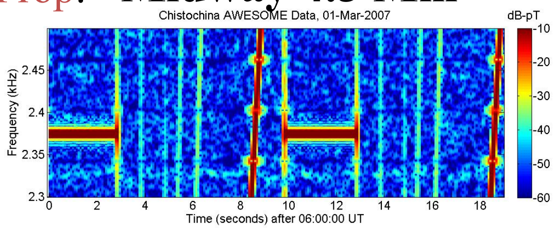
Issues with PEJ; Availability, sitting, efficiency, long propagation path

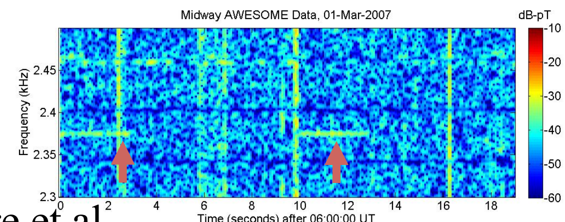
Conductivity modulation → ejet current modulation → large virtual ELF/VLF antenna

Summary Stanford VLF Results

PEJ Excitation

1.Far Prop: **Midway 4.5 Mm**

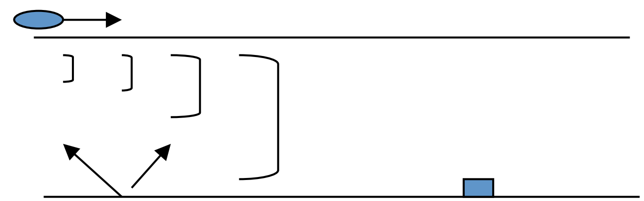


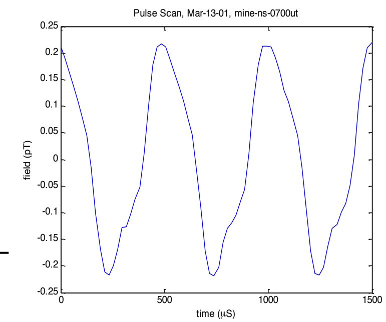


Moore et al. GRL, 2008

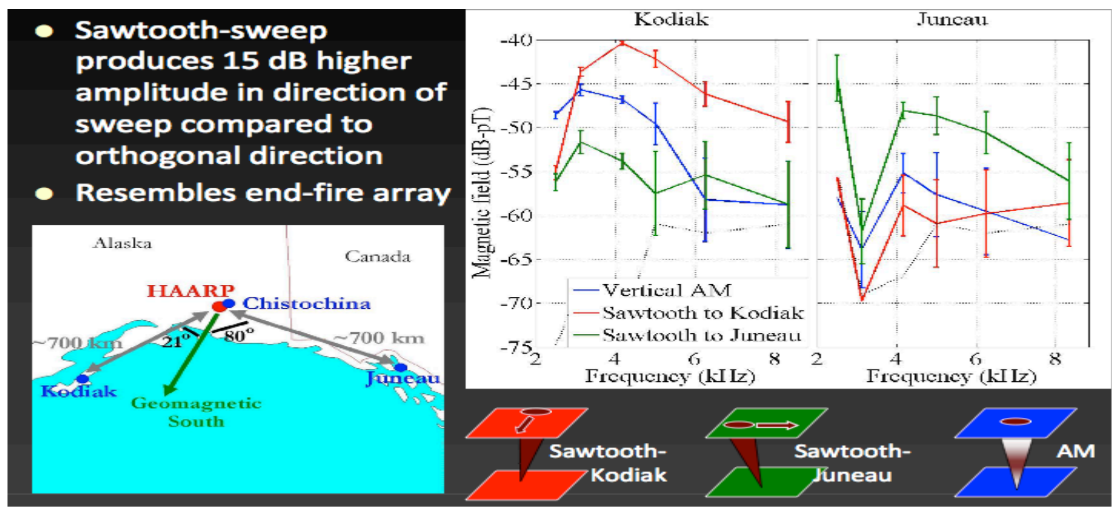
T_{det}< 1 sec

2. Coherent Painting -TWT

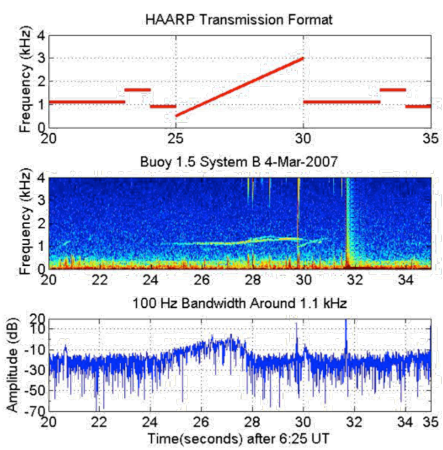




Pap.+ Wallace 2001, increase efficiency, directionality



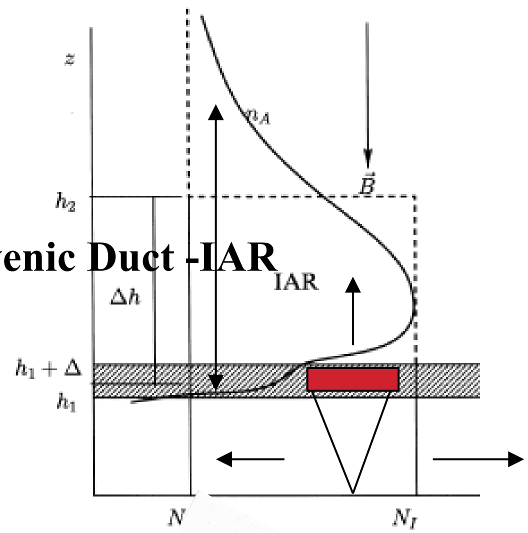
3. Art. Stim. Emissions

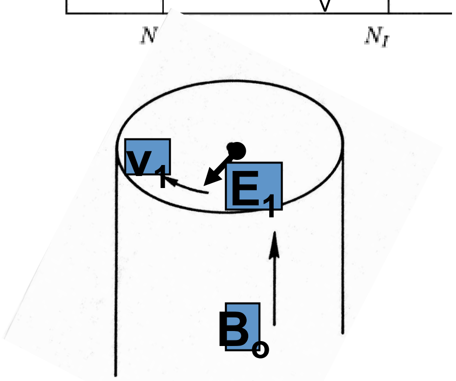


Only the pulse at 1100 Hz is amplified 10 dB/sec

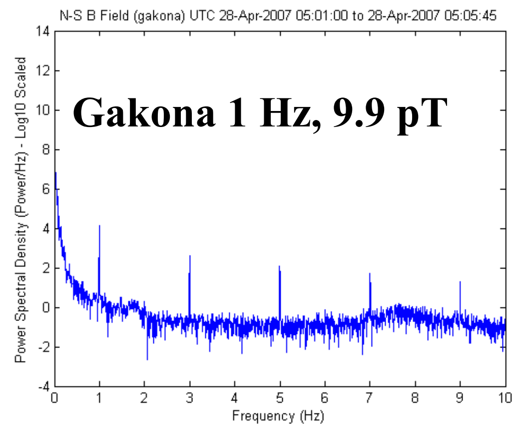
Stanford - New HARP - Cohen et al. 2009

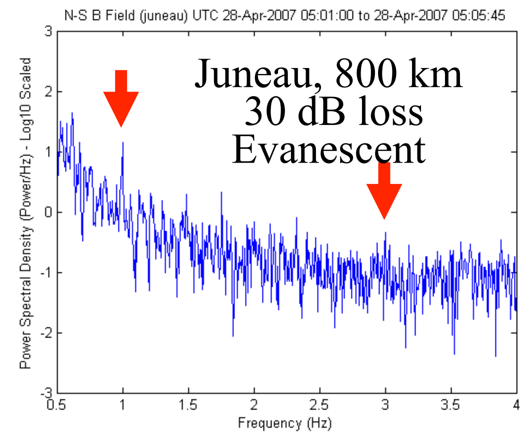
PEJ ULF Generation and Propagation

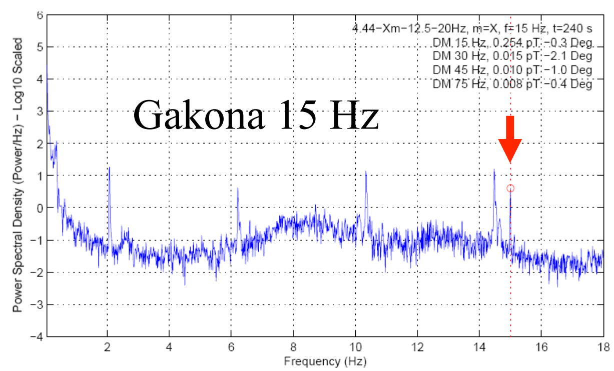


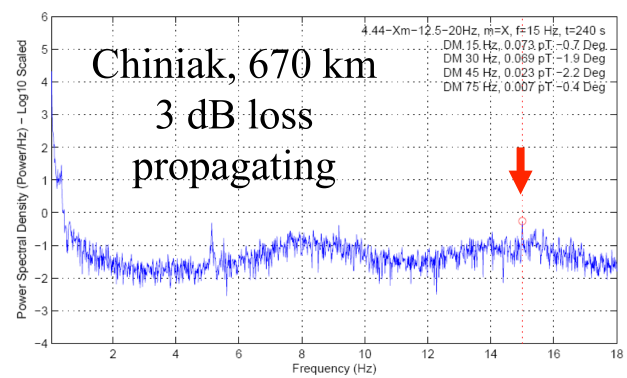


Shear Alfven Wave –Field Guided







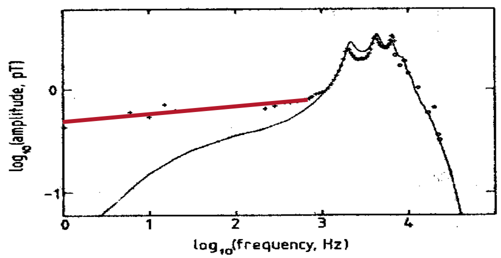


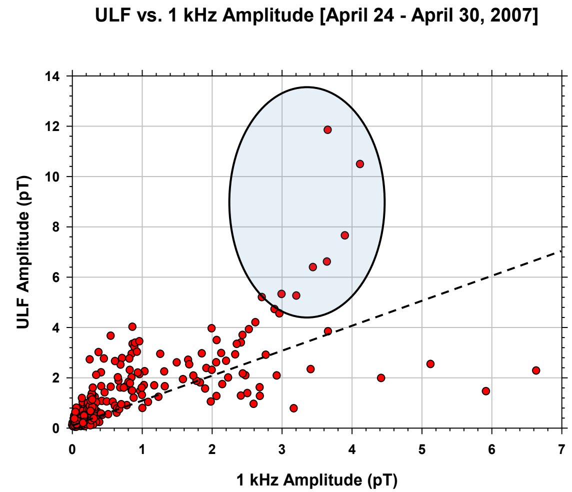
Detection by DEMETER with E~ 5-10 mV/m confined to field tube

