Electrostatic Waves Excited During Active Experiments in the Ionosphere

Paul A. Bernhardt, Craig A. Selcher
Plasma Physics Division, Naval Research Laboratory
Washington, DC 20375

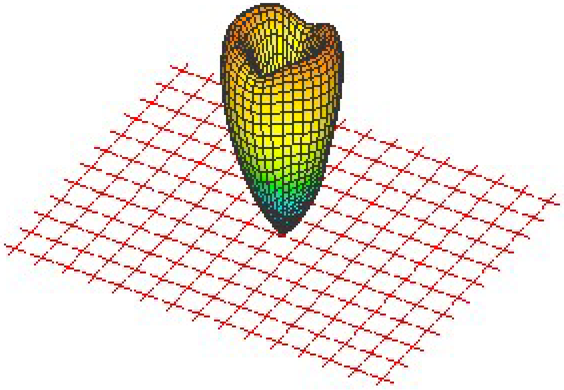
Serafin Rodriguez, Joe Thomason
Radar Division, Naval Research Laboratory, Washington, DC 20375

Mike McCarrick, BAE Systems, Washington, DC

Brent Watkins, GI University of Alaska, Fairbanks, AK

Gordon Frazer, ISR Division, DSTO, Edinburgh, SA, Australia

Phil Erickson, MIT Haystack Observatory, MA



lern Challenges in Nonlinear Plasma Physics
Halkidiki, Greece
16 June 2009

k Sponsored by the Office of Naval Research

Shuttle Ionospheric Modification with Pulsed Localized Exhaust
SIMPLEX
NRL STP JSC AFRL DSTO JRO MIT/HO NAIC USAKA

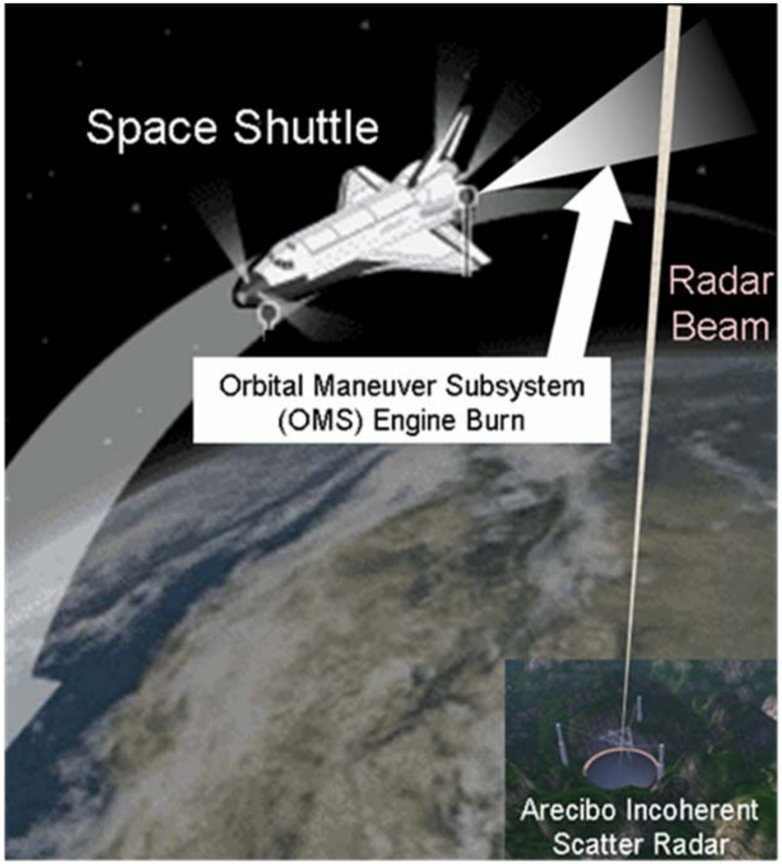
Electrostatic Wave Generation

- Fast Hypersonic Chemical Releases
  - Radar Scatter from ES Waves
- High Power Radio Waves
  - Excited Processes
  - Radar Scatter
    - Field Aligned Irregularities
    - Enhanced Ion Lines
    - Enhanced Plasma Lines
  - Stimulate Electromagnetic Emissions
    - Mode Conversion
    - Parametric Decay Instabilities

Shuttle Ionospheric Modification with Pulsed Localized Exhaust (SIMPLEX)

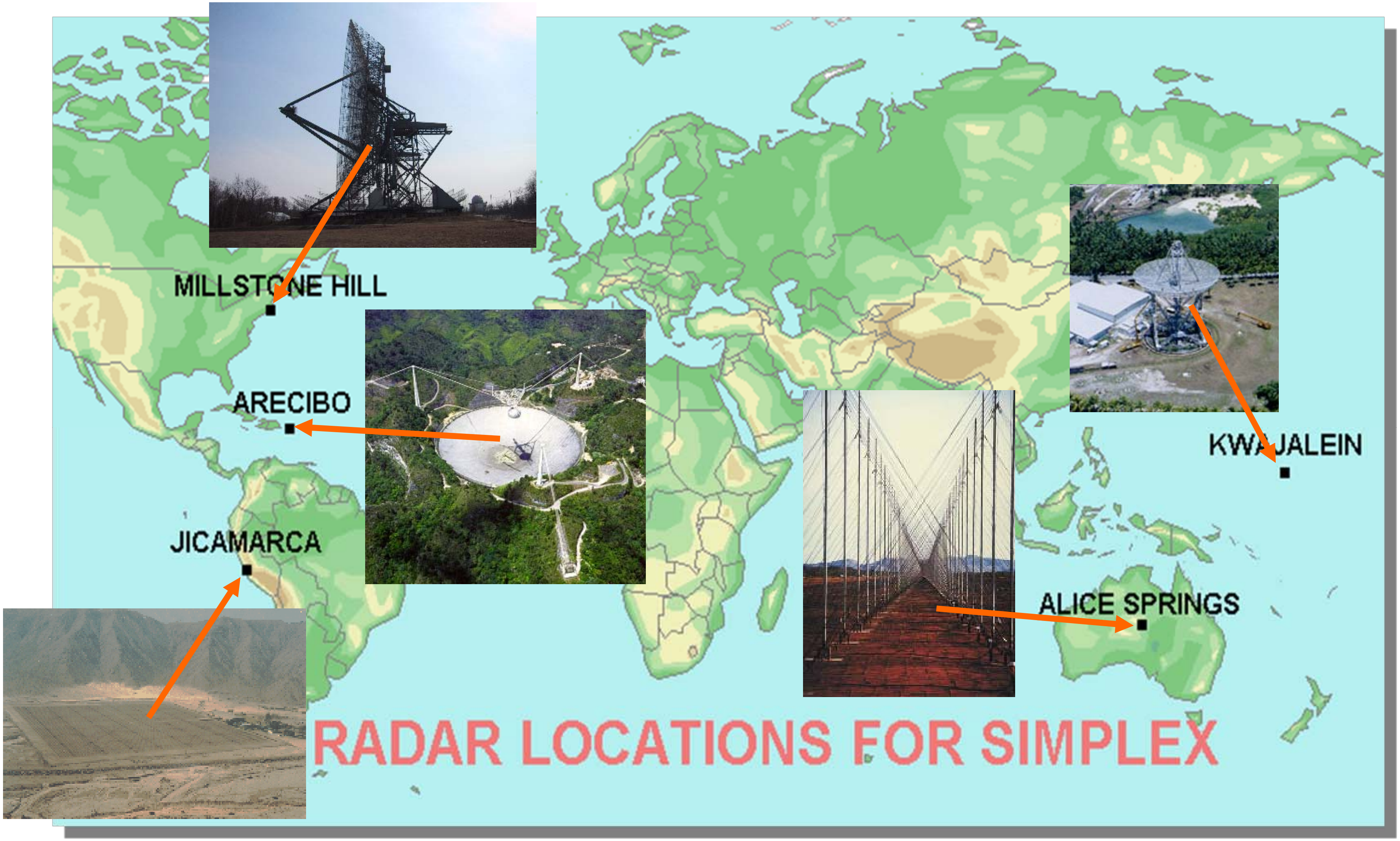
Objective: Investigate Plasma Turbulence Driven by Rocket Exhaust in the Ionosphere Using Ground Based Radars

