Using Active Experiments to SEE and HEAR the Ionosphere

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Plus Major Contributors

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Boulder, Colorado
22 June 2010
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

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Materials</th>
<th>Optical Emissions</th>
<th>Fastest Rate</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Clouds: Photo-ionization</td>
<td>Li, Na, Sr, Cs, Ba, Eu, U</td>
<td>553.5 nm (Ba)</td>
<td>0.05 s⁻¹ (Ba)</td>
<td>Ba + hν → Ba⁺ + e⁻</td>
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<tr>
<td></td>
<td></td>
<td>455.4 nm (Ba⁺)</td>
<td>0.005 s⁻¹ (Eu)</td>
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<td></td>
<td>0.00029 s⁻¹ (Li)</td>
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<tr>
<td>Plasma Clouds:</td>
<td>Sm, La, Nd, Ti</td>
<td>Molecular Bands of SmO (656 to 570 nm)</td>
<td>2 x 10⁻¹¹ (SmO)</td>
<td>Sm + O → SmO⁺ + e⁻ + 0.39 eV</td>
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<tr>
<td>Associative Ionization</td>
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<tr>
<td>Plasma Holes: Electron Attachment</td>
<td>SF₆, CF₃Br, Ni(CO)₄</td>
<td>777.4 nm (SF₆)</td>
<td>2.2 10⁻⁷ cm³/s (SF₆)</td>
<td>SF₆ + e⁻ → SF₅⁻ + F - 0.25 eV</td>
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<td></td>
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<td></td>
<td>SF₅⁻ + O⁺ → SF₅ + O⁺ + 9.91 eV</td>
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<tr>
<td>Plasma Holes: Ion-Molecule Charge</td>
<td>H₂, H₂O, CO₂</td>
<td>630 nm (CO₂)</td>
<td>3.2 10⁻⁹ cm⁻³ (H₂O)</td>
<td>H₂O + O⁺ → H₂O⁺ + O</td>
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<tr>
<td>Exchange</td>
<td></td>
<td></td>
<td></td>
<td>H₂O⁺ + e⁻ → OH⁺ + H</td>
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<tr>
<td>Neutral Wind Tracer</td>
<td>Al, NO, Na, Al(CH₃)₃, Fe(CO)₃, Ni(CO)₄</td>
<td>Molecular Bands of AlO (484, 508, 465, 534 nm)</td>
<td>--</td>
<td>Al(CH₃)₃ + O → AlO⁺ + ...</td>
</tr>
</tbody>
</table>
Space Shuttle OMS Engine Exhaust Parameters

Orbital Maneuvering System (OMS)

- Nonuniform Dual OMS Burn
- Symmetrical Dual OMS Burn in Daylight
- Single OMS Burn at Night

Flow Rate: $2.5 \times 10^{26}$ Molecules per Second per Engine

<table>
<thead>
<tr>
<th>Exhaust Species</th>
<th>Mole Fraction</th>
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<tbody>
<tr>
<td>CO</td>
<td>0.050</td>
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<tr>
<td>CO$_2$</td>
<td>0.122</td>
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<tr>
<td>H$_2$</td>
<td>0.241</td>
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<tr>
<td>H$_2$O</td>
<td>0.274</td>
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<tr>
<td>N$_2$</td>
<td>0.313</td>
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</table>
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

Radar Diagnostics of Artificial Plasma Turbulence
Dedicated Burns Scheduled Through DoD Space Test Program with NASA Johnson Spaceflight Center
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

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

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
Wave and Airglow Generation by Chemical Releases:
SIMPLEX– Space Shuttle Exhaust

High Speed Neutral Release → Ion Beam Formation → Unstable Velocity Distribution → Plasma Wave Generation → Application

Orbit Velocity → Charge Exchange with Ambient Ions → Parallel to Geomagnetic Field → Ion Acoustic Waves → Radar Scatter

