Using Active Experiments to SEE and HEAR the Ionosphere

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Plus Major Contributors

CEDAR Prize Lecture

Boulder, Colorado

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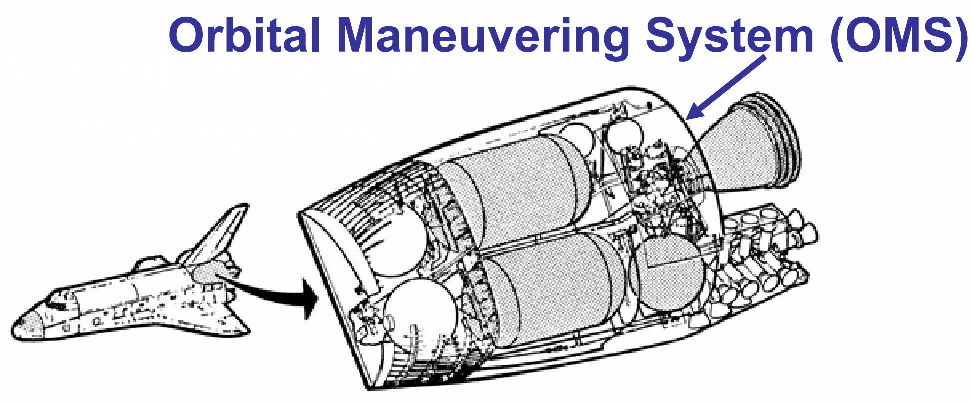
Remote Sensing with Active Experiments

- Active Experiments
  - Chemical Releases
  - High Power Radio Waves
- Enhanced Ionospheric Measurements
  - Sporadic-E Layers
    - Standard Techniques: Radar Backscatter, Radio Sounding, TMA Trails, Tomography
    - Active Techniques
      - Heater Excited Airglow Radiation (HEAR)
      - Rocket Exhaust Seeding of Irregularities
  - Equatorial Irregularities
    - Standard Techniques: Airglow, Backscatter and Incoherent Scatter, Radio Beacons
    - Active Techniques
      - Chemically Induced Electron-Ion Recombination
      - Artificially Enhanced Airglow
  - Mid- and High-Latitude Density, Temperature, Composition, and Irregularities
    - Standard Techniques: Backscatter Radar and Radio Scintillations
    - Active Technique
      - Field Aligned Irregularity Glow with HF Excitation
      - Enhanced Backscatter with Hypersonic Exhaust Interactions
      - Stimulated Electromagnetic Emissions (SEE)
  - Plasma Wave Generation and Propagation
    - MHD Waves from Space Shuttle OMS Burn
    - Ion Acoustic Wave Turbulence from Streaming Exhaust

Chemicals Used in High Altitude Release Experiments

Purpose	Materials	Optical Emissions	Fastest Rate	Reaction
Plasma Clouds: Photo-ionization	Li, Na, Sr, Cs, Ba, Eu, U	553.5 nm (Ba) 455.4 nm (Ba^+)	0.05 s^{-1} (Ba) 0.005 s^{-1} (Eu) 0.00029 s^{-1} (Li)	$Ba + h\nu \rightarrow Ba^+ + e^-$
Plasma Clouds: Associative Ionization	Sm, La, Nd, Ti	Molecular Bands of SmO (656 to 570 nm)	2 x 10^{-11} (SmO)	$Sm + O \rightarrow SmO^+ + e^-$ + 0.39 eV
Plasma Holes: Electron Attachment	SF_6, CF_3Br, $Ni(CO)_4$	777.4 nm (SF_6)	2.2 10^{-7} cm^3/s (SF_6)	SF_6 + e- $\rightarrow SF_5^- + F$ - 0.25 eV $SF_5^- + O^+ \rightarrow SF_5 + O^*$ + 9.91 eV
Plasma Holes: Ion-Molecule Charge Exchange	H_2, H_20, CO_2	630 nm (CO_2)	3.2 10^{-9} cm^{-3} (H_20)	$H_2O + O^+ \rightarrow H_2O^+ + O$ $H_2O^+ + e^- \rightarrow OH^* + H$
Neutral Wind Tracer	Al, NO, Na, $Al(CH_3)_3$, $Fe(CO)_3$, $Ni(CO)_4$	Molecular Bands of AlO (484, 508, 465, 534 nm)	--	$Al(CH_3)_3 + O \rightarrow AlO^*$ + ...

Space Shuttle OMS Engine Exhaust Parameters

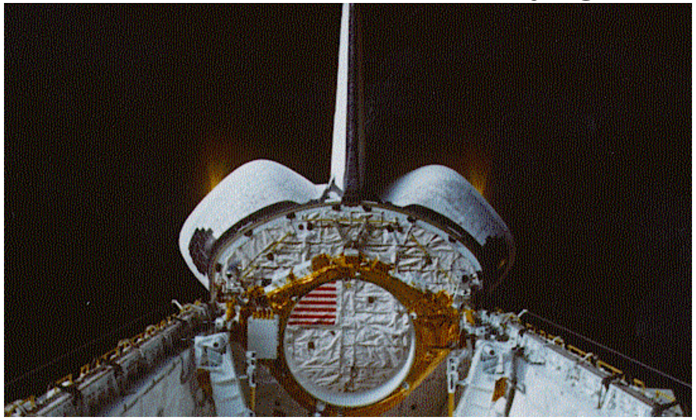


Exhaust Species	Mole Fraction
CO	0.050
CO_2	0.122
H_2	0.241
H_2O	0.274
N_2	0.313

Flow Rate: 2.5 x 10^{26} Molecules per Second per Engine

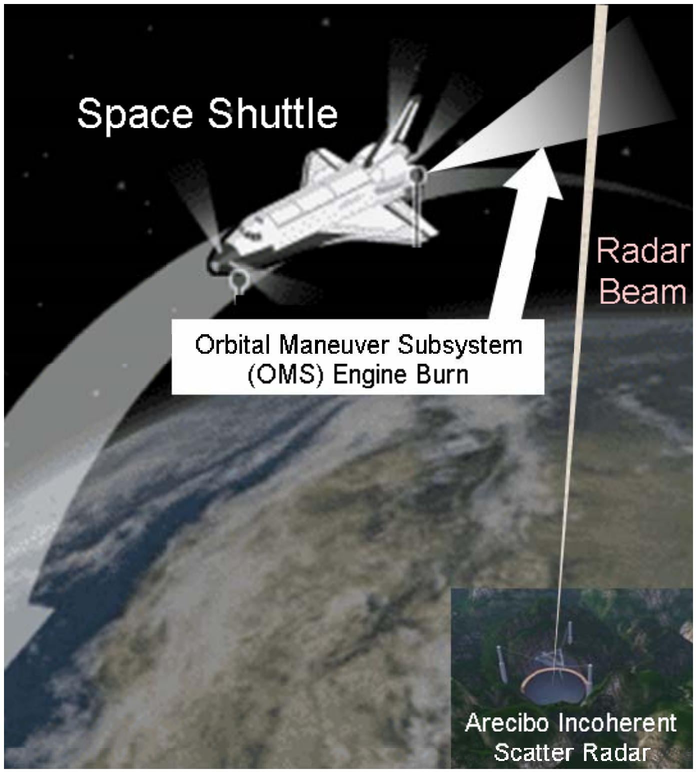
Nonuniform Dual OMS Burn

Symmetrical Dual OMS Burn in Daylight



Single OMS Burn at Night

NRL-0402 SIMPLEX
Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiment Concept



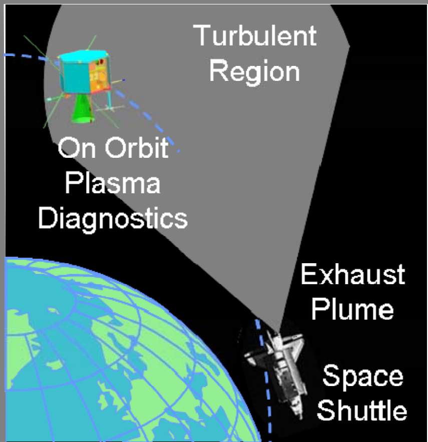
Radar Diagnostics of Artificial Plasma Turbulence

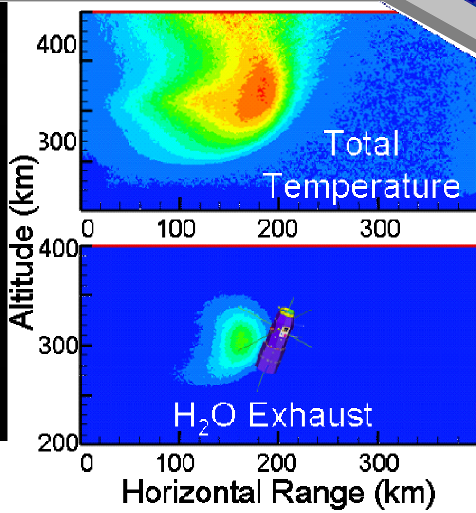
Dedicated Burns Scheduled Through DoD Space Test Program with NASA Johnson Spaceflight Center

Objective: Investigate Plasma Turbulence Driven by Rocket Exhaust in the Ionosphere Using Ground Based Radars
- Remote Sensing of Exhaust Flow Sources
- Understand Evolution of Ionospheric Disturbances
- Develop Quantitative Models of Plasma Turbulence

Description: Fire OMS Engines Over Ground Diagnostic Radar Sites
- Radar Observatories
  - Millstone Hill, Massachusetts
  - Arecibo, Puerto Rico
  - Kwajalein, Marshall Islands
  - Jicamarca, Peru
  - JORN, Australia
- Radar Data
  - Enhanced Backscatter
  - Radar Doppler Spectra
  - Identification of Ion Beam Plasma Waves
  - Radio Scintillations
- Optical Data
  - Scattered Sunlight from Exhaust Particles
  - Chemical Reaction Airglow

Shuttle Exhaust Ion Turbulence Experiment (SEITE)



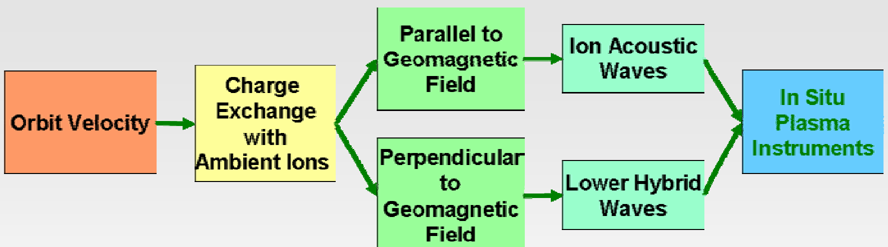


Satellite Diagnostics of Artificial Plasma Turbulence

SCIENCE ISSUES ADDRESSED

- Generation of Plasma Waves in Space
- Develop Technique for Artificial Irregularities
  - Irregularity Generation Processes
  - Wide Range of Radar Diagnostics
- Simulation of Natural Sources of Radio Scintillations
- Remote Sensing from Known Sources
- In Situ Sensors Concept Demonstration

SEITE TECHNICAL APPROACH and OBJECTIVES



- Coordinate In Situ Observations with Satellites
  - AFRL C/NOFS
  - Canadian ePOP/CASSIOPE
- Observe Strong Plasma Turbulence from Chemical Release
  - Verify Models of Plasma Wave Generation
  - Quantify Neutral Interaction Physics

PROGRAM APPROACH and OBJECTIVES

- Validation of Concept with Shuttle Exhaust Ion Beam Experiments
  - Ion Beam Excitation of Plasma Waves
  - Comparison with SIMPLEX Radar Observations
- Funded Under NRL 6.1 Nonlinear Excitation of Space Plasmas (NESP) Program
- Deliverables: Science & Modeling; Engine Burn and Satellite Diagnostics Coordination; Data Analysis and Science Publications
- Manifested by DoD Space Test Program for Space Shuttle Flight Starting April 2008

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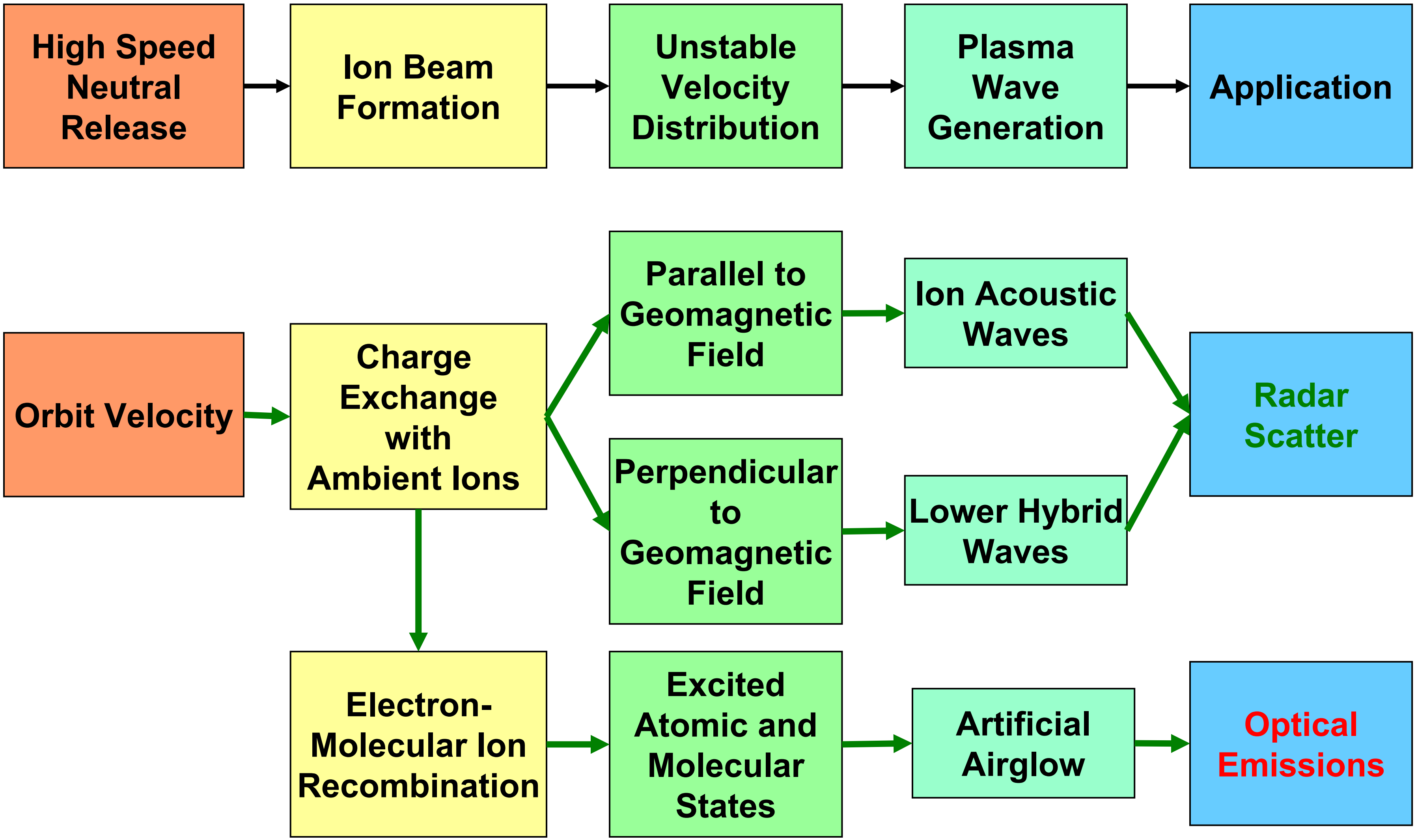
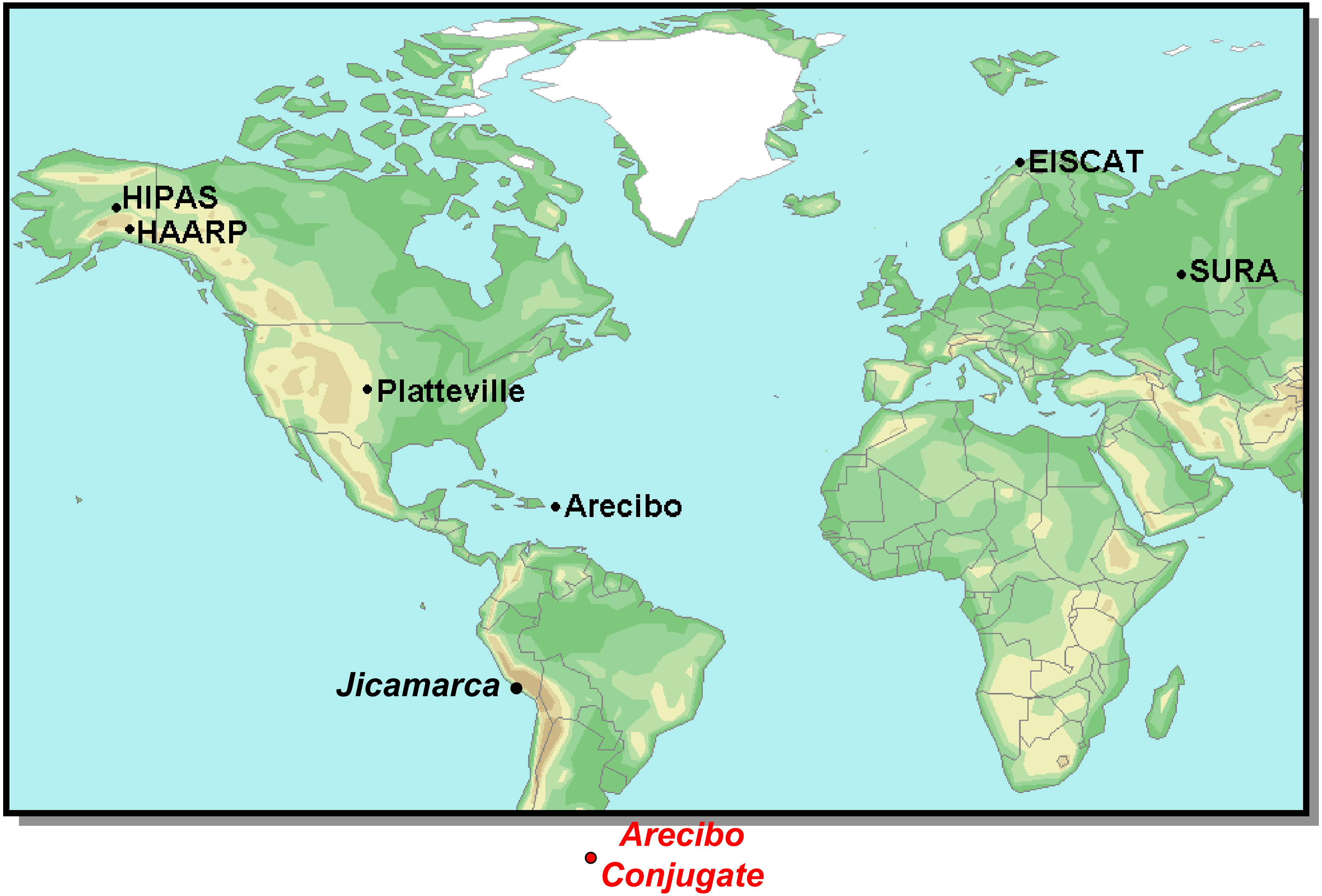
Wave and Airglow Generation by Chemical Releases:

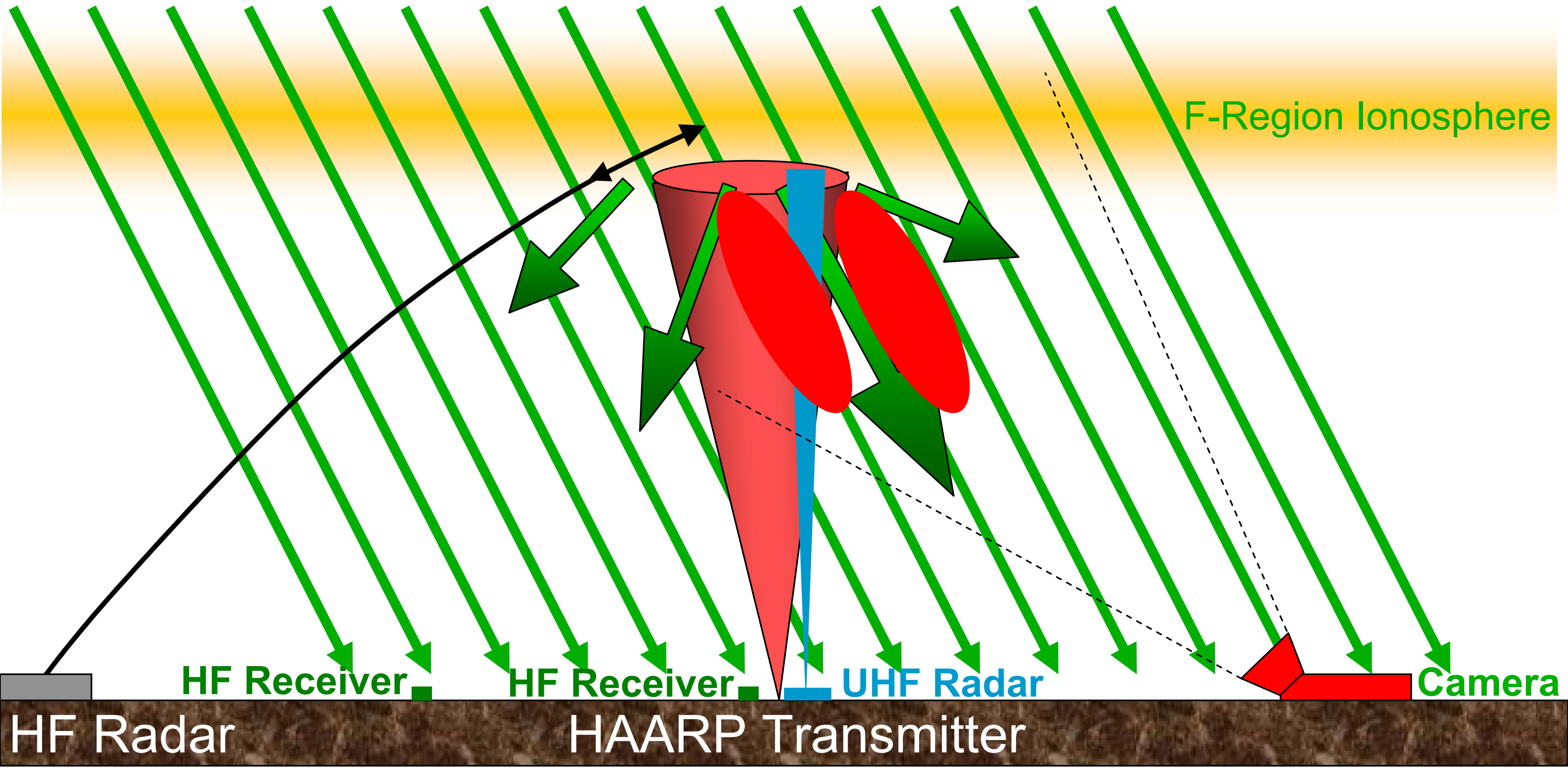
SIMPLEX– Space Shuttle Exhaust



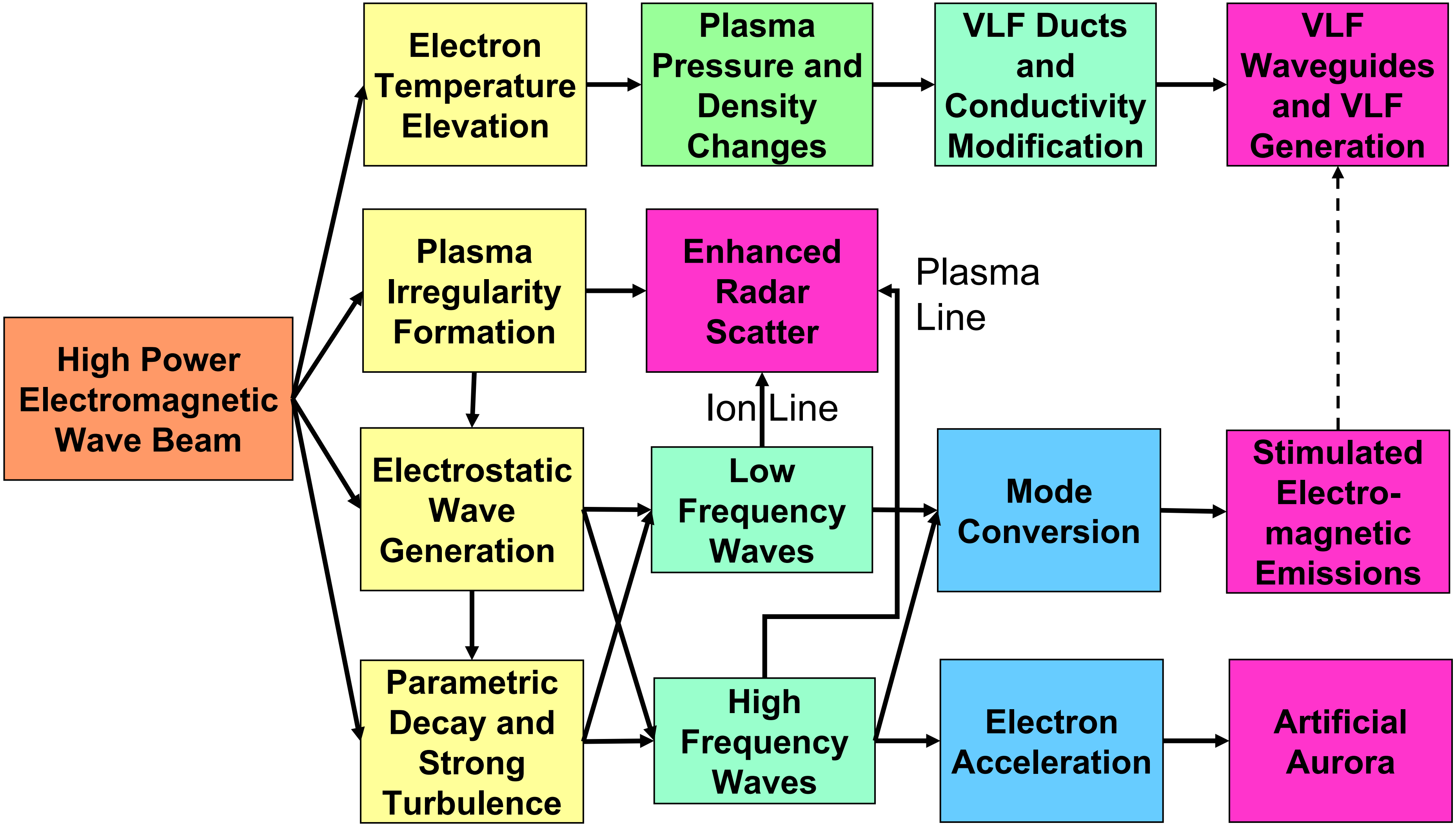
Past, Current and Future HF Ionospheric Modification Facilities



Stimulated Electromagnetic Emissions, Radar Backscatter, Enhanced Plasma Waves and Artificial Aurora