Description: Fire OMS Engines to Excite Plasma Turbulence

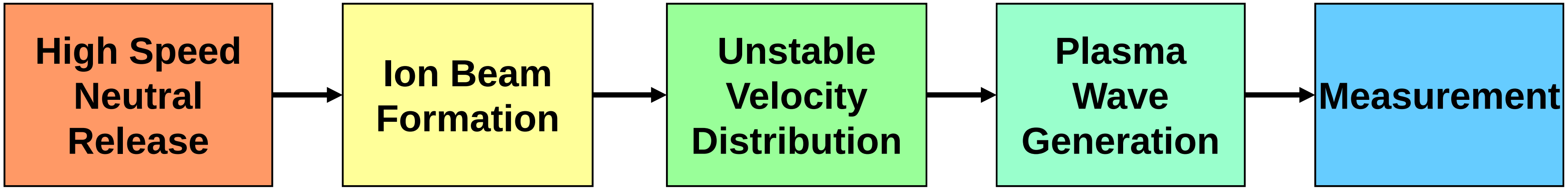


Radar Diagnostics of Artificial Plasma Turbulence

SHUTTLE IONOSPHERIC MODIFICATION WITH PULSED LOCALIZED EXHAUST ***SIMPLEX***



Wave Generation by Chemical Releases:
SIMPLEX– Space Shuttle Exhaust



High Speed Neutral Release

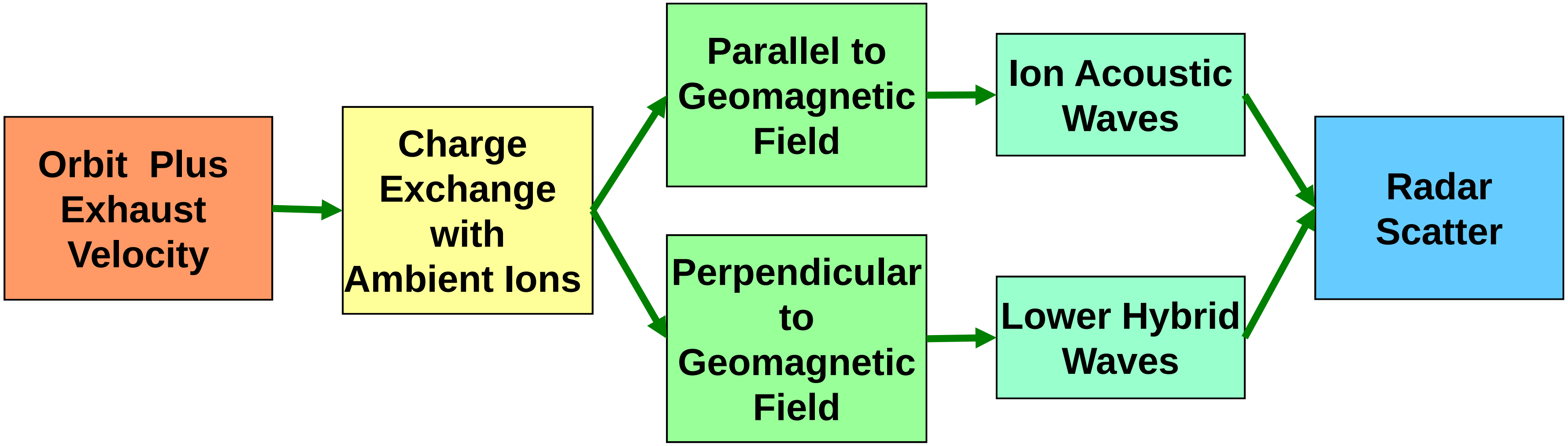
Ion Beam Formation

Unstable Velocity Distribution

Plasma Wave Generation

Measurement

$$\boxed{O^{+} + H_2O \rightarrow H_2O^{+} + O}$$



Orbit Plus Exhaust Velocity

Charge Exchange with Ambient Ions

Parallel to Geomagnetic Field

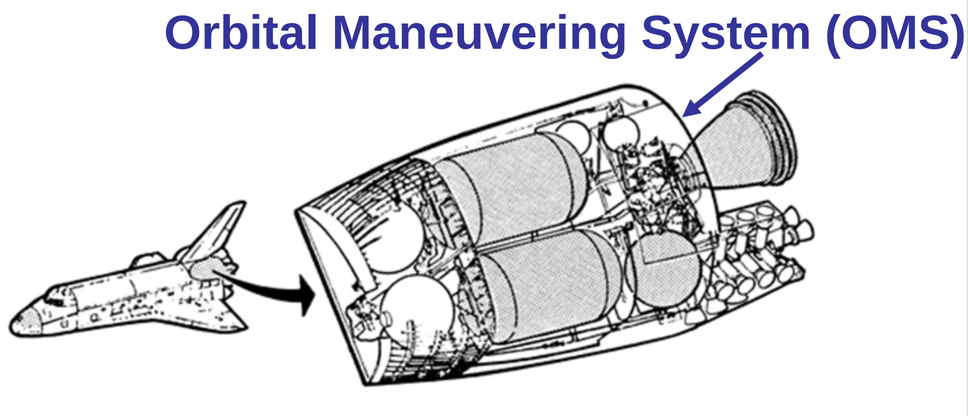
Perpendicular to Geomagnetic Field

Ion Acoustic Waves

Lower Hybrid Waves

Radar Scatter

Space Shuttle OMS Engine Exhaust Parameters

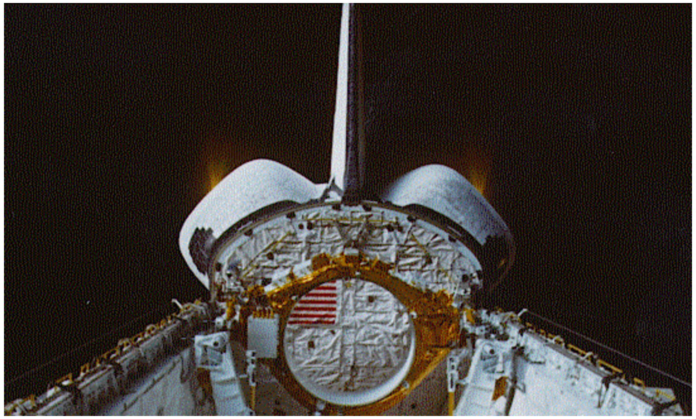


Flow Rate: 2.5 x 10^{26} Molecules per Second per Engine

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

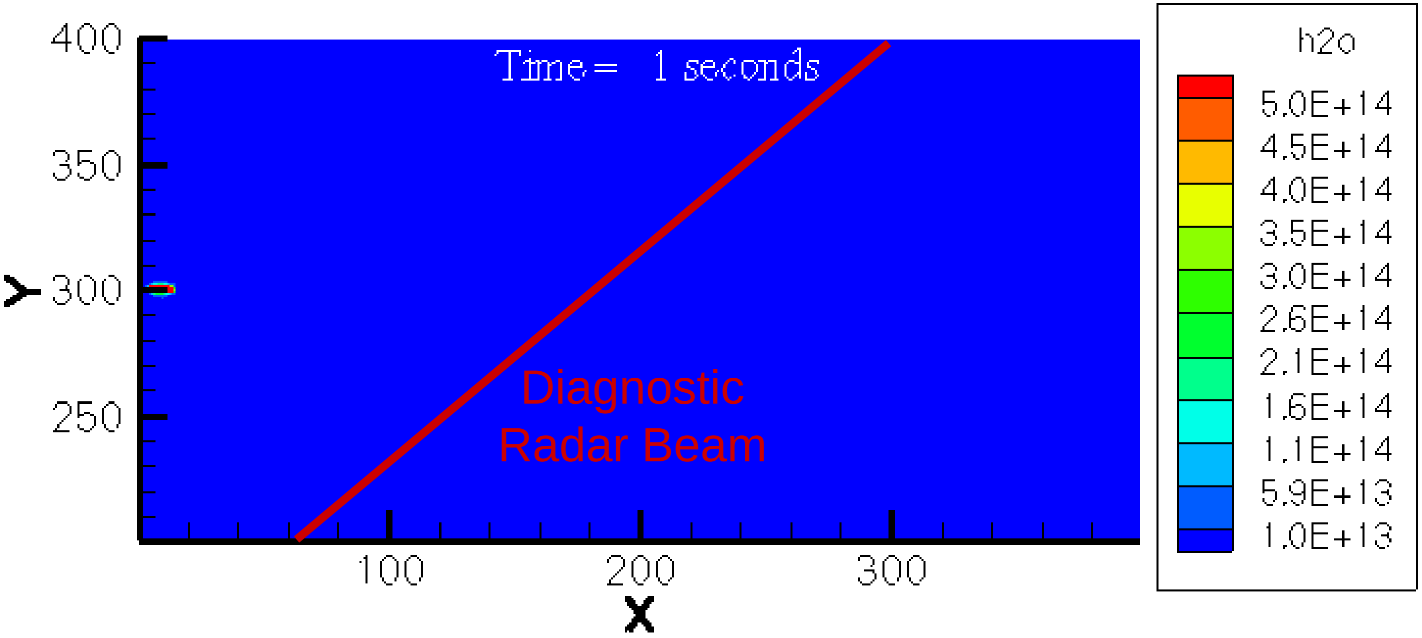
Nonuniform
Dual OMS Burn

Symmetrical
Dual OMS Burn in Daylight



Single OMS Burn at Night

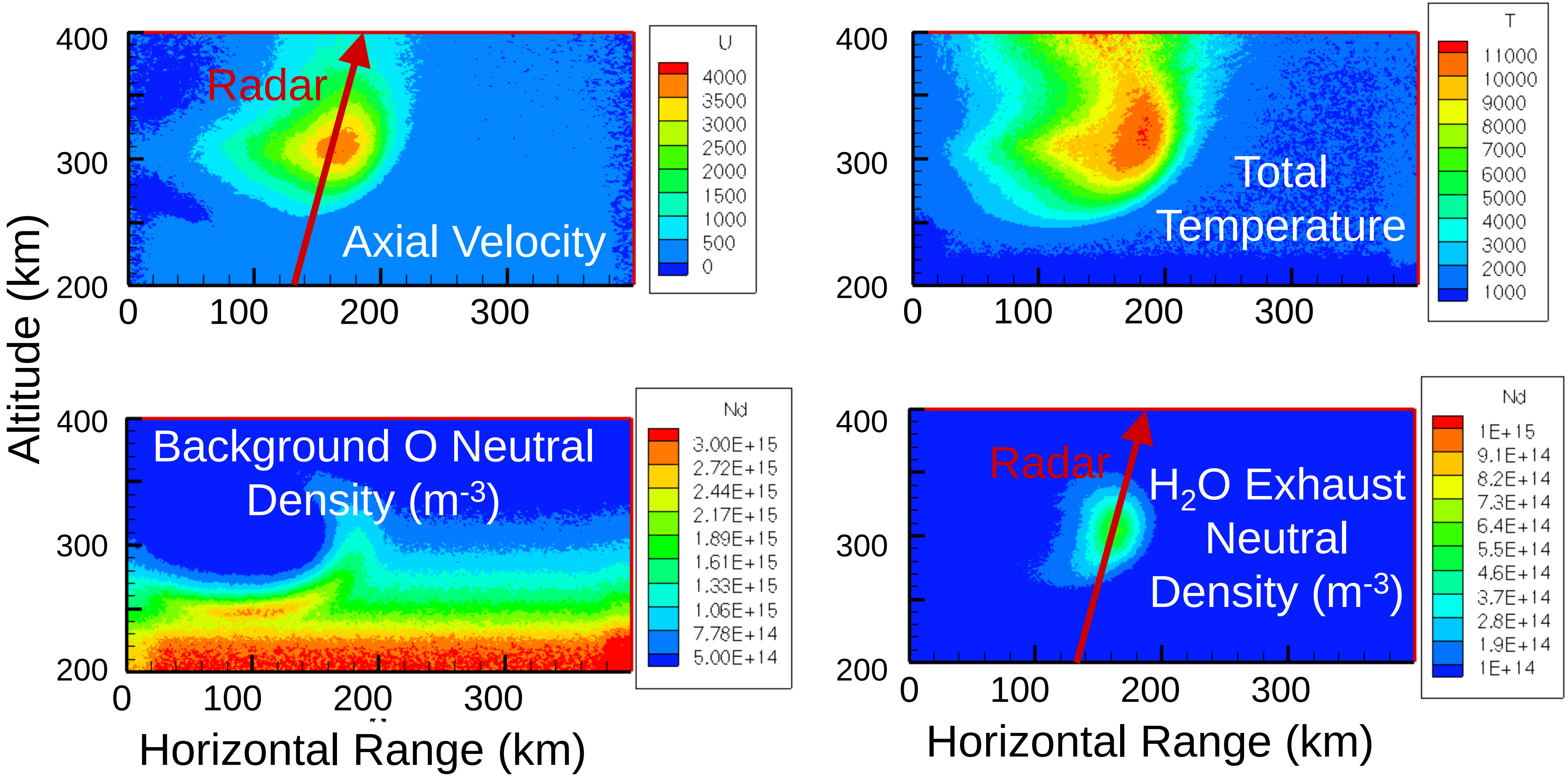
Neutral Exhaust Flow Across Radar Beam



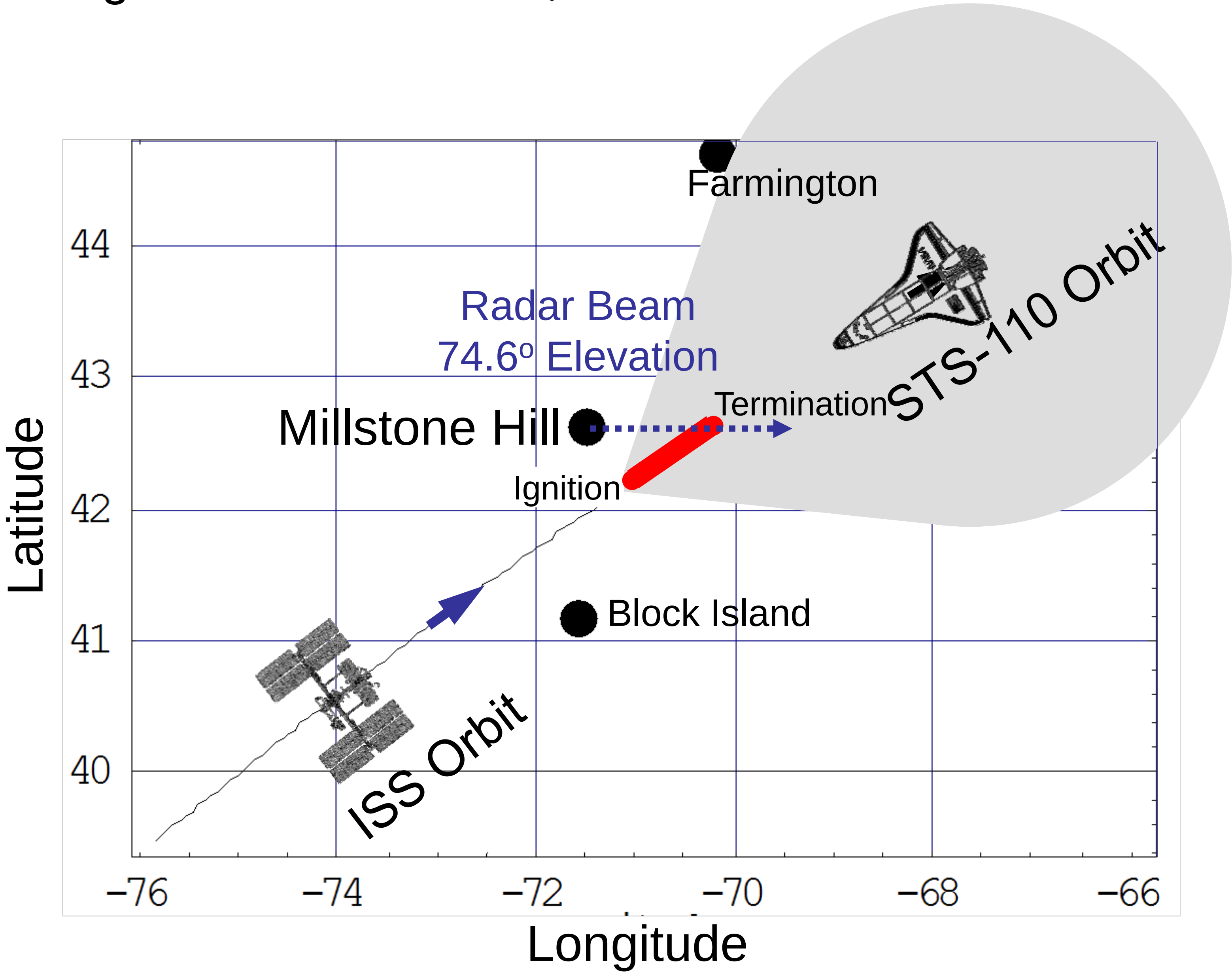
DSMC Calculations of OMS Exhaust

Shuttle Exhaust Release at 300 km altitude
50 10^{25} molecules/s for 10 seconds.
Velocity = 10.75 km/s, H_2O Temperature = 120 K