→ Perpendicular to Geomagnetic Field → Lower Hybrid Waves → Optical Emissions

→ Electron-Molecular Ion Recombination → Excited Atomic and Molecular States → Artificial Airglow
Stimulated Electromagnetic Emissions, Radar Backscatter, Enhanced Plasma Waves and Artificial Aurora
Ionospheric Modification with High Power Radio Waves

High Power Electromagnetic Wave Beam

- High Power Electromagnetic Wave Beam
- Plasma Irregularity Formation
- Electrostatic Wave Generation
- Parametric Decay and Strong Turbulence
- Electron Temperature Elevation

Plasma Pressure and Density Changes

VLF Ducts and Conductivity Modification

VLF Waveguides and VLF Generation

Enhanced Radar Scatter

Mode Conversion

Low Frequency Waves

Electron Acceleration

Artificial Aurora

Stimulated Electromagnetic Emissions

Plasma Line
Active Studies of the E-Layer
Penetration of HF Waves Through a Patchy Sporadic-E Layer

Ionogram

Ionosonde

Radio Waves

Ionospheric Reflection

F-Layer

E-Layer

Overdense Patches

Sporadic Reflection

Altitude (km)

North (km)

West (km)
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 DataCourtesy M.F. Larsen, Clemson
Quasi-periodic Echoes -- (SEEK-2)
Rocket/Radar Campaign in Japan

Neutral Wind trail reveals Kelvin-Helmholtz “whorls.”

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

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

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Receiver</th>
<th>Launch Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chesapeake Virginia</td>
<td>Fort Stewart Georgia</td>
<td>Cape Canaveral Florida</td>
</tr>
<tr>
<td>1050 km Range to Launch</td>
<td>402 km Range to Launch</td>
<td>0 km Range to Launch</td>
</tr>
<tr>
<td>199.5° Azimuth to Launch</td>
<td>163.5° Azimuth to Launch</td>
<td>---</td>
</tr>
<tr>
<td>167° ± 50° Azimuth Target Illumination</td>
<td>165° ± 50° Azimuth Target Viewing</td>
<td>---</td>
</tr>
</tbody>
</table>
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)

23 January 1998

Modified F-Layer Near 340 km Altitude

Descending Layer

Sporadic-E Layer Near 120 km Altitude
HF Electromagnetic Waves Interacting with a Plasma Density Enhancement

References:
Two Color (Red/Green) Composite Image of Radio Induced Aurora
Arecibo, Puerto Rico 23 January 1998

02:38 UT

E_s Irregularity at 120 km Altitude

F-Layer at 260 km Altitude

02:41 UT

E_s Irregularity at 120 km Altitude

F-Layer at 260 km Altitude
Arecibo HF Facility Antenna Gain at 8.175 MHz Giving 220 MegaWatts ERP Available Starting January 2011
Field Line Connecting Arecibo and Argentina

4 eV Electron Velocity = 1.2 \times 10^6 \text{ m/s}
Field Line Distance = 9.8 \times 10^6 \text{ m}
4 eV Electron Free Streaming Transit Time = 8 \text{ s}
Pulsed Heating Yields Transit Time for Suprathermal Electrons Between Hemispheres

HF Source of Suprathermal Electrons
Active Studies of the Equatorial Ionosphere
Simulations of Radio Scintillations and Optical Intensities

Electron Density

630 nm Volume Emission

Altitude (km)  
Horizontal Range (km)

$10^6 \text{ cm}^{-3}$  

$10^6 \text{ cm}^{-3}$  

$4.5 \text{ cm}^{-3}\text{s}^{-1}$

$150 \text{ MHz Scintillation Index}$  

$400 \text{ MHz Scintillation Index}$  

$630 \text{ nm Red-Line Intensity}$
Combining Radio Scintillations and Plasma Bubble Images

SIMPLEX Burn Viewed from Kwajalein
25 July 1999

Longitude (°E)

Latitude (°N)