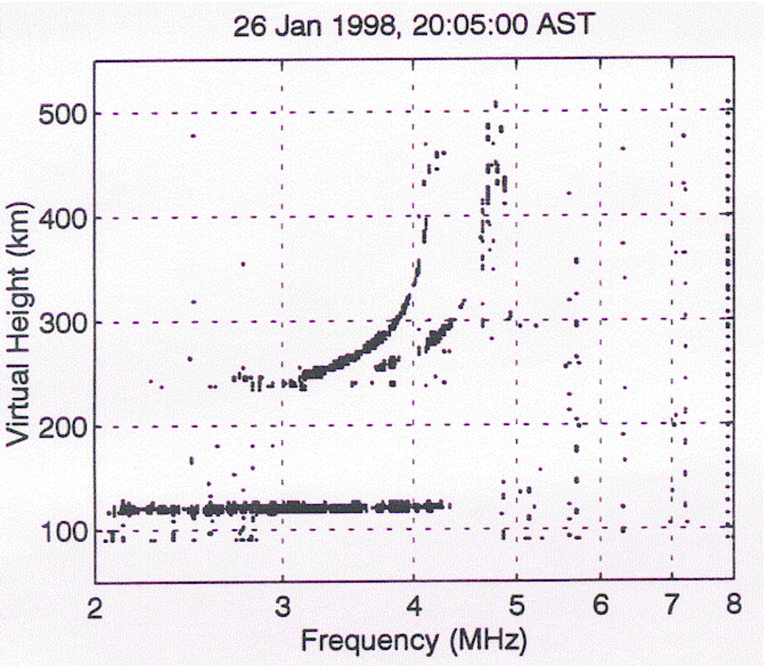


Ionospheric Modification with High Power Radio Waves

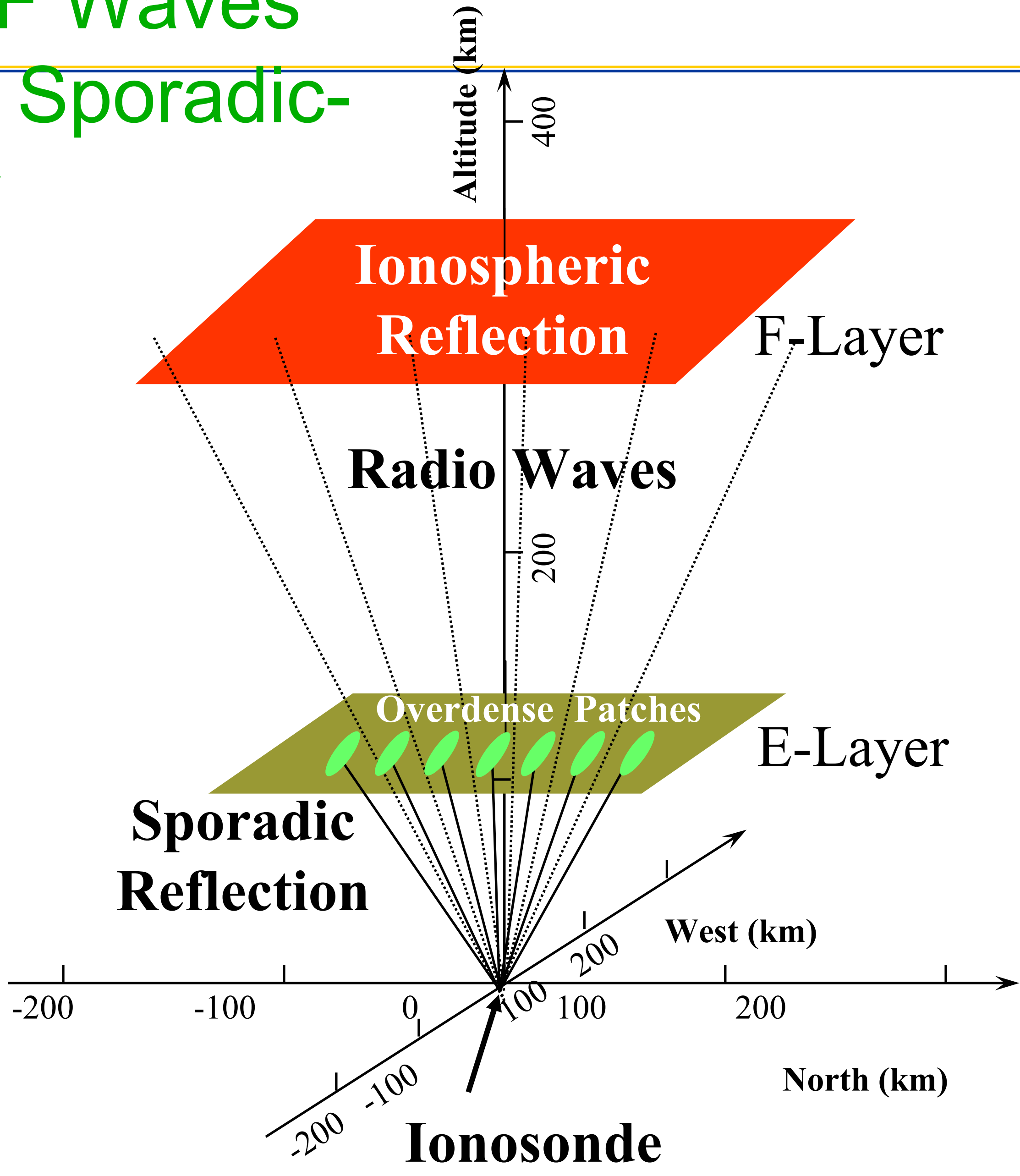


Active Studies of the E-Layer

Penetration of HF Waves Through a Patchy Sporadic-E Layer



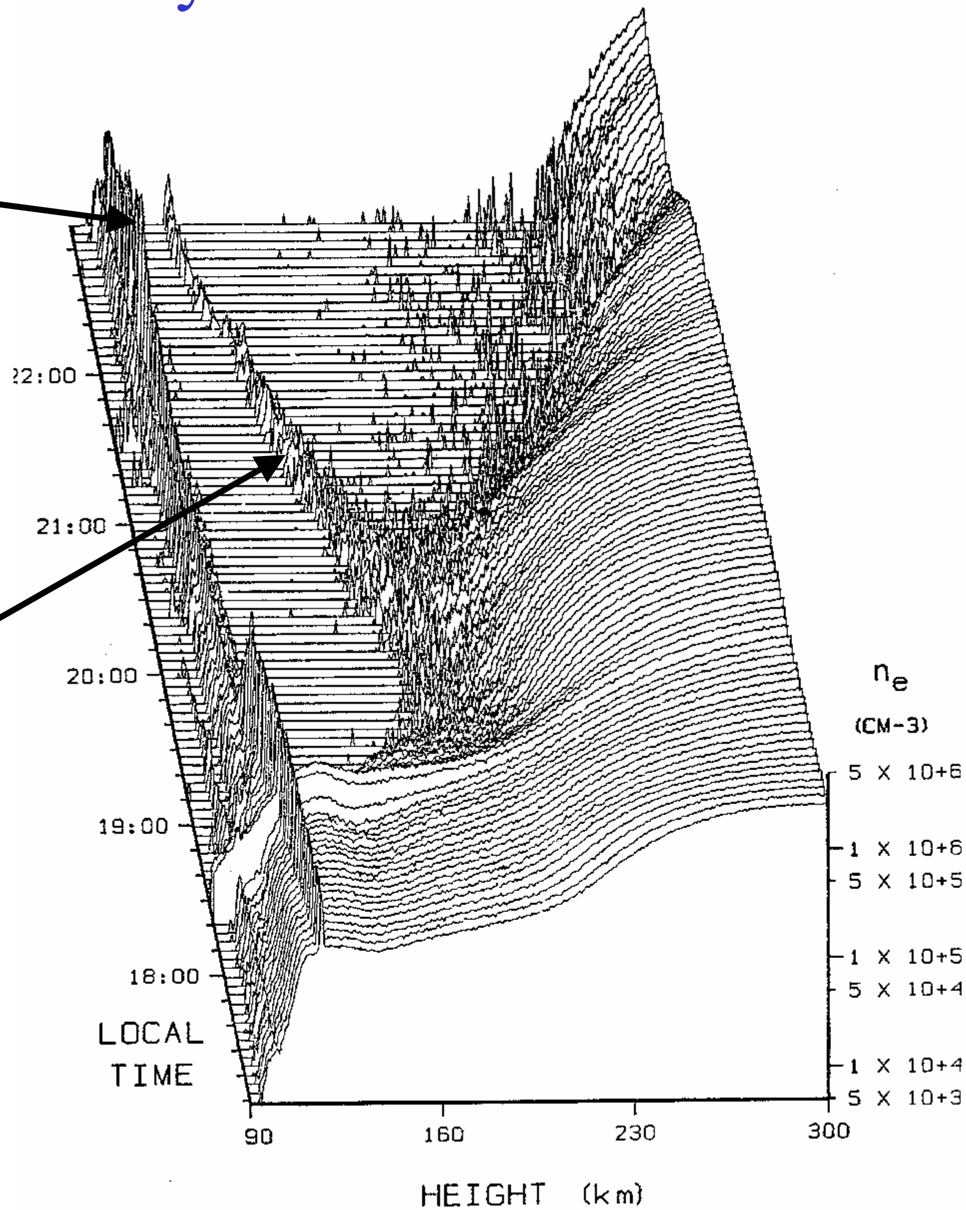
Ionogram



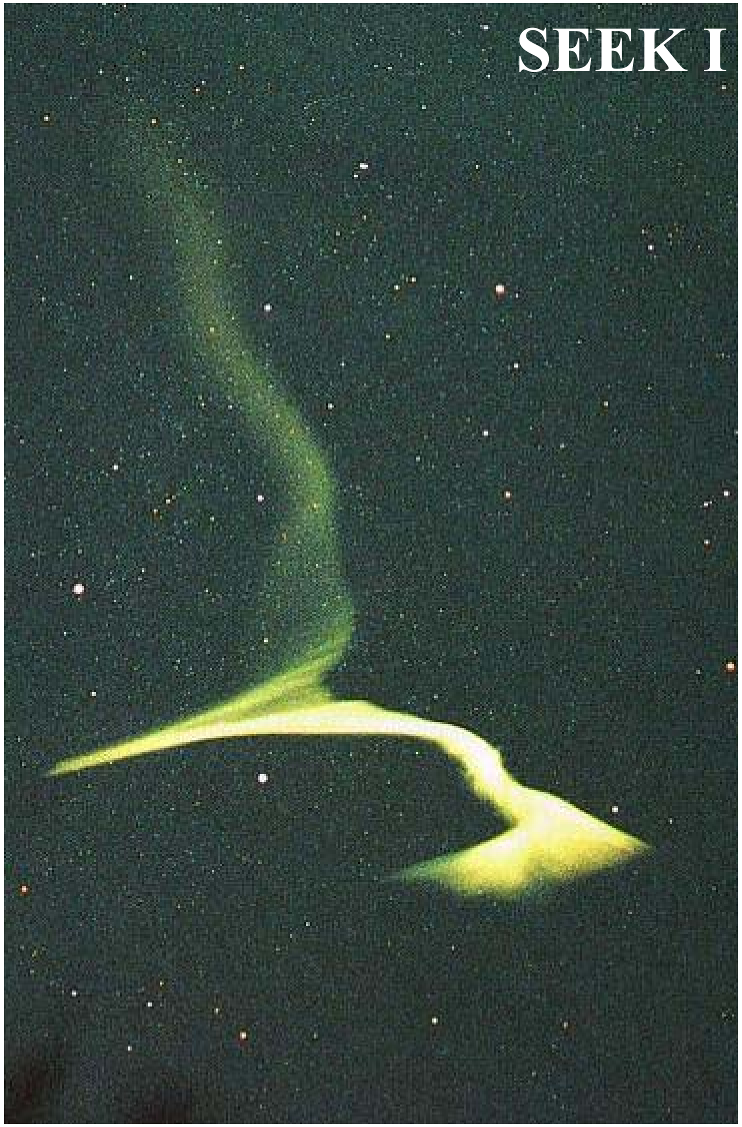
Sporadic-E and Intermediate Layers
Arecibo, 7 May 1983

- Sporadic E-Layers
  - Near 100-120 km
  - Variable Density
  - Tied to Wind Shears
  - Theories on E-Layer Patches
    - K-H Turbulence
    - Plasma Instabilities
    - Gravity Waves

- Intermediate Layers
  - Near Sunset
  - Break-Off from F-layer
  - Descend to a Stable Altitude Above Strong E-Region



Tri-Methyl Aluminum (TMA) Trail for Determination of Wind Shears



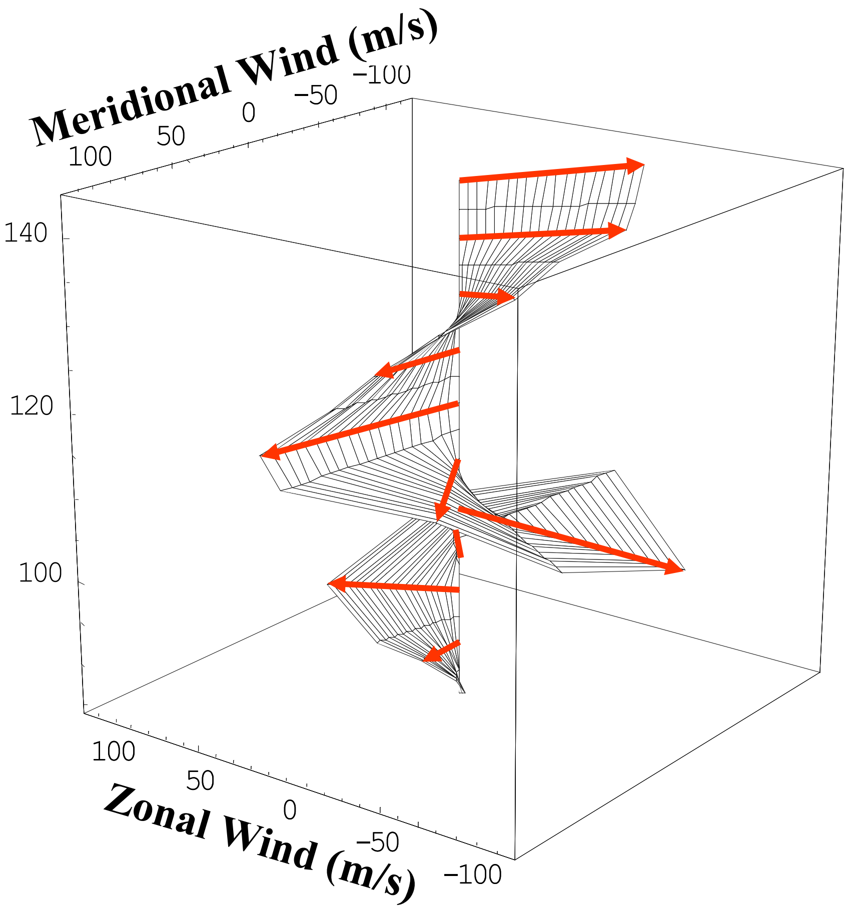
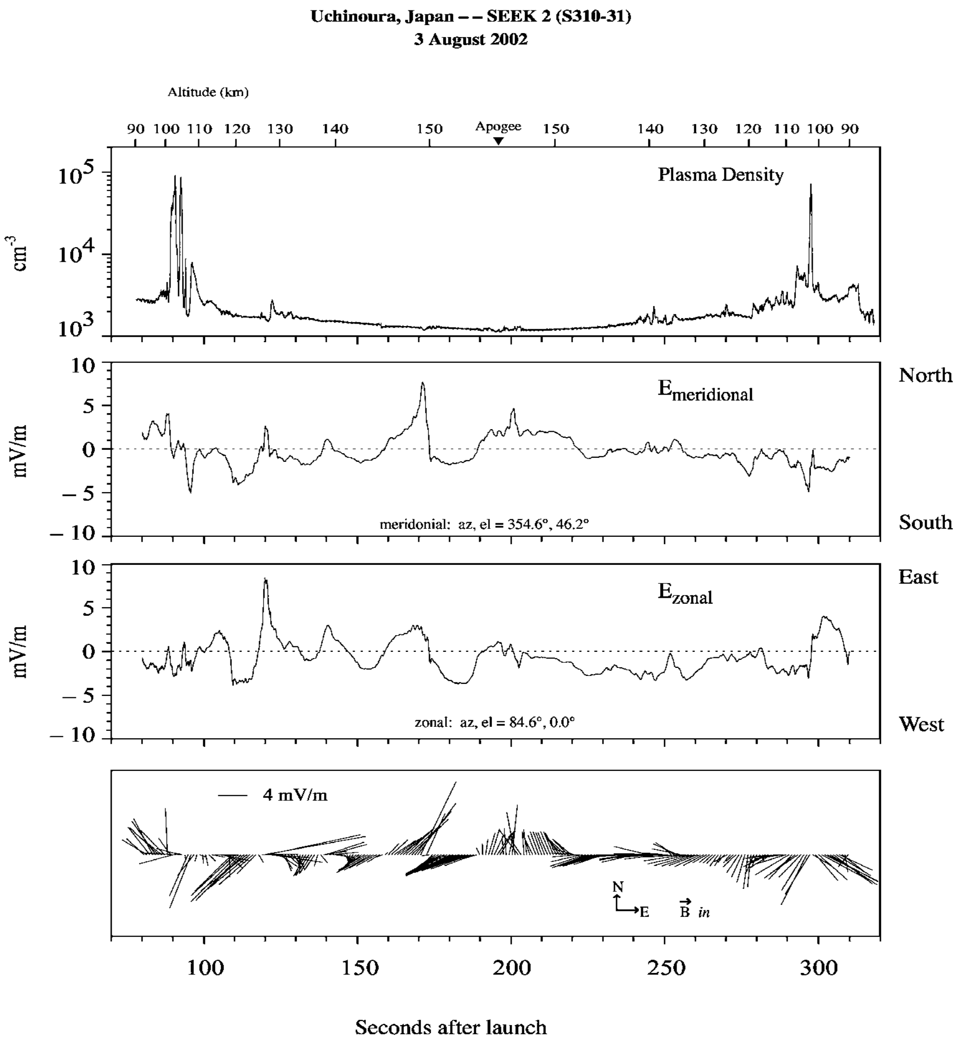
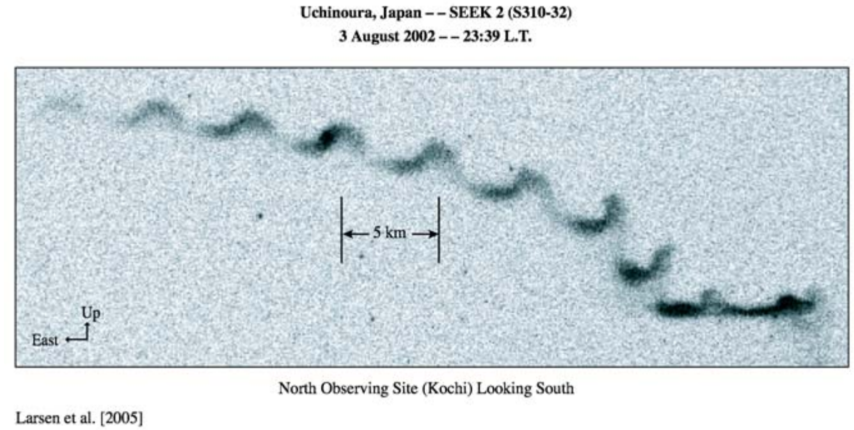


Image and Data Courtesy M.F. Larsen, Clemson

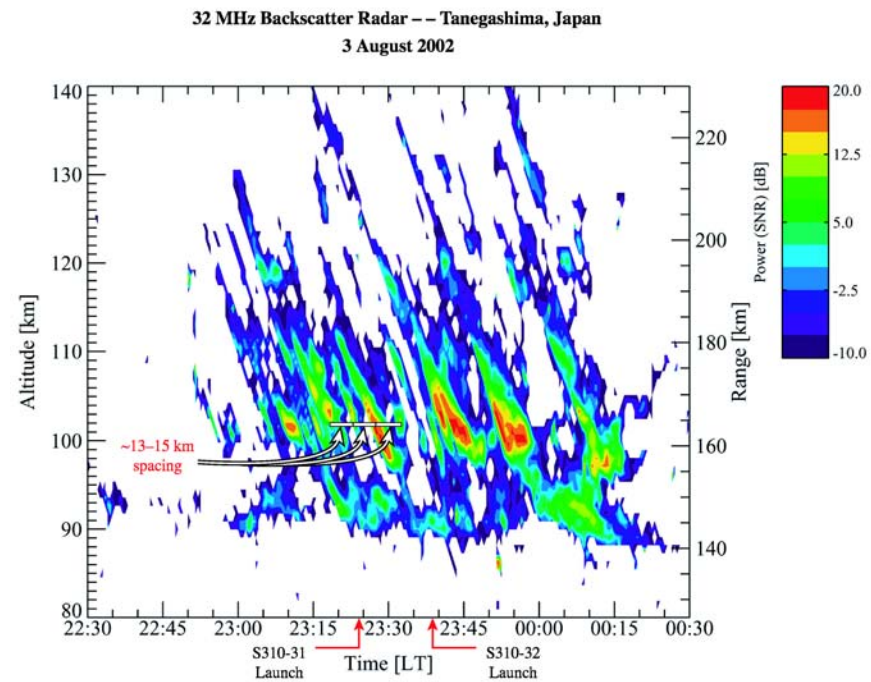
Quasi-periodic Echoes -- (SEEK-2) Rocket/Radar Campaign in Japan



Electric fields reveal quasi-periodic structures. (Pfaff et al., 2005)

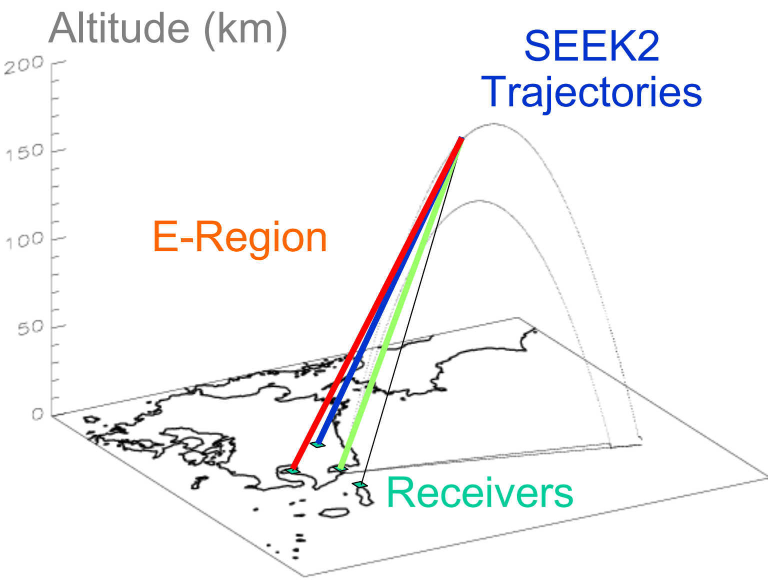


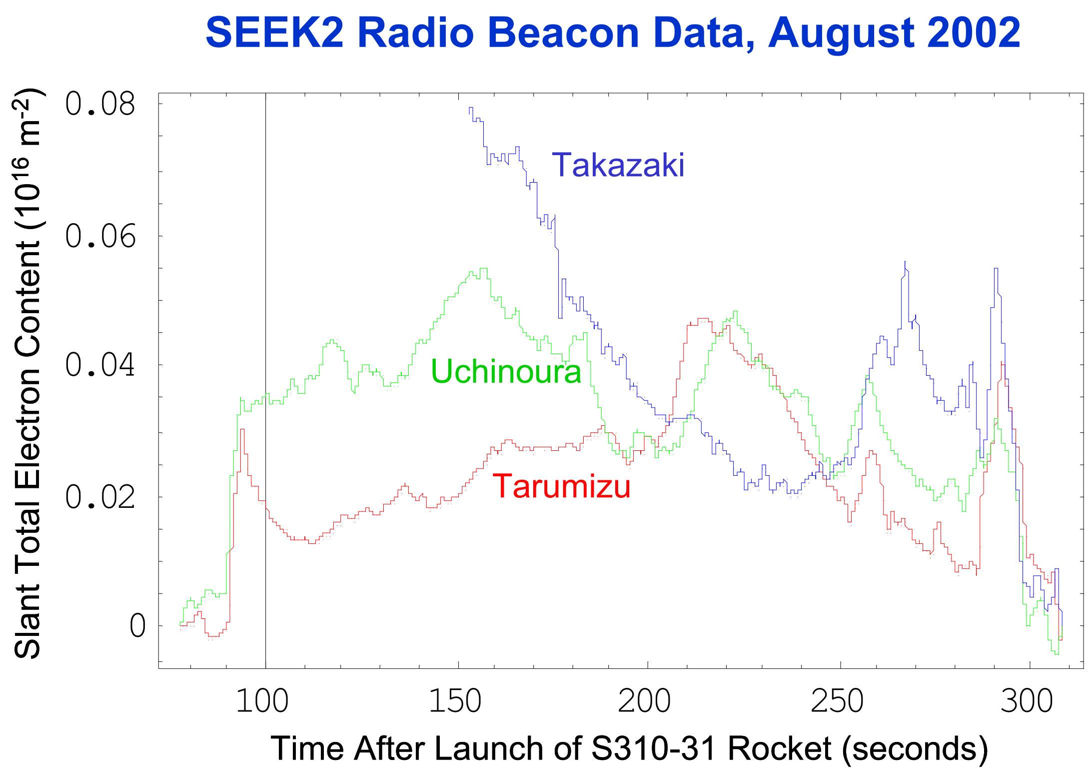
Neutral Wind trail reveals Kelvin-Helmholtz "whorls."



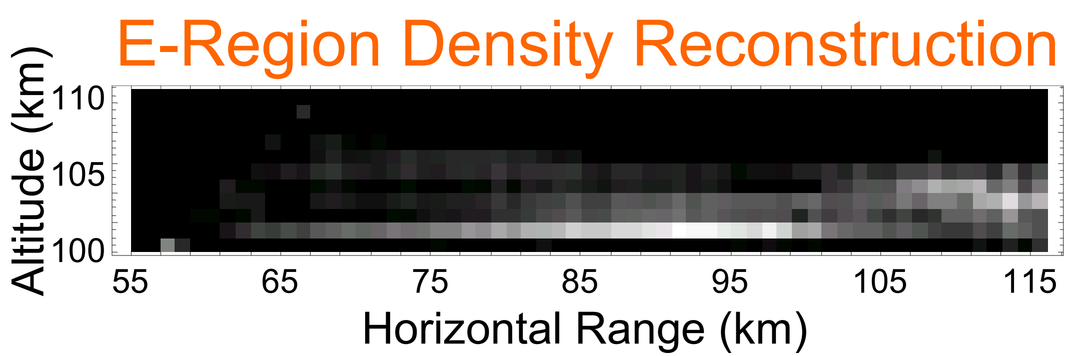
Radar echoes show quasi-periodic patterns (Saito et al., 2005)

Tomographic Study of E-Region Irregularities

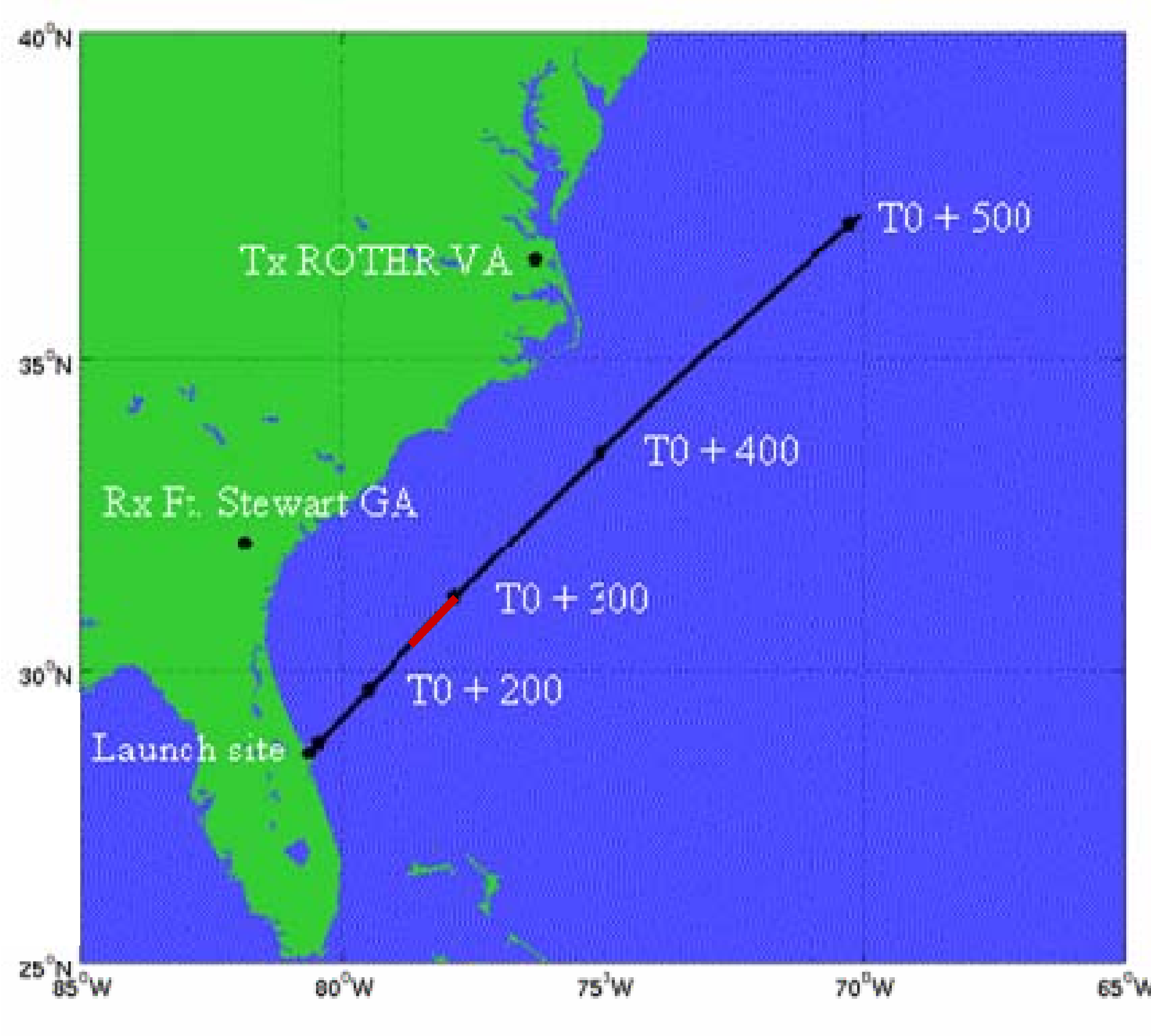




- Radio Beacon Detection of E-layer Structures
- Tomographic Analysis of Data Using Singular Value Decomposition (SVD) Algorithm