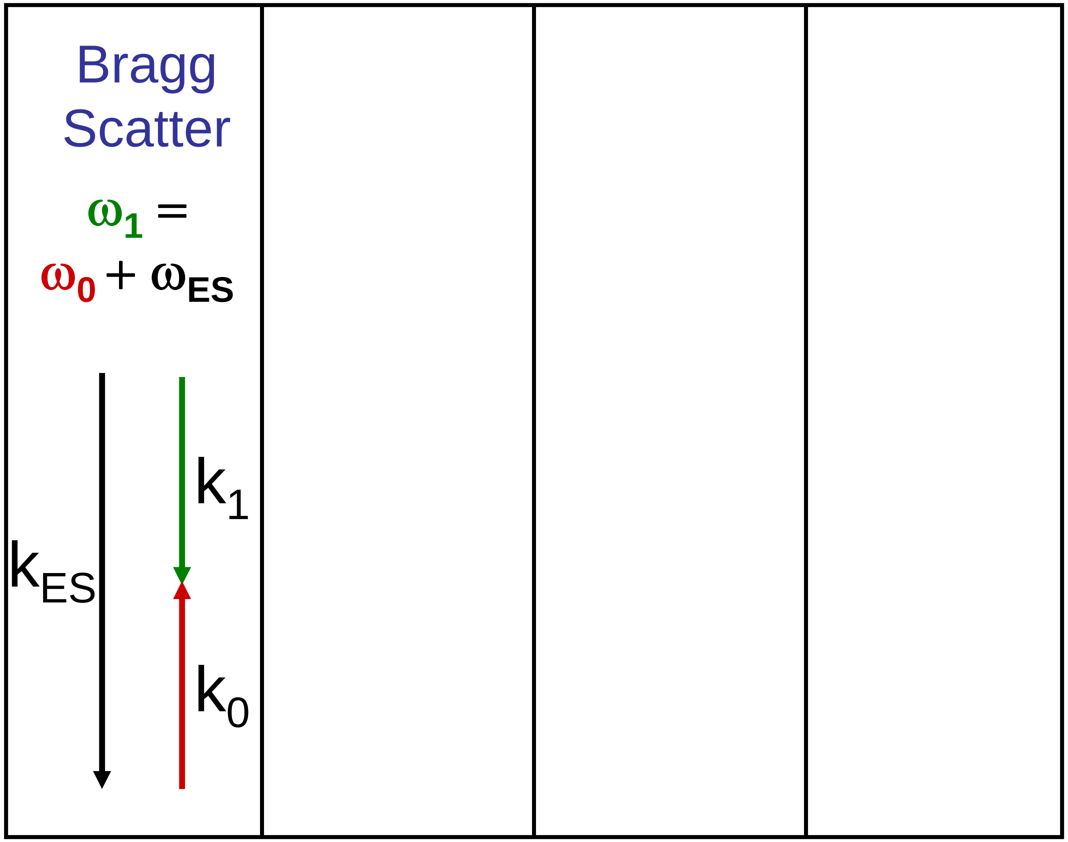
Time = 30 Seconds



STS-110 Burn Location, 18 April 2002 GMT
Ignition: 17:26:18.95, Termination: 17:26:28.95