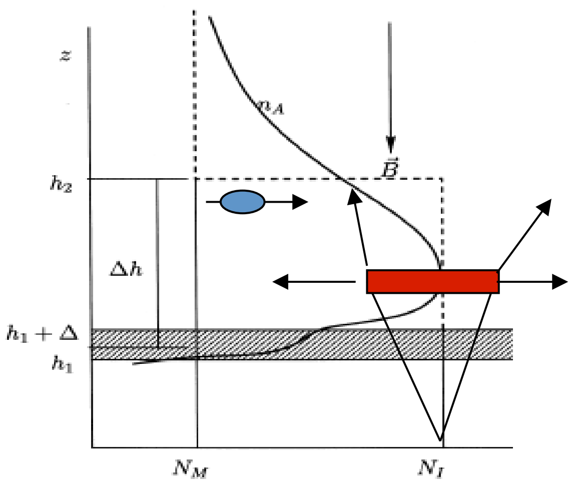
ICD a glimpse at ULF

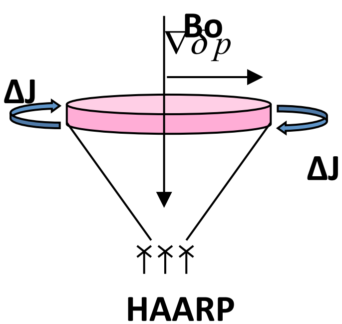
$$B(f < 1kHz)/B(1kHz) \approx 1$$

Marker of PEJ generation



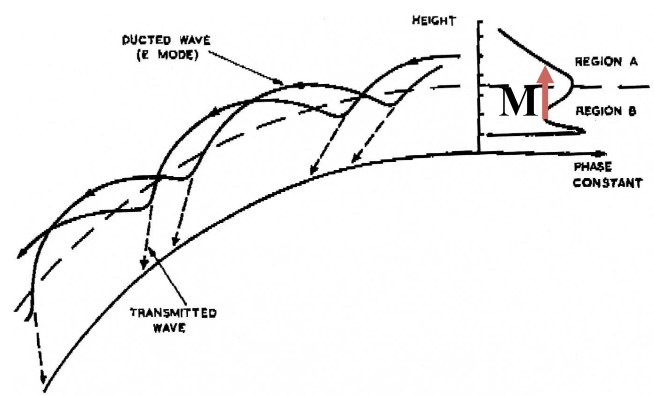




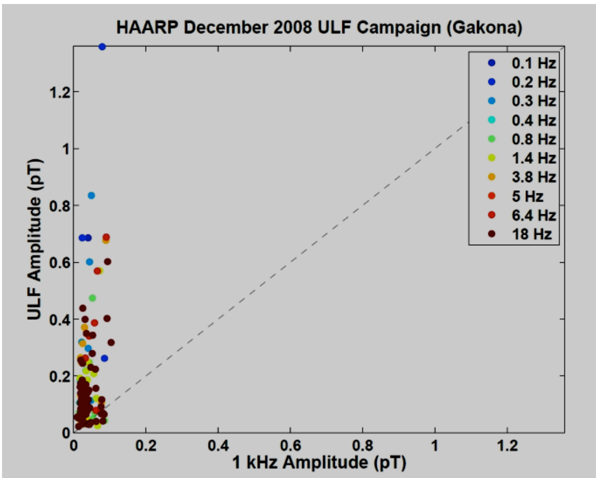


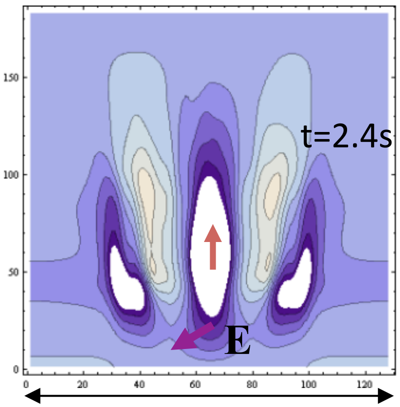
Collisionless heating drives isotropic **Magnetosonic** wave

$$\Delta \vec{J} \sim \vec{B}_o \times \nabla p$$



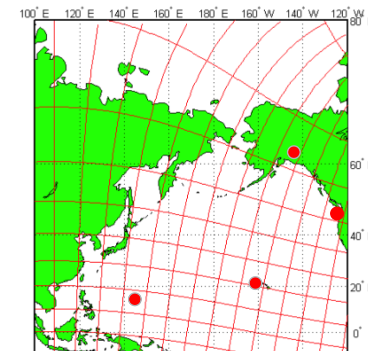
ICD Confirmed





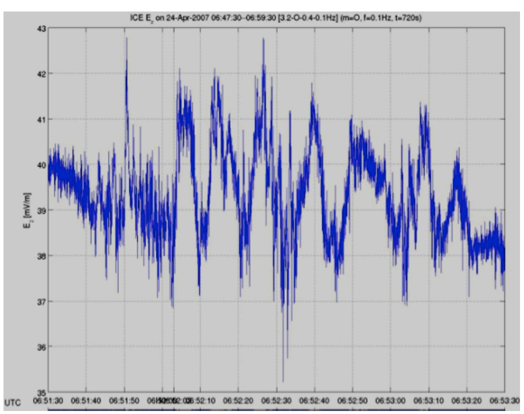
5000 km

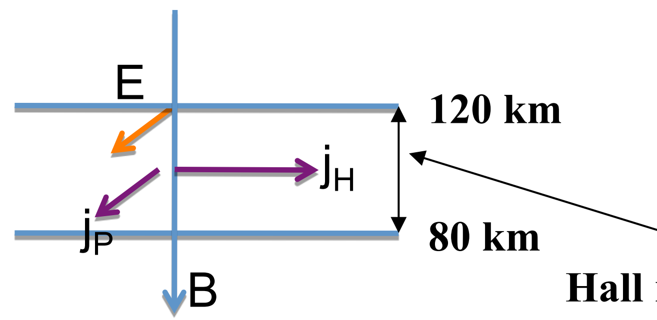
May 2009 simultaneous measurements at 3.8 Hz



> 8 Mm

DEMETER 1 mV/m



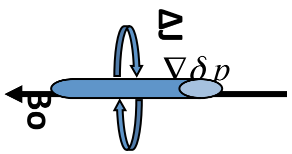


Ground signature due to j_H Transducer

Hall region – Plasma similar to semiconductor

Equatorial ICD

F-region



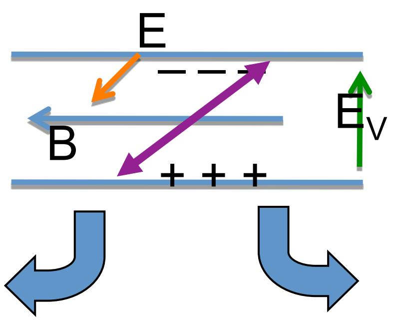
$$\sigma_H E - \sigma_P E_V = 0$$

$$E_V / E = \sigma_H / \sigma_P \approx 20$$

$$j_P = \sigma_P E + \sigma_H E_V = [[1 + (\sigma_H / \sigma_P)^2] E$$

System by about 400 times
more efficient

E-region



Current closure through field aligned helicons

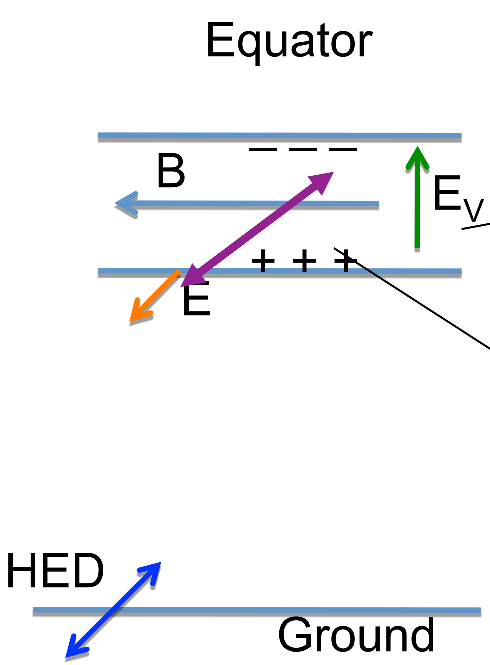
Interesting potential system but maximum frequency limited by F-region response time to may-be low ELF