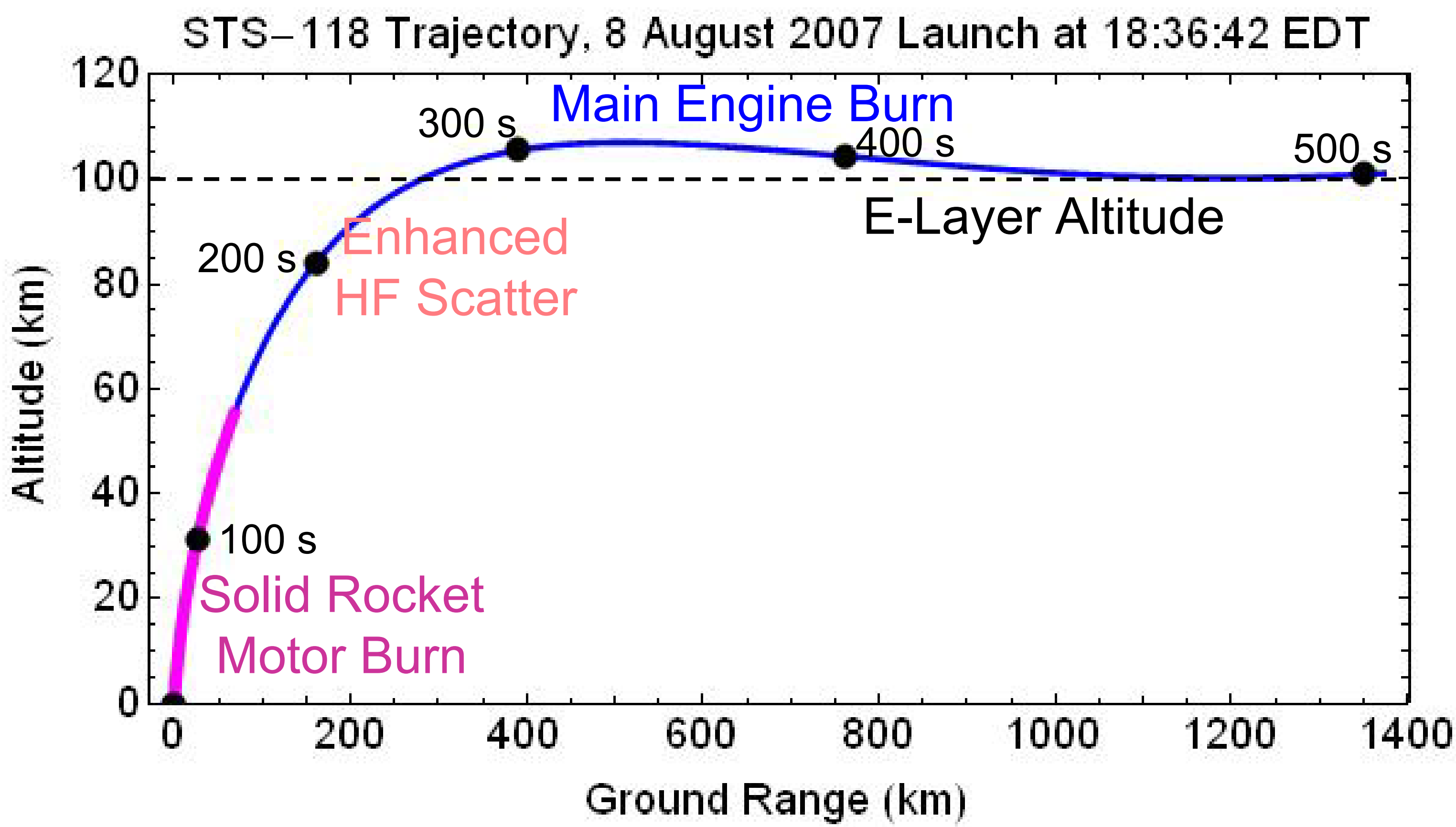


Geometry for HF OTHR Scatter Experiment with the Launch of STS-118

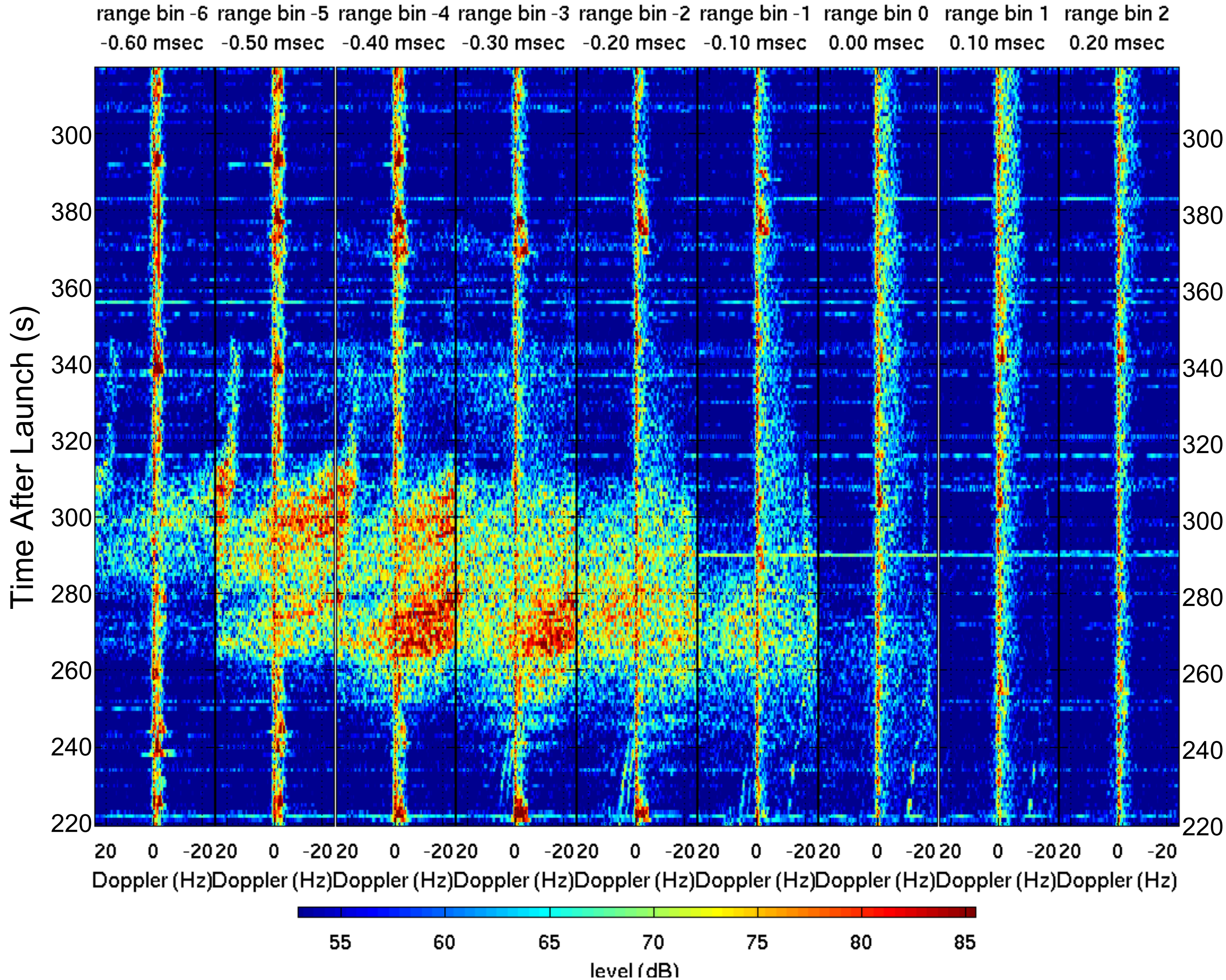


Transmitter	Receiver	Launch Site
Chesapeake Virginia	Fort Stewart Georgia	Cape Canaveral Florida
1050 km Range to Launch	402 km Range to Launch	0 km Range to Launch
199.5° Azimuth to Launch	163.5° Azimuth to Launch	---
167° ± 50° Azimuth Target Illumination	165° ± 50° Azimuth Target Viewing	---

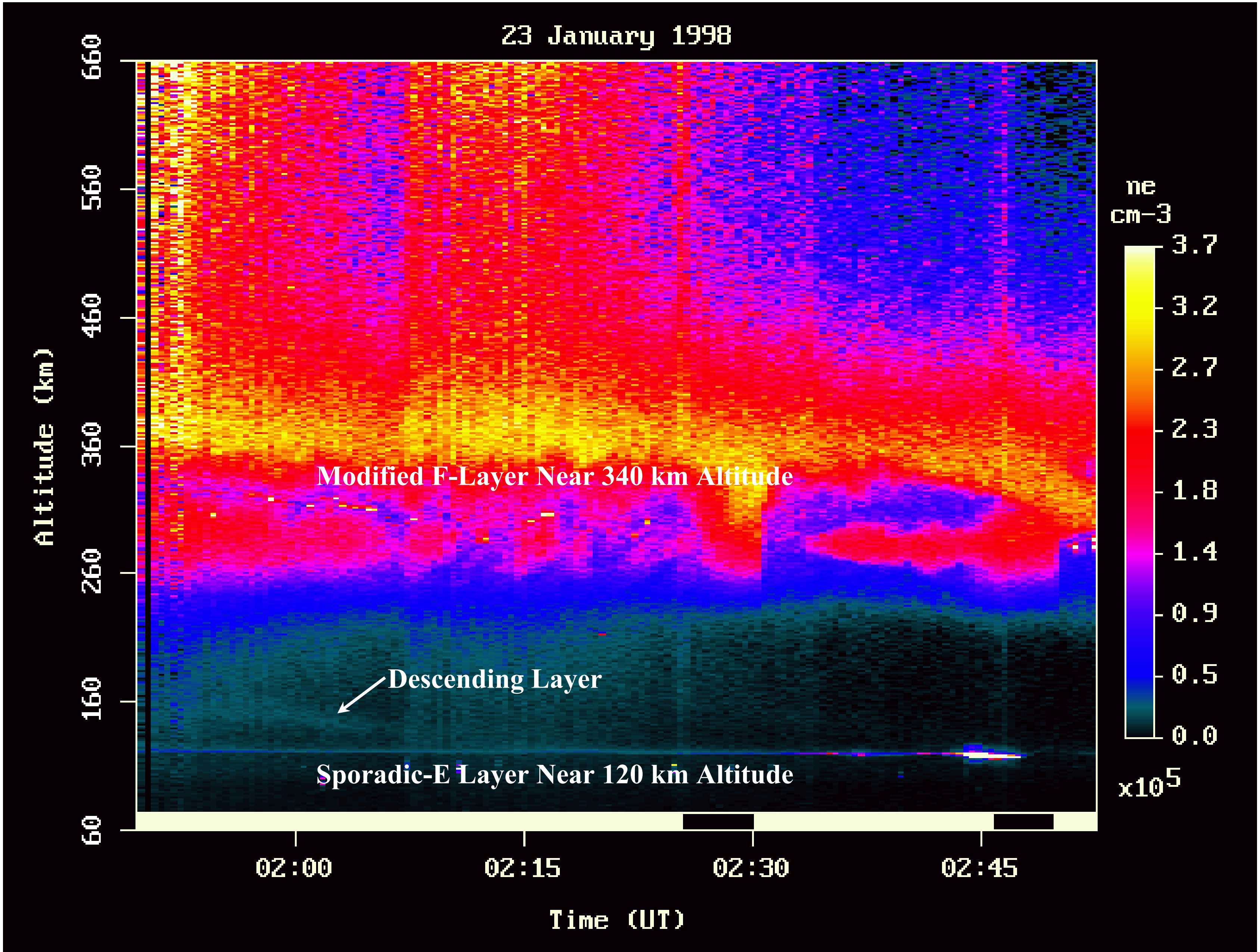
Solid Rocket and Main Engine Burns of Space Shuttle Endeavor for STS-118



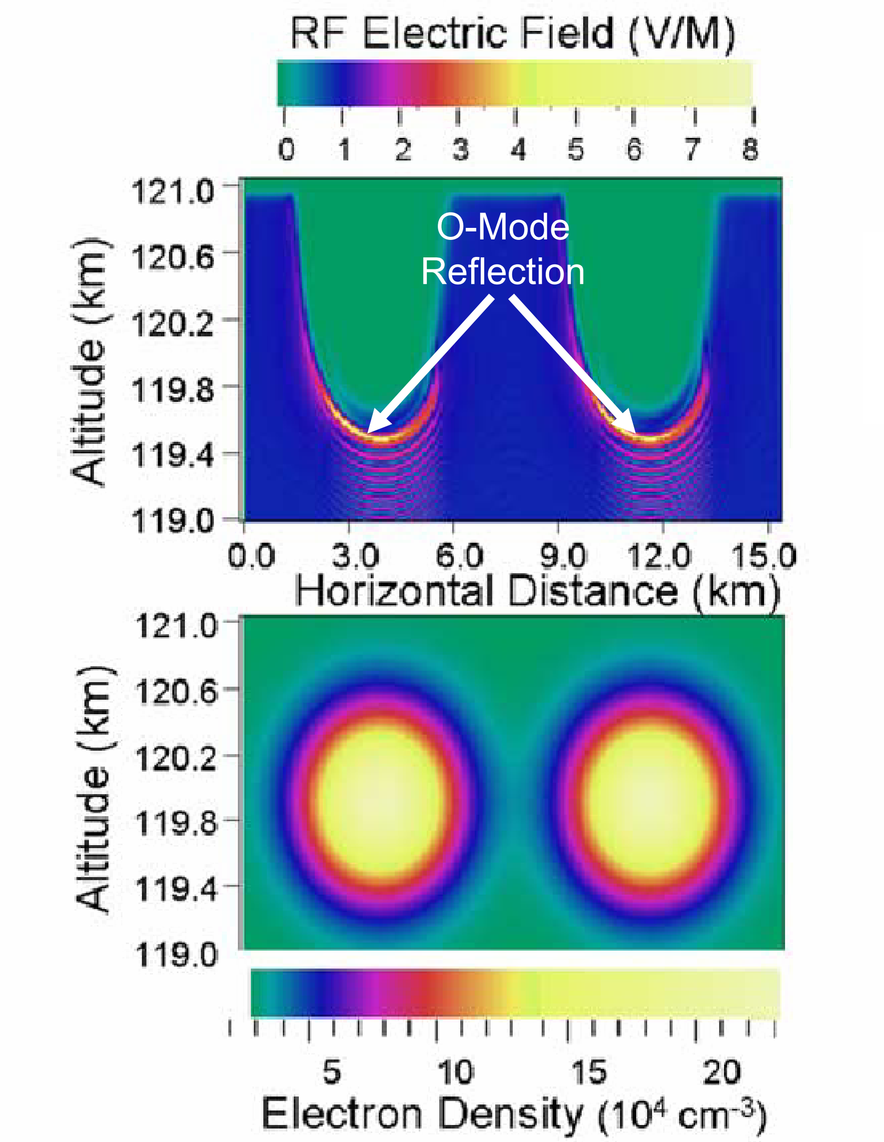
Beam Left of Boresight Showing the Ionospheric Scatter from Rocket Transiting E-layer at 22:36:26 on 8 August 2007

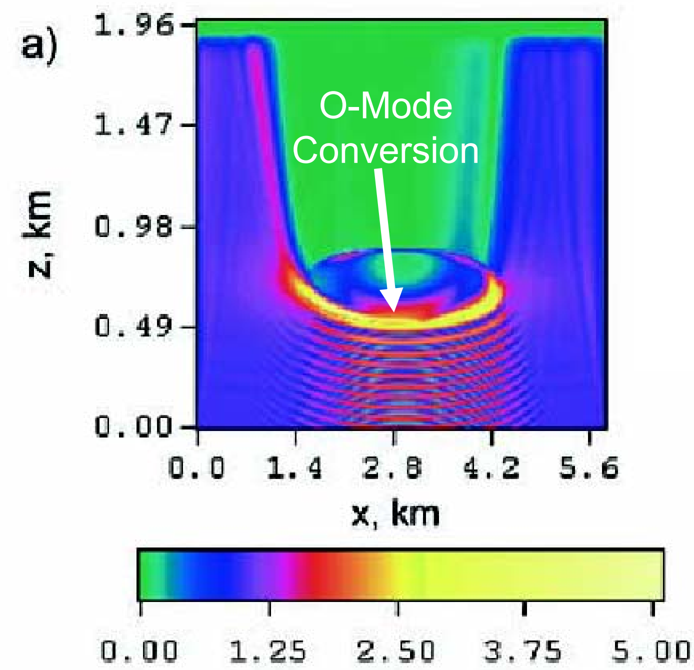


F-Layer and Overdense Intermediate Layer
Arecibo IRS Data, 23 Jan 1998 (FTD)



HF Electromagnetic Waves Interacting with a Plasma Density Enhancement





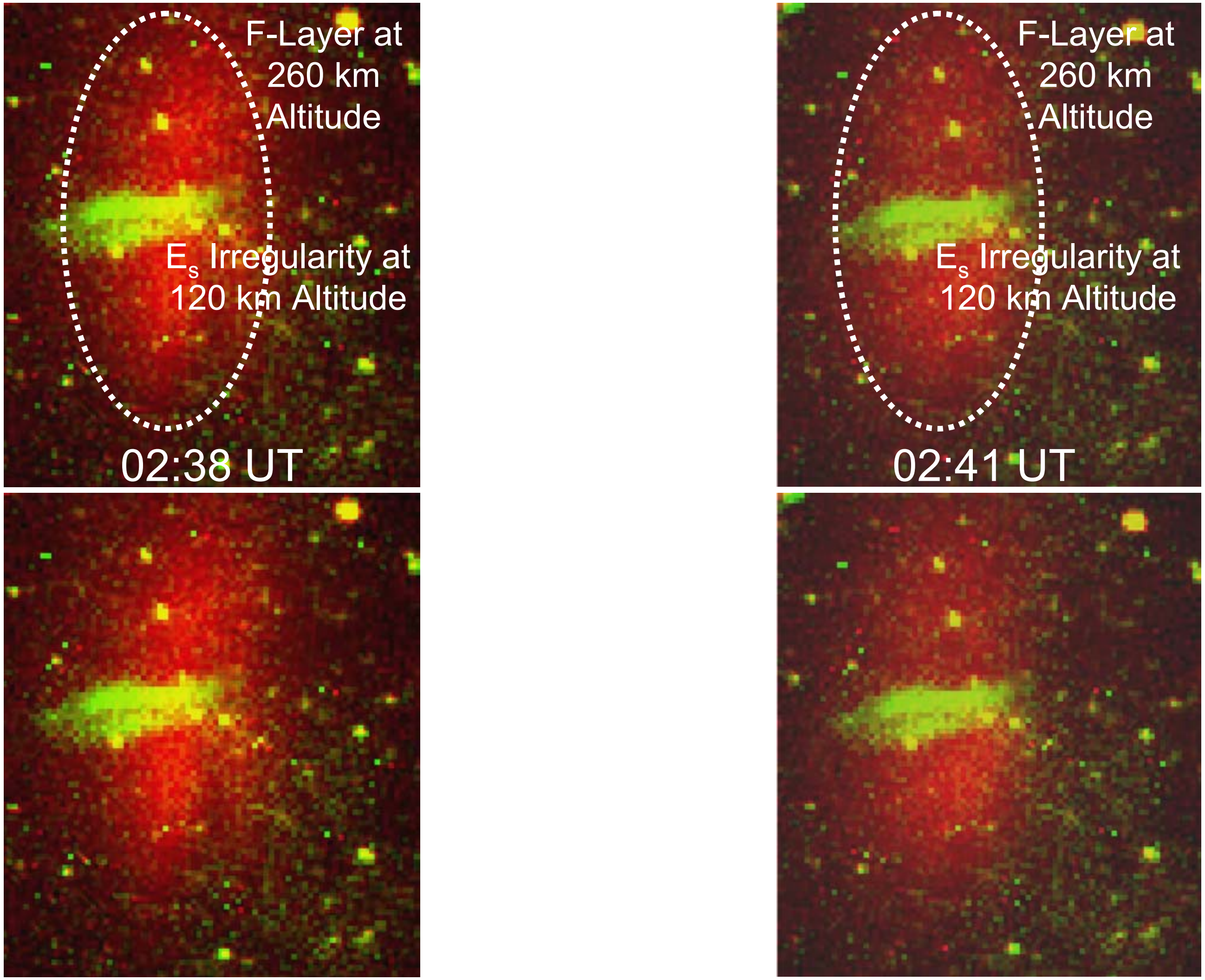
References:

Bernhardt et al., **J. Geophys. Res.**, (108), 1336-1346, 2003.

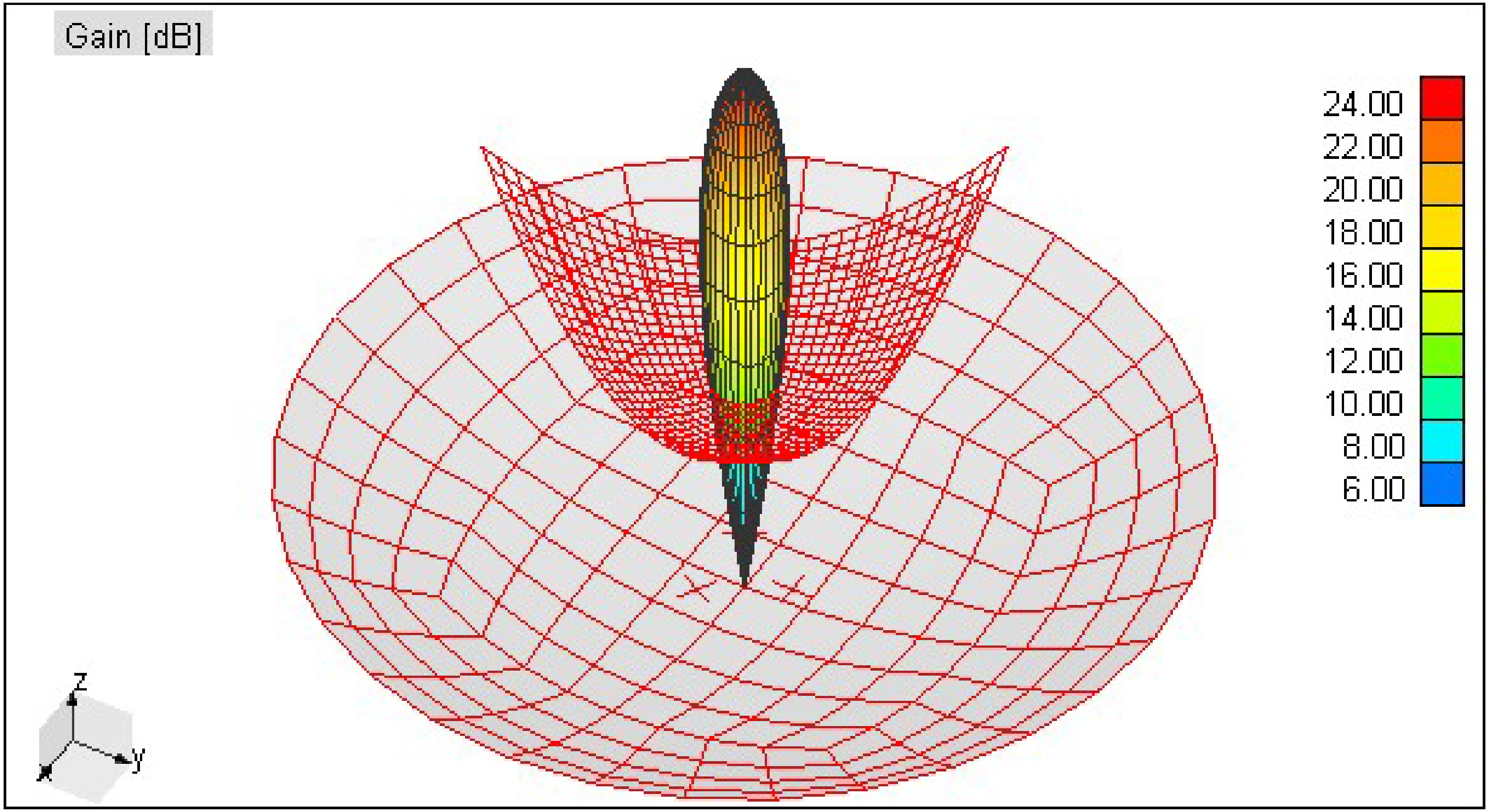
Gondarenko et al., **J. Geophys. Res.**, (108), 1470-1480, 2003.

Two Color (Red/Green) Composite Image of Radio Induced Aurora

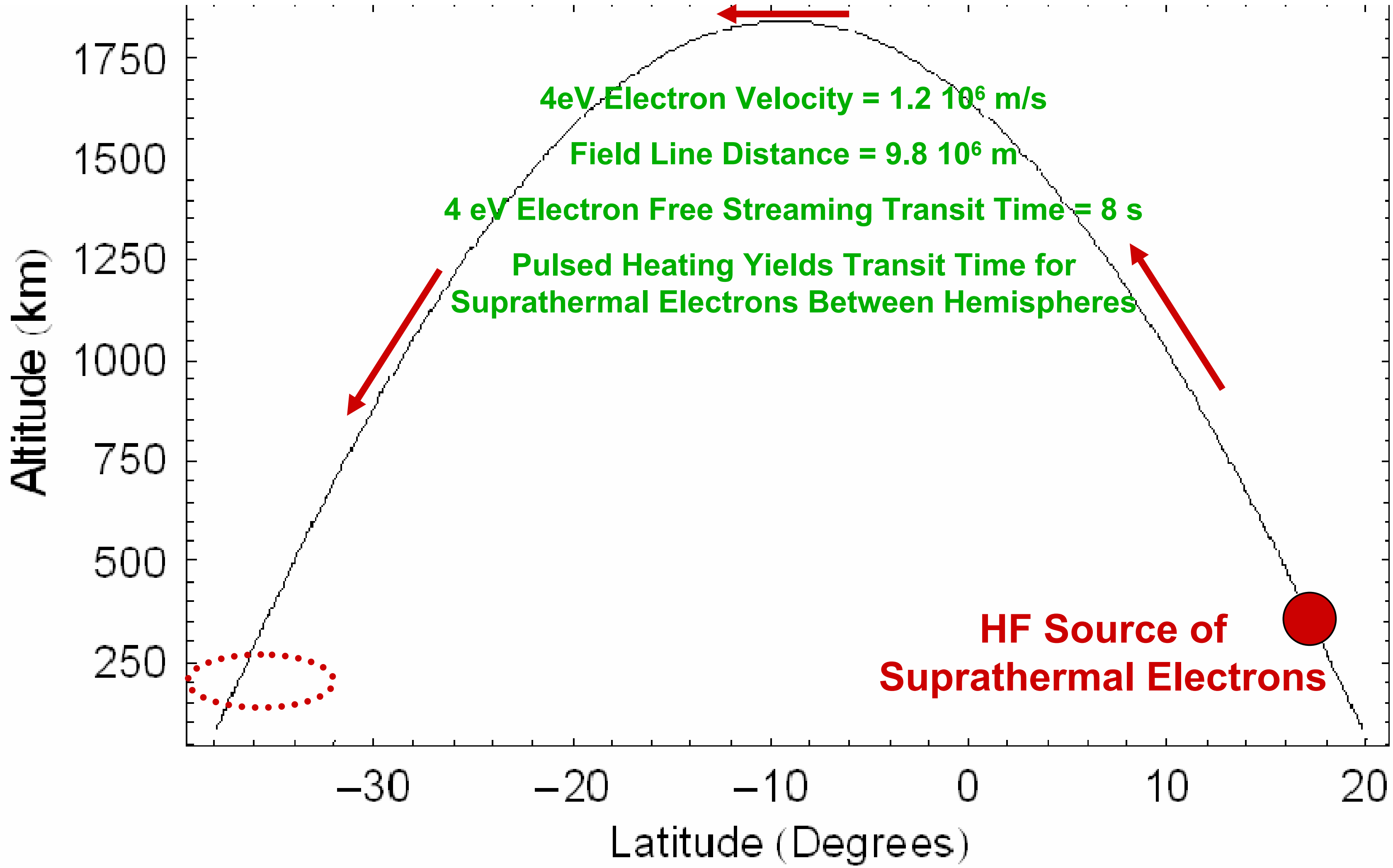
Arecibo, Puerto Rico 23 January 1998



Arecibo HF Facility Antenna Gain at 8.175 MHz Giving 220 MegaWatts ERP Available Starting January 2011