Radar
58.7° Elevation
147.6° Azimuth

Burn

Orbit

52.5°
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

Expected Region of Turbulent Scatter
Burn
Shuttle Echo
Shuttle Orbit

Log_{10}(SNR)
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

Time After Burn (Hours)

Zonal Latitude Offset from Burn (Degrees)

Samoa Receiver Data

GPS TEC Disturbances

Kwajalein Receiver Data

100 m/s Zonal Drift
GPS TEC from Samoa Receiver for the Hours after the STS-93 SIMPLEX Burn Over Kwajalein

Result of Burn?
SIMPLEX K3 – STS 122

- OMS Burn - 08 February 2008
- 12:43 UT (23:53 LT)
- Spread-F Event
- ALTAIR not available
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
SIMPLEX K3

Kwajalein Atoll
12:45:05 UT
5577 Å

Kwajalein Atoll
12:44:03 UT
6300 Å

~10km Wide Field
Aligned Irregularities

Structure in 557.7 nm
observations
Mid- and High-Latitude F-Region Irregularities
NRL SIMPLEX-5 Burn on STS-119, 27 March 2009

Experiment Planning and Sensor Coordination

DSMC Simulation

HF Radar Backscatter

UHF Radar Thompson Scatter

Ne (m⁻³)
Artificial Aurora Experiments

- 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 ($\omega_p$)
  $$-\nabla^2 E_p + \nabla (\nabla \cdot E_p) - k_p^2 [I + X_{sp}] \cdot E_p = 0$$

- Scattered Electromagnetic Wave ($\omega_s$)
  $$-\nabla^2 E_s + \nabla (\nabla \cdot E_s) - k_s^2 [I + X_{ss}] \cdot E_s = k_p^2 \bar{X}_{sl} \cdot E_p$$

- Low Frequency Ion Velocity Waves ($\omega_L$)
  - Ion Acoustic/Slow Magnetosonic
  - Electrostatic Ion Cyclotron
  $$\nabla (\nabla \cdot \vec{v}_i) + \frac{\omega_{L\pm}^2}{c_{IA}^2} \left(U_i \vec{v}_i - i \frac{\Omega_i \times \vec{v}_i}{\omega_{L\pm}^2} \right) = \frac{i \omega_{L\pm} q_e^2}{4 m_i m_p \omega_p^2 c_{IA}^2} \nabla (E_T \cdot E_T)$$

- Result: Parametric Decay Instability
  $$\omega_p = \omega_s + \omega_L$$
  $$k_p = k_s + k_L$$
ES and EM Wave Generation

- **EM Pump Wave**
  - Optional Mode Conversion
  - High Power EM or ES Wave
  - Parametric Decay
  - Low Frequency ES Wave
  - Possible Mode Conversion?

<table>
<thead>
<tr>
<th>Wave</th>
<th>Examples Transverse to B</th>
<th>Examples Quasi-Parallel to B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM Pump</strong></td>
<td>O-Mode, X-Mode</td>
<td>L-Mode, R-Mode</td>
</tr>
<tr>
<td><strong>Low Frequency Electromagnetic</strong></td>
<td>Magnetosonic</td>
<td>Alfvén Whistler</td>
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<tr>
<td><strong>Low Frequency Electrostatic</strong></td>
<td>Lower Hybrid Ion Acoustic Ion Bernstein</td>
<td>Slow Magnetosonic Ion Cyclotron Ion Acoustic</td>
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<tr>
<td><strong>High Frequency Electromagnetic</strong></td>
<td>O-Mode, X-Mode</td>
<td>L-Mode, R-Mode</td>
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<tr>
<td><strong>High Frequency Electrostatic</strong></td>
<td>Upper Hybrid Electron Cyclotron Electron Bernstein</td>
<td>Electron Plasma</td>
</tr>
</tbody>
</table>
Pairs of Waves Produced by Parametric Decay of Strong Pump Waves