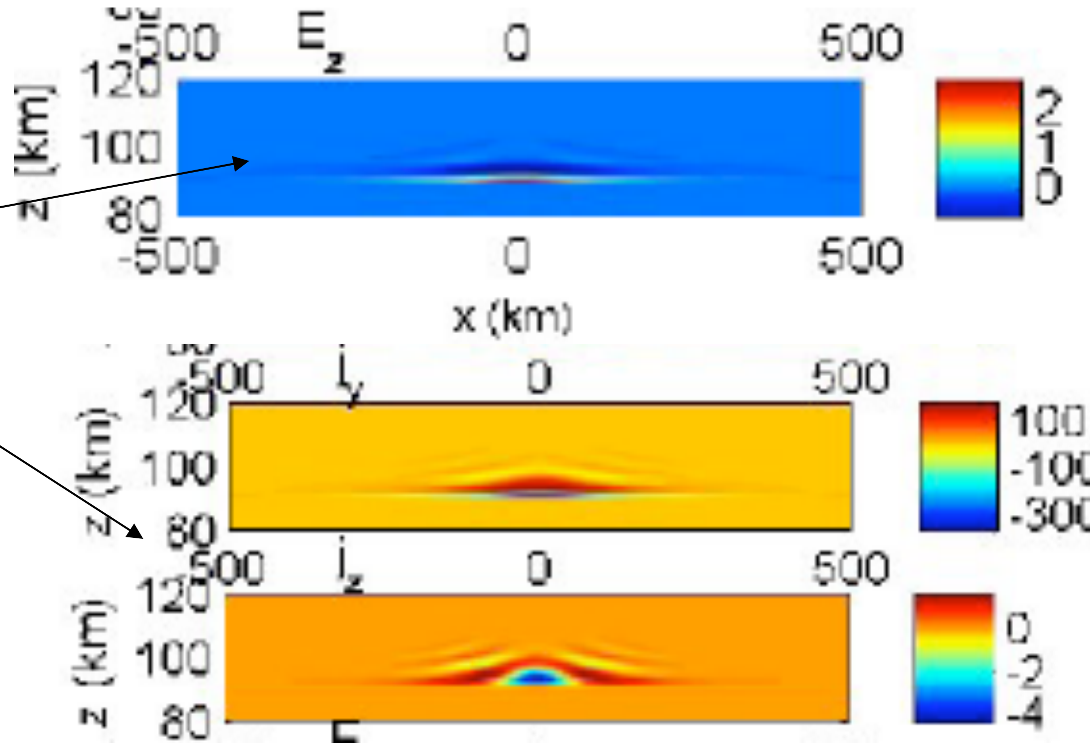
Ground

Image current doubles signal

ICD at VLF/ELF Frequencies

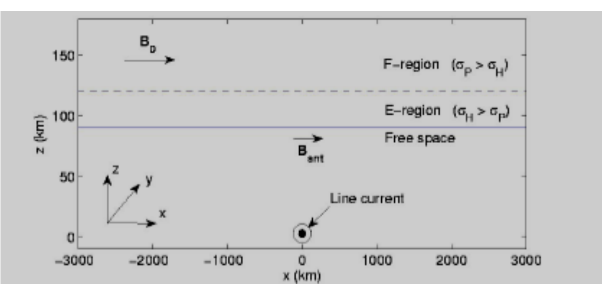
Artificially Constructed Electrojet (ACE)





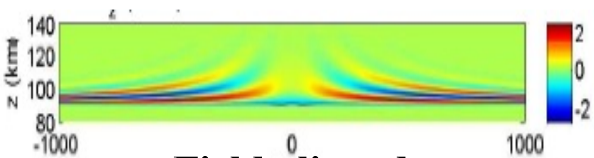
mV

nA/m²

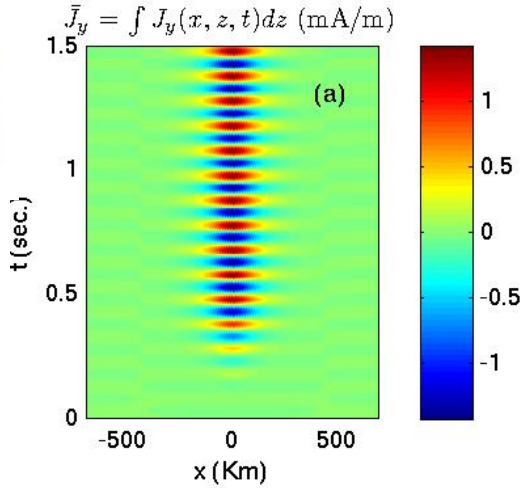


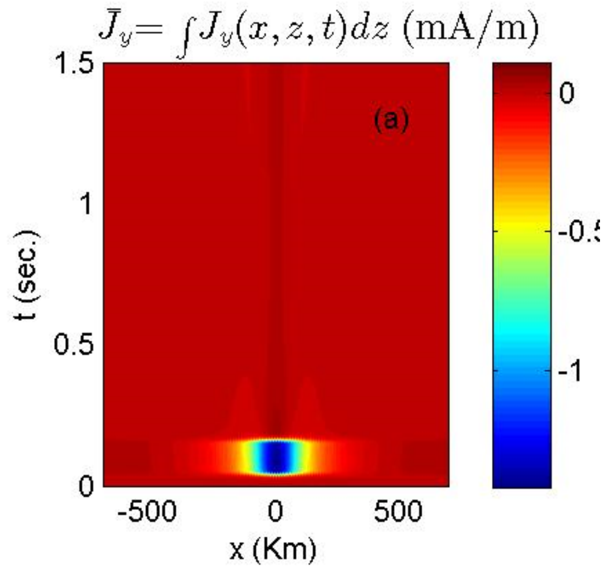
Incident pulse .1 mV/m or 1 nT

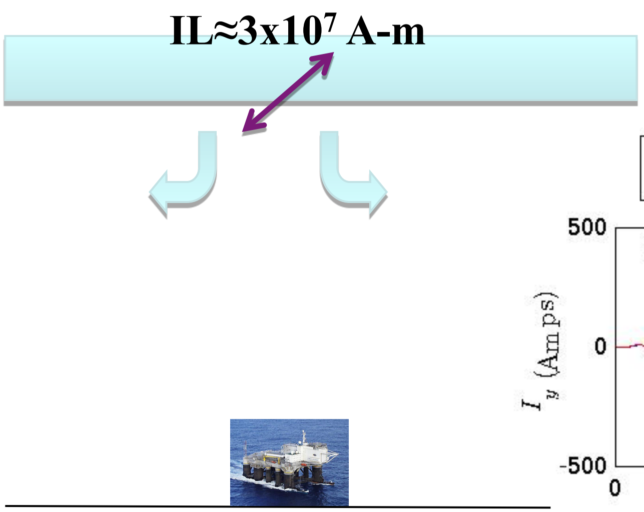
Equatorial ICD - Modeling

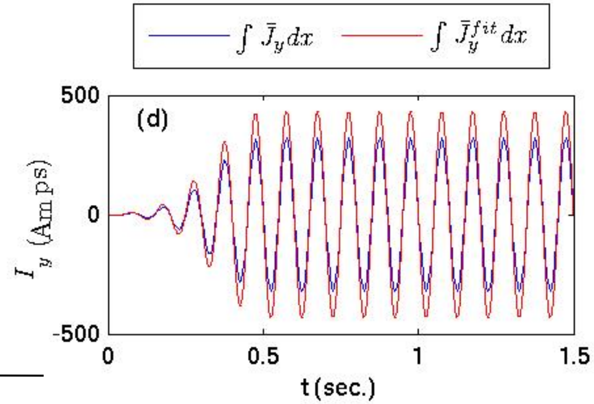


Field aligned helicon driven current closure









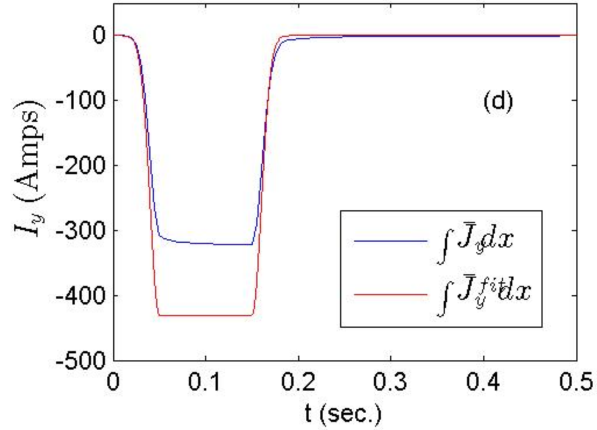


Image current increases field by factor of 2

Eliasson and Pap, JGR 2009

Getting .1 mV field at 75 km

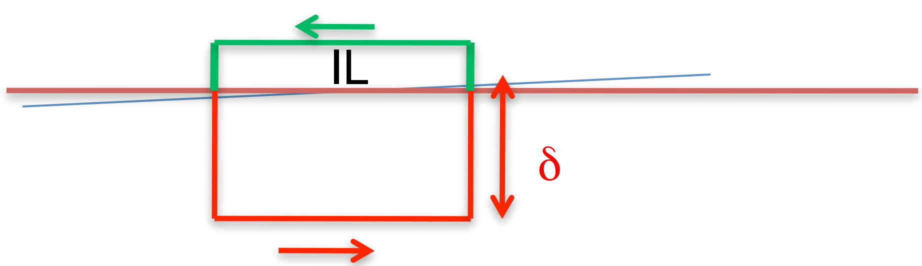
$$E(75km) = (IL / 2\times10^{6} A - m)(\delta / 75km) mV / m$$

75 km

Skin depth km like
Conductivity dependent

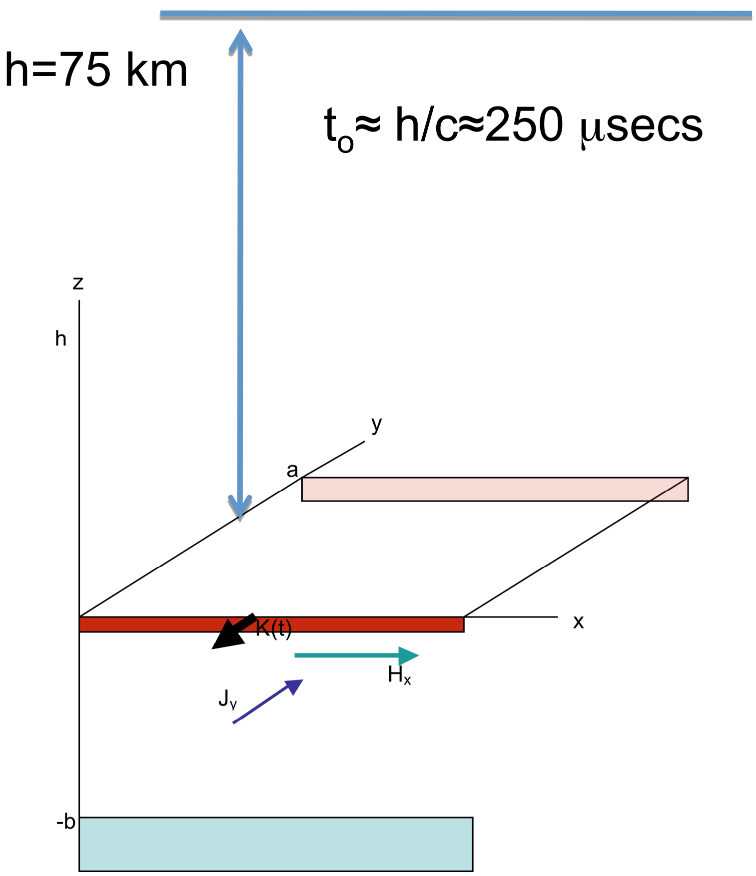
$$IL \approx 2\times10^{5}(75km / \delta) A - m$$