Radar Scatter from ES Waves



Bragg Scatter

$\omega_1 =$

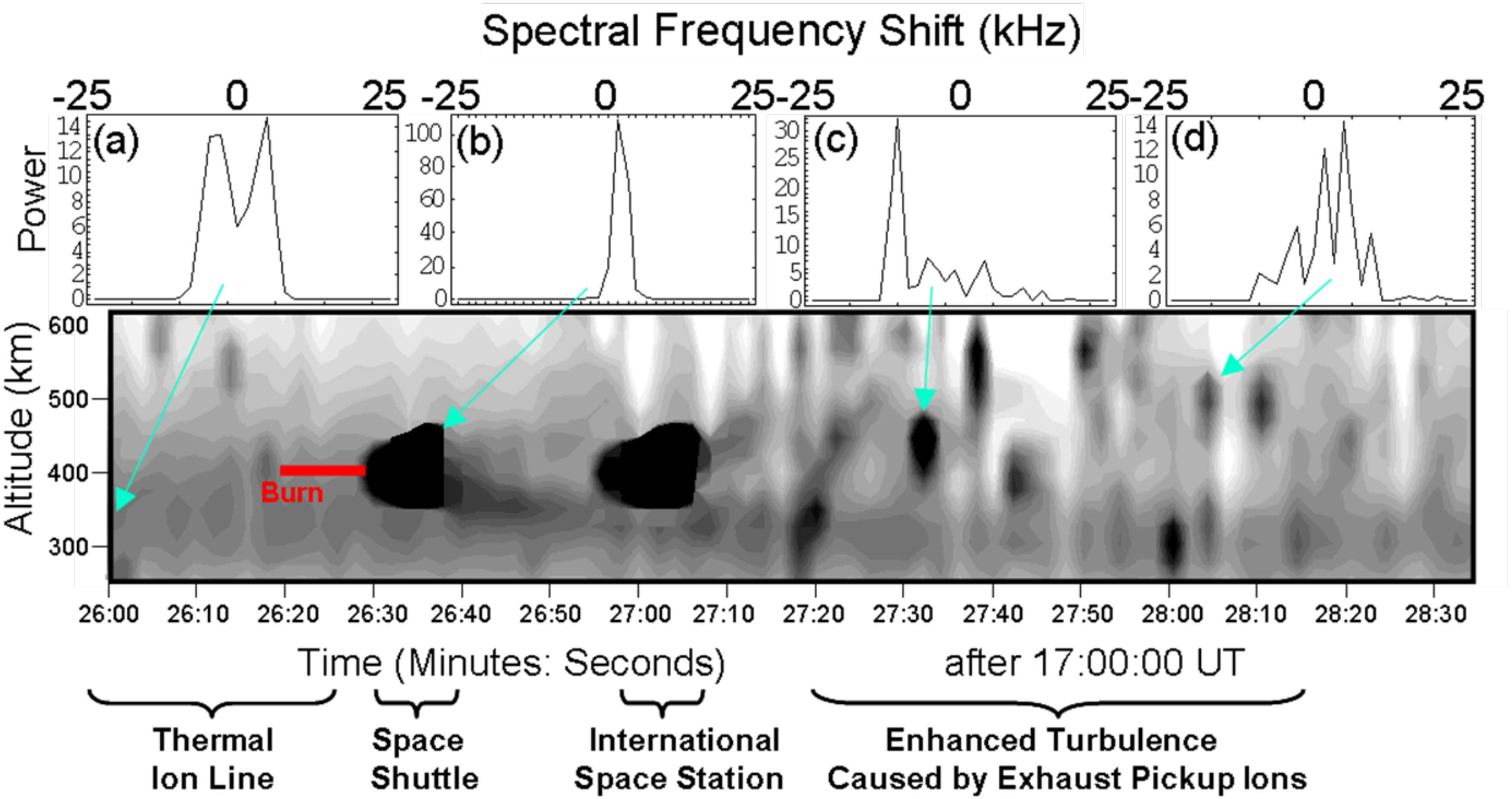
$\omega_0 + \omega_{ES}$

SIMPLEX IV Radar Backscatter

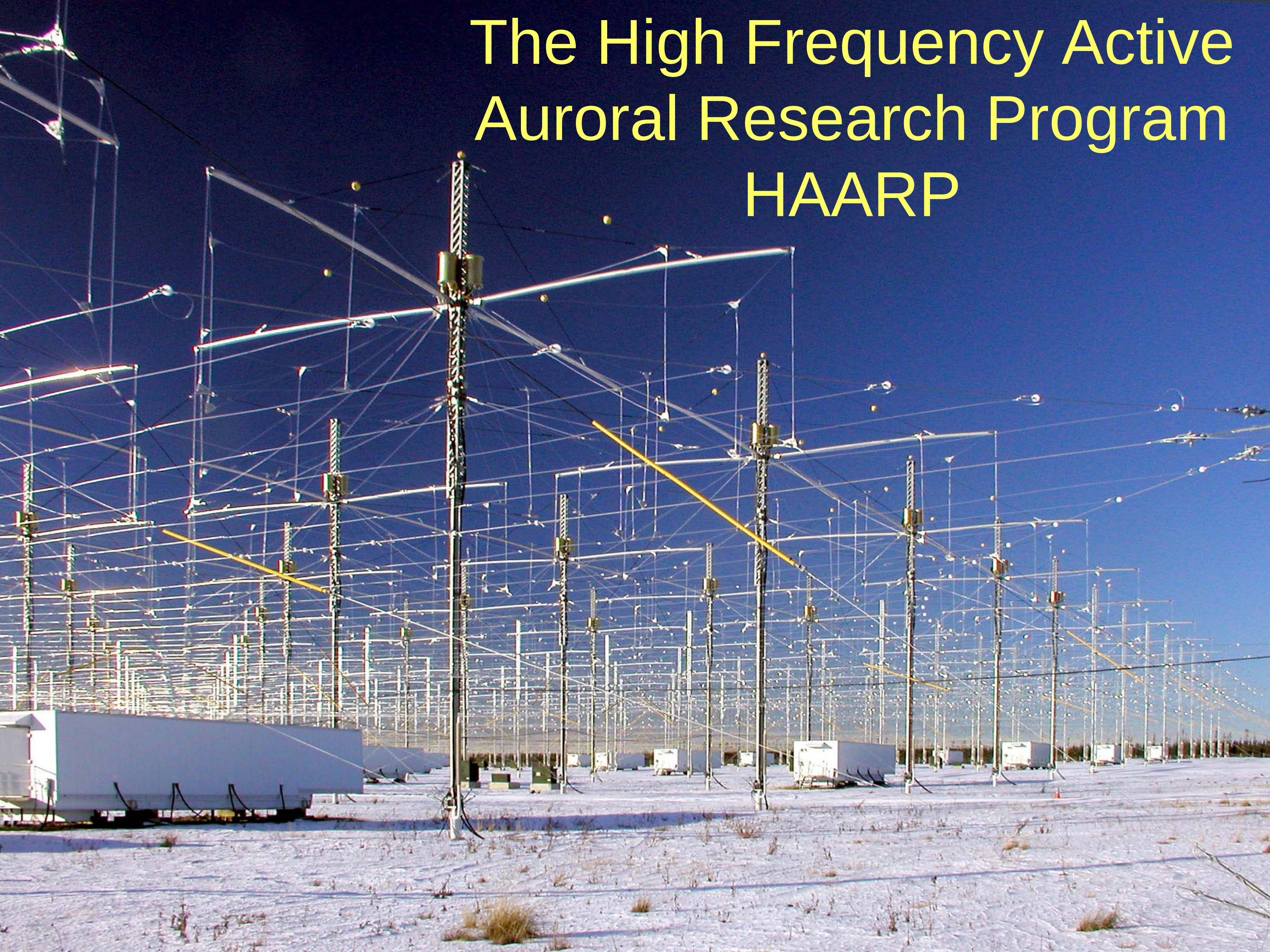
Millstone Hill Radar, 18 April 2002

Burn Time 17:26:19 – 17:26:29 UT

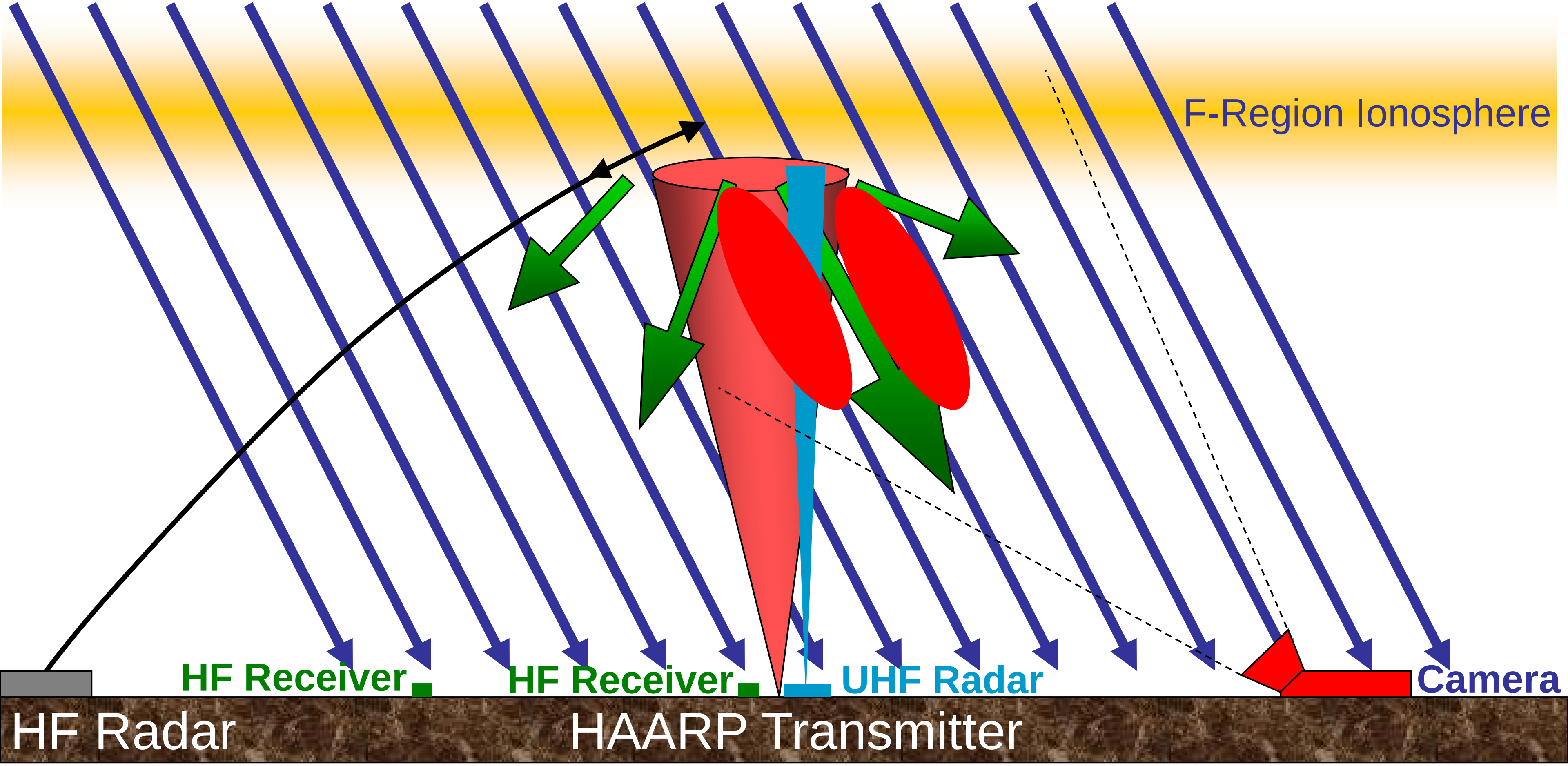
2 Second and 24 km Resolution



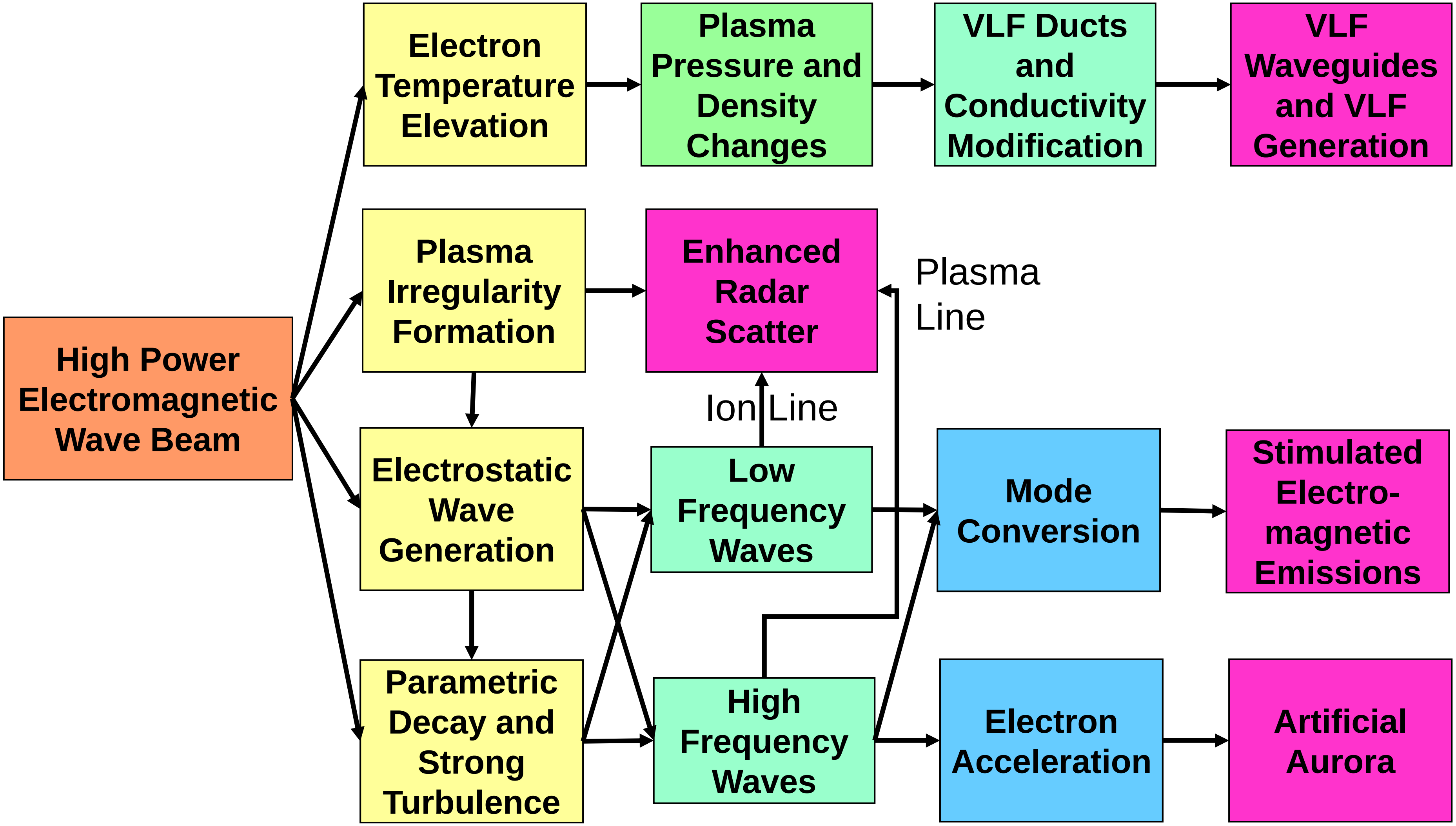
The High Frequency Active Auroral Research Program
HAARP



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



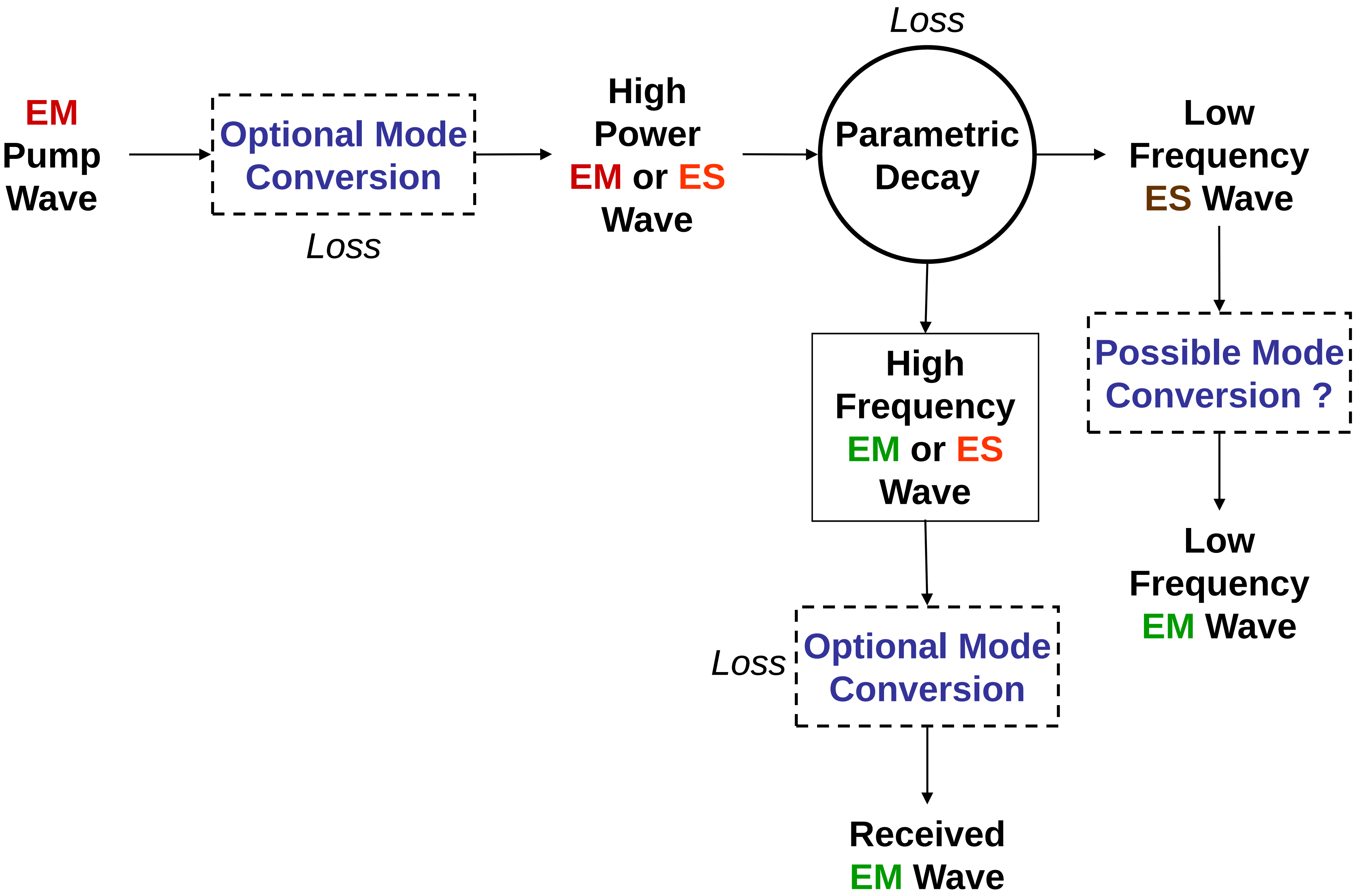
Ionospheric Modification with High Power Radio Waves



Stimulated Electrostatic (ES) Emissions

- Basic Theory
  - Matching Conditions
  - Low and High Frequency Electrostatic Waves
  - Electromagnetic Waves
- Observations
  - Radar Scatter (Enhanced Ion and Plasma Lines)
  - Stimulated Electromagnetic Emissions (SEE)
- Applications of SEE and Radar Scatter
  - Validation of Non-Linear Plasma Interactions
  - Electron Temperature Measurements
  - Altitude Profile of Scattered Electromagnetic Waves

ES and EM Wave Generation



EM Pump Wave

Optional Mode Conversion

Loss

High Power EM or ES Wave

Loss

Parametric Decay

Low Frequency ES Wave

Possible Mode Conversion ?