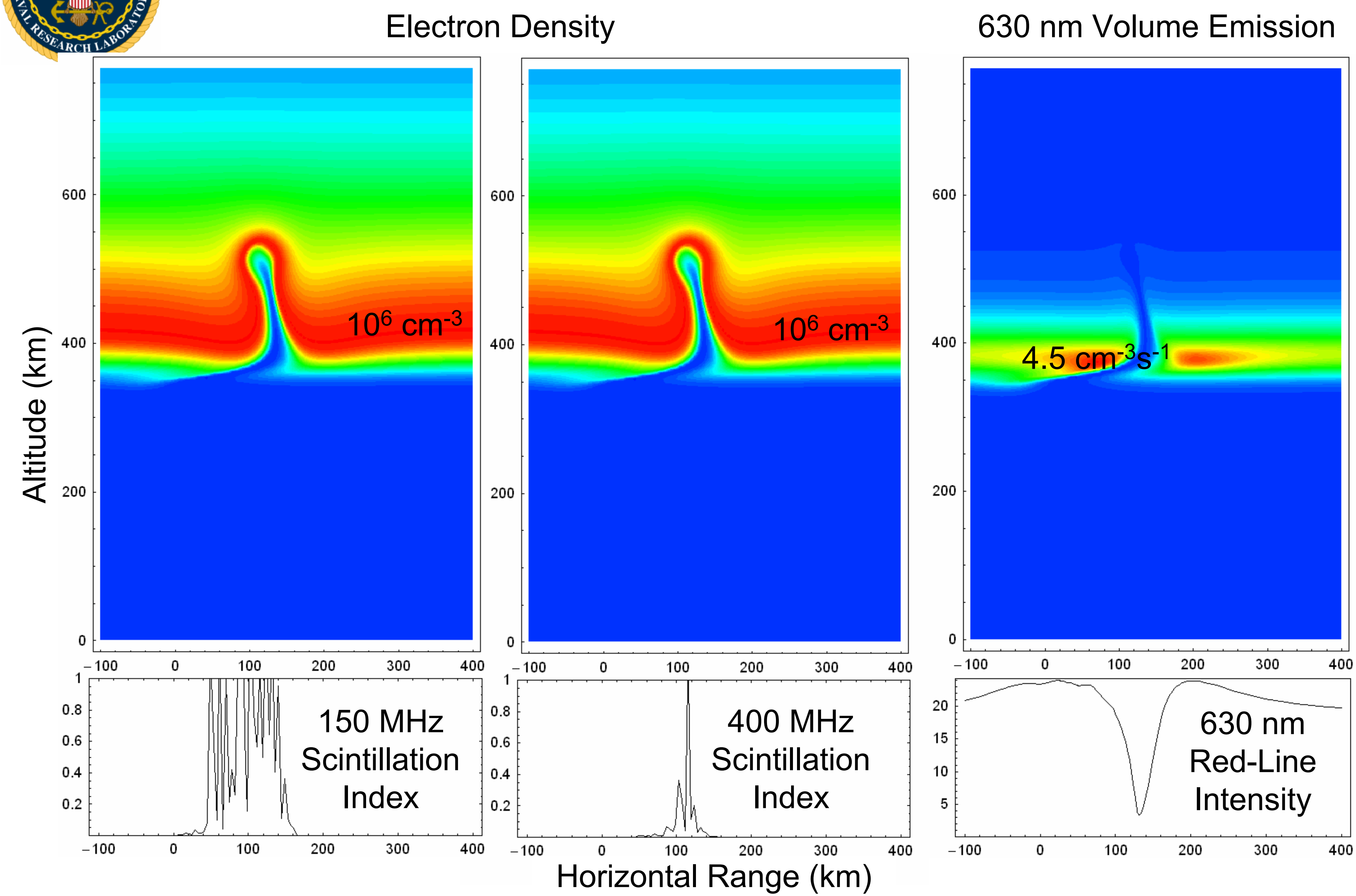


Field Line Connecting Arecibo and Argentina

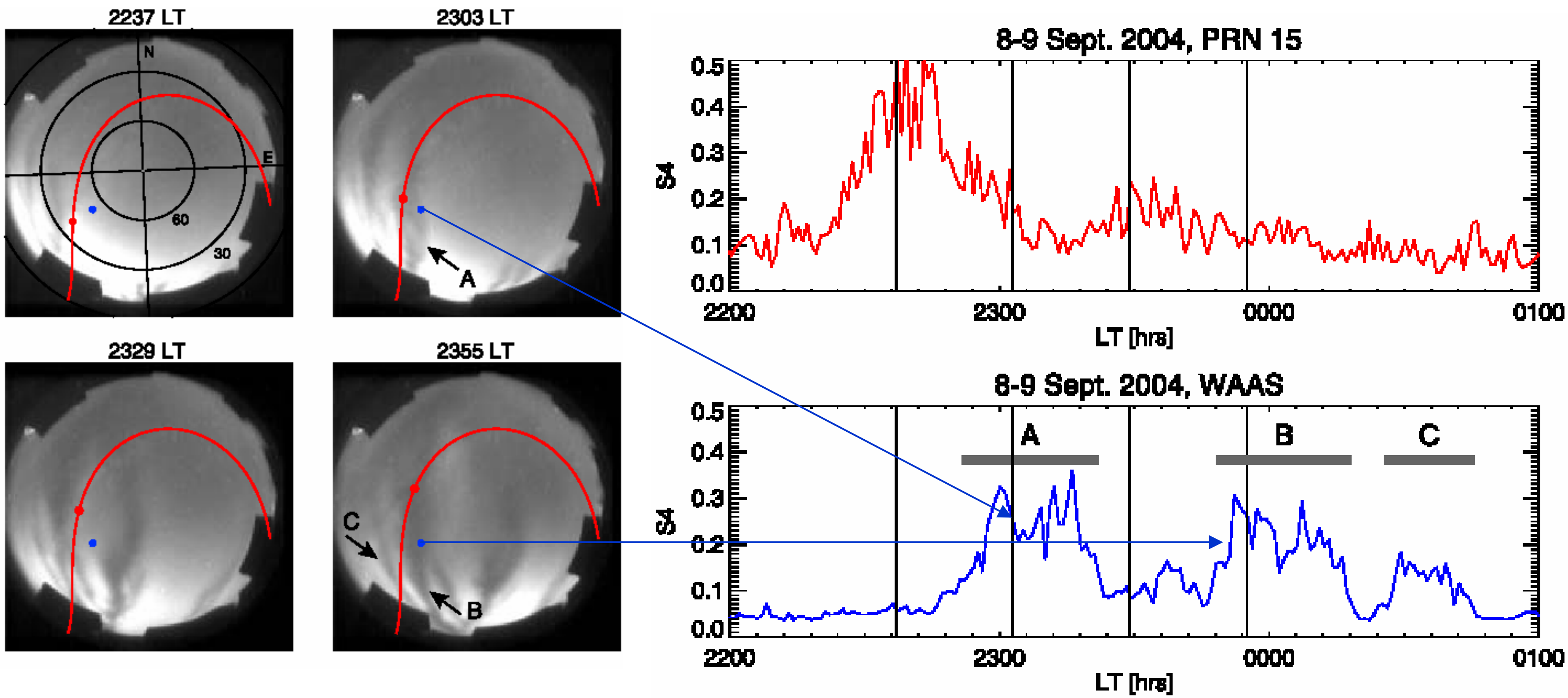


Active Studies of the Equatorial Ionosphere

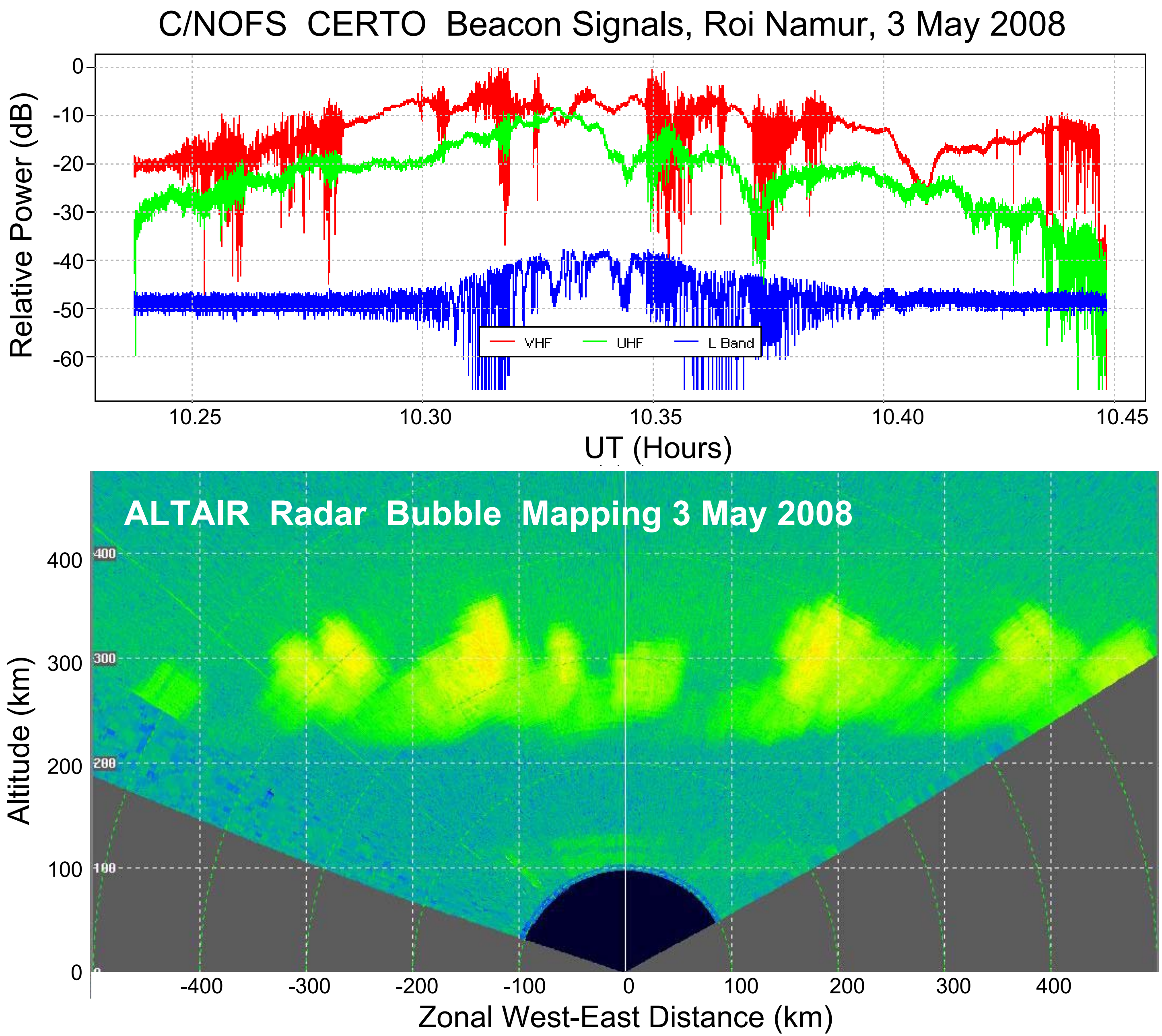
Simulations of Radio Scintillations and Optical Intensities



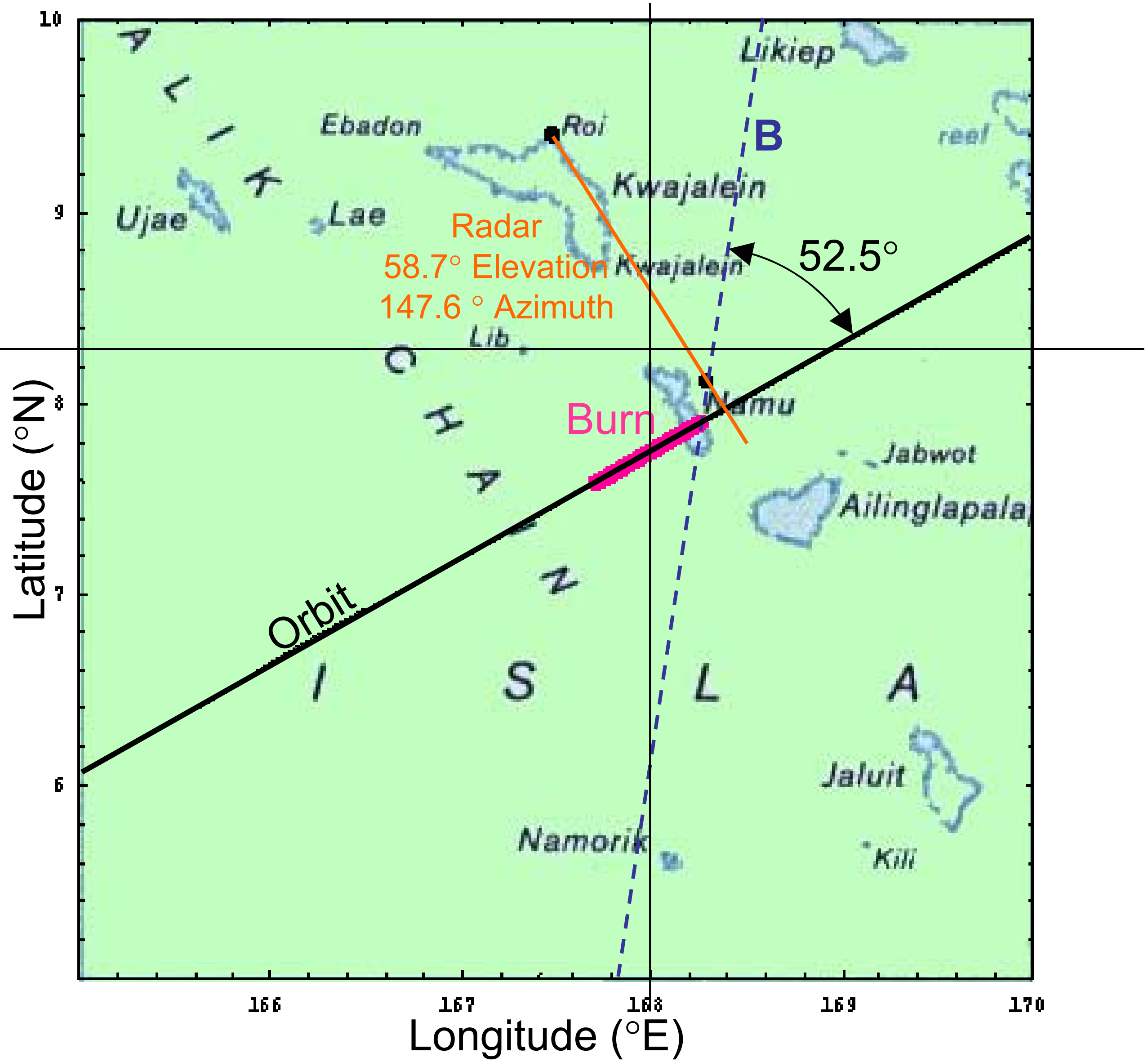
Combining Radio Scintillations and Plasma Bubble Images



Source: Ledvina, B. M., and J. J. Makela , *Geophys. Res. Lett.*, *32*, 2005


C/NOFS CERTO Beacon Signals, Roi Namur, 3 May 2008
Relative Power (dB)
0
-10
-20
-30
-40
-50
-60
VHF
UHF
L Band
10.25
10.30
10.35
10.40
10.45
UT (Hours)
ALTAIR Radar Bubble Mapping 3 May 2008
Altitude (km)
400
300
200
100
0
-400
-300
-200
-100
0
100
200
300
400
Zonal West-East Distance (km)

SIMPLEX Burn Viewed from Kwajalein
25 July 1999

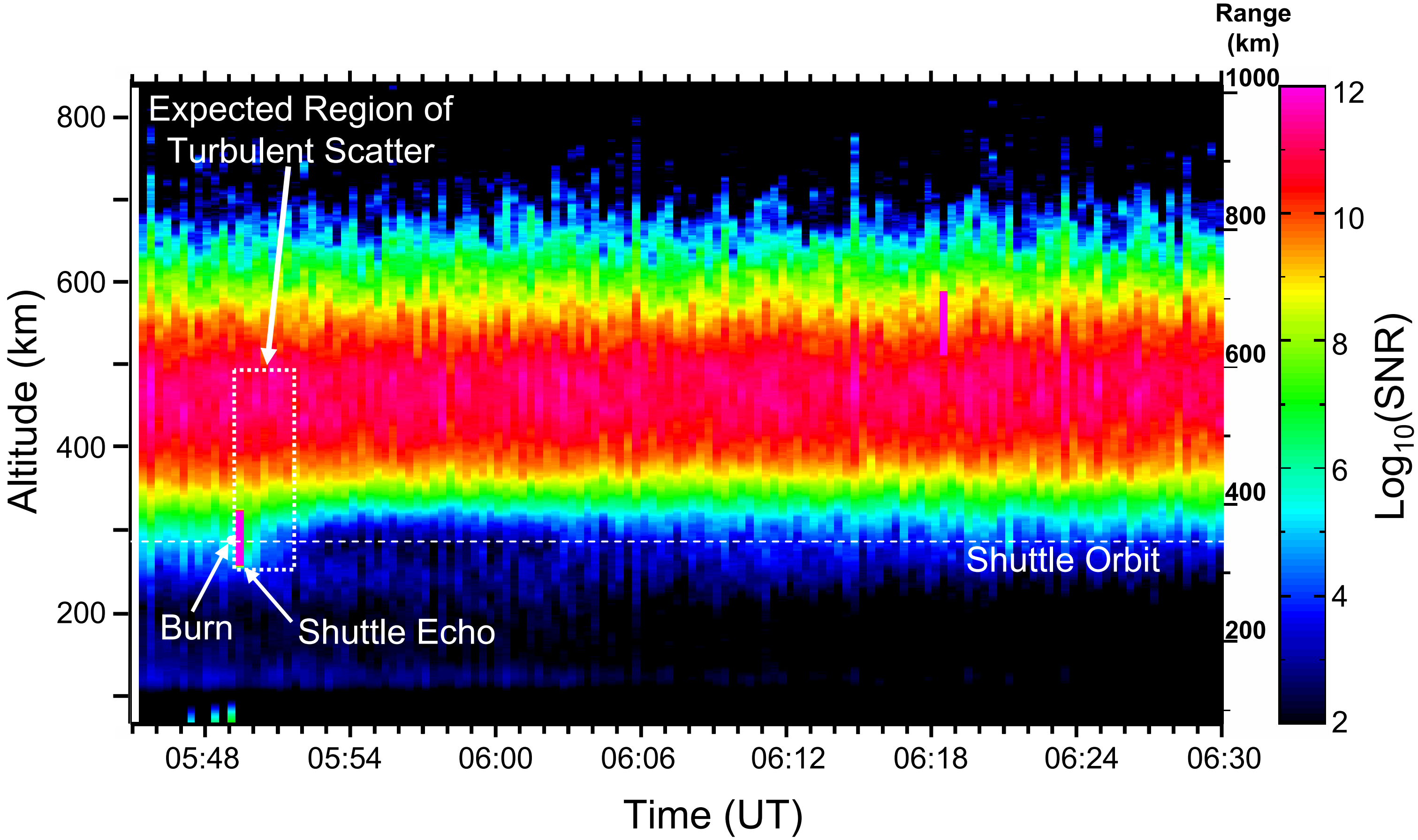


STS-93 Burn, Kwajalein, 25 July 1999

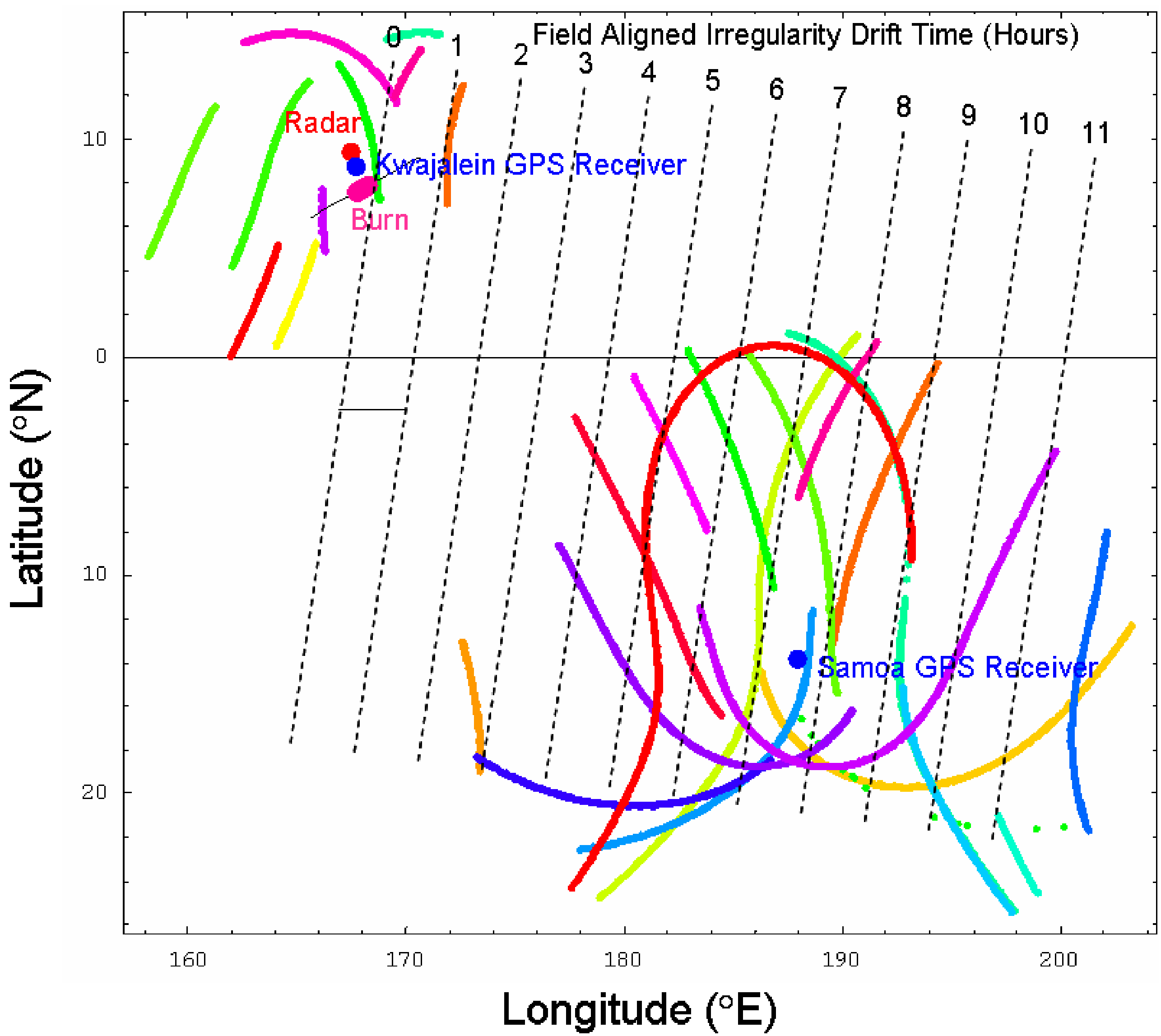
Single Engine OMS 10 s Burn Start 05:49:01 UT(18:49:01 Local Time)

Altair Radar Pointing: 147.6° Azimuth, 58.7° Elevation

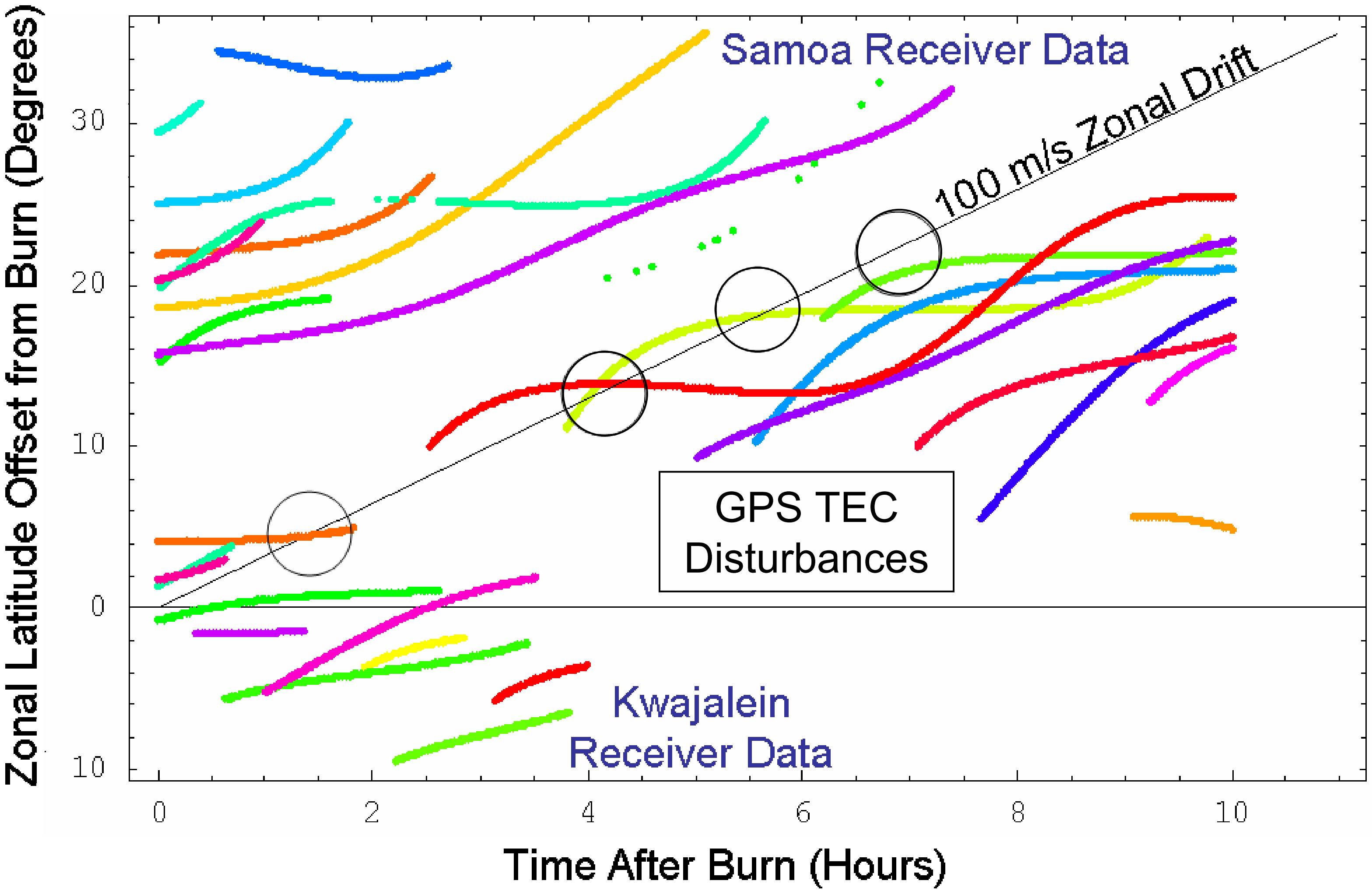
Burn Altitude = 292 km, Range to Burn = 342 km



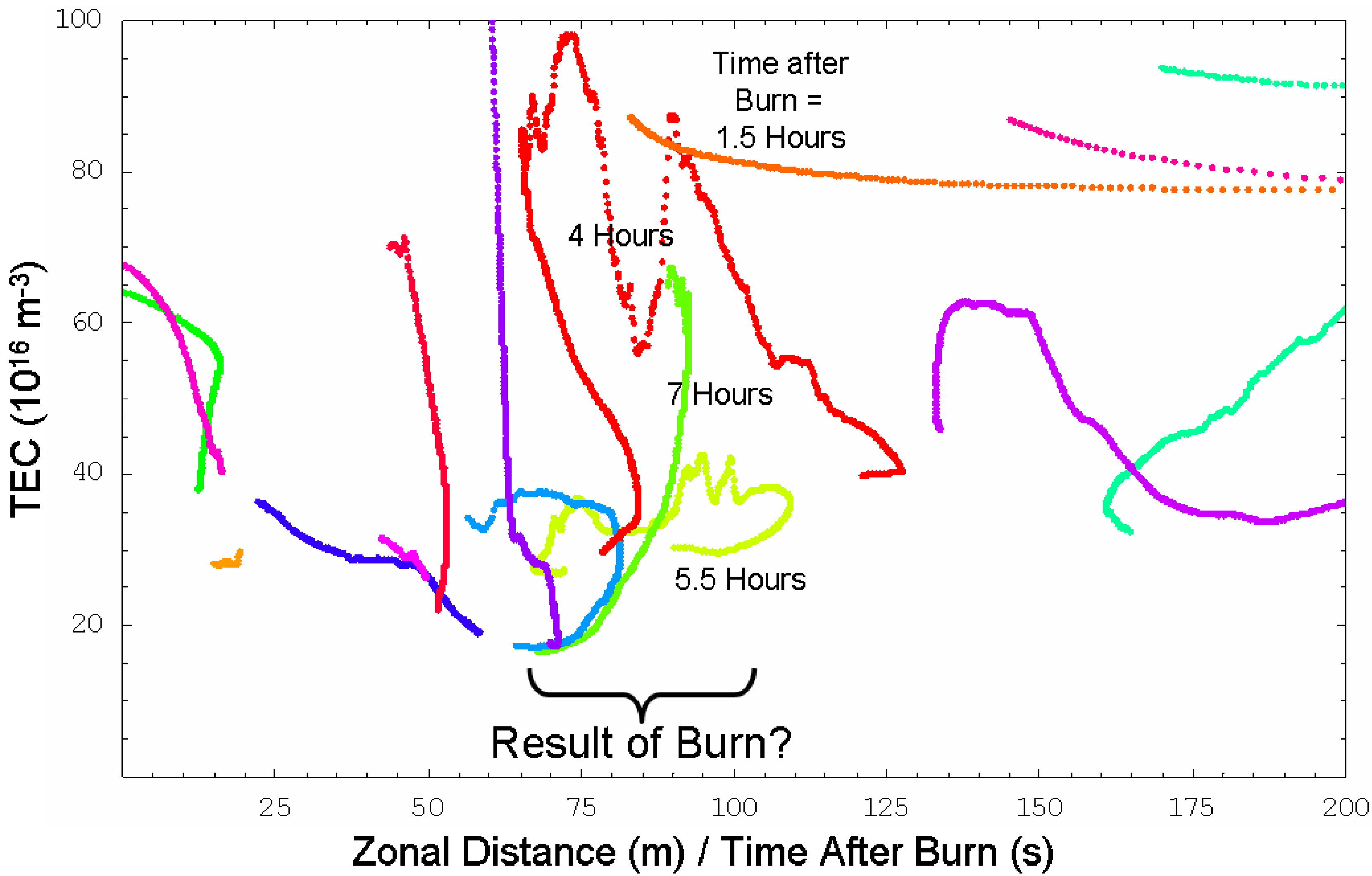
GPS Pierce Point Trajectories for the Hours after the STS-93 SIMPLEX Burn Over Kwajalein



GPS TEC from Kwajalein Receiver for 4 Hours after the STS-93 SIMPLEX Burn Over Kwajalein



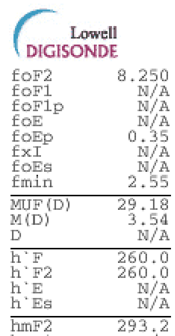
GPS TEC from Samoa Receiver for the Hours after the STS-93 SIMPLEX Burn Over Kwajalein