<table>
<thead>
<tr>
<th>Daughter Wave #2</th>
<th>EM</th>
<th>EP</th>
<th>UH</th>
<th>EB</th>
<th>IA</th>
<th>EIC</th>
<th>LH</th>
<th>IB</th>
<th>W</th>
<th>ZFE</th>
<th>ZFI</th>
<th>FAI</th>
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<tr>
<td>Daughter Wave #1</td>
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<td>Electromagnetic (EM)</td>
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<td>Upper Hybrid (UH)</td>
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<td>EM</td>
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<td>Electron Bernstein (EB)</td>
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<td>EB</td>
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<td>Electrostatic Ion Cyclotron (EIC)</td>
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<td>Lower Hybrid (LH)</td>
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<td>Ion Bernstein (IB)</td>
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<td>Zero Frequency Electron (ZFE)</td>
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<td>Zero Frequency Ion (ZFI)</td>
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<td>Field Aligned Irregularities (FAI)</td>
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</tbody>
</table>
Waves in a Fluid Plasma for Oblique Propagation

Plasma Wave Mode
Characteristic Branches for
Typical Ionospheric Parameters

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

\[ \Omega_e = (2\pi) 1.43 \times 10^6 \text{ Rad/s} \]
\[ \omega_{pe} = 2 \Omega_e = (2\pi) 2.86 \times 10^6 \text{ Rad/s} \]
\[ \omega_{UH} = (2\pi) 3.2 \times 10^6 \text{ Rad/s} \]
\[ \omega_{LH} = (2\pi) 7460 \text{ Rad/s} \]
\[ \Omega_i = (2\pi) 48.7 \text{ Rad/s} \]
\[ B_0 = 5.1 \times 10^{-5} T \]
\[ n_e = 1.01 \times 10^{11} m^{-3} \]
\[ T_e = 2500 K \]
\[ T_i = 800 K \]
\[ V_A = 8.75 \times 10^5 m/s \]
\[ c_s = 1590 m/s \]
\[ \rho_e = 0.022 m \]
\[ \rho_i = 3.64 m \]
### Parametric Decay Instabilities and Stimulated Electromagnetic Emissions

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

Reference:
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 $\rightarrow$ Electron Temperature
  – Stimulated Brillouin of Electrostatic Ion Cyclotron Waves $\rightarrow$ Ion Mass
  – Stimulated Ion Bernstein Waves $\rightarrow$ Electron Acceleration Resonance
Upper Hybrid and Lower Hybrid Wave Generation is Complex

EM1 → UH1 → LH1 → LH2

EM1 → FAI → UH2 → EM2 → DM1

EM3 → FAI → DM2
SEE Observations Near the Third Electron Gyro Harmonic SIERRA Site: Glennallen, AK, 20 March 2004

In Situ Source: Upper Hybrid Waves

In Situ Source: Electron Bernstein Modes

Frequency (MHz)

Relative Power (dB)
Stimulated Brillouin Scatter with Ion Acoustic Wave Generation is Simple
Brillouin Scattering of the 4.5 MHz HAARP Vertical Beam in the Ionosphere

Date 2008/10/24, Time 19:47:50

Power (dB)
-120 Hz
-120 Hz
-31 Hz

SBS-2
SBS+2
30 Hz
120 Hz

Frequency Offset (Hz) from 4.5 MHz
Determination of Electron Temperature at UH Resonance Altitude

**Assumptions**

- \( T_e \gg 3 \, T_i \)
- \( \Omega_e, \Omega_i \) known
- \( \omega_0 = (\omega_p + \Omega_e)^{1/2} \)

**Ion Acoustic Speed**

\[
c_{IA} = \sqrt{\frac{\gamma_e T_e + \gamma_i T_i}{m_i}}
\]

where \( \gamma_e = 1 \) and \( \gamma_i = 3 \)