Low Frequency EM Wave

High Frequency EM or ES Wave

Loss

Optional Mode Conversion

Received EM Wave

Parametric Decay Instabilities

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

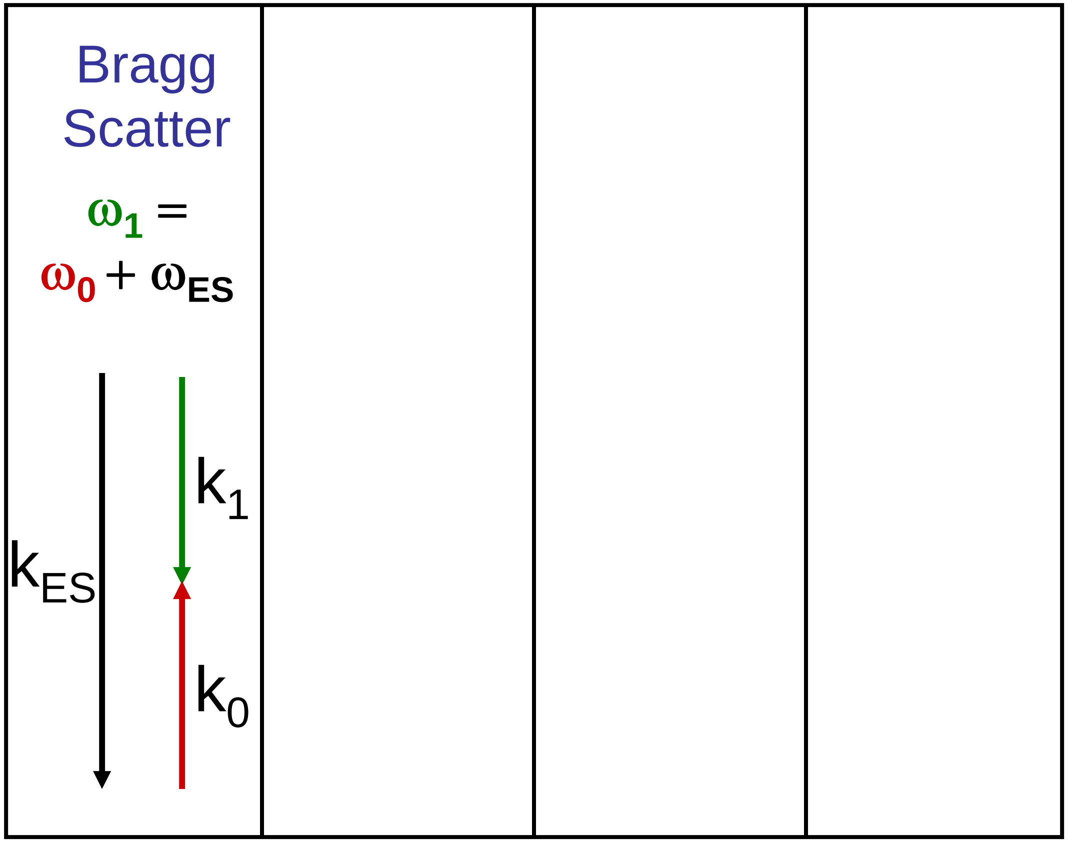
Magnetized ES Waves

Parametric Decay Instabilities Observed by Radar Scatter

Parent Wave 0	**Daughter Wave 1**	**Daughter Wave 2**	**Instability Name**	**Observed for HF**
Electromagnetic Wave	Electron Plasma Wave	Ion Acoustic Wave	Parametric Decay Instability	Yes Radar/SEE
Electron Plasma Wave	Electron Plasma Wave	Ion Acoustic Wave	Electron Decay Instability	Yes Radar/SEE
Electromagnetic Wave	Zero Frequency Electron Wave	Zero Frequency Ion Wave	Oscillating Two-Stream Instability	Yes Radar/SEE

Radar Scatter from ES Waves

$$\lambda_{ES} = \lambda_0/2$$



Bragg Scatter

$\omega_1 =$
$\omega_0 + \omega_{ES}$

Radar Scatter from ES Waves

Generation of HF (ω_0) Pumped Plasma-Lines and Ion-Lines in Backscatter Radar Spectra (ω_R, k_R)

First, Third, Fifth Order
Ion Lines and *Plasma Lines*

Pump Wave

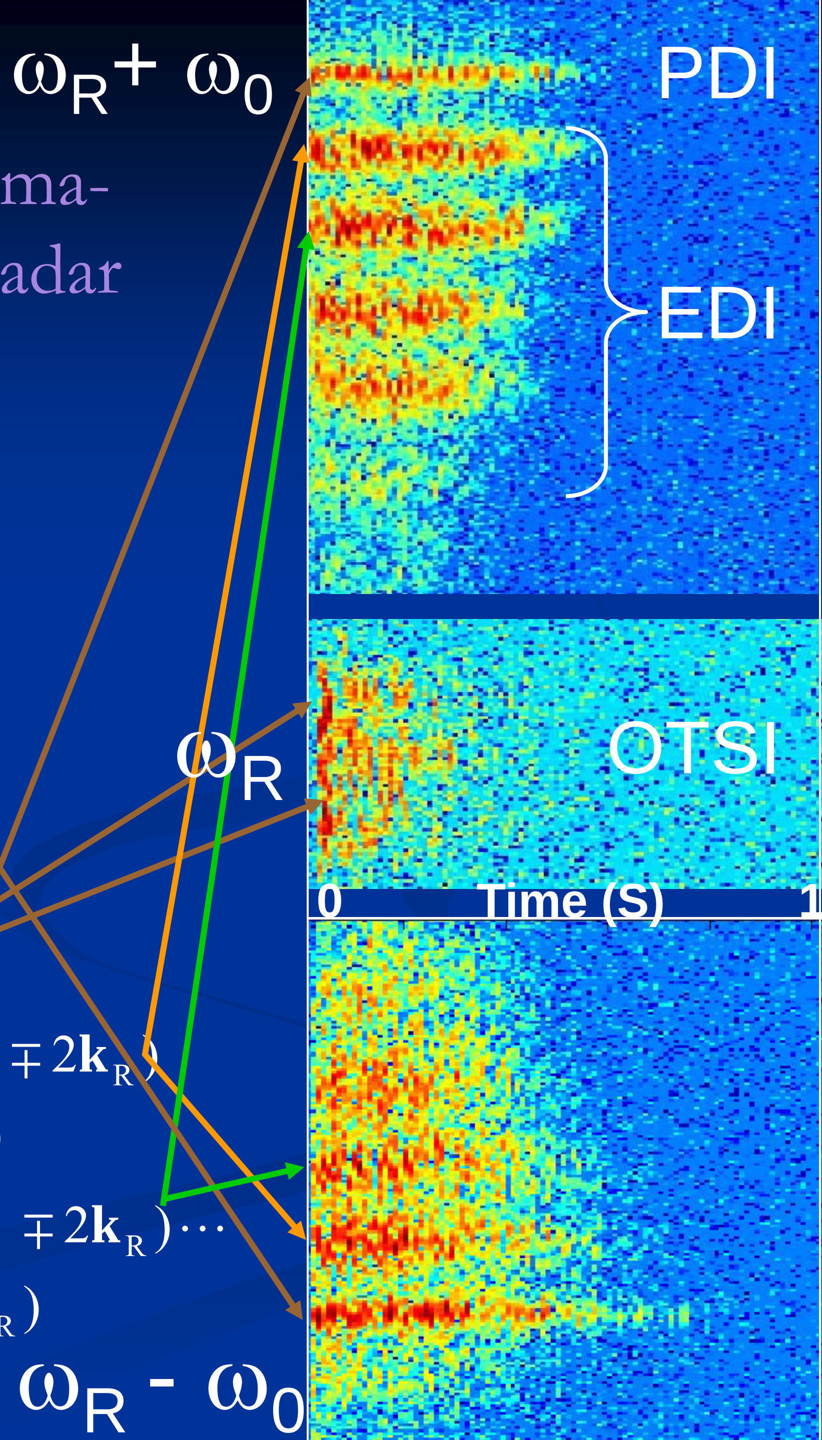
Electrostatic Waves

$$EM_0(\omega_0, \mathbf{k}_0 = 0) \xrightarrow{\text{PDI}} \begin{cases} EP_1(\omega_0 - \omega_{IAR},\ \pm 2\mathbf{k}_R) \\ IA_1(\ \omega_{IAR},\ \mp 2\mathbf{k}_R) \end{cases}$$

$$EP_1(\omega_0 - \omega_{IAR},\ \pm 2\mathbf{k}_R) \xrightarrow{\text{PDI}} \begin{cases} EP_2(\omega_0 - 3\omega_{IAR},\ \mp 2\mathbf{k}_R) \\ IA_2(\ 2\omega_{IAR},\ 4\mathbf{k}_R) \end{cases}$$

Electrostatic Waves

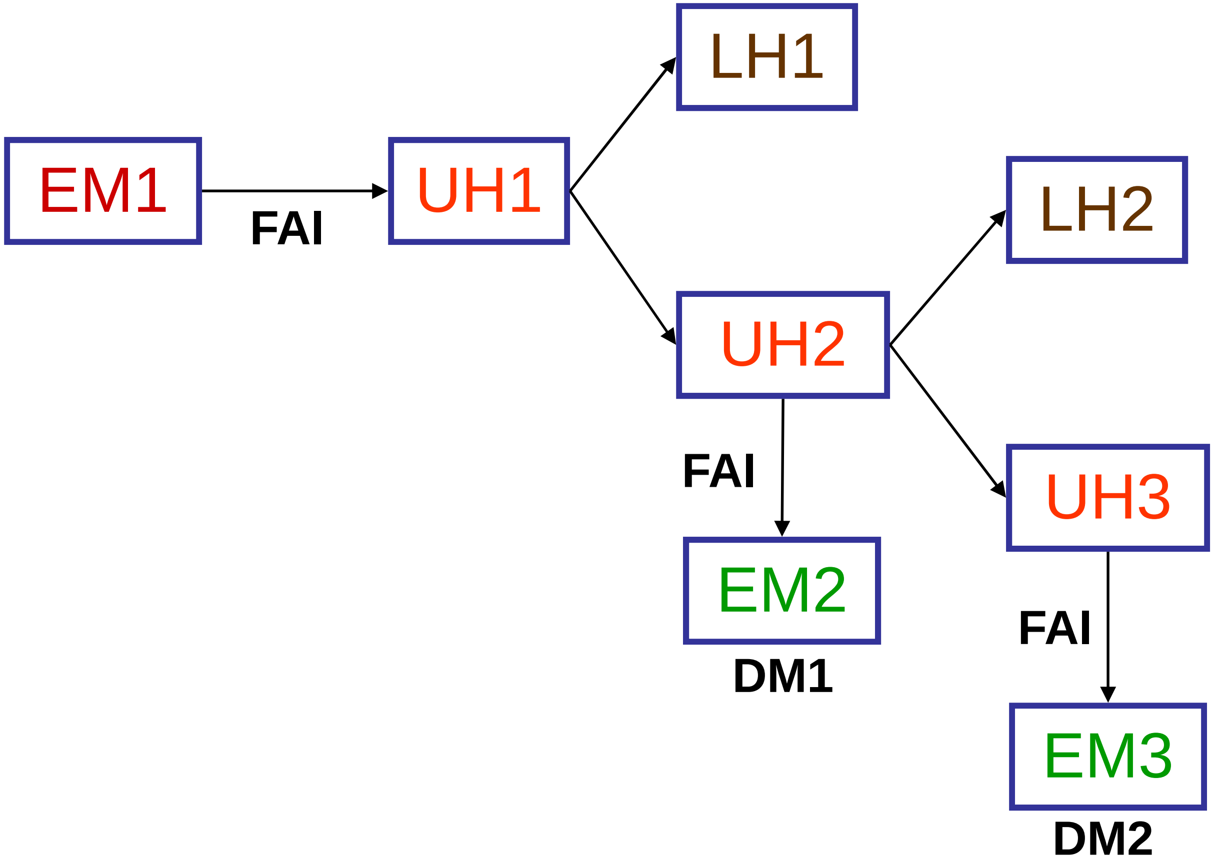
$$EP_2(\omega_0 - 3\omega_{IAR},\ \pm 2\mathbf{k}_R) \xrightarrow{\text{PDI}} \begin{cases} EP_2(\omega_0 - 5\omega_{IAR},\ \mp 2\mathbf{k}_R)\cdots \\ IA_2(\ 2\omega_{IAR},\ 4\mathbf{k}_R) \end{cases}$$