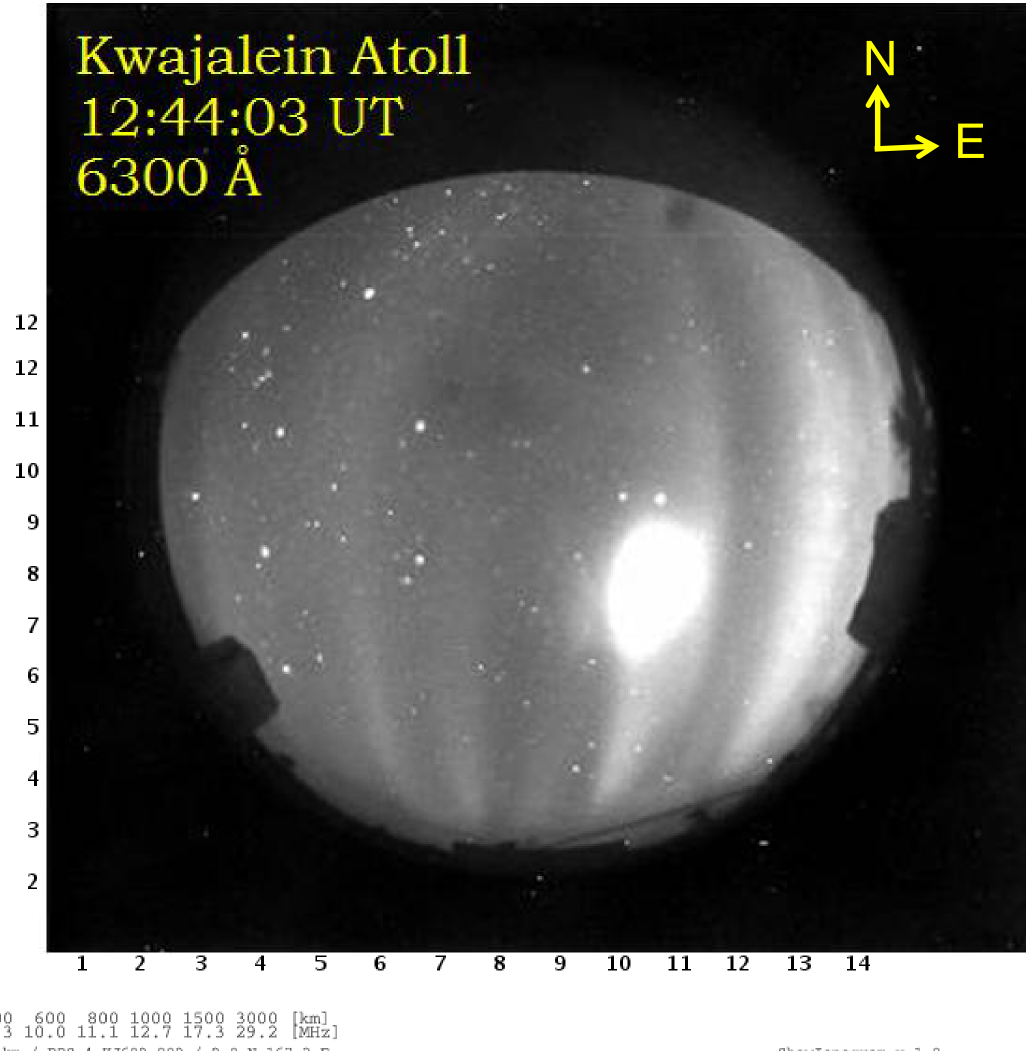


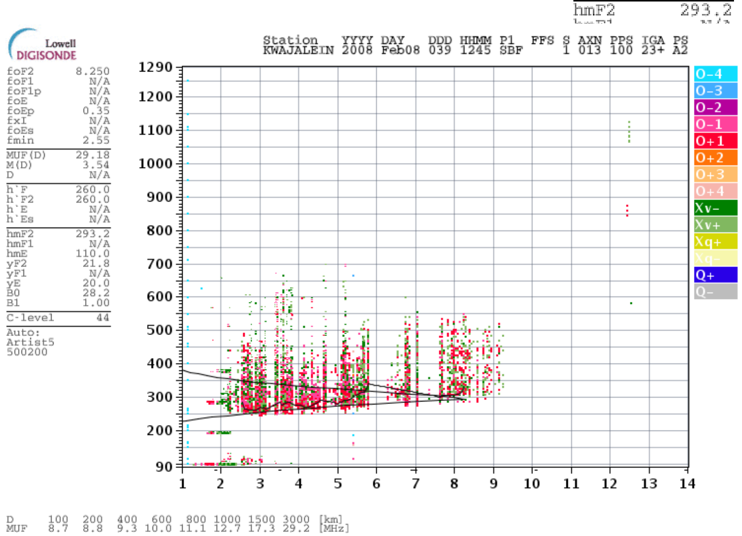
SIMPLEX K3

SIMPLEX K3 – STS 122

- OMS Burn - 08 February 2008
- 12:43 UT (23:53 LT)
- Spread-F Event
- ALTAIR not available





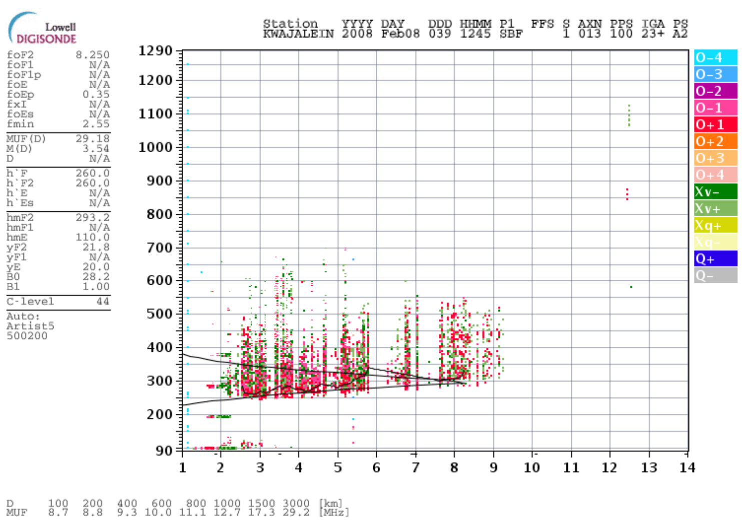


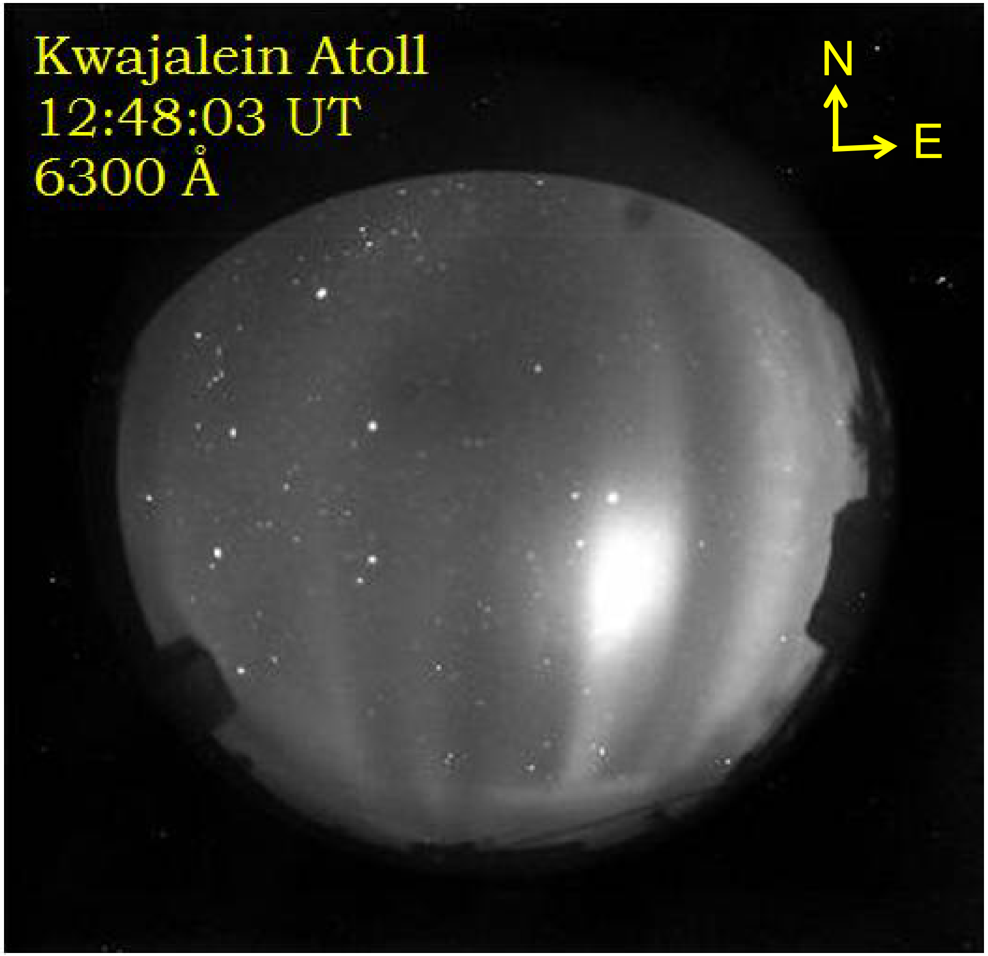
SIMPLEX K3

SIMPLEX K3 – STS 122

- OMS Burn - 08 February 2008
- 12:43 UT (23:53 LT)
- Spread-F Event

- ALTAIR not available
- Region of enhanced airglow somewhat bound by existing ionospheric structure





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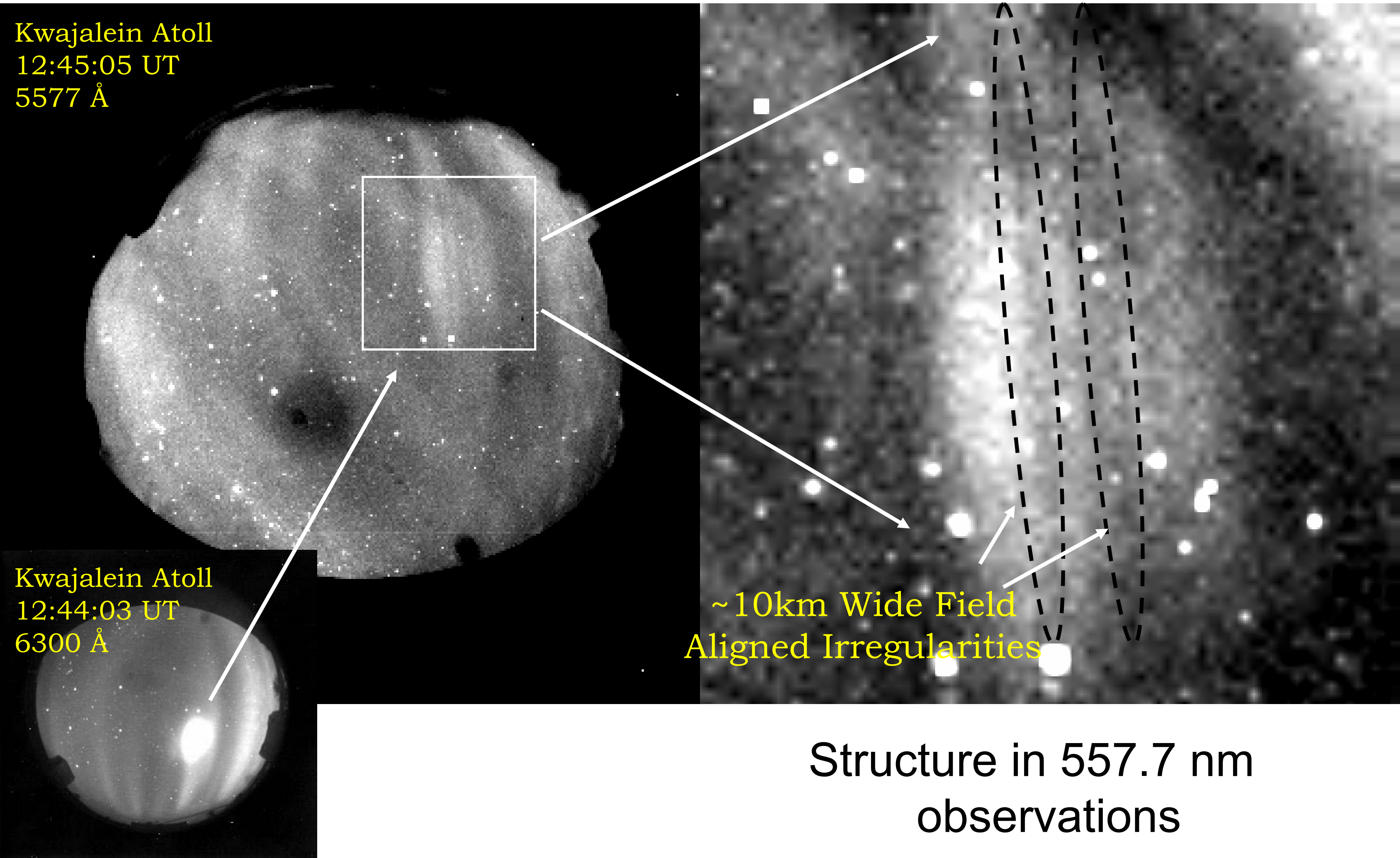
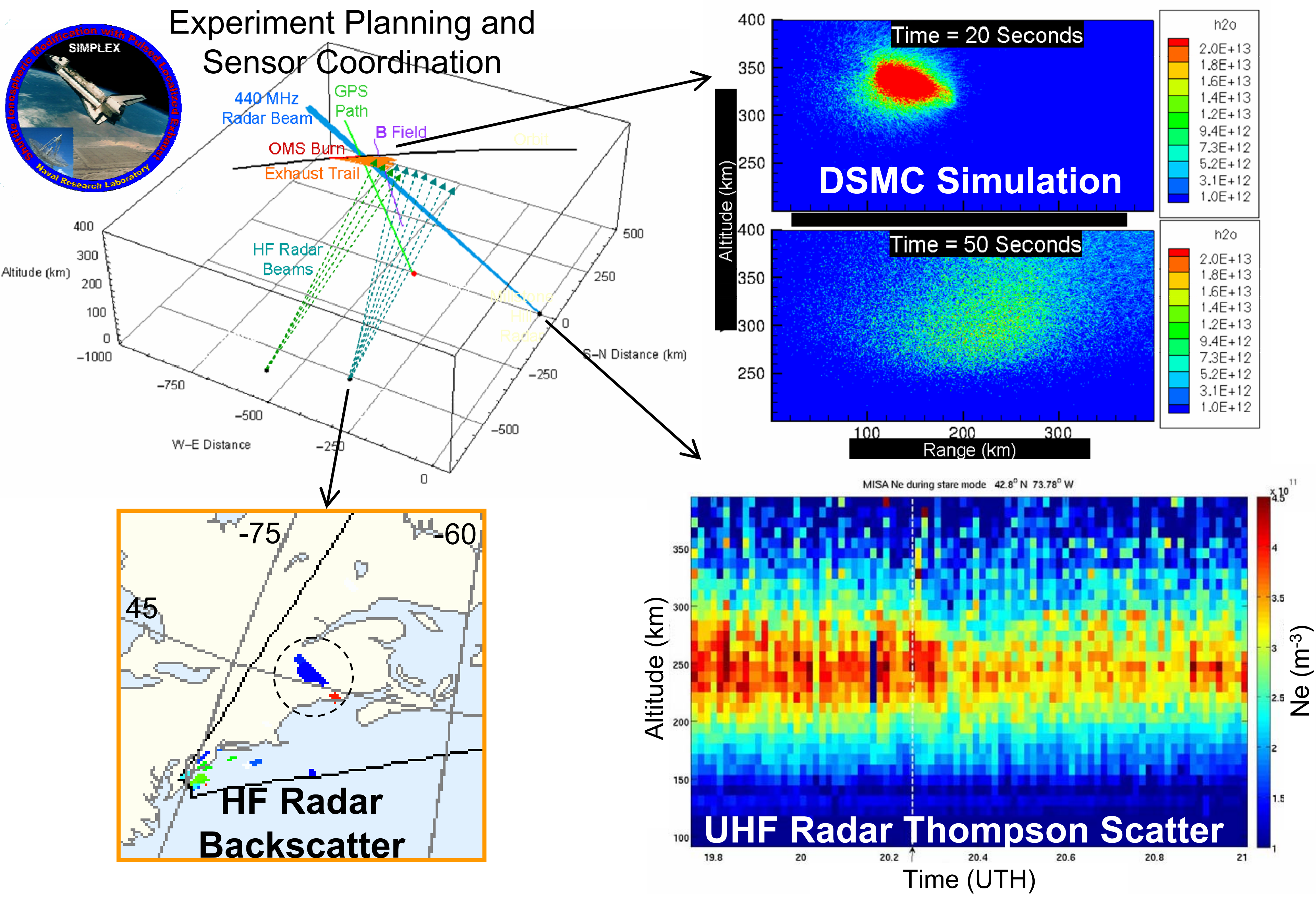
SIMPLEX K3



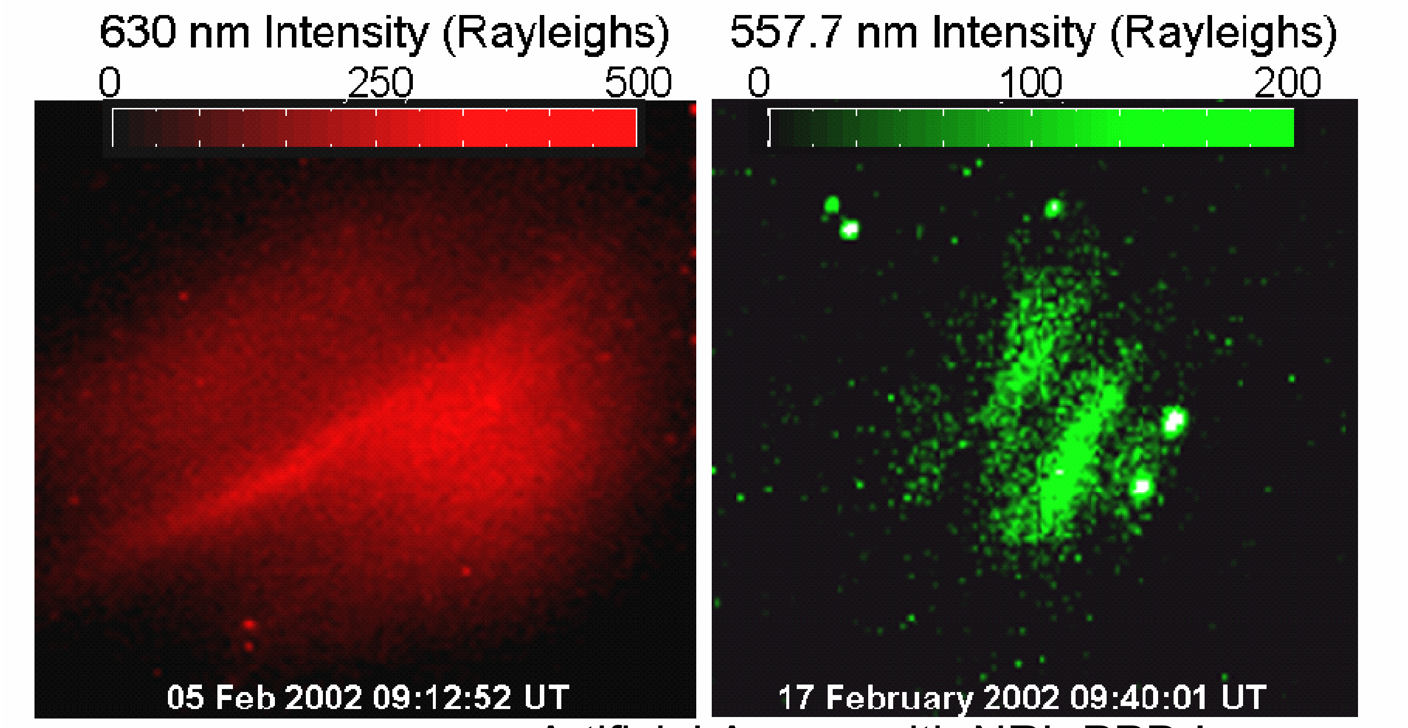
Structure in 557.7 nm observations

Mid- and High-Latitude F-Region Irregularities

NRL SIMPLEX-5 Burn on STS-119, 27 March 2009



Artificial Aurora Experiments



Artificial Aurora with NRL PPD Imager

- High Latitude Artificial Aurora
  - Not Visible with Unaided Eye
  - Primarily Red-Line and Green-Line Emissions
  - Maximum Optical Emissions with HF Beam Aligned with Geomagnetic (**B**) Field
  - Illumination of Natural Field Aligned Irregularities

Drifting Irregularities View Using Artificially Generated Optical Emissions Excited by HAARP

- HAARP antenna beam pointed at magnetic zenith (240°Az, 85° Elev)
- Narrow field of view camera at HIPAS (300 km NW of HAARP Facility).
- Narrowband filter at 630 nm
- Natural Field Aligned Irregularities Modulate Artificial Aurora
- Electron Acceleration Along **B**

Plasma Wave Generation

Coupled Wave Equations Driven by Large Pump Electric Fields

- Electromagnetic Pump Wave (ω_P)

$$-\nabla^2\mathbf{E}_P + \nabla(\nabla\cdot\mathbf{E}_P) - k_P^2[\mathbf{I}+\mathbf{X}_{eP}]\cdot\mathbf{E}_P = 0$$

- Scattered Electromagnetic Wave (ω_S)

$$-\nabla^2\mathbf{E}_S + \nabla(\nabla\cdot\mathbf{E}_S) - k_S^2[\mathbf{I}+\mathbf{X}_{eS}]\cdot\mathbf{E}_S = k_S^2\bar{\mathbf{X}}_{eL}\cdot\mathbf{E}_P$$

- Low Frequency Ion Velocity Waves (ω_L)
  - Ion Acoustic/Slow Magnetosonic
  - Electrostatic Ion Cyclotron)

$$\nabla(\nabla\cdot\bar{\mathbf{v}}_i) + \frac{\omega_{L\pm}^2}{c_{IA}^2}\left(U_i\bar{\mathbf{v}}_i - i\frac{\mathbf{\Omega}_i\times\bar{\mathbf{v}}_i}{\omega_{L\pm}^2}\right) = \frac{i\omega_{L\pm}q_e^2}{4m_e m_i\omega_P^2 c_{IA}^2}\nabla(\mathbf{E}_T\cdot\mathbf{E}_T) \text{ where } \mathbf{E}_T = \mathbf{E}_P + \mathbf{E}_S$$

- Result: Parametric Decay Instability

$$\omega_P = \omega_S + \omega_L$$

$$\mathbf{k}_P = \mathbf{k}_S + \mathbf{k}_L$$

ES and EM Wave Generation

EM Pump Wave → Optional Mode Conversion (Loss) → High Power EM or ES Wave → Parametric Decay (Loss) → Low Frequency ES Wave → Possible Mode Conversion ? → Low Frequency EM Wave

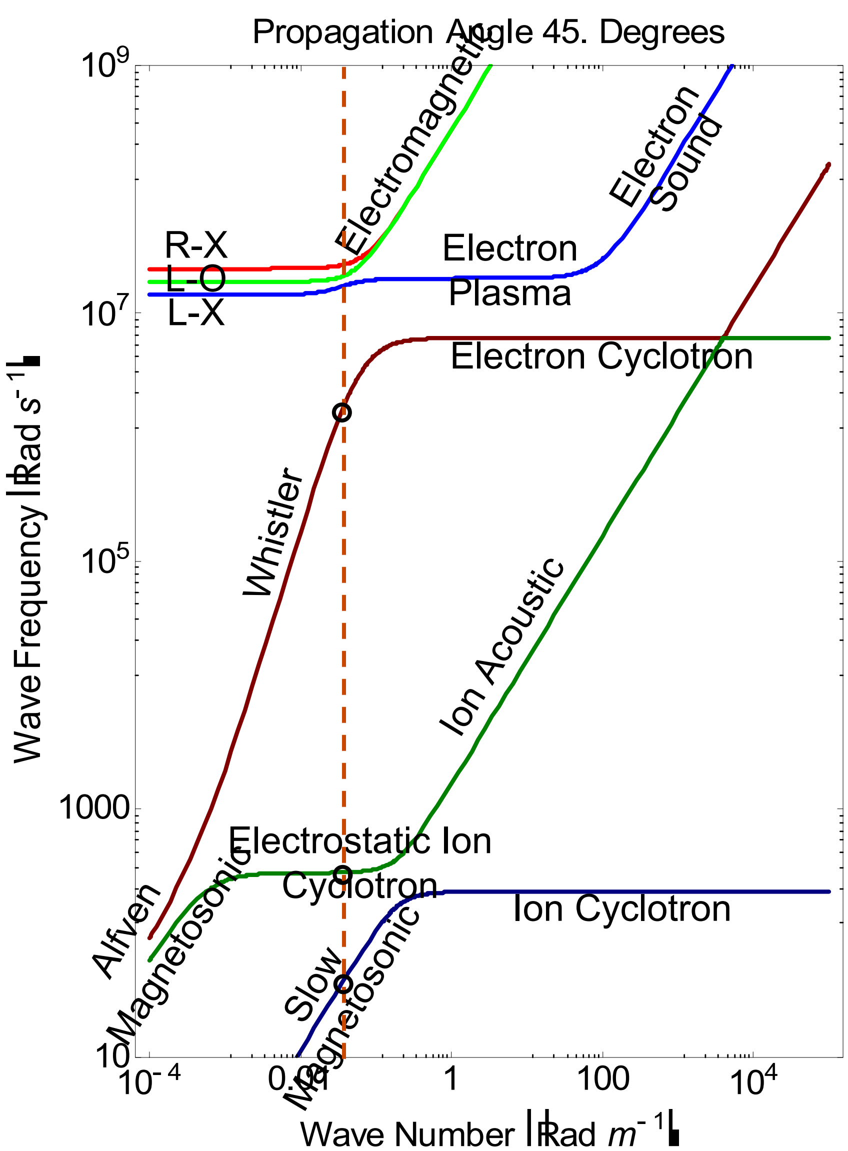
Parametric Decay → High Frequency EM or ES Wave → Optional Mode Conversion (Loss) → Received EM Wave

Wave	Examples Transverse to B	Examples Quasi-Parallel to B
EM Pump	**O-Mode, X-Mode**	**L-Mode, R-Mode**
Low Frequency Electromagnetic	**Magnetosonic**	**Alfven Whistler**
Low Frequency Electrostatic	**Lower Hybrid Ion Acoustic Ion Bernstein**	**Slow Magnetosonic Ion Cyclotron Ion Acoustic**
High Frequency Electromagnetic	**O-Mode, X-Mode**	**L-Mode, R-Mode**
High Frequency Electrostatic	**Upper Hybrid Electron Cyclotron Electron Bernstein**	**Electron Plasma**

Pairs of Waves Produced by Parametric Decay of Strong Pump Waves

Daughter Wave #2→ ✵Daughter Wave #1	EM	EP	UH	EB	IA	EIC	LH	IB	W	ZFE	ZFI	FAI
Electromagnetic (EM)					EM	EM						
Electron Plasma (EP)					EM/EP							
Upper Hybrid (UH)							UH					EM
Electron Bernstein (EB)								EB				EM
Ion Acoustic (IA)												
Electrostatic Ion Cyclotron (EIC)												
Lower Hybrid (LH)												
Ion Bernstein (IB)												
Magnetosonic (M)												
Zero Frequency Electron (ZFE)											EM	
Zero Frequency Ion (ZFI)												
Field Aligned Irregularities (FAI)												

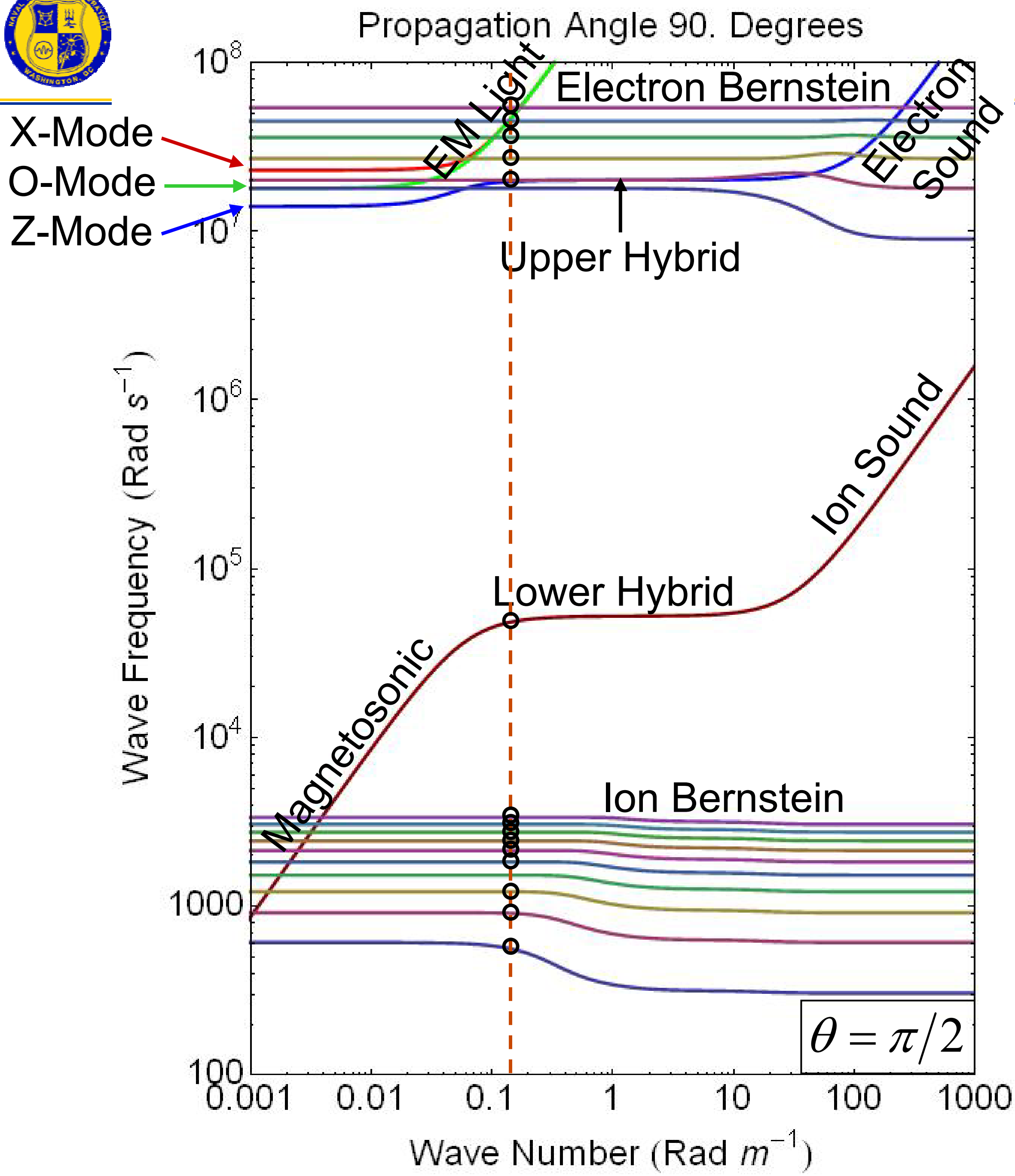
Waves in a Fluid Plasma for Oblique Propagation