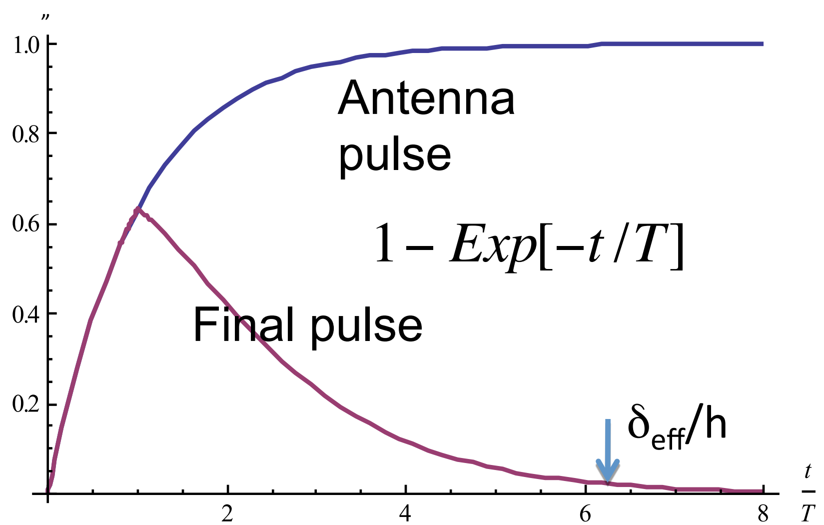
Get rid of 75/δ factor



Use pulsed antenna
sneak-through concept
ACE to PACE

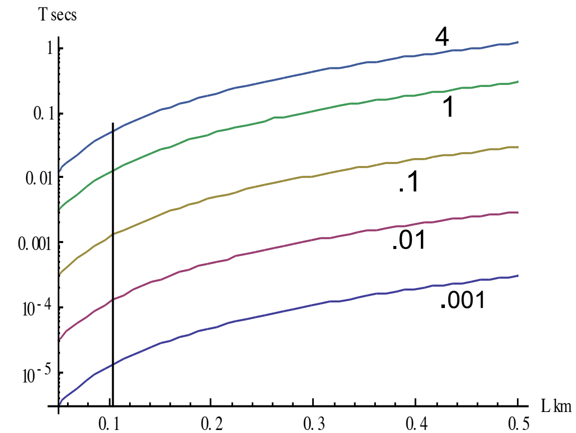
Sneak-through Concept





Reduces IL to 4x10⁵ A-m

Optimum medium seawater



Concept to be tested in September – DARPA seedling
Peder Hansen

Technical Accomplishments- Transition to DoD Applications

- First models of enhanced RB proton precipitation
  - Design of a ground based Proton RBR system – DARPA conducted environmental impact study in anticipation of new start
- First demonstration of ionospheric generation of ELF/ULF waves without relying on electrojet currents (HF to ELF/ULF conversion)
  - Simultaneous detection in Alaska-Seattle-Hawai-Guam (~ 8Mm)
  - Injection in the magnetosphere of more than 5 kW ULF power
  - Spin-off – PACE-New concept for HED current drive – 30-50 dB more efficient than traditional ELF/ULF radiators – First test (DARPA seedling) in August, 2009
- First laboratory demonstration of high efficiency antenna radiation in plasma using Rotating Magnetic Fields (RMF)
- Laboratory resolution of controversy of electric dipole antenna radiation efficiency – AF DSX mission antenna design support
- New 2-D off plane code provided guidance to NRL's SPIDER test
- Global effects of VLF transmitters – VLF mode conversion to LHW

PRBR – The Inner Belt Protons

Starfish protons

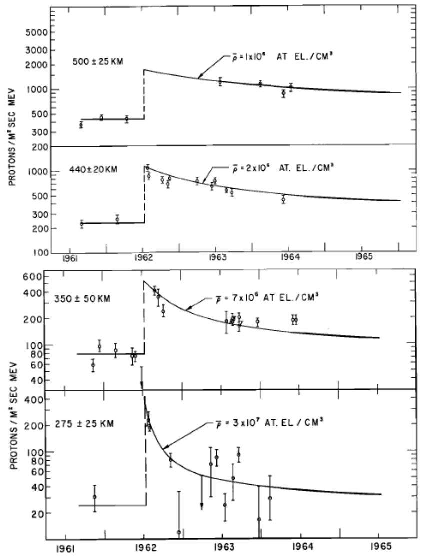
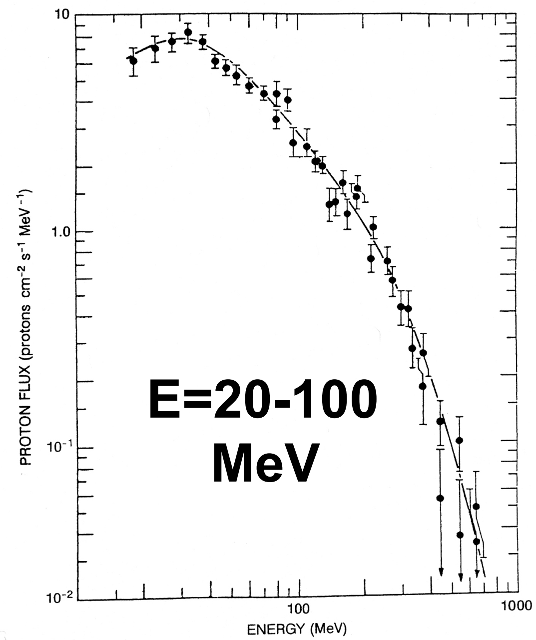
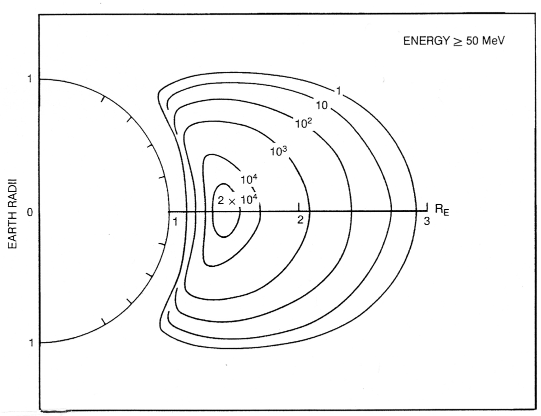


Fig. 10. Time variation of the 55-Mev proton flux for altitudes of H_a = 275, 350, 440, and 500 km from August 1961 to July 1964. The solid curves drawn for the period after July 1962 are the theoretical decay curves based on the first data point following July 1962.



. Differential energy spectrum of protons in the inner radiation zone.

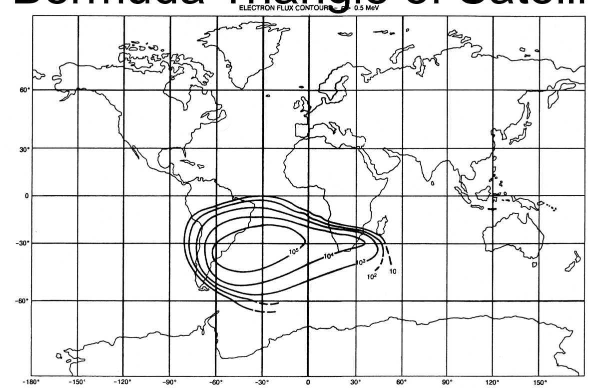


. Omnidirectional, integral proton flux with energy greater than 50 MeV. Based on data supplied by the National Space Science Data Center.

L= 1.5-1.8

Bermuda Triangle of Satellites

SAA



. Radiation concentration at the South Atlantic anomaly. Isointensity contours of electrons above 0.5 MeV at an altitude of 400 km.

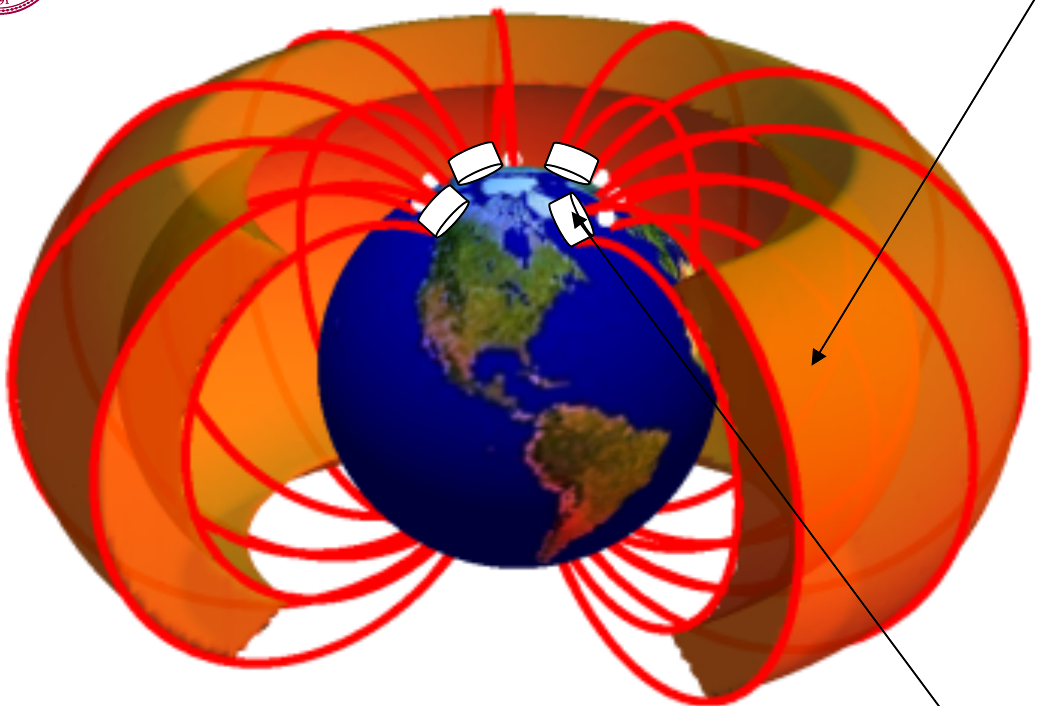
Issues with using COTS in LEO Orbiting Platforms