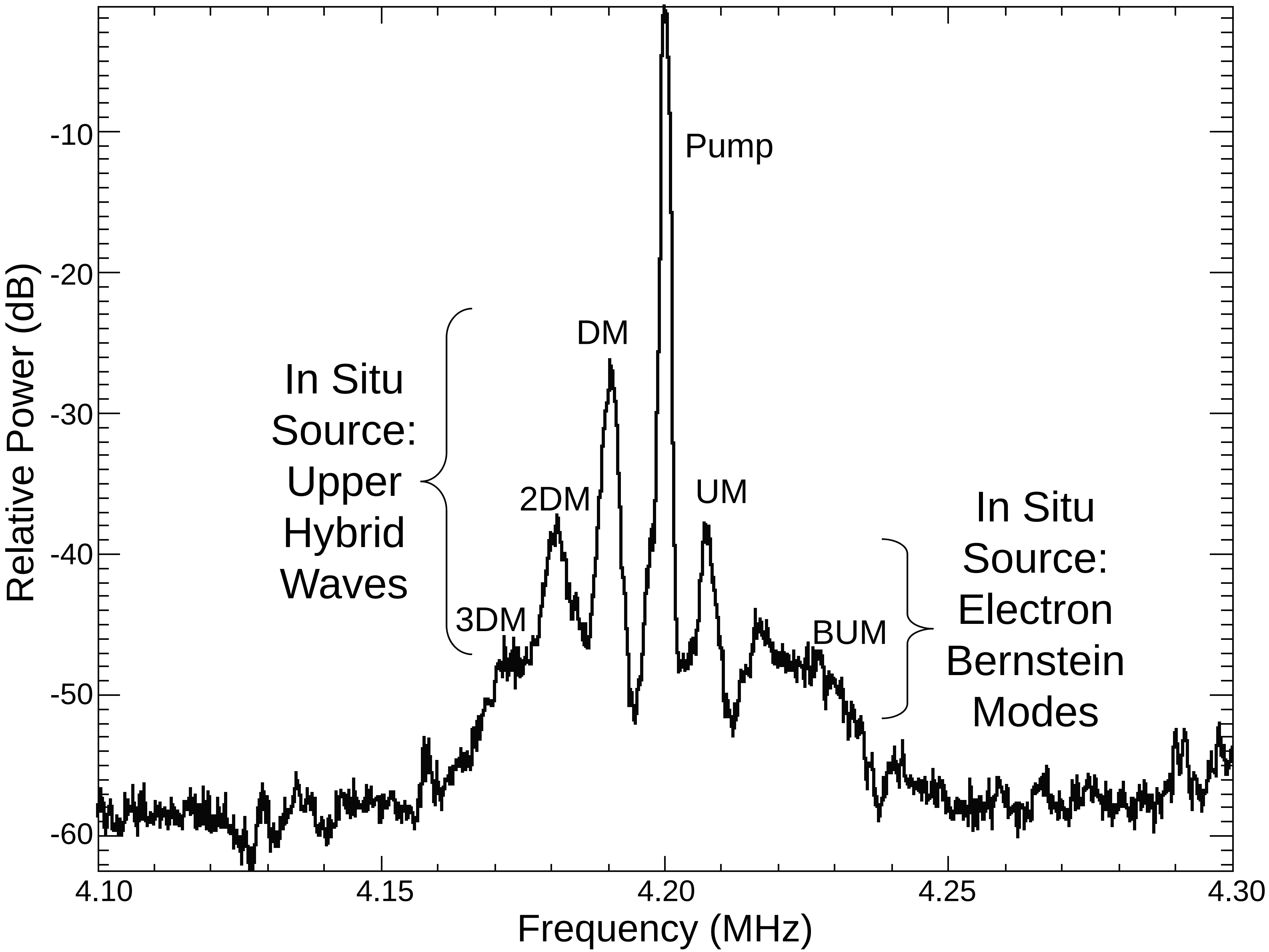
Parametric Decay Instabilities Observed by Stimulated Electromagnetic Emissions

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

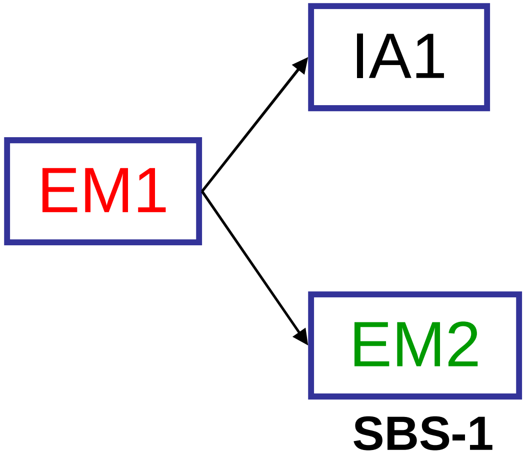
DM Generation is Complex



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



SBS Generation is Simple



Coupled Wave Equations for Magnetized PDI

- Pump Electromagnetic Wave at Frequency ω_P

$$\frac{\partial^2 F_P^{(O)}(z)}{\partial z^2} + (\omega_P / c)^2 [n_P^{(O)}]^2 F_P^{(O)}(z) = 0$$

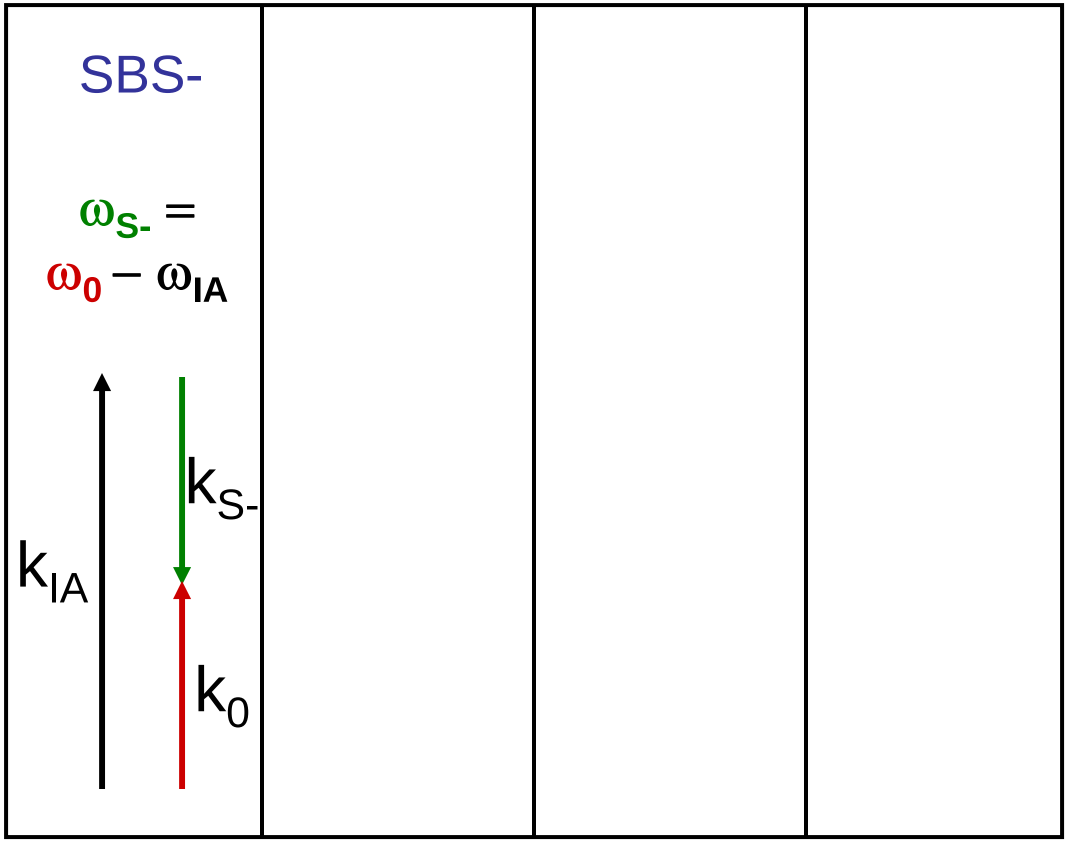
- Scattered Electromagnetic Wave at Frequency ω_S

$$\frac{\partial^2 F_S^{(O)}(z)}{\partial z^2} + (\omega_S / c)^2 [n_S^{(O)}]^2 F_S^{(O)}(z) = -\frac{i(\omega_S / c)^2 (1 - [n_P^{(O)}]^2)}{4\omega_L} \frac{\partial \tilde{\mathrm{v}}_{\mathrm{iz}}^*}{\partial z} F_P^{(O)}(z)$$