Plasma Wave Mode Characteristic Branches for Typical Ionospheric Parameters

$$\Omega_e = (2\pi)\ 1.43\ 10^6\ Rad/s$$
$$\omega_{pe} = 2\ \Omega_e Rad/s = (2\pi)\ 2.86\ 10^6\ Rad/s$$
$$\omega_{UH} = (2\pi)\ 3.2\ 10^6\ Rad/s$$
$$\omega_{LH} = (2\pi)\ 7460\ Rad/s$$
$$\Omega_i = (2\pi)\ 48.7\ Rad/s$$
$$n_e = 1.01\ 10^{11}\ m^{-3}$$
$$T_e = 2500K$$
$$T_i = 800K$$
$$V_A = 8.75\ 10^5\ m/s$$
$$c_s = 1590\ m/s$$
$$\rho_e = 0.022\ m$$
$$\rho_i = 3.64\ m$$

Plasma Waves for Normal Propagation



$$\Omega_e = (2\pi)\ 1.43\ 10^6\ Rad/s$$

$$\omega_{pe} = 2\ \Omega_e$$

$$= (2\pi)\ 2.86\ 10^6\ Rad/s$$

$$\omega_{UH} = (2\pi)\ 3.2\ 10^6\ Rad/s$$

$$\omega_{LH} = (2\pi)\ 7460\ Rad/s$$

$$\Omega_i = (2\pi)\ 48.7\ Rad/s$$

$$B_0 = 5.1\ 10^{-5}\ T$$

$$n_e = 1.01\ 10^{11}\ m^{-3}$$

$$T_e = 2500 K$$

$$T_i = 800 K$$

$$V_A = 8.75\ 10^5\ m/s$$

$$c_s = 1590\ m/s$$

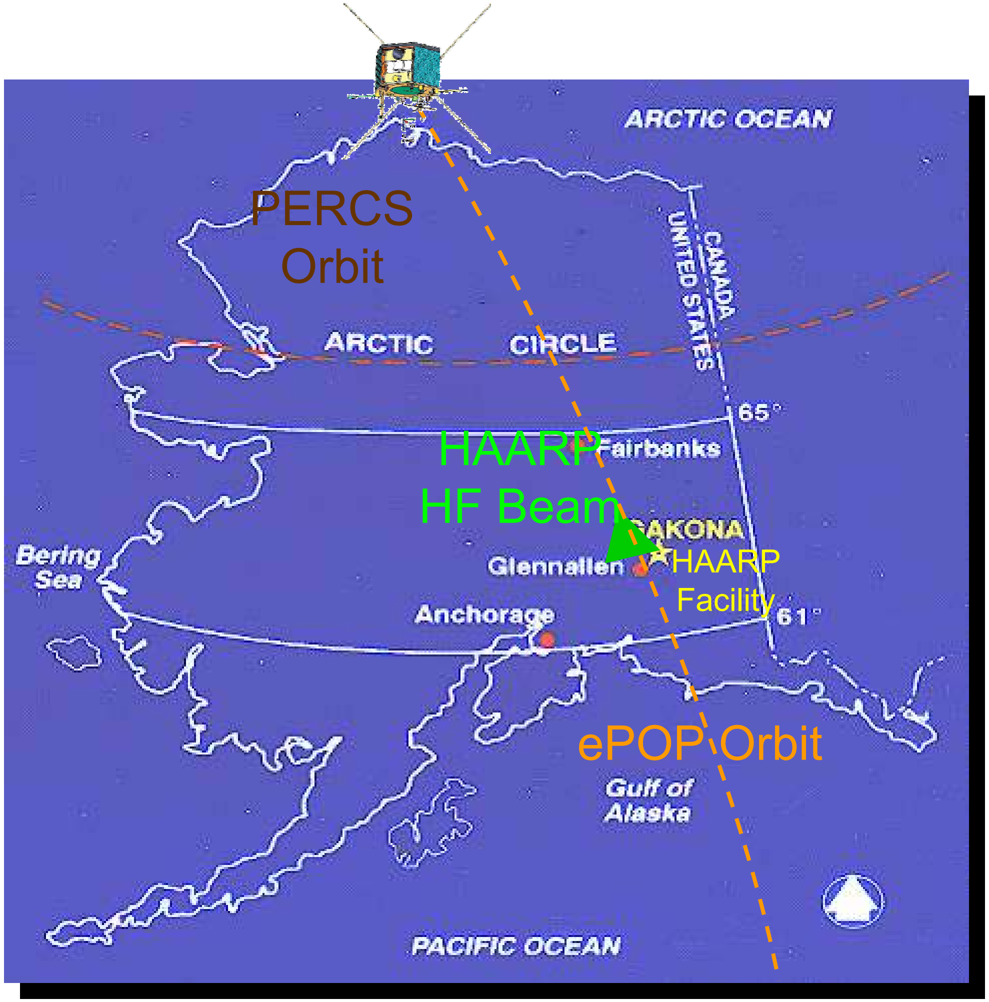
$$\rho_e = 0.022\ m$$

$$\rho_i = 3.64\ m$$

Parametric Decay Instabilities and Stimulated Electromagnetic Emissions

Parent Wave 0	Daughter Wave 1	Daughter Wave 2	Instability Name	Observed for HF
Electromagnetic Wave	Electron Plasma Wave	Ion Acoustic Wave	*Parametric Decay*	Yes Radar/SEE
Electron Plasma Wave	Electron Plasma Wave	Ion Acoustic Wave	*Electron Decay*	Yes Radar/SEE
Electromagnetic Wave	Electron Plasma Wave	Zero Frequency Ion Wave	*Oscillating Two-Stream*	Yes Radar/SEE
Electromagnetic Wave	Electromagnetic Wave	Ion Acoustic Wave	*Stimulated Brillouin Scattering*	Yes SEE
Electromagnetic Wave	Electron Plasma Wave	Electron Plasma Wave	*Two-Plasmon Decay*	No
Electromagnetic Wave	Electromagnetic Wave	Electron Plasma Wave	*Stimulated Raman Scattering*	No
Upper Hybrid Wave	Upper Hybrid Wave	Lower Hybrid Wave	*Lower-Hybrid Decay*	Yes SEE
Electron Plasma Wave	Electron Plasma Wave	Electrostatic Ion Cyclotron Wave	*Stimulated EIC Brillouin Scatter*	Yes Radar/SEE
Electron Bernstein Wave	Electron Bernstein Wave	Ion Bernstein Wave	*Electron Bernstein Decay*	Yes SEE

HAARP Instrument Experiments with the PERCS



- PERCS Operational Utility
  - Absolute Calibration of HAARP Antenna Pattern from 2.8 to 10 MHz
  - Precise Measurements of Performance for HF Radars that Support HAARP

In Situ Measurements by NRL IFH Rocket

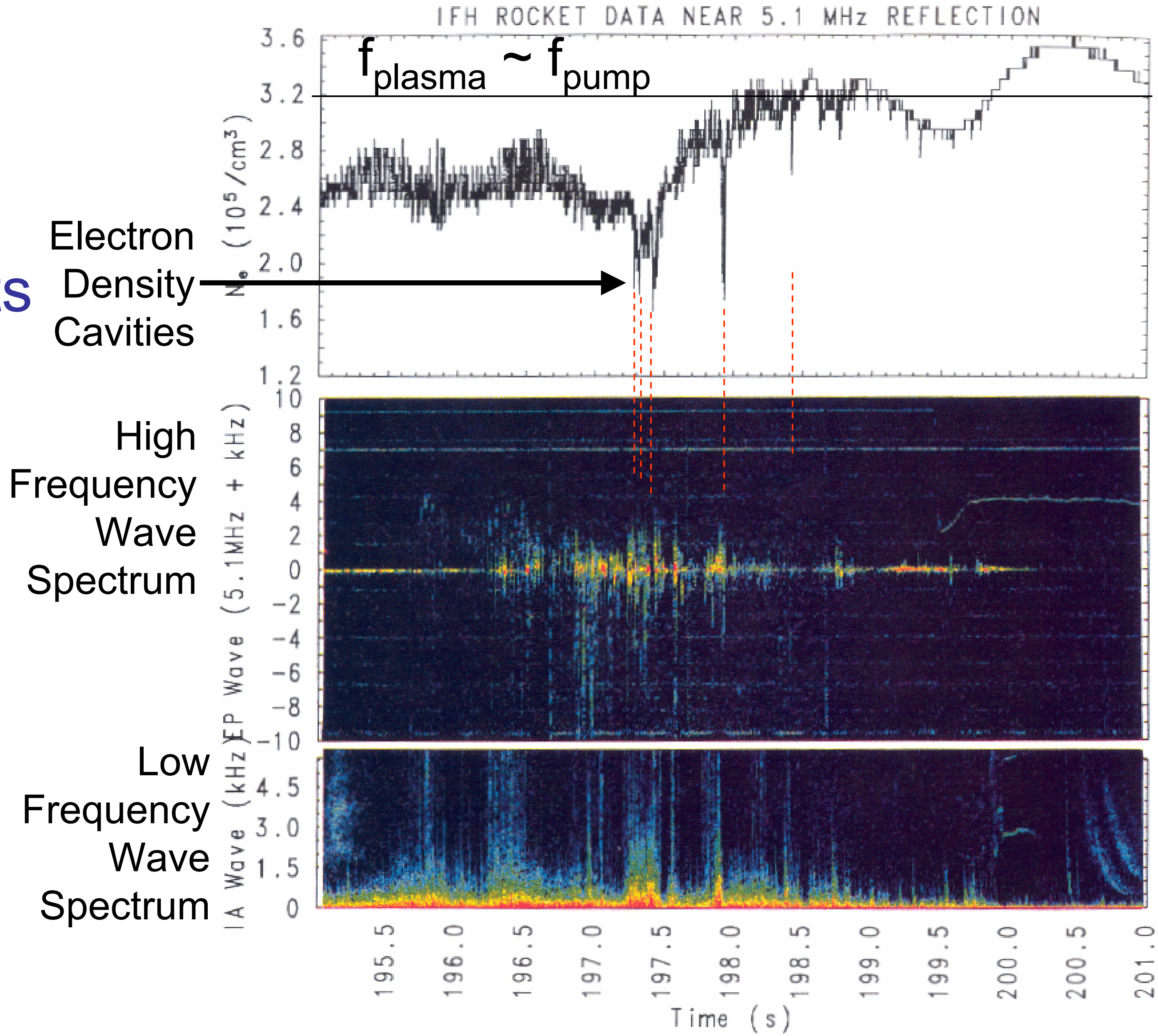


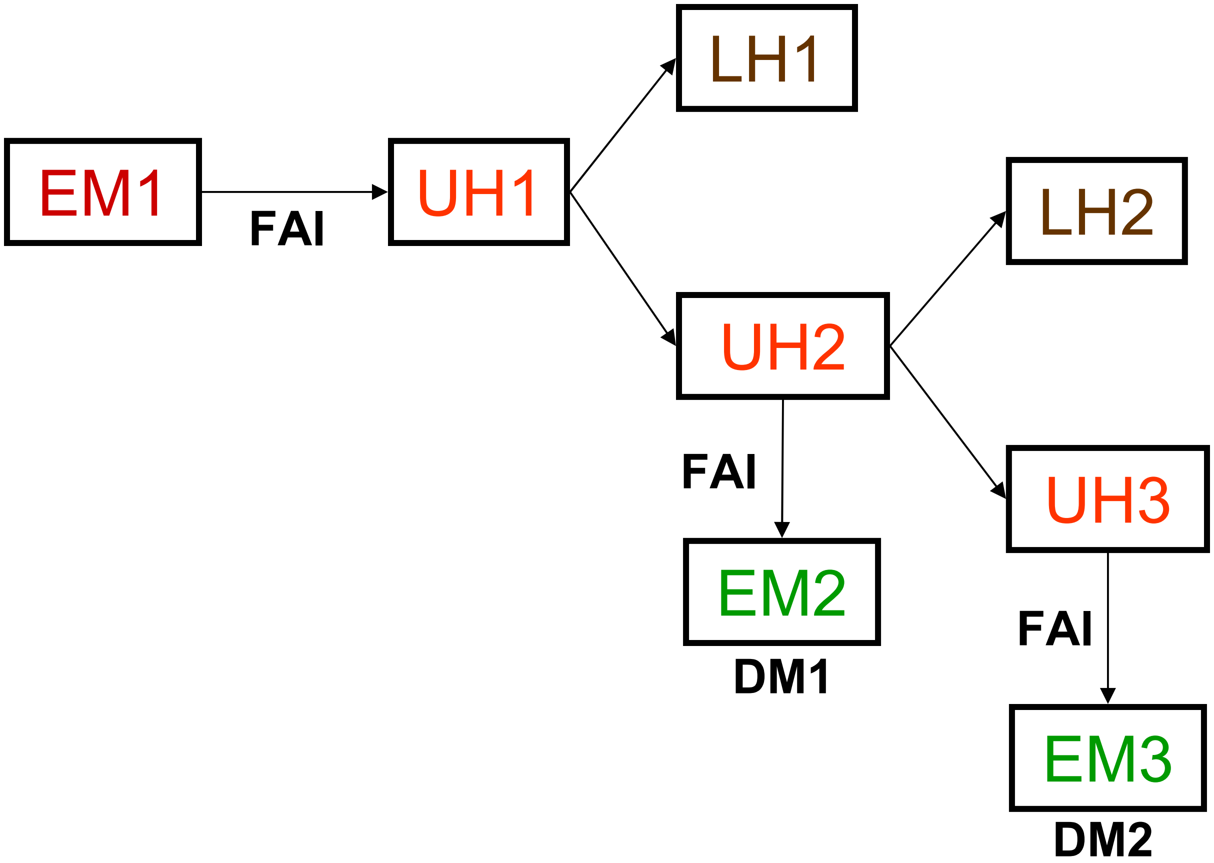
Plate 2. Detail of the electron density, Langmuir waves around 5.1 MHz and low-frequency ion acoustic waves near the HF reflection level. The Langmuir waves and ion acoustic waves seem to be trapped or guided by the density cavities. Spectra of low-frequency electric fields are measured between sensors EF1 and EF4 of Figure 2.

Reference: Rodriguez, P., C.L. Siefring, P.A. Bernhardt, D.G. Haas, and M.M. Baumback, Frequency-shifted signature of the HF pump in the ionospheric focused heating experiment, **Geophys. Res. Lett.**, 24, 635-638, 1997.

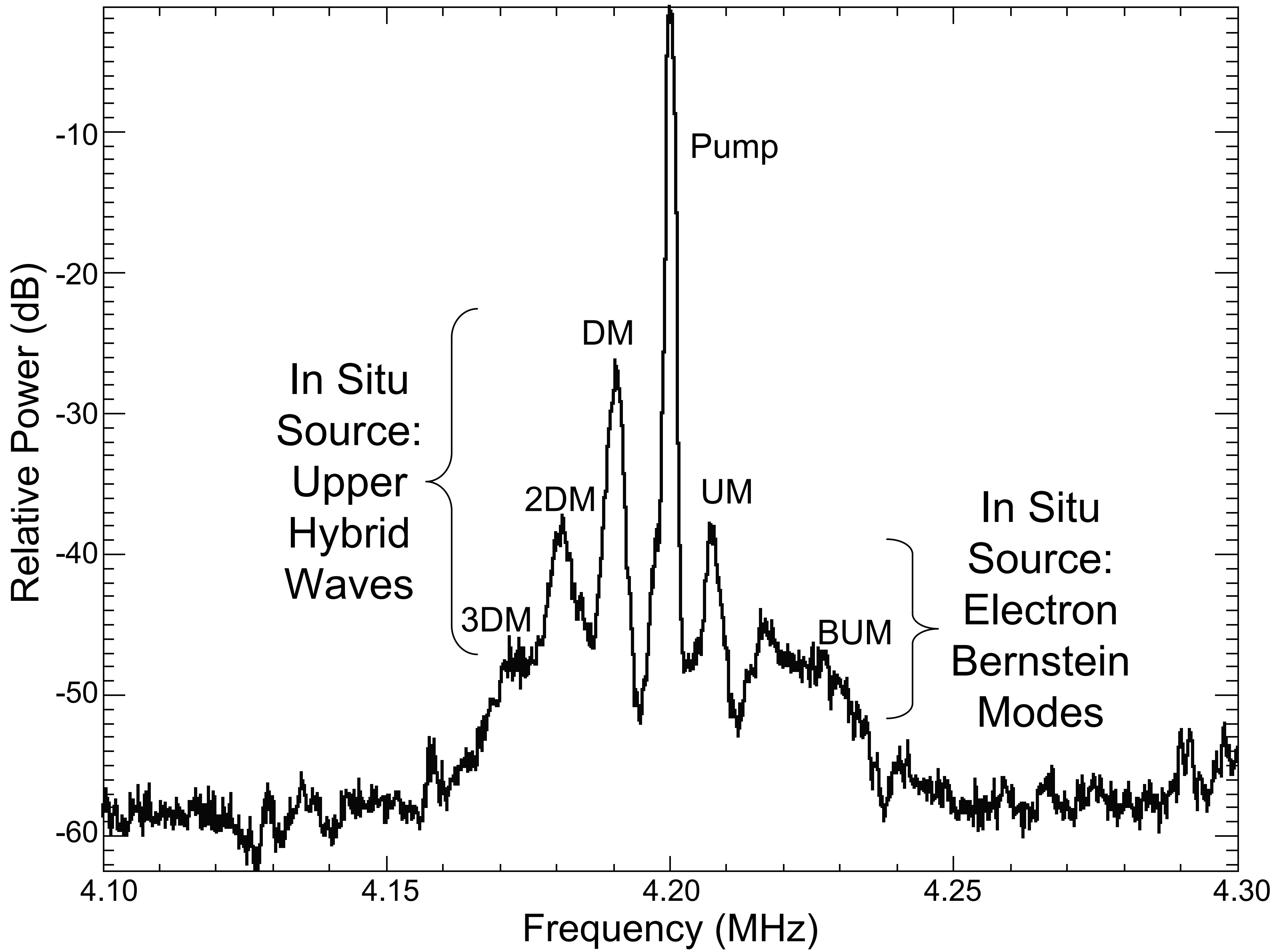
Stimulated Electromagnetic Emissions (SEE)

- SEE Generation by High Power Radio Waves
  - Mode Conversion on Field Aligned Irregularities
  - Parametric Decay of Strong Wave to Two Modes
- Ionospheric Measurements by Low Frequency SEE
  - Stimulated Brillouin of Ion Acoustic Waves → Electron Temperature
  - Stimulated Brillouin of Electrostatic Ion Cyclotron Waves → Ion Mass
  - Stimulated Ion Bernstein Waves → Electron Acceleration Resonance

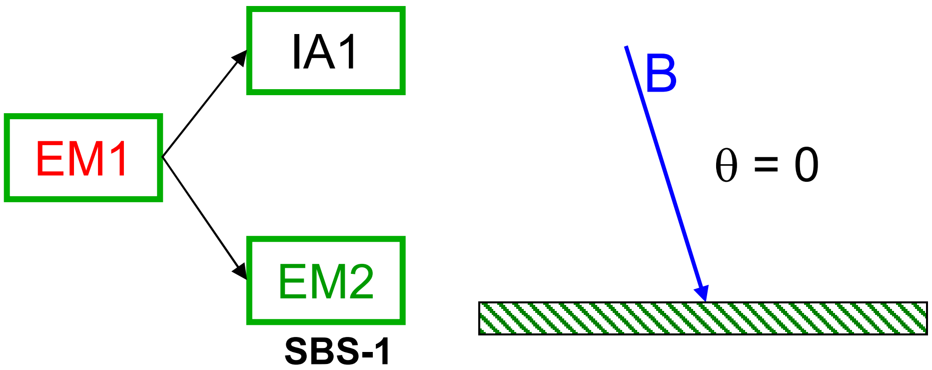
Upper Hybrid and Lower Hybrid Wave Generation is Complex

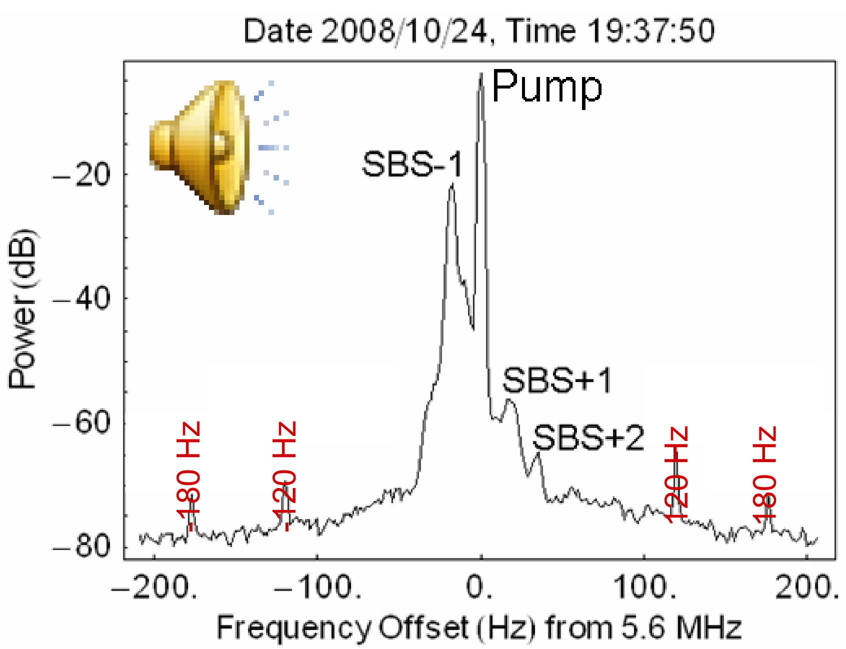


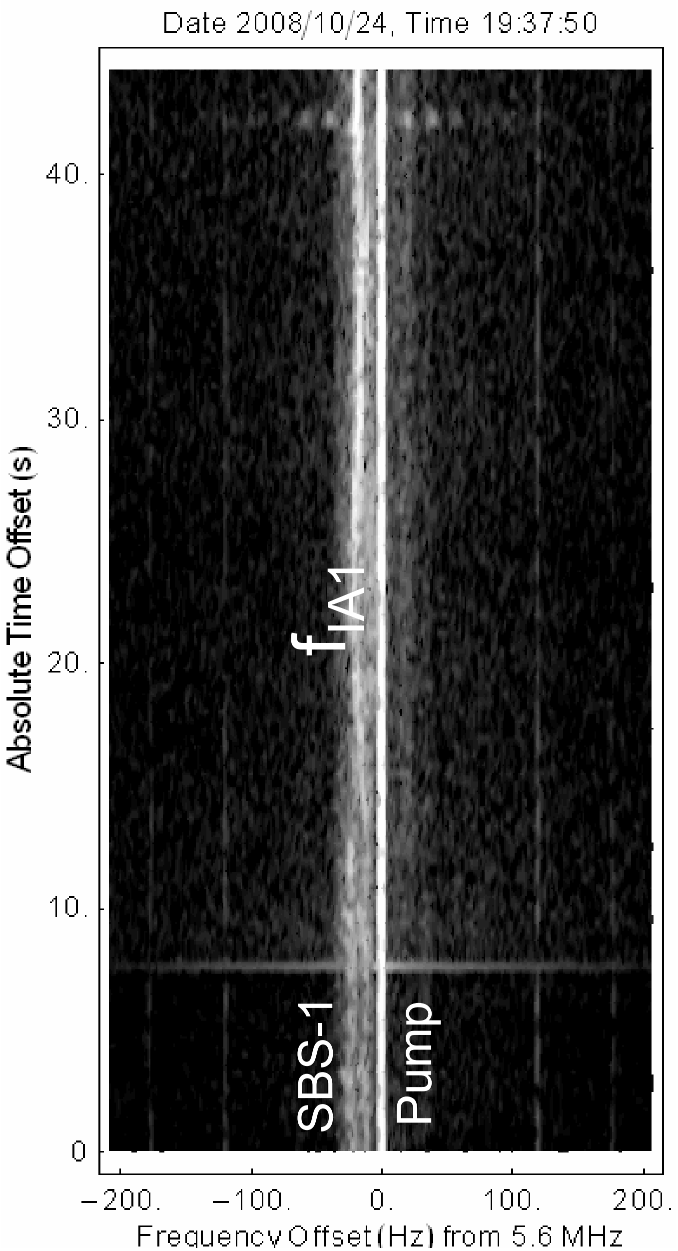
SEE Observations Near the Third Electron Gyro Harmonic SIERRA Site: Glennallen, AK, 20 March 2004



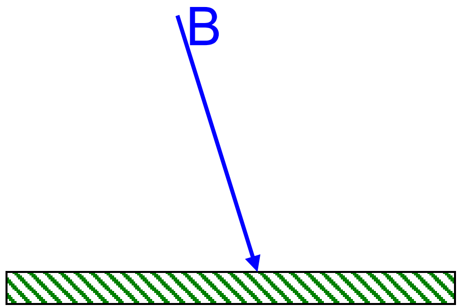
Stimulated Brillouin Scatter with Ion Acoustic Wave Generation is Simple

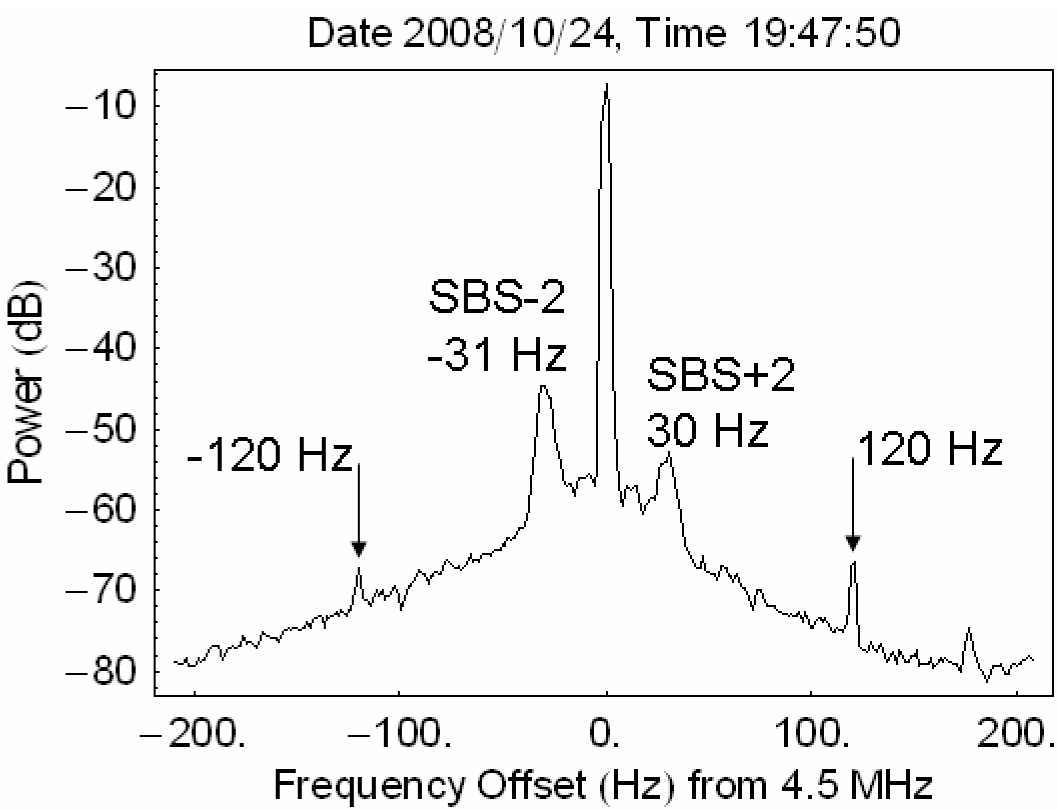


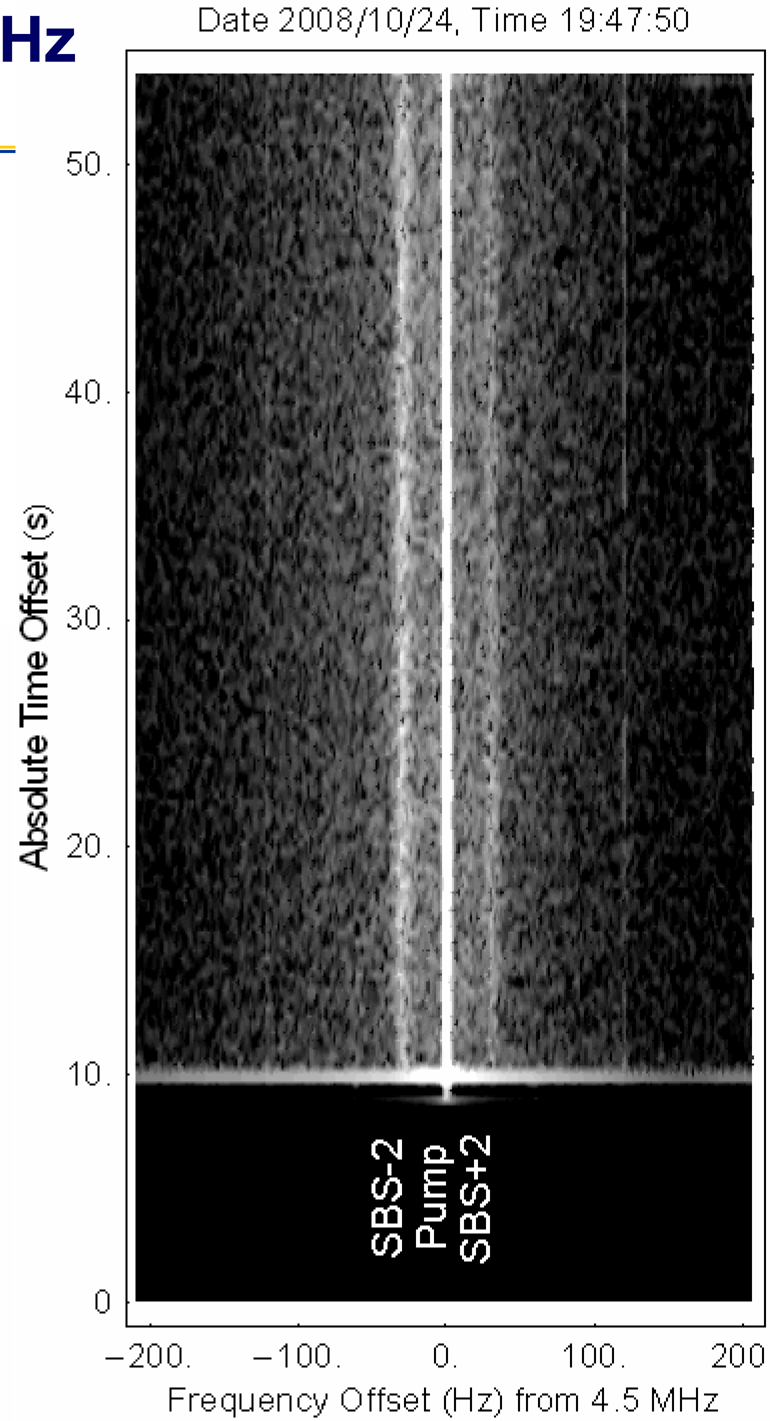




Brillouin Scattering of the 4.5 MHz HAARP Vertical Beam in the Ionosphere







Determination of Electron Temperature at UH Resonance Altitude

- Assumptions

  $T_e \approx 3\,T_i$

  Ω_e, Ω_i known

  $\omega_0 = (\omega_p + \Omega_e)^{1/2}$

- Ion Acoustic Speed

$$c_{IA} = \sqrt{\frac{\gamma_e T_e + \gamma_i T_i}{m_i}} \text{ where } \gamma_e = 1 \text{ and } \gamma_i = 3$$