- As commercial feature sizes scale down, proton upsets will become much more frequent
- Critical charge for upset scales as $(\text{feature size})^2$
- For large feature sizes, protons cause upsets by hitting nuclei and releasing secondary particles that deposit charge
- At 65 nm and smaller, a proton deposits enough charge in silicon to cause an upset directly
- This can increase the proton SEU cross section by 2-3 orders of magnitude for deep submicron devices
- Major issue for micro-satellites

PRBR by Injection of Shear Alfven Waves (SAW) from Ground Transmitters

- **Removal same way as HANE RBR. Increase proton precipitation rate by enhancing proton pitch angle scattering into the loss cone.**
- **Enhanced pitch angle scattering requires interaction with resonant waves – SAW with frequency in the 1 – 15 Hz band.**
- **Unlike HANE electrons, inner belt protons are injected slowly (>30 years) (CRAND). PRBR can be done periodically (e.g. for 1-2 years every 10 years) as well as monitored**
- **PRBR would have an immediate operational impact, as well as alleviate current problems**
- **Physics of PRBR by SAW mature enough for new start (see Papadopoulos and Shao, Gomtact 2009; Shao et al., JGR 2009)**

Schematic of PRBR Concept



Maintain an average amplitude of approximately 25 pT of Shear Alfven Waves (SAW) with 5-15 Hz frequency in the L=1.5-1.8 shells of the inner belt. These waves induce Pitch Angle Diffusion (PAD) on 30-100 MeV protons, by satisfying the resonance condition

$$\omega - k_z v_z = \pm\Omega$$

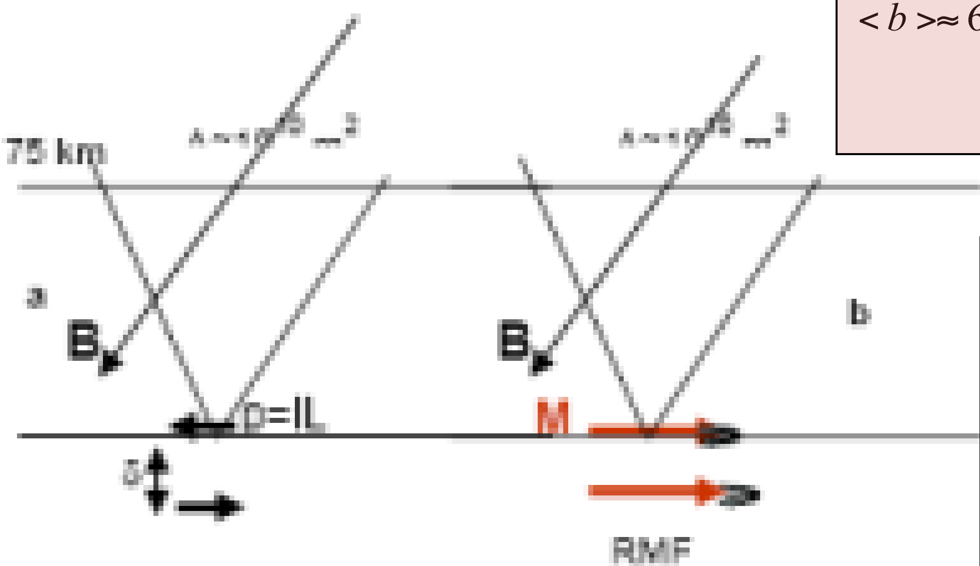
$$k_z v_z \approx \Omega$$

SAW injected using ground based transmitters

- Energy stored in volume for ΔL=.1 is 75 kJ
- Loss time for 30-100 MeV protons < 3 years
- Injection power required to maintain it depends on SAW confinement time ~ 3-7 KW

How to Inject kW Level SAW Power Ground-based Transmitter Options

- Conventional ULF/ELF transmitters HED (grounded dipoles)
- Rotating electromagnets (conventional and low and high temperature superconducting)



HED

$$<b>\approx 60(IL^2/2\times10^{10})[\frac{\delta}{2(L+\delta)}]pT \approx 30(IL^2/2\times10^{10})pT$$

Need $M \sim IL^2 \sim$ 2×10^{10} A-m^2

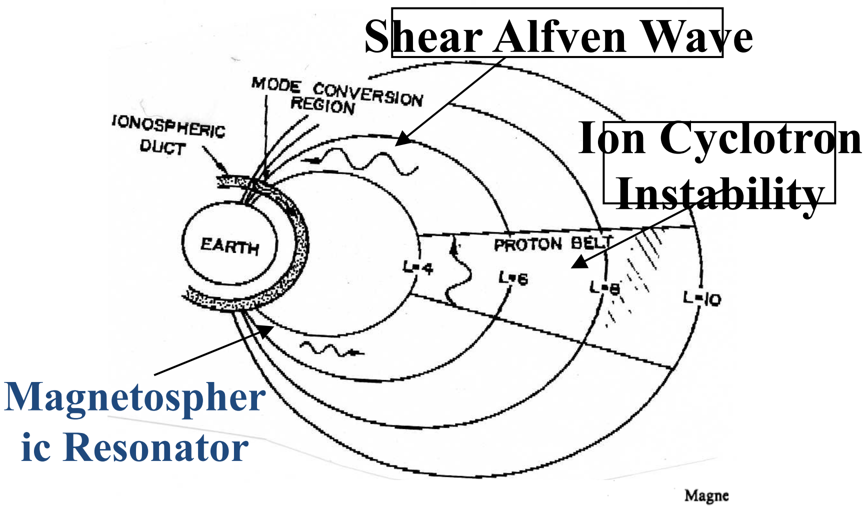
RMF

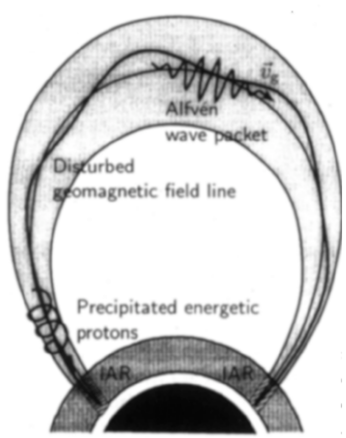
$$<b>\approx 30(M/5\times10^{9})pT$$

Need RMF with $M \sim 5\times10^9$ A-m^2

Alfven Masers –Triggered Proton Precipitation

Pearls -> repetitive wave-packets with characteristic frequency drift inside each one





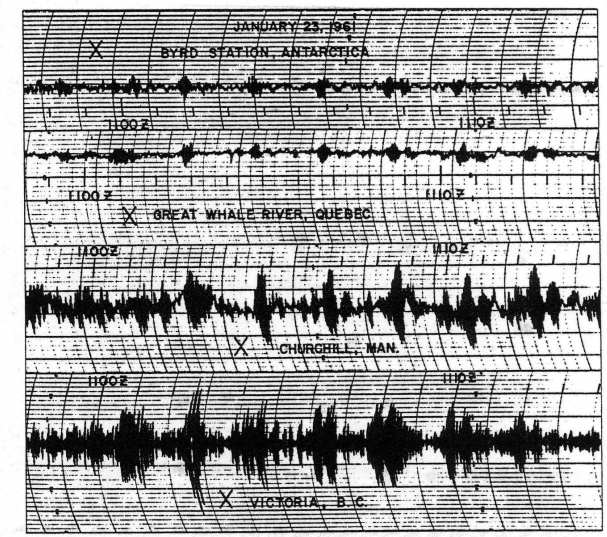
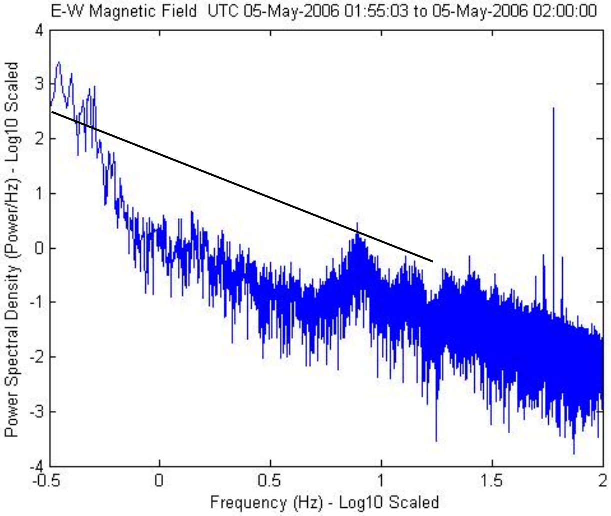
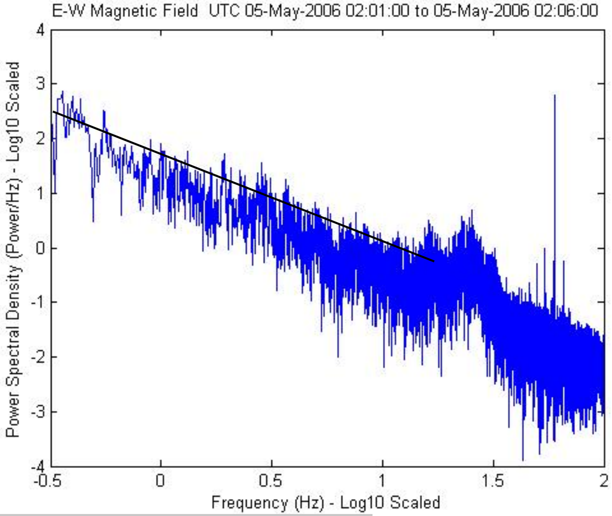


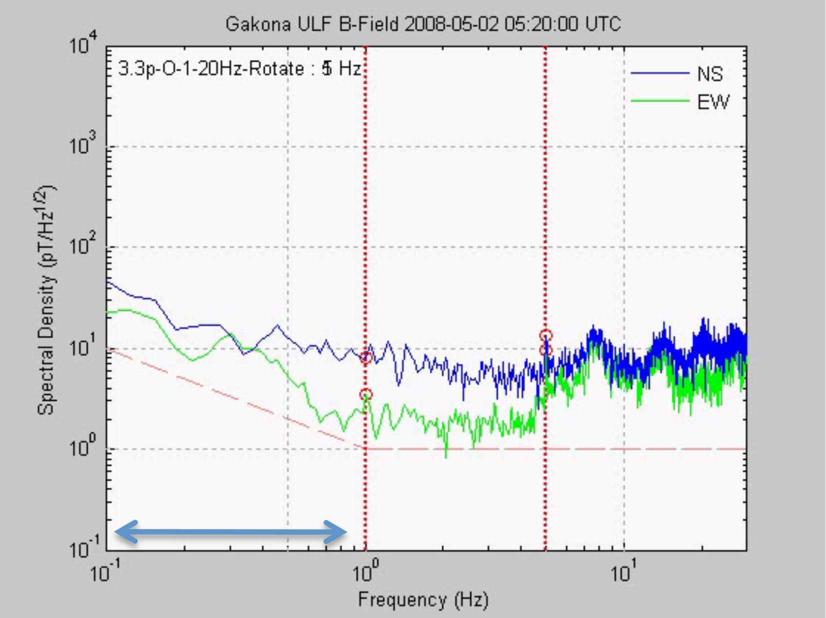
Fig. 2.1. Example of Pc 1's (pearls) recorded at four stations simultaneously. (After J. E. Lokken, J. A. Shand, and C. S. Wright, DREP photograph 2751)

Conjugate stations detect anti-phased pearl wave-packets

Any Evidence ?