**QL Solution**

\[
T_e = \frac{m_i c^2 \omega_{IA}^2}{(\gamma_e + \gamma_i / 3)4\Omega_e \omega_0} \quad \frac{\Omega_i^2 - \omega_0^2}{\Omega_i^2 \cos^2 \theta - \omega_0^2} \quad \frac{\omega_0 + \Omega_e \cos \theta}{\omega_0 \cos \theta + \Omega_e}
\]

<table>
<thead>
<tr>
<th>Time (UT)</th>
<th>19:48</th>
<th>19:58</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>SBS-2</td>
<td>SBS+2</td>
</tr>
<tr>
<td>( f_{IA} ) (Hz)</td>
<td>-30.56</td>
<td>30.56</td>
</tr>
<tr>
<td>( C_{IA} ) (m/s)</td>
<td>1780</td>
<td>1780</td>
</tr>
<tr>
<td>( T_e ) (K)</td>
<td>3506</td>
<td>3506</td>
</tr>
</tbody>
</table>

24 October 2008
SBS with EIC Generation Yields Ion Mass

\[ m_i = e \frac{B}{f_{EIC}} = m[O^+] \]

Radio Beam Angle with \( B \) and \( \theta \)

Stimulated Brillouin Lines at 4.2 MHz

Ion Acoustic Frequencies

Ion Cyclotron Frequency

Absolute Time Offset (s)

Frequency Offset (Hz) from 4.2 MHz
Electrostatic Ion Cyclotron Waves Excitation by at 2\textsuperscript{nd} 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
Stimulated Ion Bernstein (SIB) Generation by Tuning to the Second Electron Gyro Frequency
Stimulated Ion Bernstein Waves

\[ \Delta \omega = n \Omega_i \]

\[ \Omega_i = 48.7 \text{ Hz} \]

\[ \Omega_i = 45.6 \text{ Hz} \]
Electron Acceleration, ES and EM Wave Generation

EM Pump Wave → Optional Mode Conversion → High Power EM or ES Wave → Parametric Decay → Loss

Resonant Electron Acceleration

$O + e^-* \rightarrow O^* + e^-$

$O^* \rightarrow O + h\nu (630 \text{ nm}, 135.6 \text{ nm})$

Airglow Production

Low Frequency EM Wave

Possible Mode Conversion?

Low Frequency ES Wave

Received EM Wave

Loss
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
    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

CNOFS Orbit

Endeavour Orbit

STS-127 Endeavour – CNOFS Separation

Endeavour to CNOFS

Exhaust to CNOFS

226 km Separation

9 km

87 km

0 50 100
Time to Ignition (s)

0 200 400 600 800
Distance (km)

-100 -50 0 50 100

Time = 1 seconds

Y

X

400 500 600

200

425 400 375 350 350

Altitude (km)

-45 -40 -35

Longitude (Deg)

-20 -15 -10

Latitude (Deg)

-200 -175 -150 -125 -100 -75 -50 -25 0 25 50 75 100 125 150 175 200

h2o

3.4E+14

3.0E+14

2.6E+14

2.3E+14

1.9E+14

1.5E+14

1.1E+14

7.6E+13

3.8E+13

2.0E+11
STS-127
OMS Burn
Observed by C/NOFS
MHD Waves Excited by Rocket Burns

- Magnetized Plasma Driven by a Neutral Pulse

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

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

- Three Waves
  
  Slow Magnetosonic or Sound: \( \Sigma_0 = \xi \cdot \mathbf{b} \)
  
  Alfvén: \( \Sigma_1 = (\nabla \times \xi) \cdot \mathbf{b} \)
  
  Fast Magnetosonic: \( \Sigma_2 = \nabla \cdot \xi \)

- Wave Equations

\[
\frac{\partial^2 \Sigma_i}{\partial t^2} + \nu_i \frac{\partial \Sigma_i}{\partial t} = C_i^2 \nabla \Sigma_i \cdot \mathbf{b} + \nu_n \mathbf{v}_n \cdot \mathbf{b}
\]

VEFI Detection of STS–127 OMS Burn for CNOFS

![Graph showing electric field vs. time](image)
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