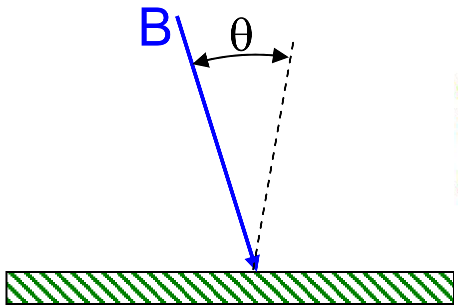
- QL Solution

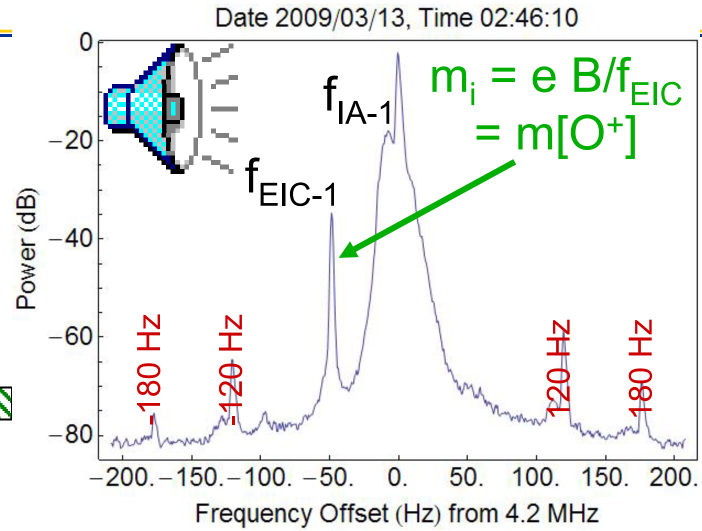
$$\boxed{\boxed{T_e} = \frac{m_i c^2 \boxed{\omega_{IA}^2}}{(\gamma_e + \gamma_i / 3) 4 \Omega_e \omega_0} \frac{\Omega_i^2 - \omega_0^2}{\Omega_i^2 Cos^2\theta - \omega_0^2} \frac{\omega_0 + \Omega_e Cos\theta}{\omega_0 Cos\theta + \Omega_e}}$$

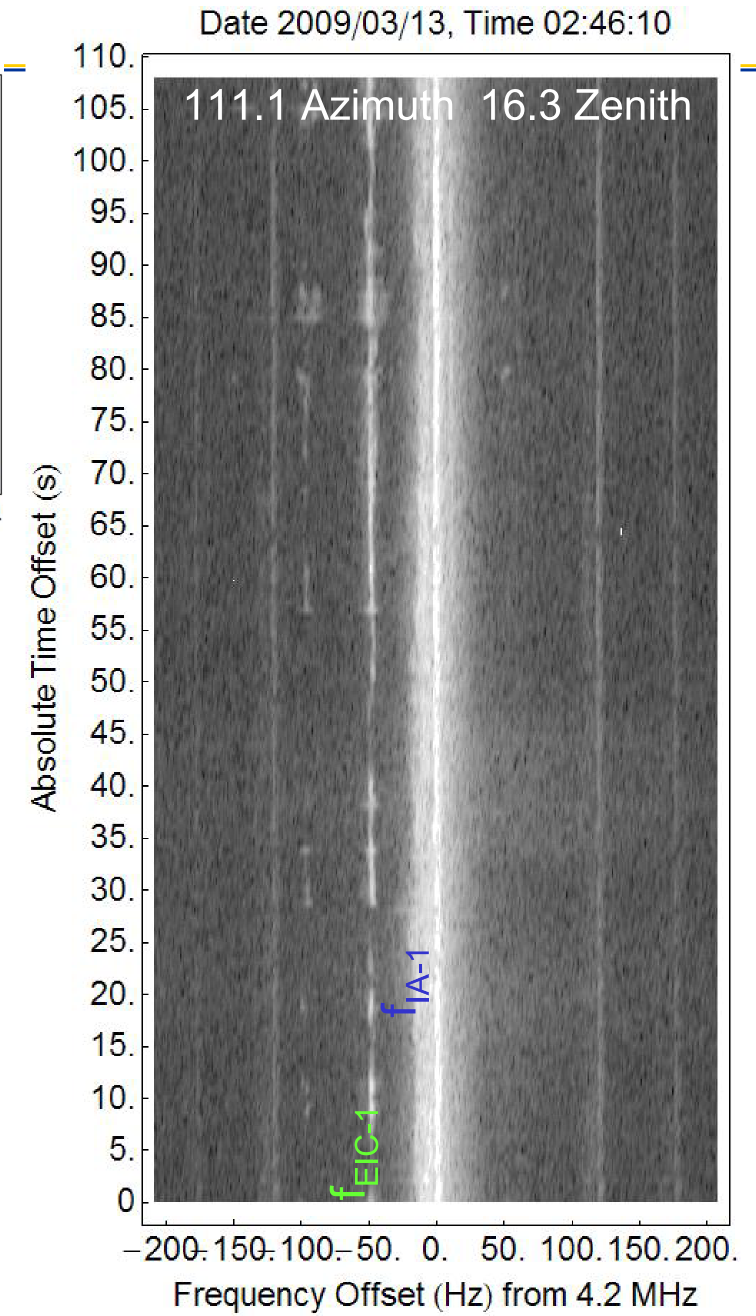
24 October 2008

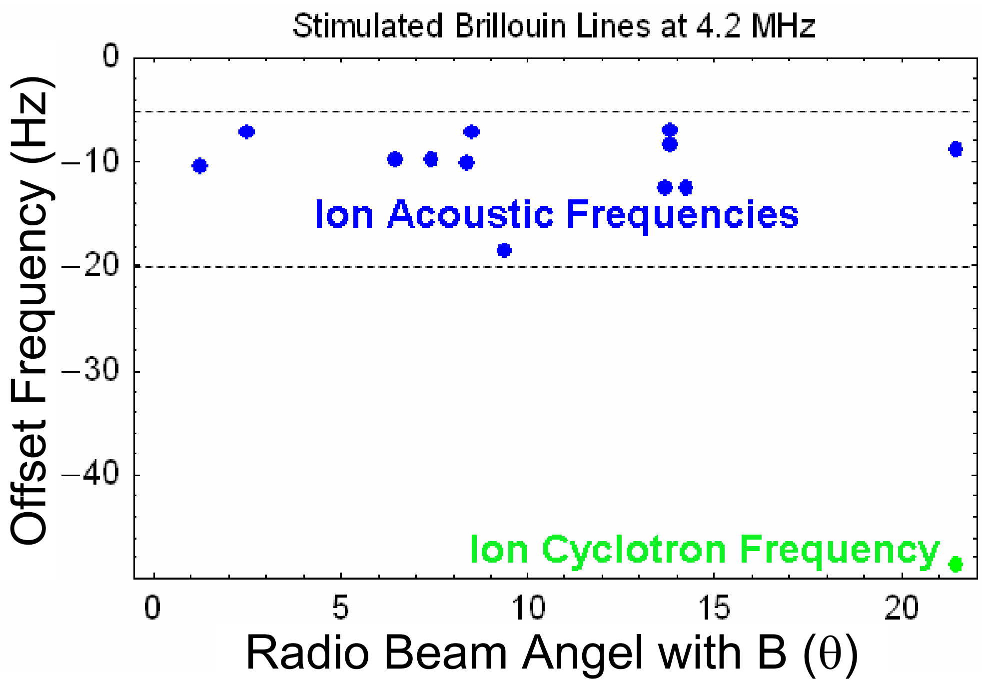
Time (UT)	19:48		19:58	
Line	SBS-2	SBS+2	SBS-2	SBS+2
f_{IA} (Hz)	-30.56	30.56	-29.17	27.78
C_{IA} (m/s)	1780	1780	1690	1580
Te (K)	3506	3506	3176	2866

SBS with EIC Generation Yields Ion Mass



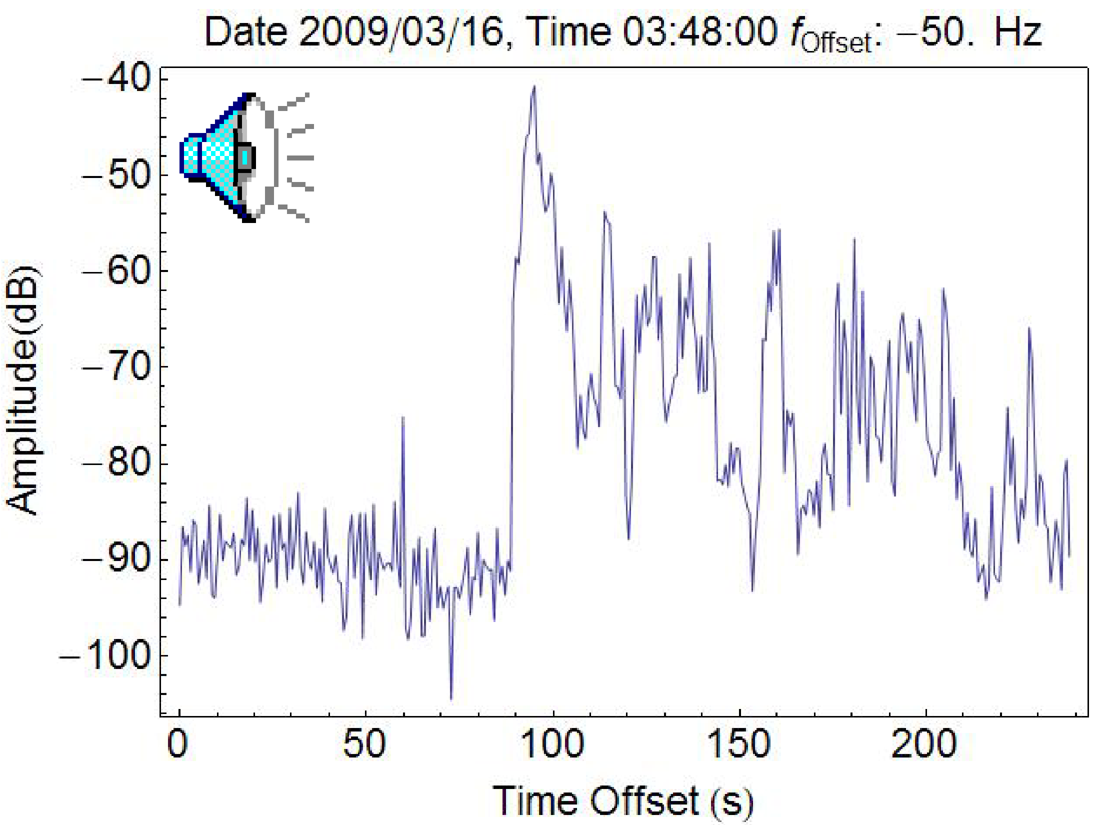


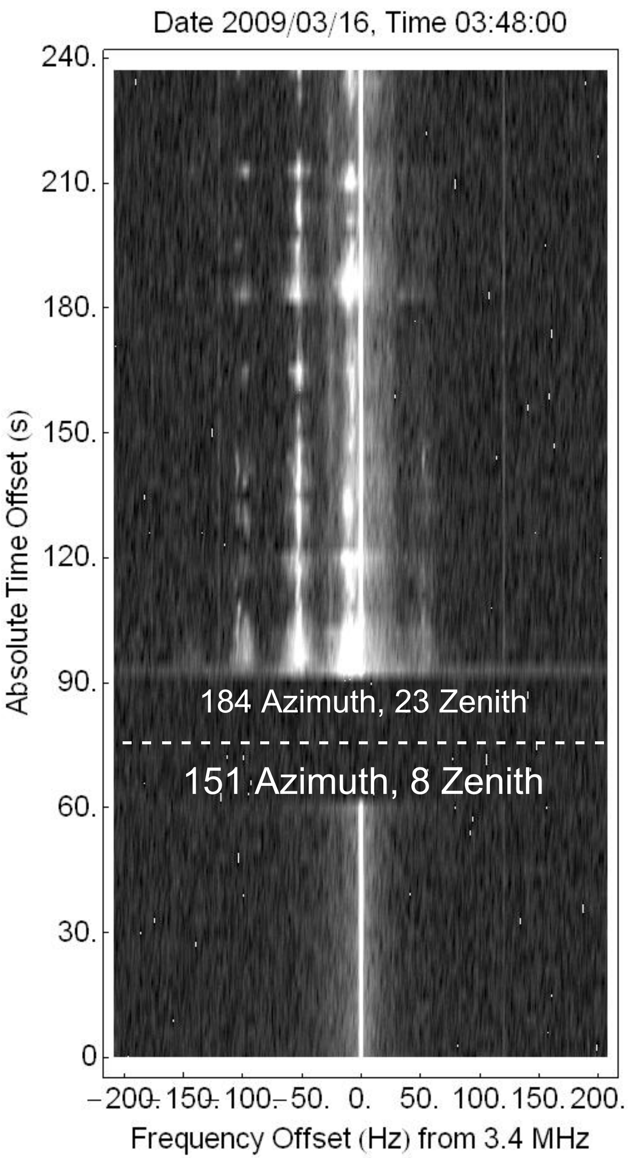




Electrostatic Ion Cyclotron Waves Excitation by at 2nd Electron Gyro Harmonic

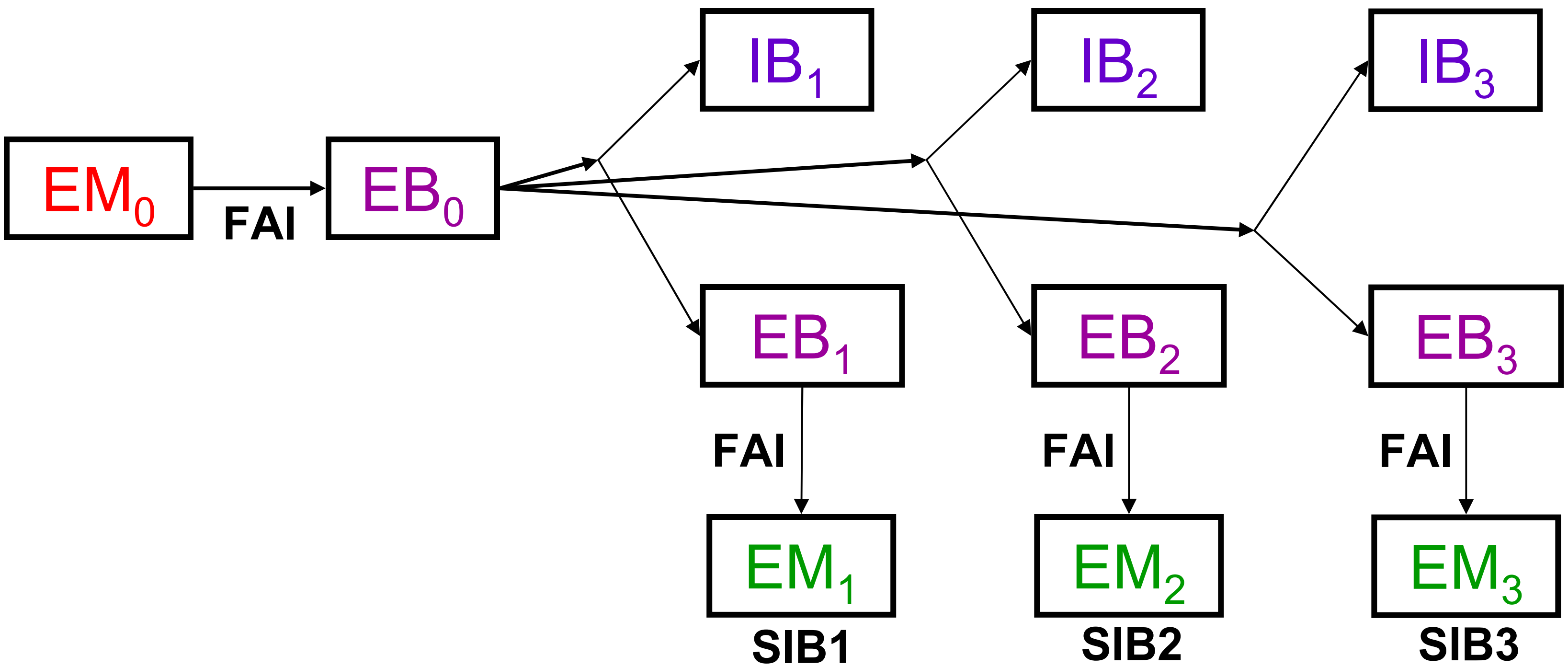
- Ion Cyclotron Frequency = 48.6 Hz
- 40 dB On/Off Fluctuations in Amplitude
- Only Observed Oblique Pointing Angle
- Search for Narrowband Ground ELF Signal

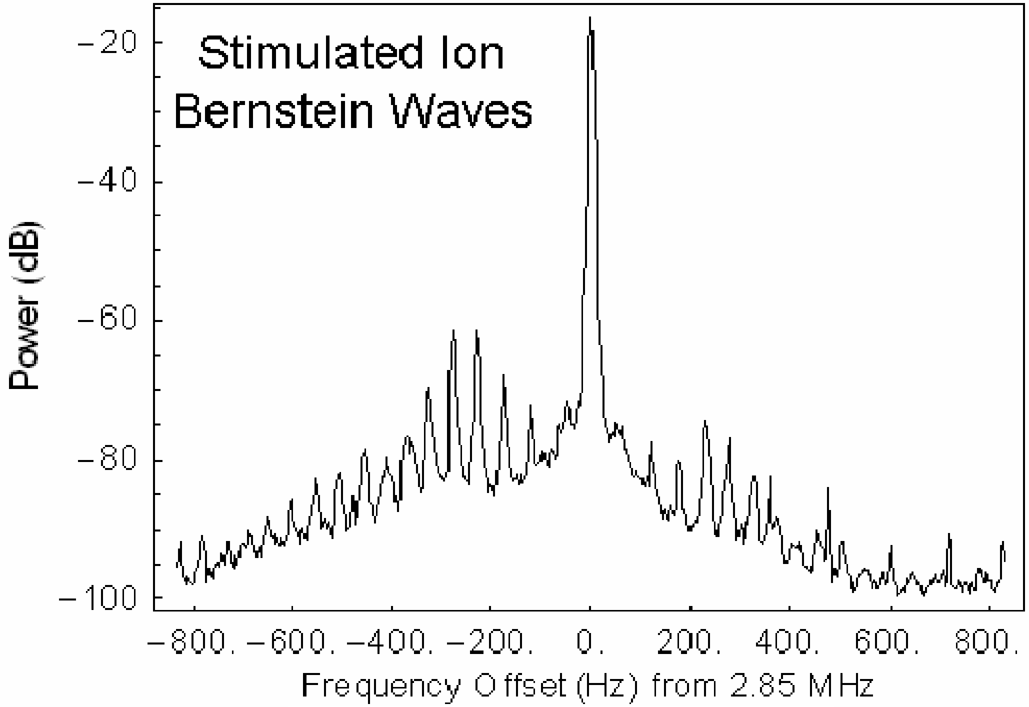


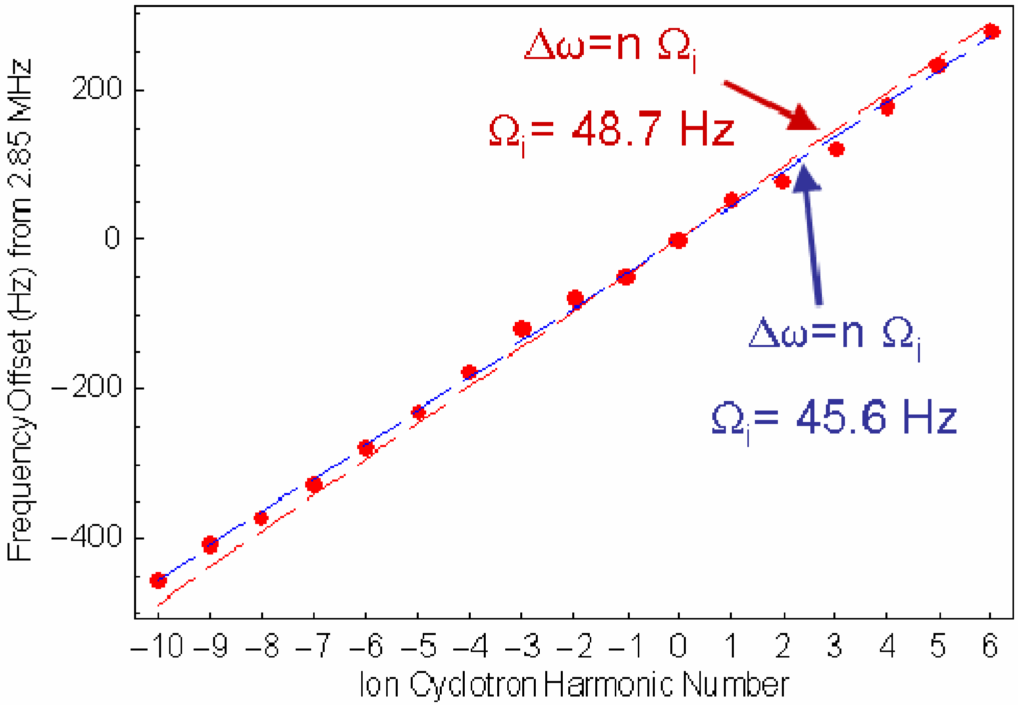


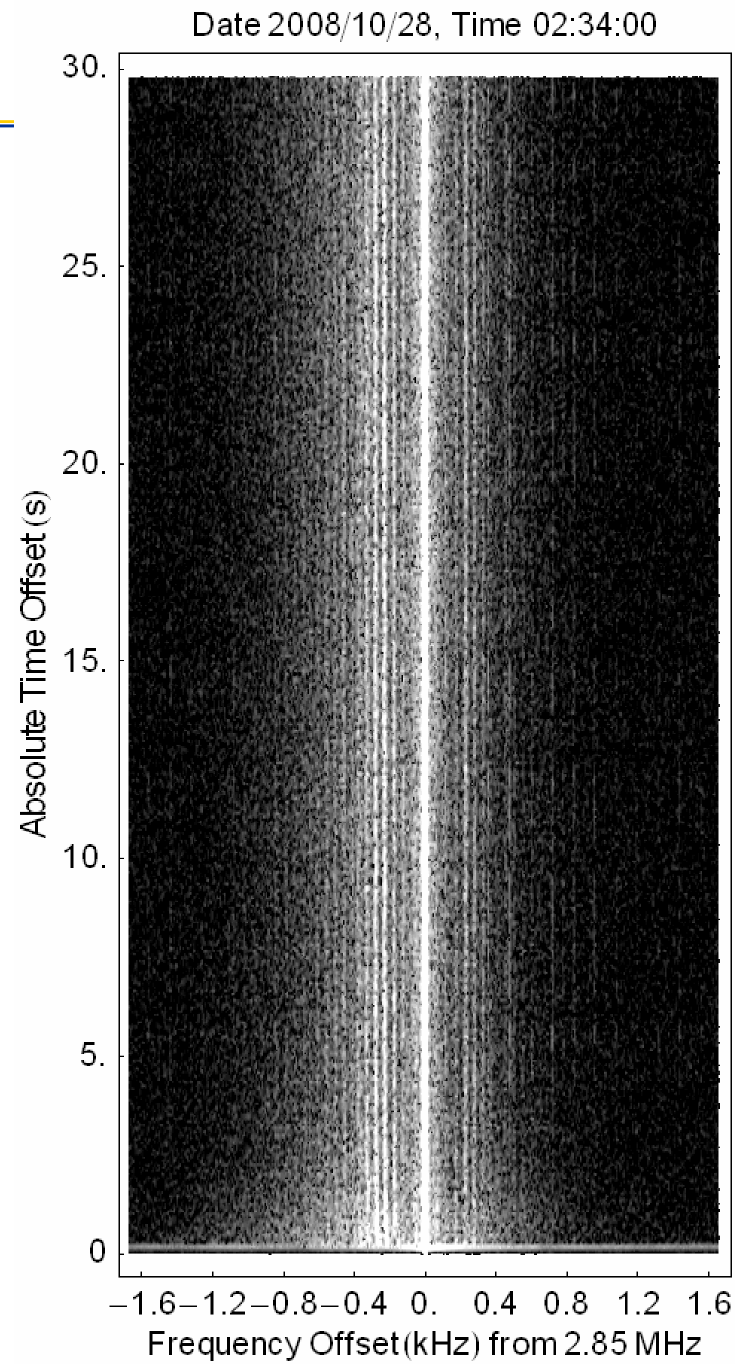
111.1 Azimuth 16.3 Zenith

Stimulated Ion Bernstein (SIB) Generation by Tuning to the Second Electron Gyro Frequency

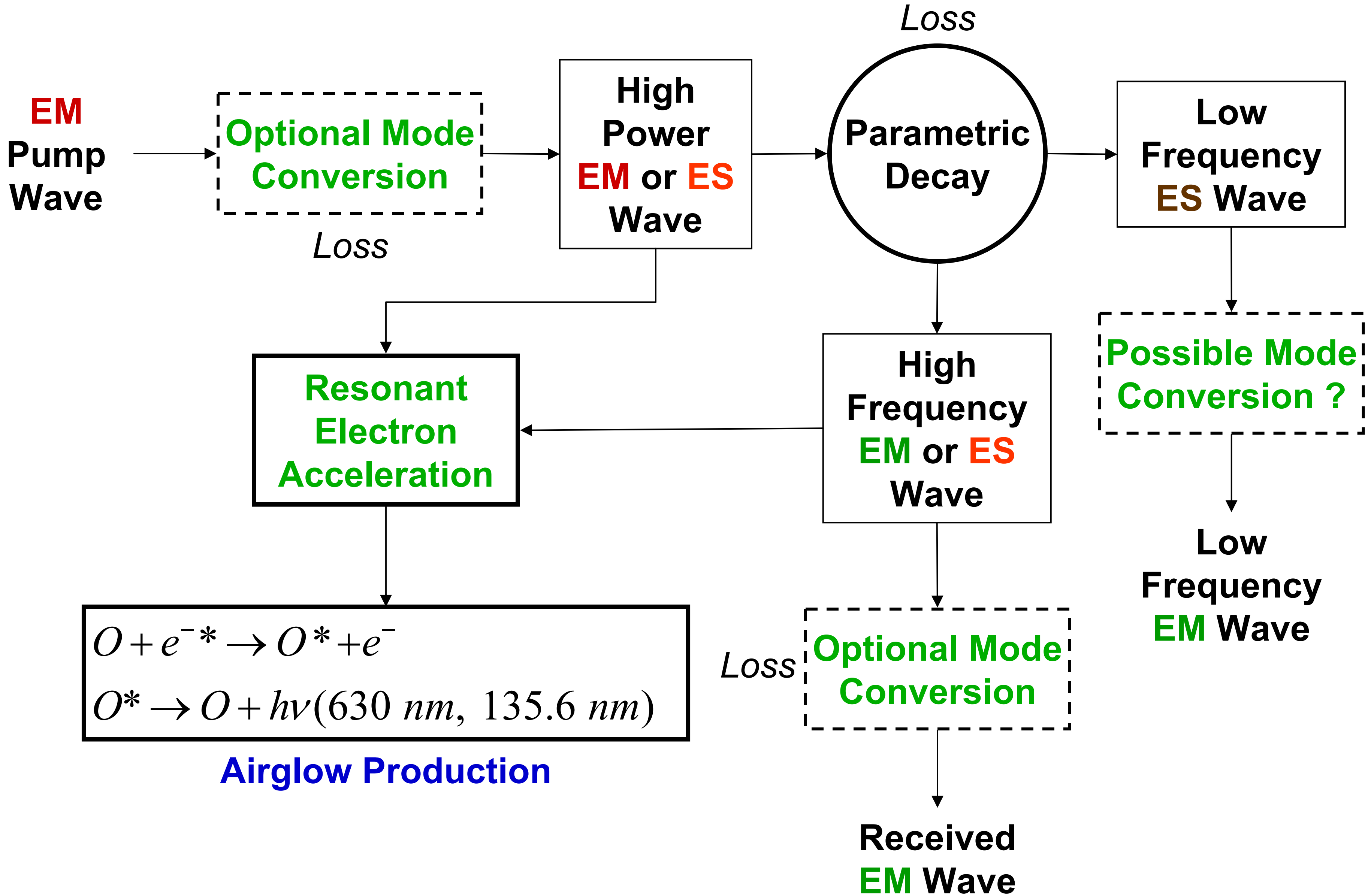



Stimulated Ion Bernstein Waves
Power (dB)
−20
−40
−60
−80
−100
−800. −600. −400. −200. 0. 200. 400. 600. 800.
Frequency Offset (Hz) from 2.85 MHz