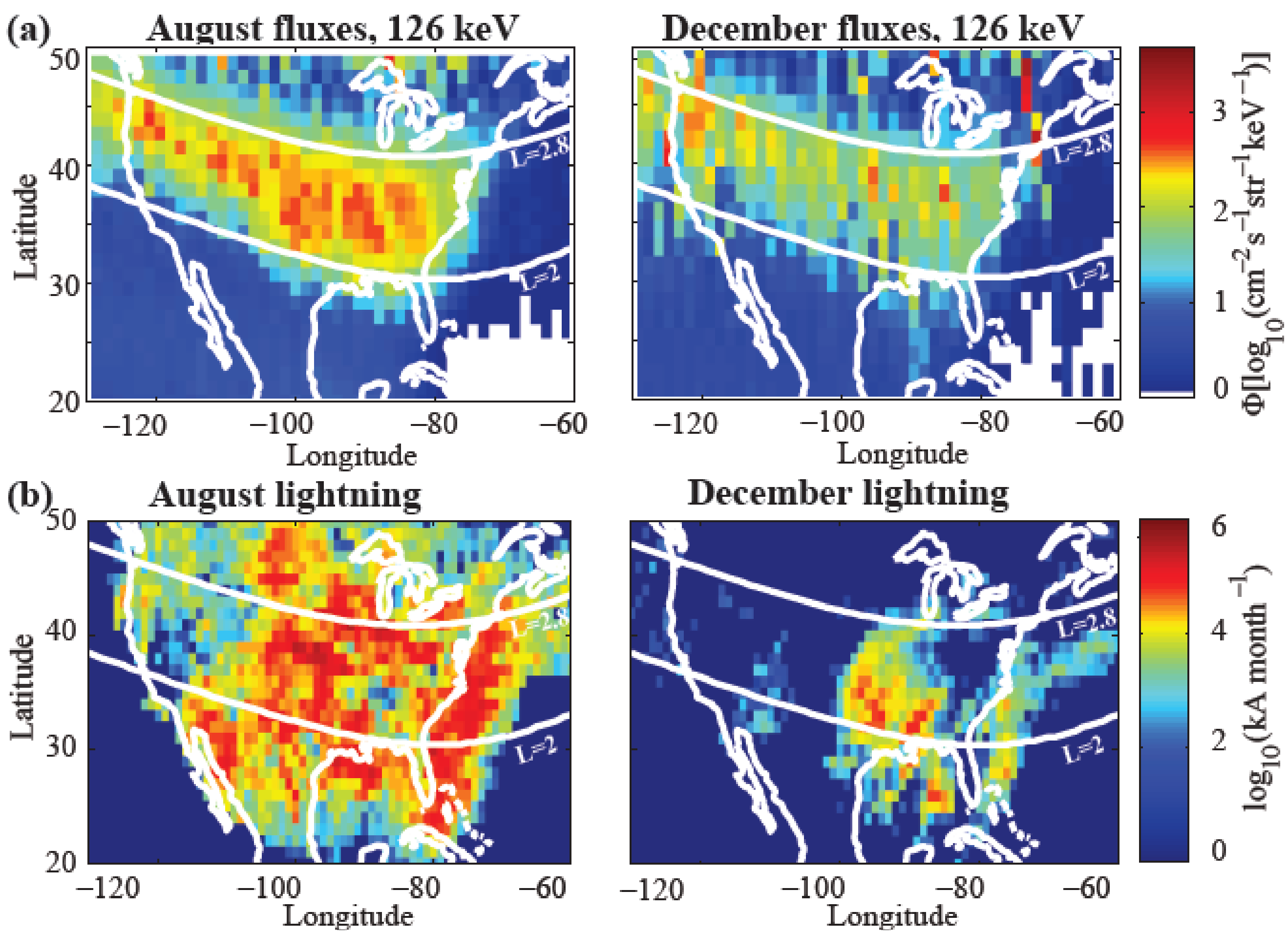


Technical Accomplishments (cont.)

- Amplification – Artificially Stimulated Emissions (ASE)
  - Empirical ASE model using the Stanford Sipple facility digitized data
  - MURI-DARPA joint ASE tests using HAARP/Conjugate buoy system (> 20 dB amplification)
  - Joint NRL-MURI modeling optimizes probability of ASE gain
  - New ASE targeted experiments using Alpha (Russian) VLF transmitter (inner RB)
  - Generation of artificial propagation ducts using HAARP with Demeter detection
- Light- Induced Electron Precipitation(LEP)
  - New Demeter measurements reveal it as key to slot maintenance
  - New global detection of LEP via VLF paths
  - Global effects of VLF transmitters – Irregularity triggering -VLF mode conversion to Lower Hybrid Waves – Possible proton precipitation
- Development of new efficient numerical simulation codes
  - Three dimensional MHD, EMHD, whistler and hybrid codes simulating VLF/ELF/ULF generation and injection and modeling precipitation
  - Many of the codes implemented on new GPU processors (game platforms) accelerating their performance by factors between 20-50

The Physics of the Gap Formation

More than 15 dB lower values of VLF from Navy Transmitters. Cannot cause gap. What about lightning ?



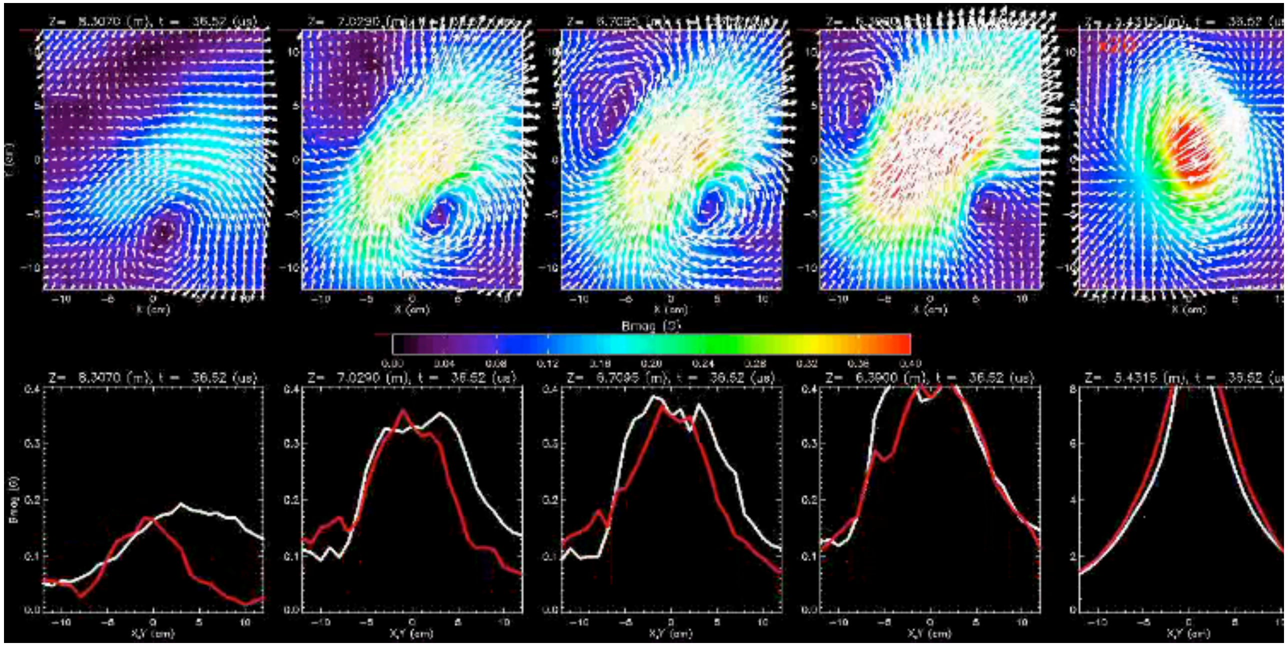
LEP as Benchmark for RBR Assessments

- Lightning-induced precipitation is a significant contributor to radiation belt loss in the inner-belt and slot regions
- Individual LEP bursts have been detected on satellites and on the ground
- Quantification of wave-induced precipitation requires that individual LEP bursts be measured together with whistler-mode waves
- Powerful lightning discharges illuminate the belts with waves of intensities of ~10 to 200 pT
- Waves generated for RBR must compete with lightning to significantly affect electron lifetimes