- Scattered Low Frequency IA/EIC Wave at Frequency ω_L

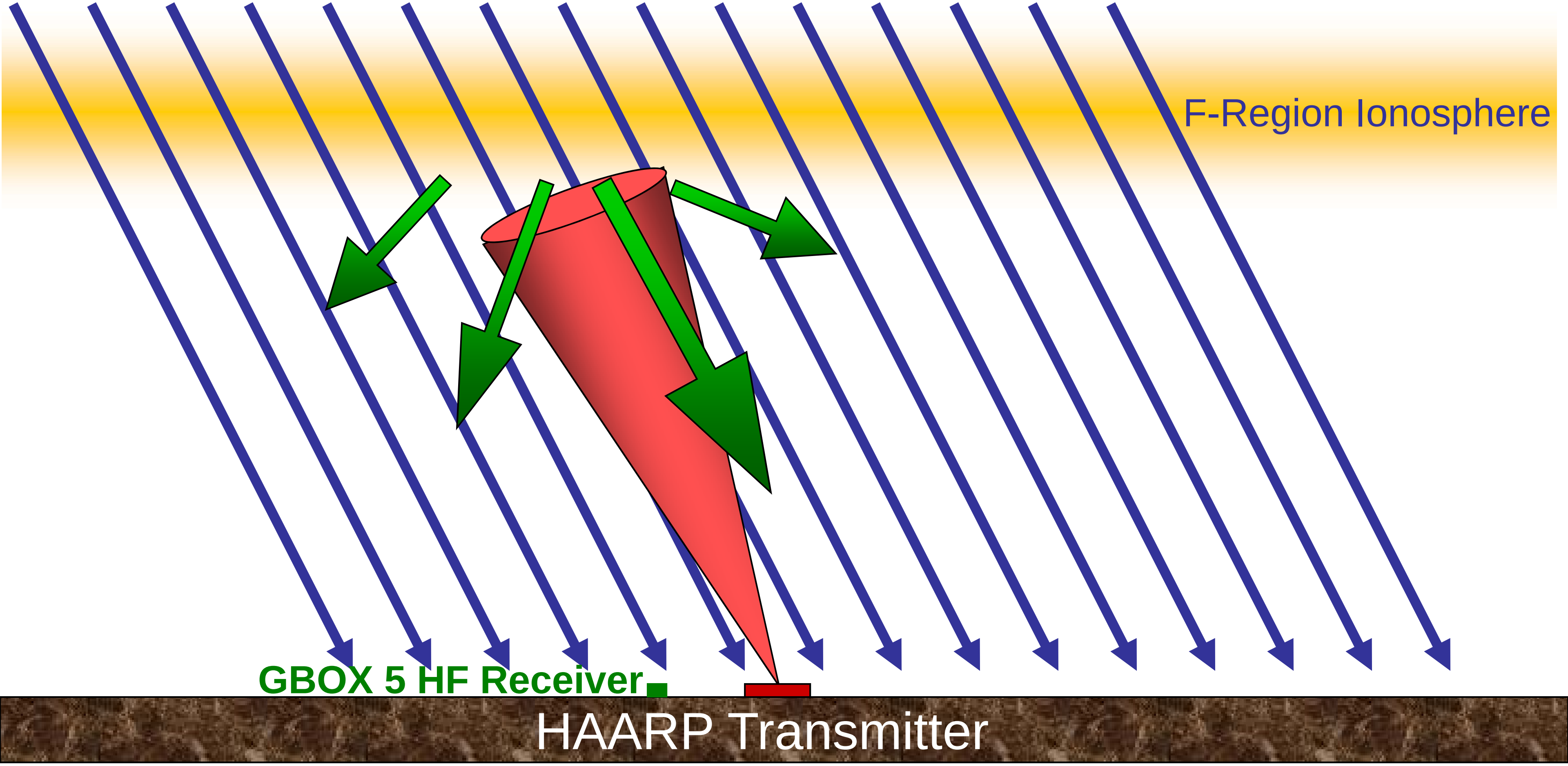
$$\frac{\partial^2 \tilde{\mathrm{v}}_{iz}}{\partial z^2} + \frac{U_i \omega_L^2}{c_{IA}^2} \frac{\Omega_{\mathrm{i}}^2 - U_i^2 \omega_L^2}{\Omega_{\mathrm{iz}}^2 - U_i^2 \omega_L^2} \tilde{\mathrm{v}}_{iz} = \frac{i q_e^2 L_P}{8 c_{IA}^2 m_e m_i \omega_L} \left[\frac{\partial (F_P^{(O)} F_S^{(O)*})}{\partial z} \right]$$

Downshifted and Upshifted Spectral Line Formation by SBS

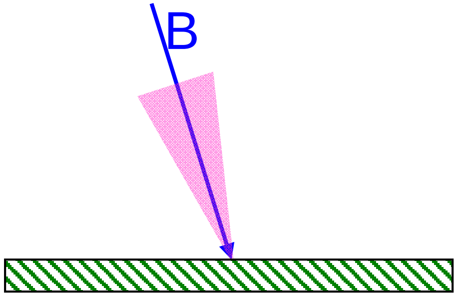

SBS-

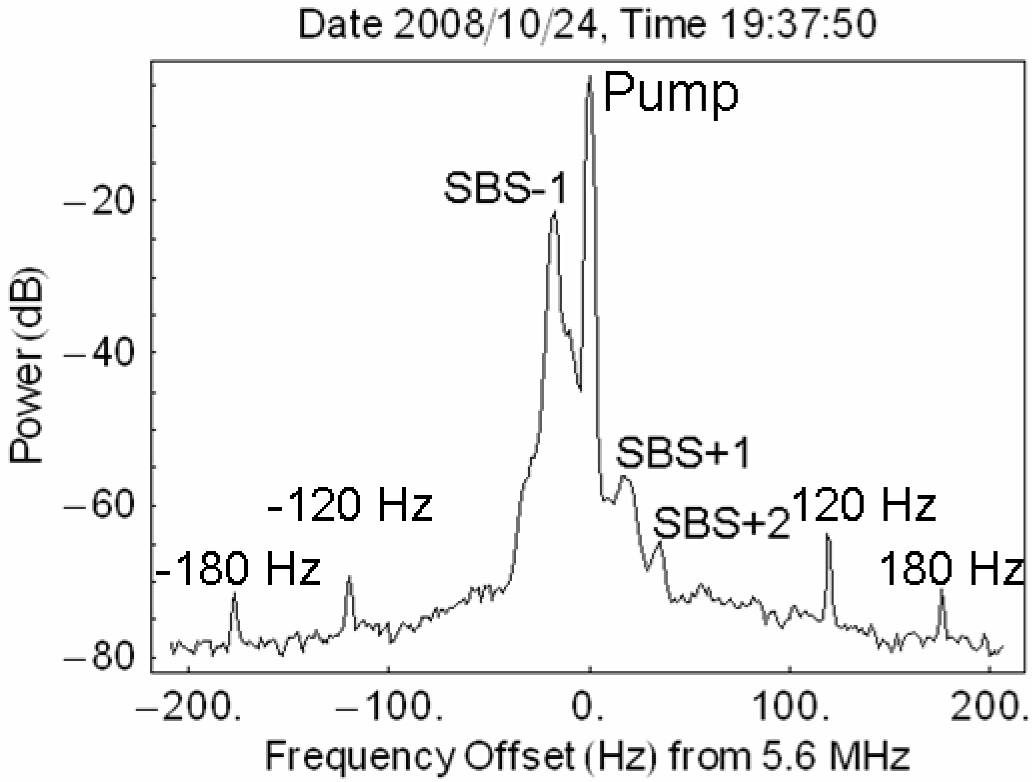
$\omega_{S-} = \omega_0 - \omega_{IA}$

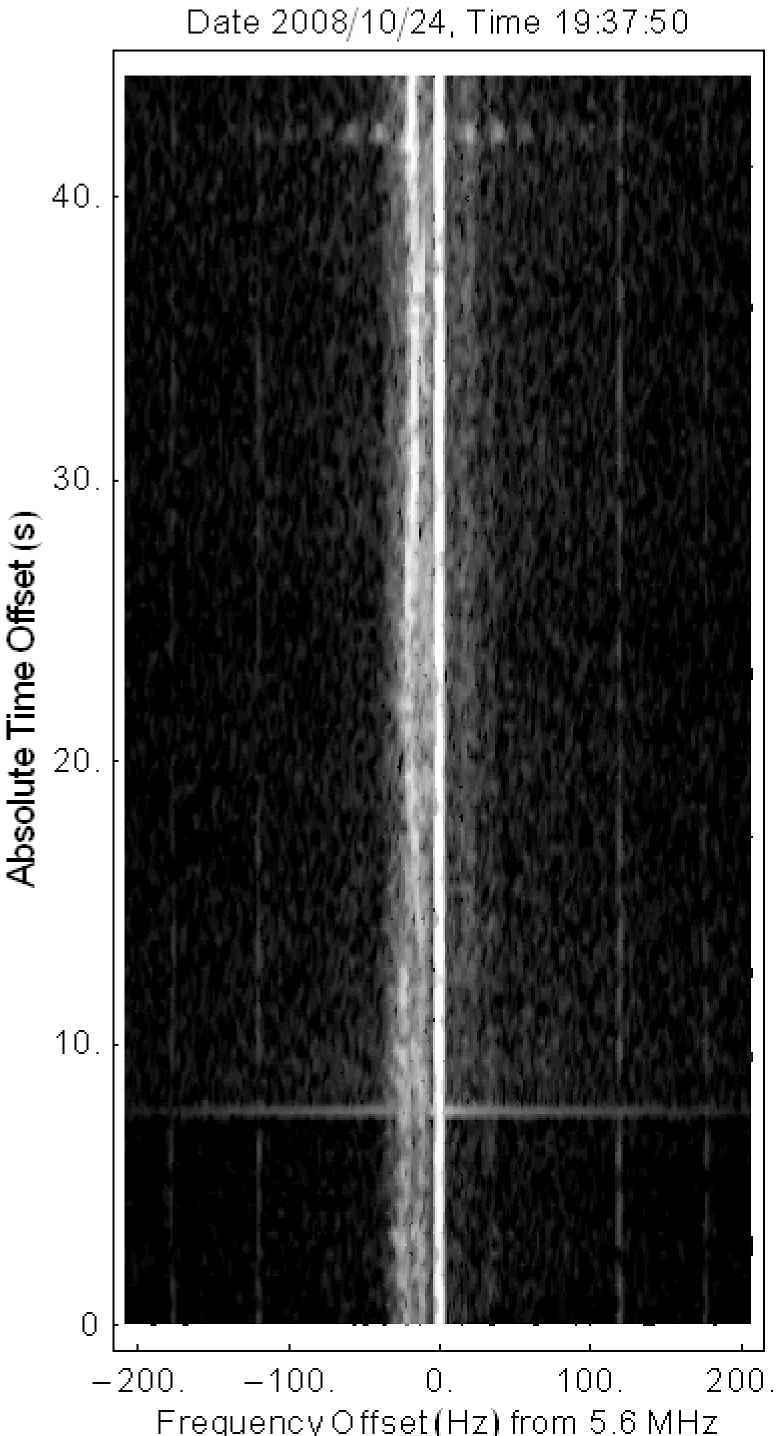
Stimulated Electromagnetic Emissions Measurements Near HAARP with Magnetic Zenith Beam