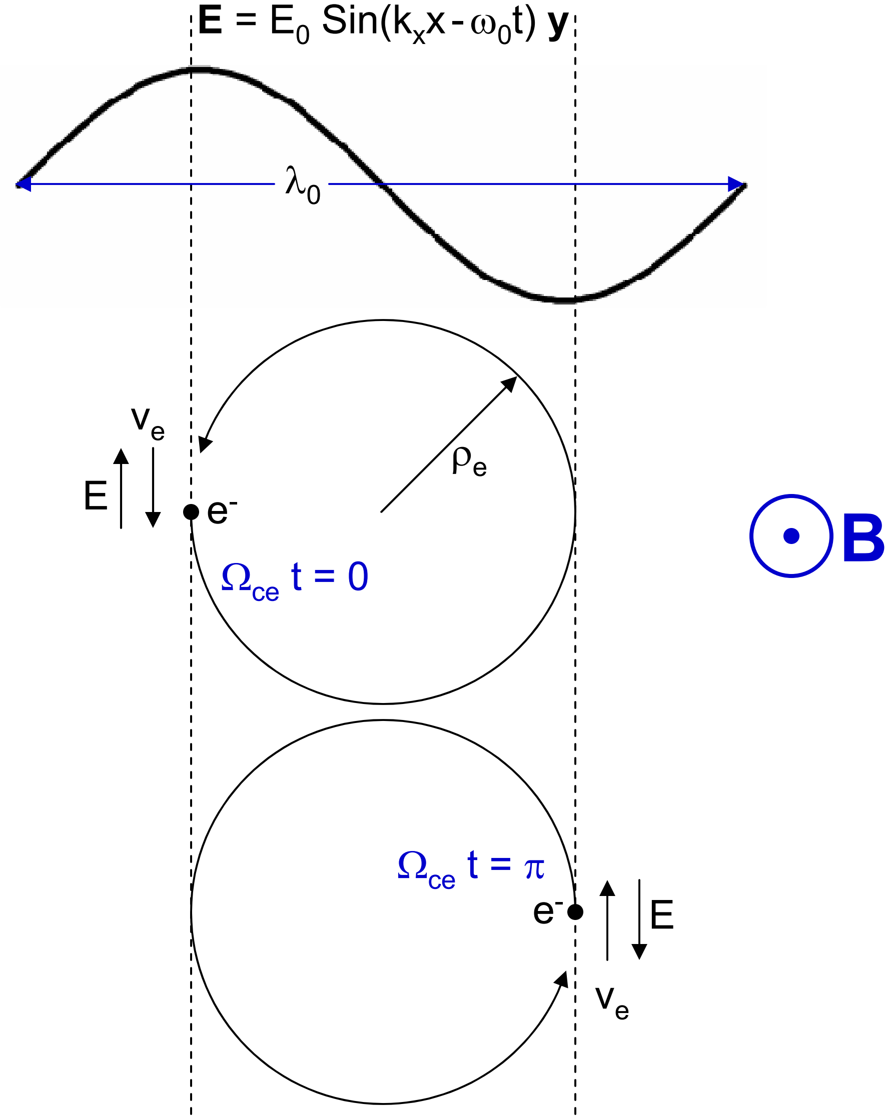

$\Delta\omega$=n Ω_i
Ω_i= 48.7 Hz
$\Delta\omega$=n Ω_i
Ω_i= 45.6 Hz
Frequency Offset (Hz) from 2.85 MHz
200
0
−200
−400
−10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
Ion Cyclotron Harmonic Number


Date 2008/10/28, Time 02:34:00
Absolute Time Offset (s)
30.
25.
20.
15.
10.
5.
0
−1.6 −1.2 −0.8 −0.4 0. 0.4 0.8 1.2 1.6
Frequency Offset (kHz) from 2.85 MHz

Electron Acceleration, ES and EM Wave Generation



Electron Cyclotron Resonance at Twice the Electron Gyro Frequency

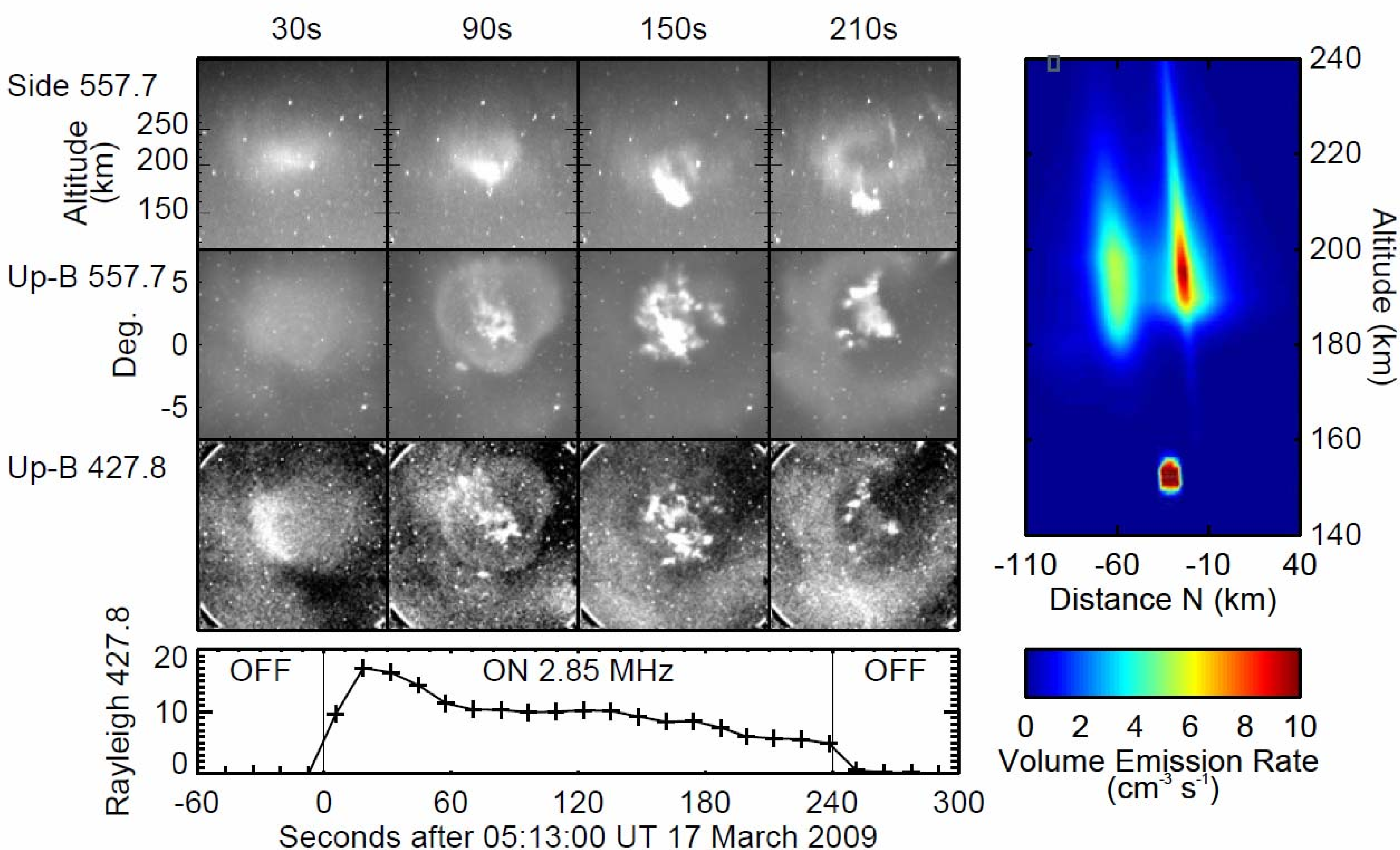


Resonance Conditions

$\omega_0 = 2\,\Omega_{ce}$

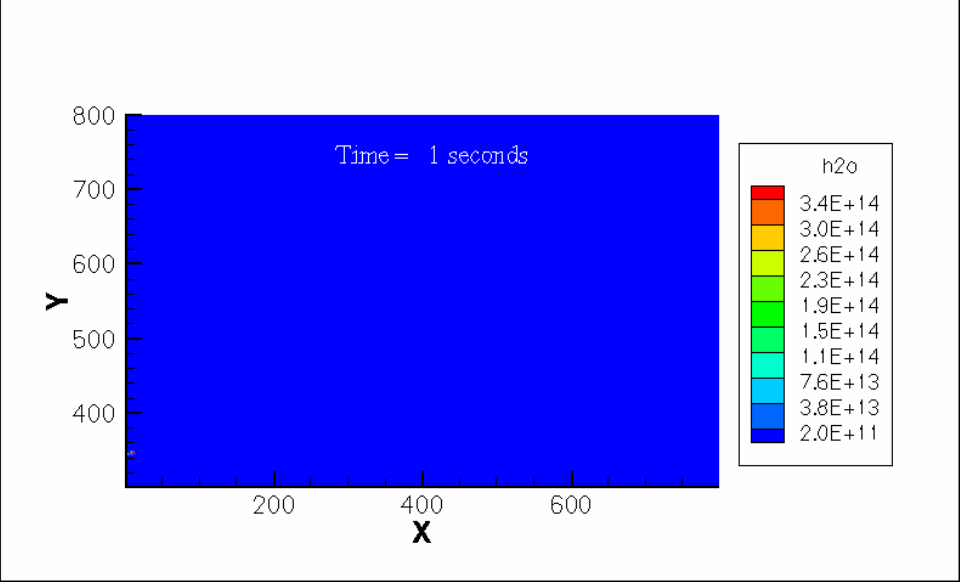
$\lambda_0 = 4\,\rho_e$

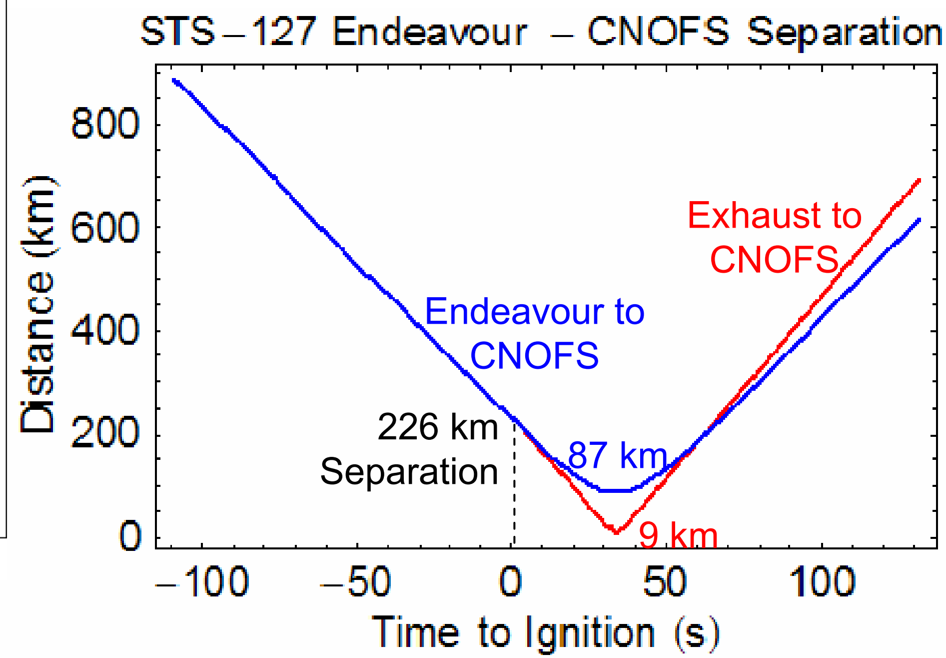
HAARP Enhanced Airglow, Todd Pedersen, AFRL

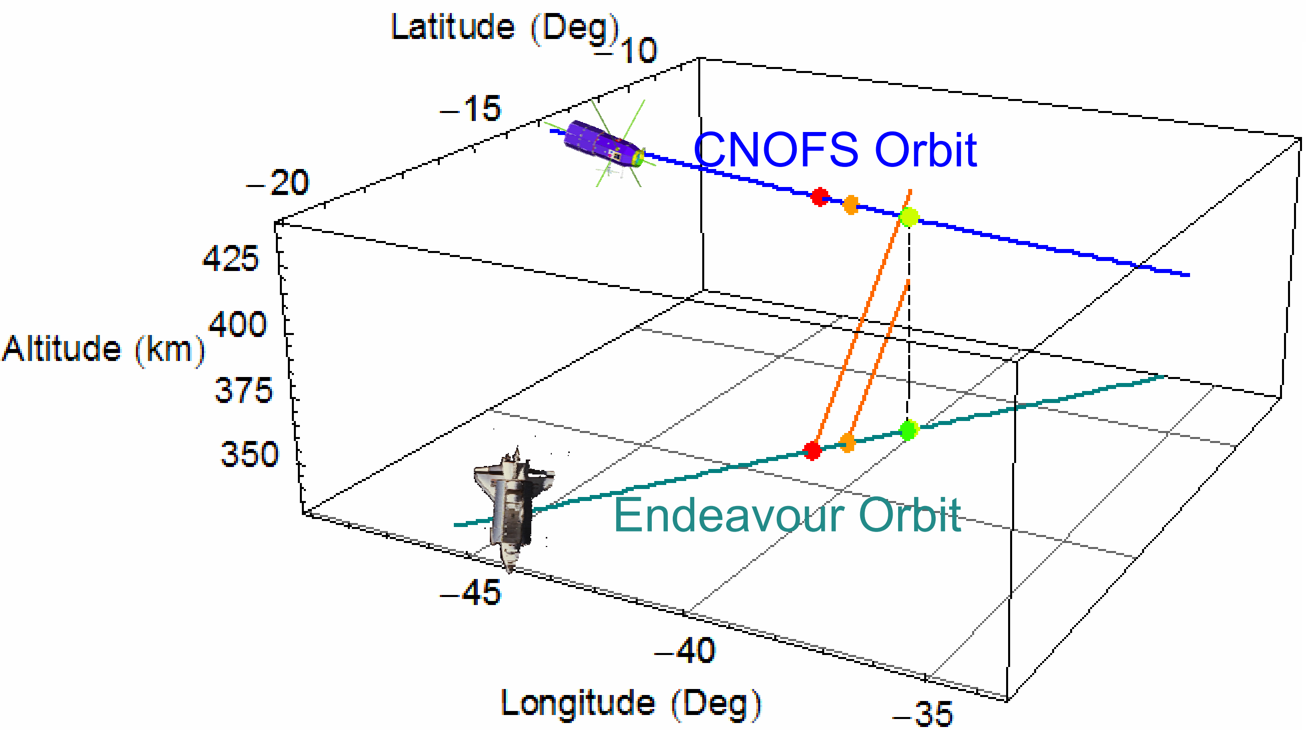


Recent Measurements of Artificial Electrostatic Waves in the Ionosphere

- Electrostatic Waves Generated By High Power Radio Waves.
  - Stimulated Low Hybrid Waves Common
  - Stimulated Brillouin Scatter (SBS) is the strongest SEE Mode
    - Sometimes SBS Emissions is Stronger than HF Pump Return
    - SBS by Overdense High-Power HF in the Ionosphere
    - Discovered by Norin et al. [*PRL*, 2009] in February 2008.
    - This work published by Bernhardt et al., *Annales Geophysicae* , 2009.
    - SBS Produces Extremely Strong SEE Emissions up to 10 dB Below the HF Pump Return
    - SBS Comes from Both the *Reflection Region* and the *UH Resonance Height*
  - The SBS Ion Acoustic Frequency
    - Offset from the Pump Frequency
    - Electron Temperature Measurements from the UH Resonance Region
    - Validation Possible with ISR Measurements of Te at EISCAT or Arecibo Heating Sites
  - The SBS Electrostatic Ion Cyclotron Frequency
    - Precisely at Ion Gyro Frequency
    - Provides Measurement of Ionospheric Ion Composition
    - Paper Just Published [PRL, 2010].
  - Stimulated Ion Bernstein Scatter Discovery
    - First SEE Observations at HAARP
    - Slight Offsets from Ion Cyclotron Frequency Harmonics
  - Many Modes with Unknown Origin
  - Provides Links to Artificial Airglow Generation

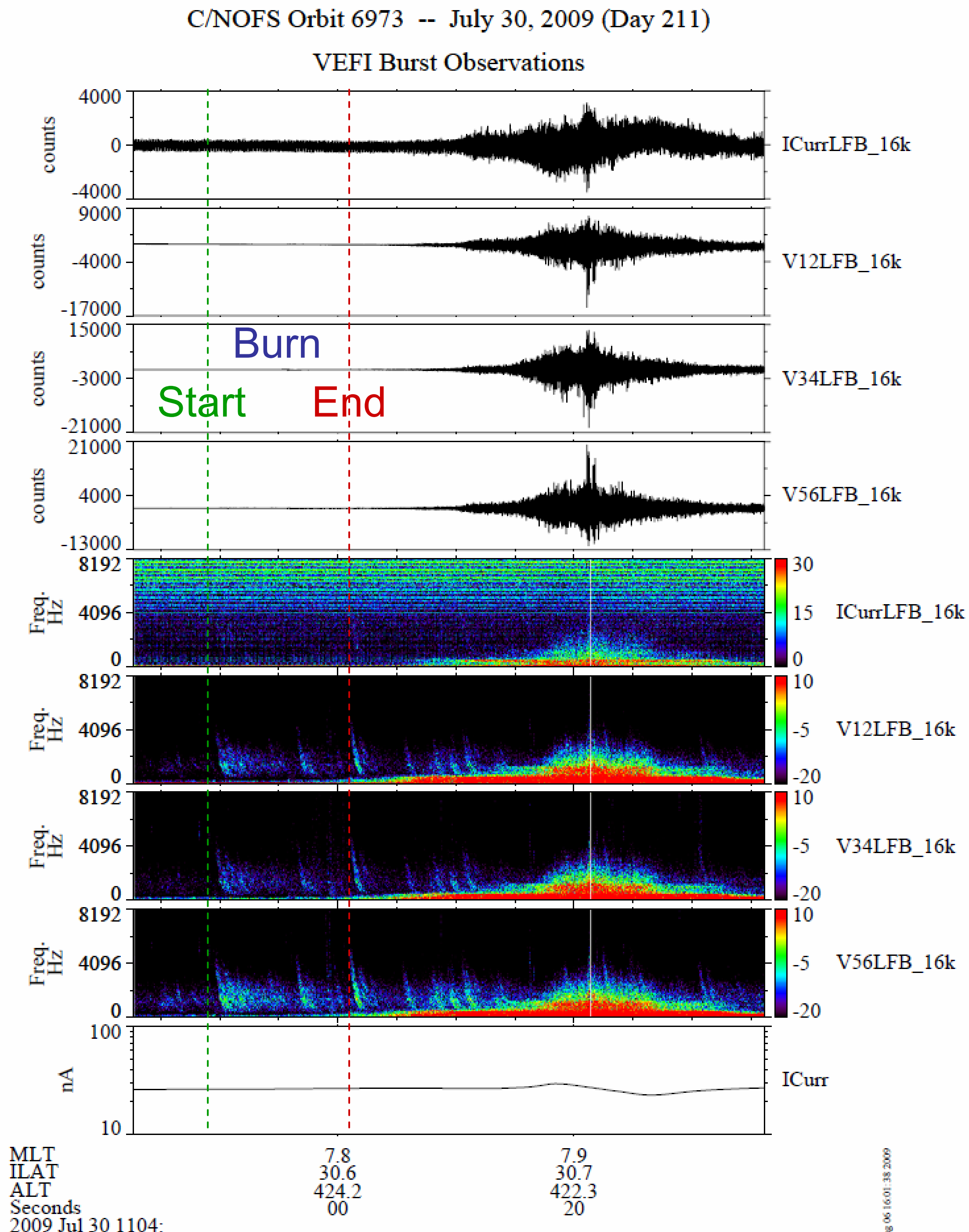






OMS Burn for the STS-127 Conjunction with CNOFS

STS-127 OMS Burn Observed by C/NOFS



MHD Waves Excited by Rocket Burns

- Magnetized Plasma Driven by a Neutral Pulse

$$\frac{\partial n}{\partial t} + n_0 \nabla \cdot \mathbf{v} = 0, \frac{\partial \boldsymbol{\xi}}{\partial t} = \mathbf{v}, \quad \frac{\partial \mathbf{v}}{\partial t} = -\frac{\nabla (nkT)}{n_0 m_i} + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}_0}{\mu_0 n_0 m_i} + \nu_{in} (\mathbf{v}_n - \mathbf{v})$$

$$\frac{\partial nkT}{\partial t} - \gamma k T_0 \frac{\partial n}{\partial t} = 0, \quad \mathbf{E} + \mathbf{v} \times \mathbf{B}_0 = 0, \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \mathbf{B}_0 = B_0 \mathbf{b}$$

- Three Waves

Slow Magnetosonic or Sound: $\Sigma_0 = \boldsymbol{\xi} \cdot \mathbf{b}$

Alfven: $\Sigma_1 = (\nabla \times \boldsymbol{\xi}) \cdot \mathbf{b}$

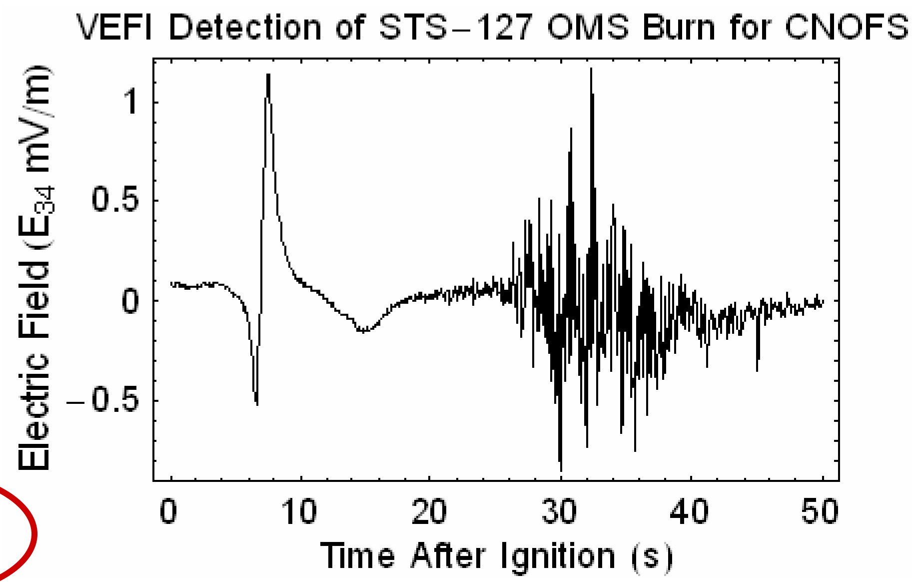
Fast Magnetosonic: $\Sigma_2 = \nabla \cdot \boldsymbol{\xi}$

- Wave Equations

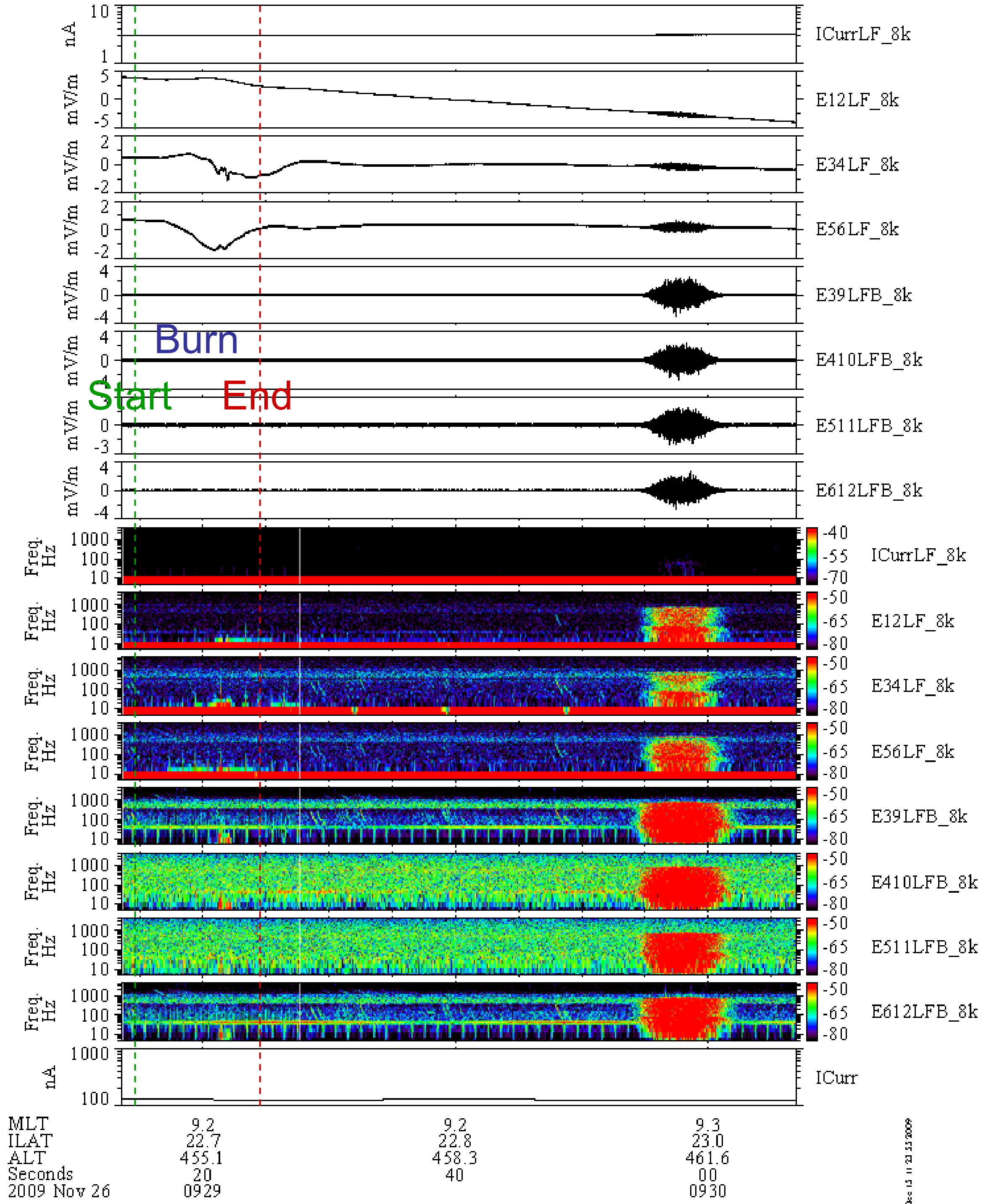
$$\frac{\partial^2 \Sigma_0}{\partial t^2} + \nu_i \frac{\partial \Sigma_0}{\partial t} = C_S^2 \nabla \Sigma_2 \cdot \mathbf{b} + \nu_{in} \mathbf{v}_n \cdot \mathbf{b}$$

$$\frac{\partial^2 \Sigma_1}{\partial t^2} + \nu_i \frac{\partial \Sigma_1}{\partial t} = C_A^2 \nabla (\nabla \Sigma_1 \cdot \mathbf{b}) \cdot \mathbf{b} + \nu_{in} (\nabla \times \mathbf{v}_n) \cdot \mathbf{b}$$

$$\frac{\partial^2 \Sigma_2}{\partial t^2} + \nu_i \frac{\partial \Sigma_2}{\partial t} = \nabla^2 [(C_A^2 + C_S^2) \Sigma_2 - C_A^2 \nabla \Sigma_0 \cdot \mathbf{b}] + \nu_{in} \nabla \cdot \mathbf{v}_n$$



STS-129 OMS Burn Observed by C/NOFS



Conclusions

- Active Experiments Can "Illuminate" the Physics of the Ionosphere
  - High Power Radio Waves Excite Optical and Radio Emissions
    - Irregularities Images
    - Ion Composition Measurements
    - Ion Sound Speed and Plasma Temperature Determination
    - Conditions for Resonant Acceleration of Electrons
  - Rocket Exhaust is a Remote Sensing Tool
    - Enhance Glow from Plasma Irregularities
    - Triggering of Instabilities
      - Ion Beams
      - Small Scale Field Aligned Irregularities
      - Large Scale Plasma Bubbles
    - Stimulation of Plasma Wave Modes
      - MHD Waves for Large Distance Propagation
      - Local Enhancements in Plasma Wave Turbulence
- Active Experiments Complement Passive Remote Sensing Tools