Technical Accomplishments- Transition to DoD Applications

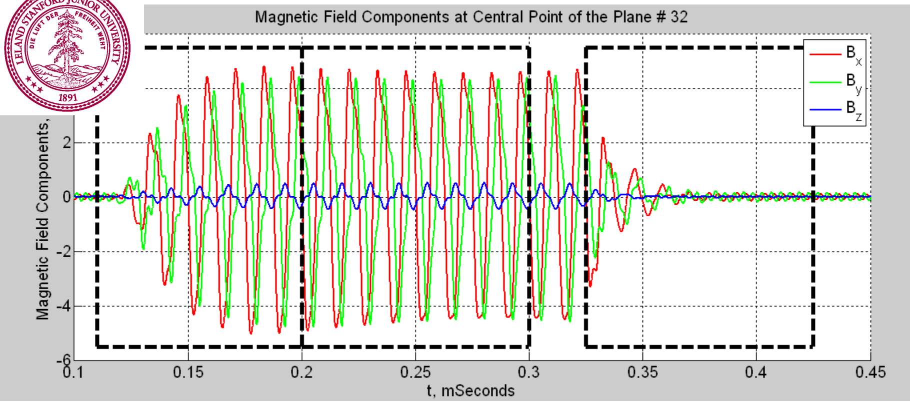
- **First models of enhanced RB proton precipitation**
  - **Design of a ground based Proton RBR system – DARPA conducted environmental impact study in anticipation of new start**
- **First demonstration of ionospheric generation of ELF/ULF waves without relying on electrojet currents (HF to ELF/ULF conversion)**
  - **Simultaneous detection in Alaska-Seattle-Hawai-Guam (~ 8Mm)**
  - **Injection in the magnetosphere of more than 5 kW ULF power**
  - **Spin-off – PACE-New concept for HED current drive – 30-50 dB more efficient than traditional ELF/ULF radiators – First test (DARPA seedling) in August, 2009**
- **First laboratory demonstration of high efficiency antenna radiation in plasma using Rotating Magnetic Fields (RMF)**
- **Laboratory resolution of controversy of electric dipole antenna radiation efficiency – AF DSX mission antenna design support**
- **New 2-D off plane code provided guidance to NRL's SPIDER test**
- **Global effects of VLF transmitters – VLF mode conversion to LHW**

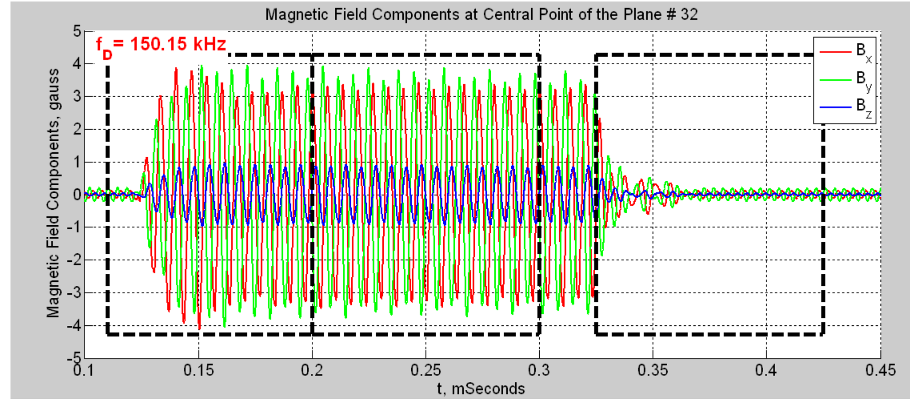
Whistler Generation by RMF

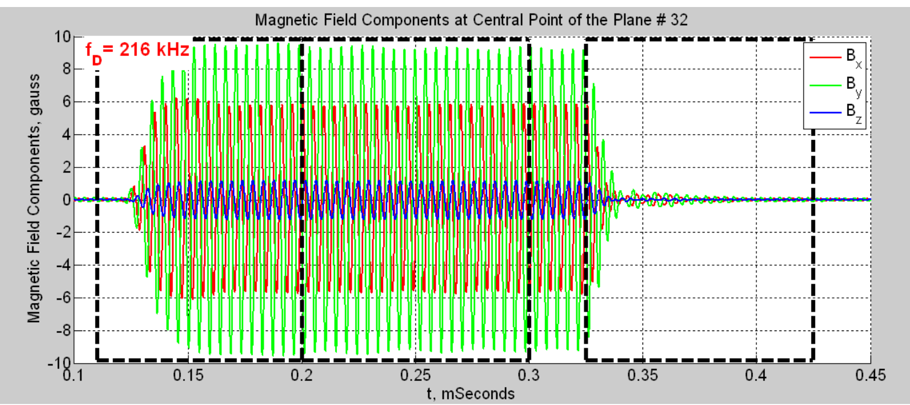


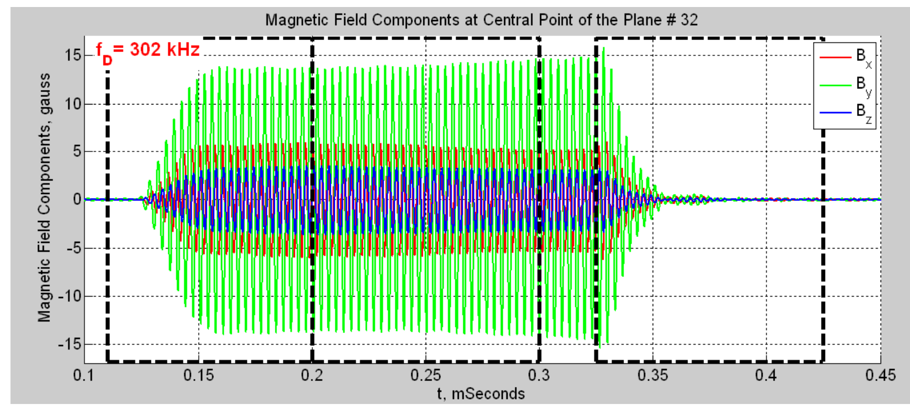
- Gradient generation requires frequencies above the ion cyclotron frequency (≈60 Hz at L=2)
- Breaks the adiabatic invariance of relativistic electrons for gradient lengths shorter than the electron gyroradius – no need for resonance
- Will require superconducting RMF with rotation speed in excess of 60 Hz and Tesla level B
- Physics analysis including coverage under study
- Potential as supplement to RBR for final clean-up

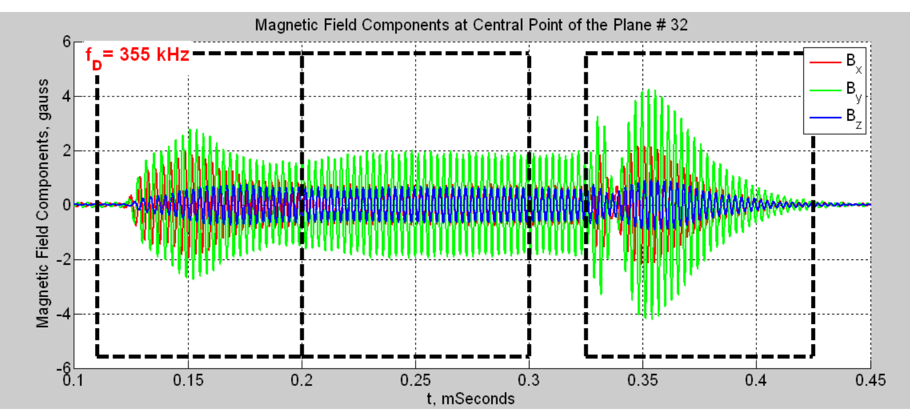
SAW Generation by RMF









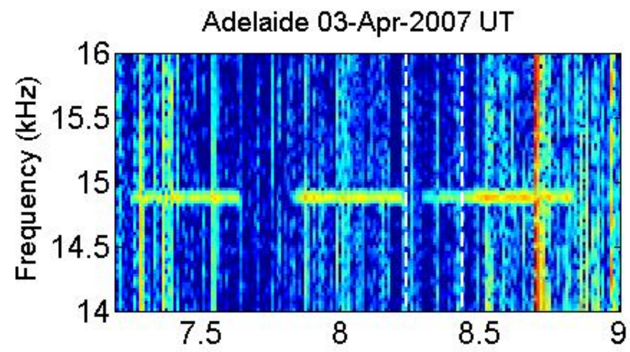


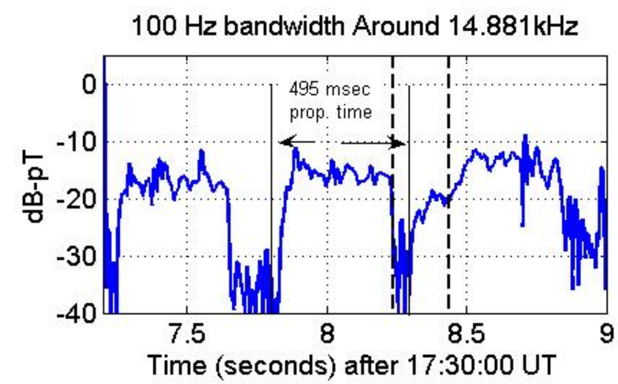
SAW generation by RMF in the 5-15 Hz Hz range could be an important space component of PRBR

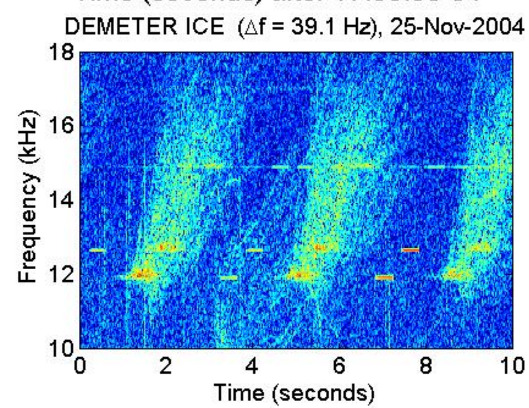
Targeted VLF Wave Injection Experiments

Mark Golkowski

- Investigation of wave injection from Russian Alpha Navigation transmitters (11-15 kHz)
- Observe 1-hop signals at Conjugate point in Adelaide Australia and on DEMETER satellite
- Results show growth and variation with geomagnetic conditions on ground
- Triggered emissions observed on satellite but not on ground

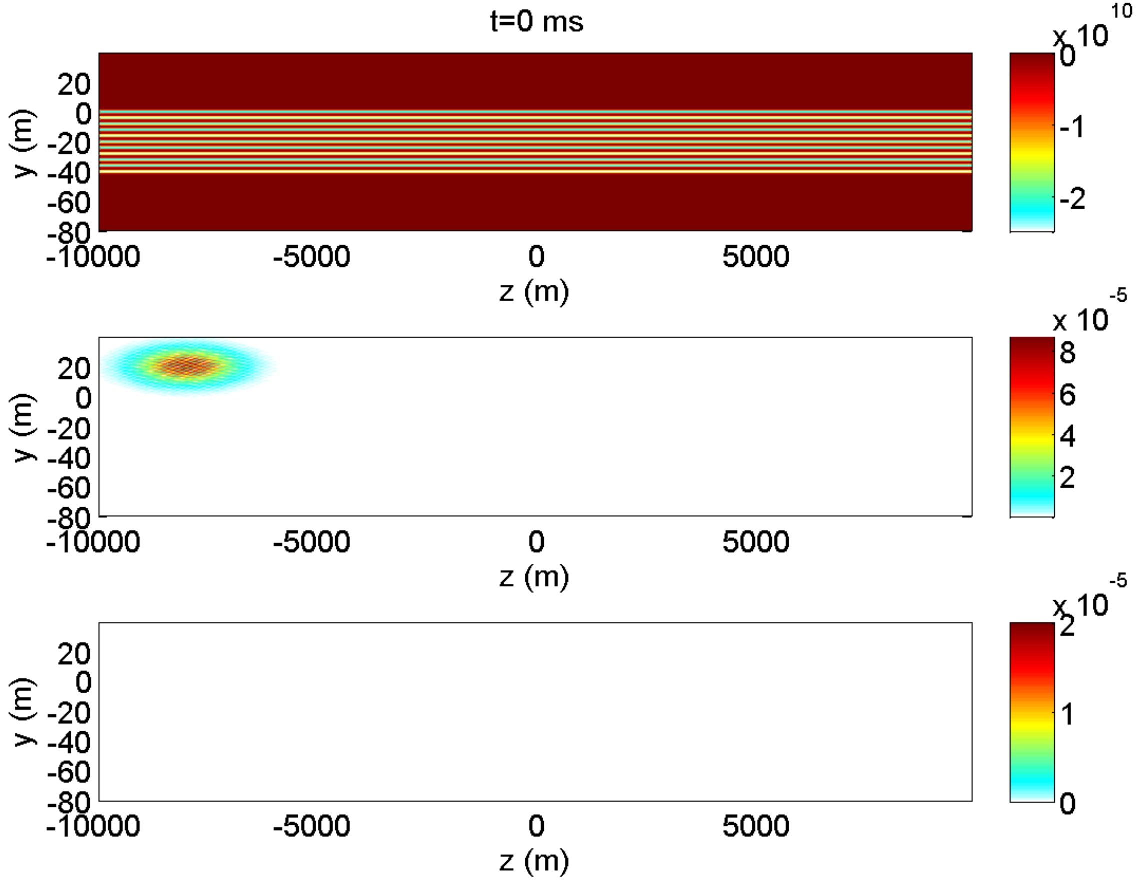






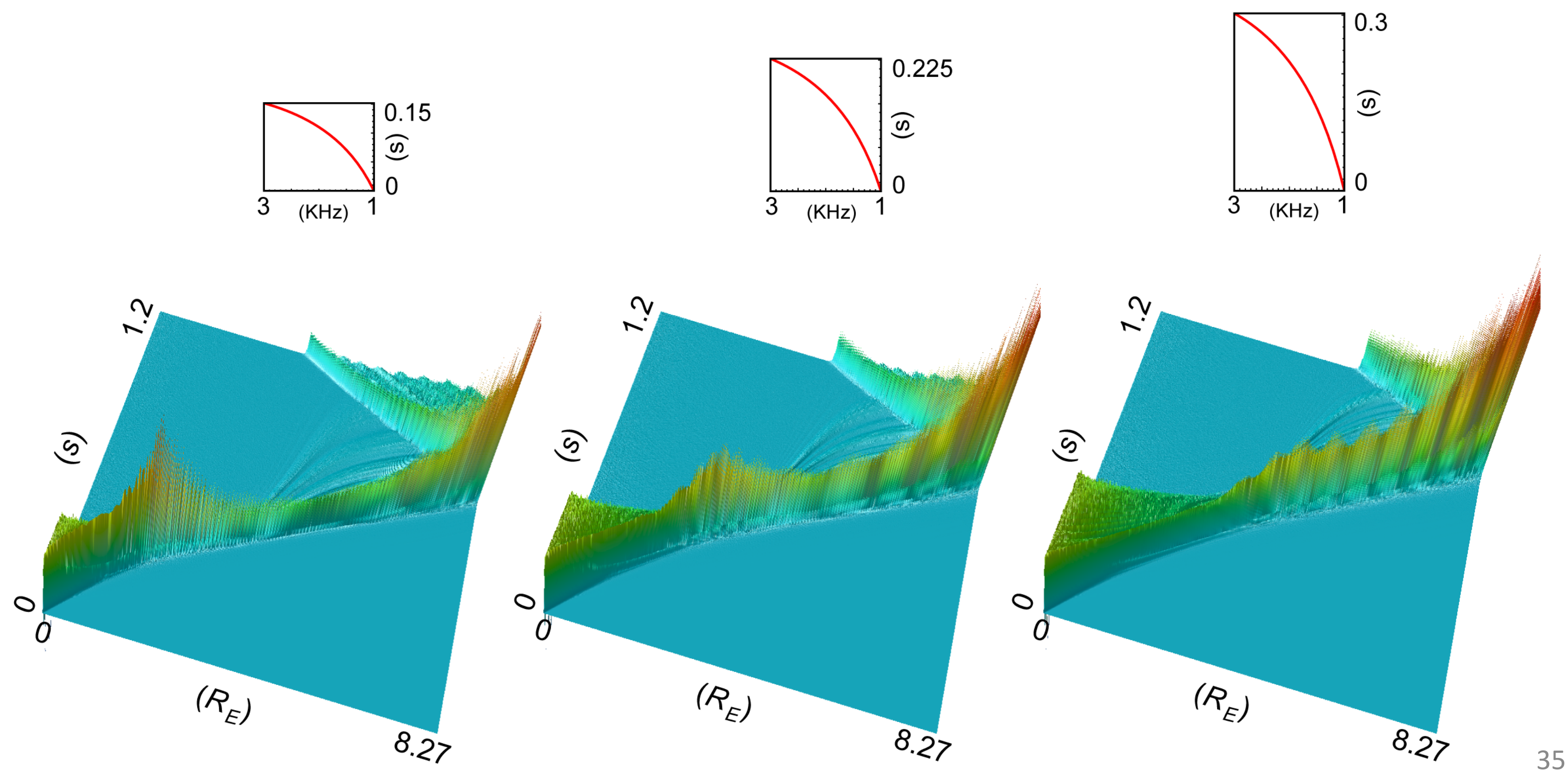
Whistler to LH and LH to Whistler

Eliasson-Pap. 2008



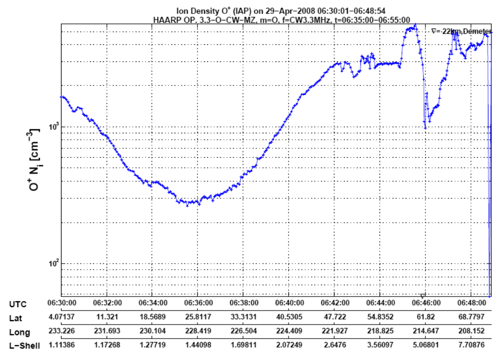
Optimize Probability for Triggering ASE

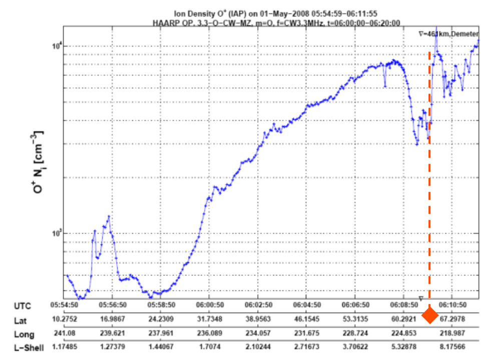
Strletsov et al. presentation – Use full field line code to study frequency and chirp rate required to maximize trigger whistler amplitude at the equator – Collaborated with Stanford in conducting HAARP test

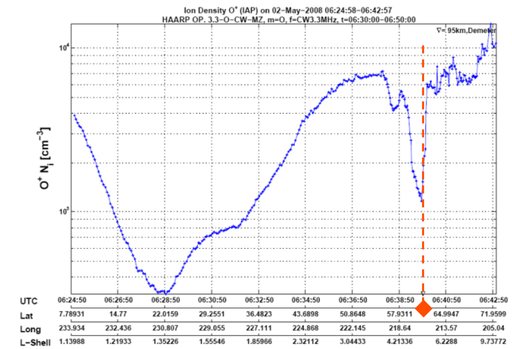


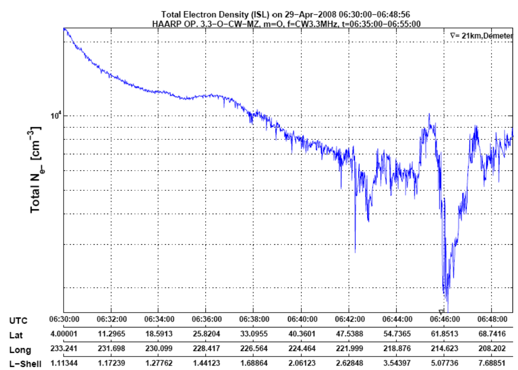
Duct Formation

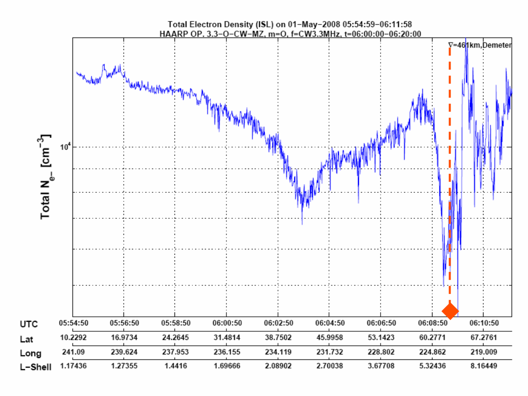
April 29 08 | May 1 08 | May 2 08

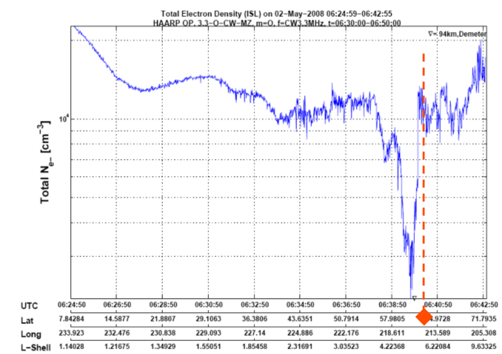












Gennady Milikh – DEMETER detection