SBS Signals for 5.6 MHz Pump HF Beam at Magnetic Zenith

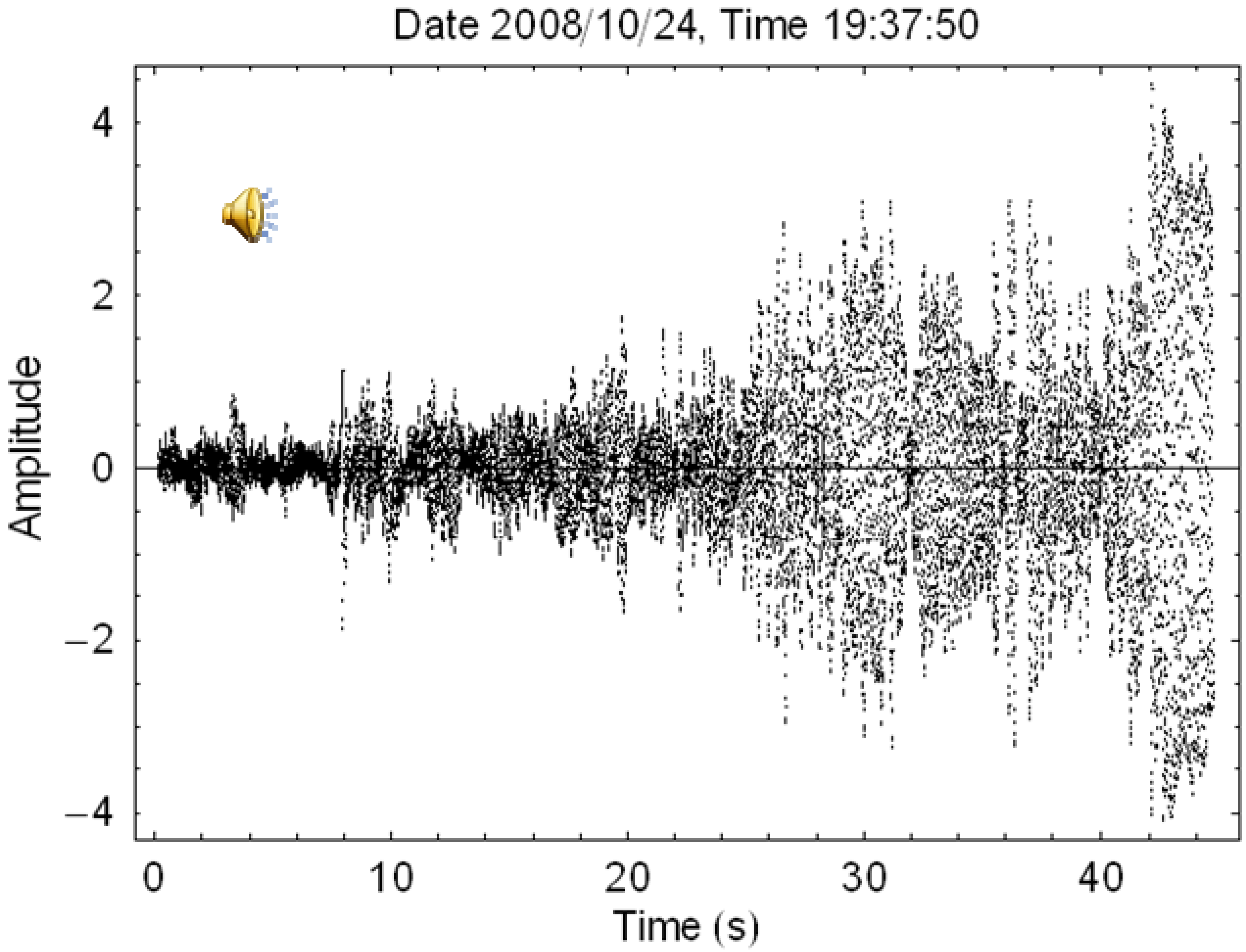






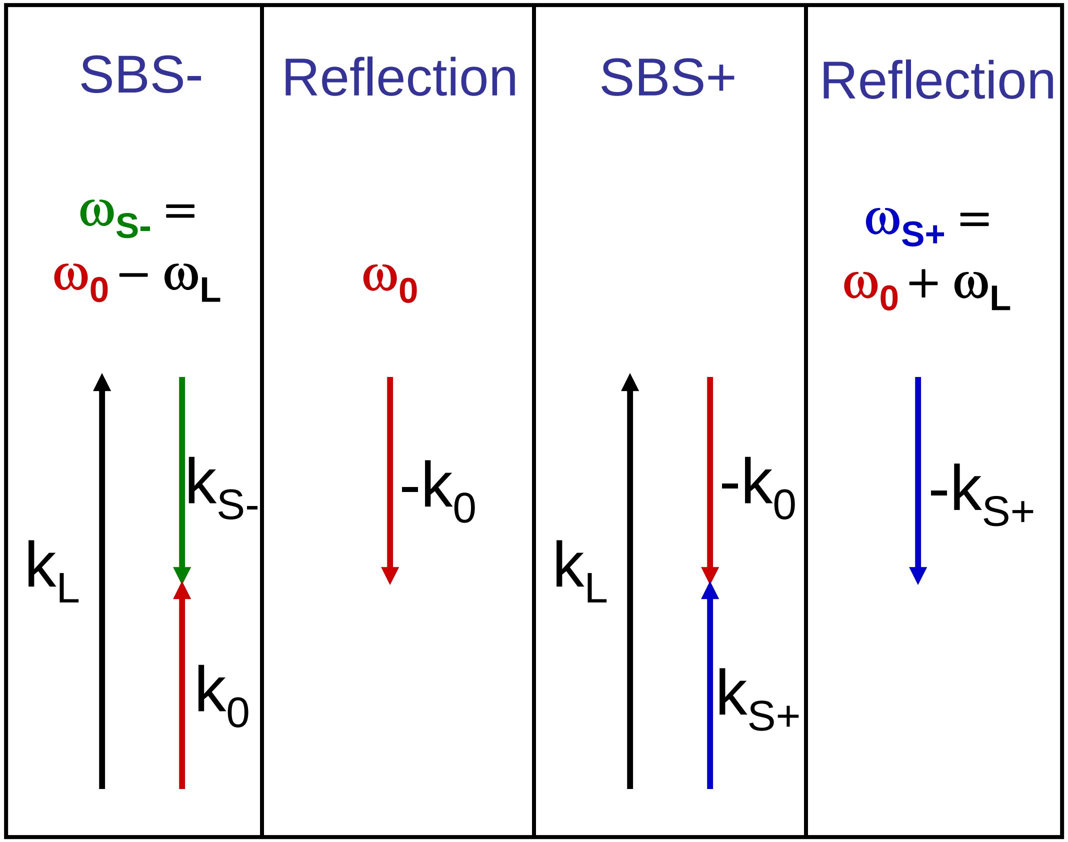
Time Sample of SBS Signal Demodulated from 5.6 MHz

Audio Sped Up by Factor of 20



Date 2008/10/24, Time 19:37:50

Upshifted and Downshifted Spectral Line Formation by SBS



SBS-

$\omega_{S-} = \omega_0 - \omega_L$

k_L k_{S-} k_0

Reflection

ω_0

$-k_0$

SBS+

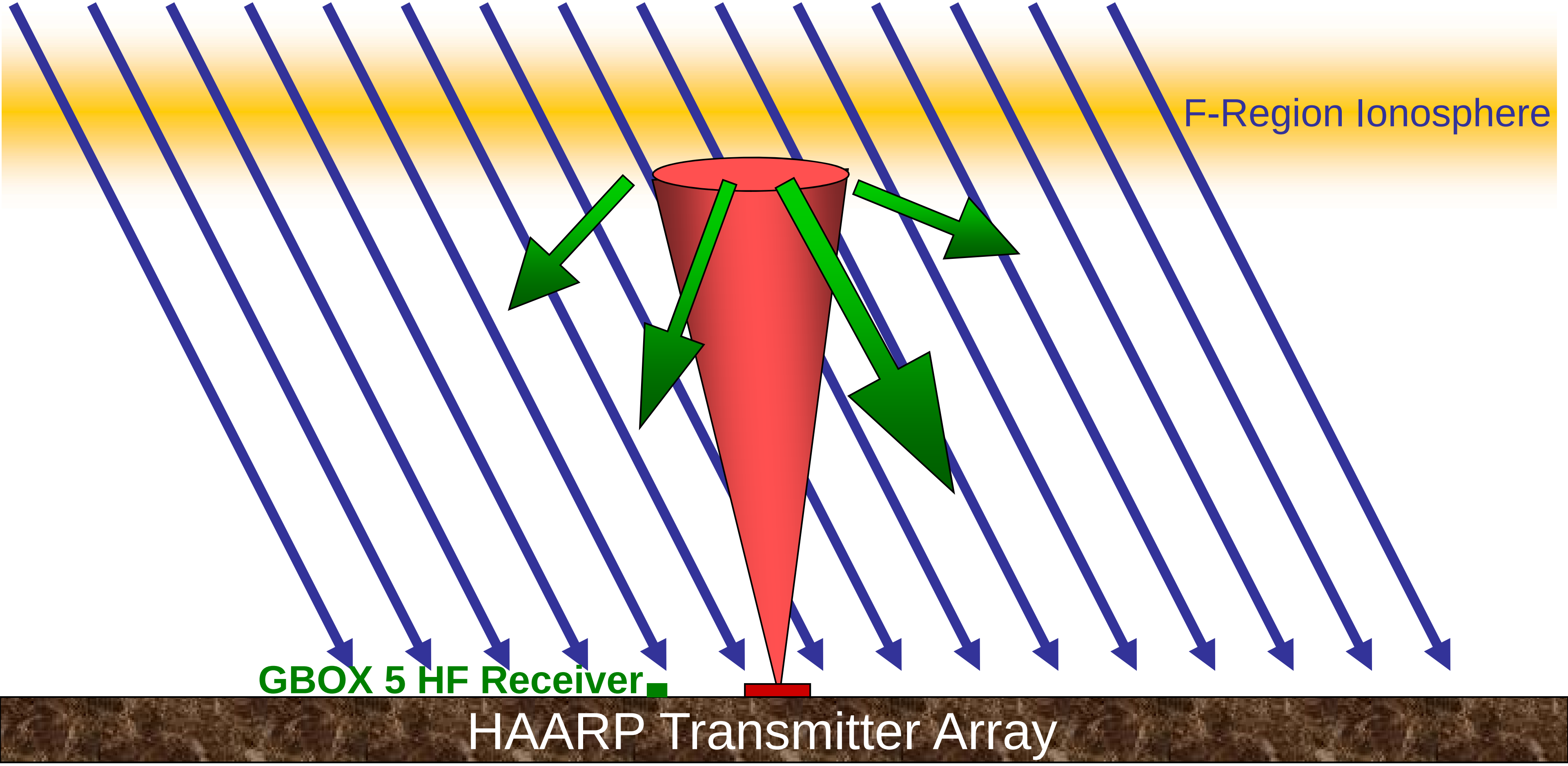
k_L $-k_0$ k_{S+}

Reflection

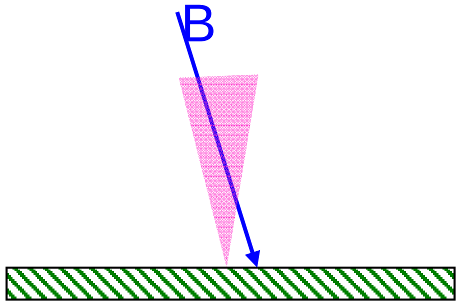
$\omega_{S+} = \omega_0 + \omega_L$

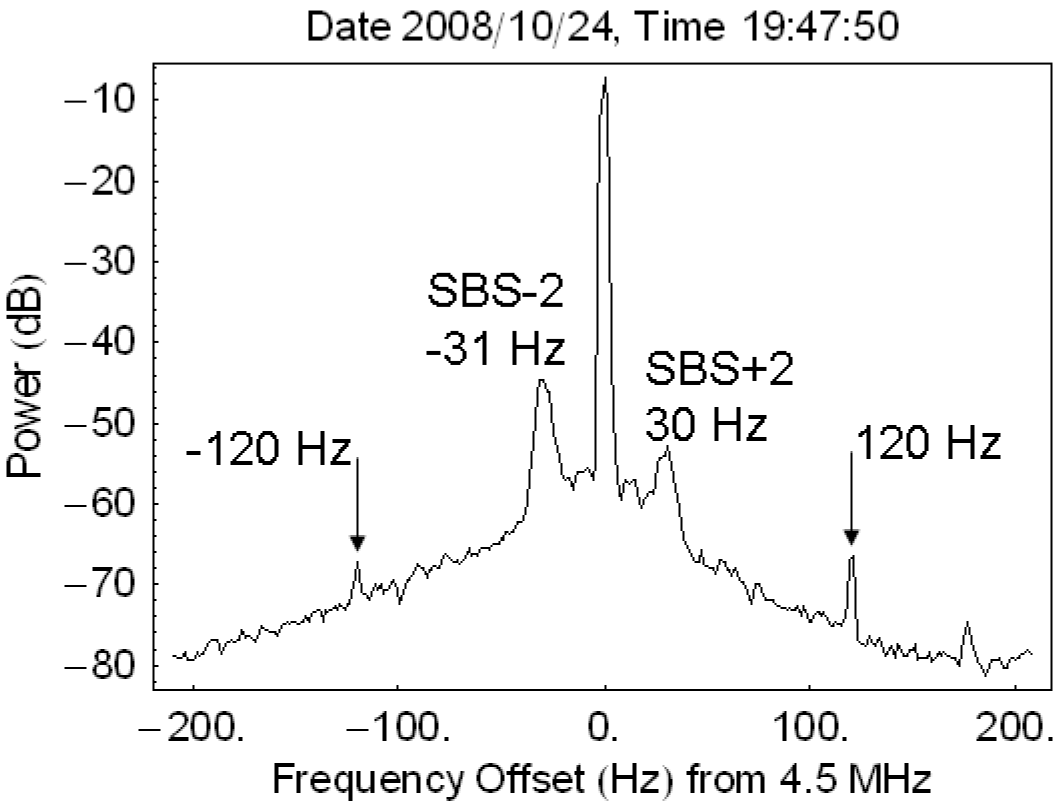
$-k_{S+}$

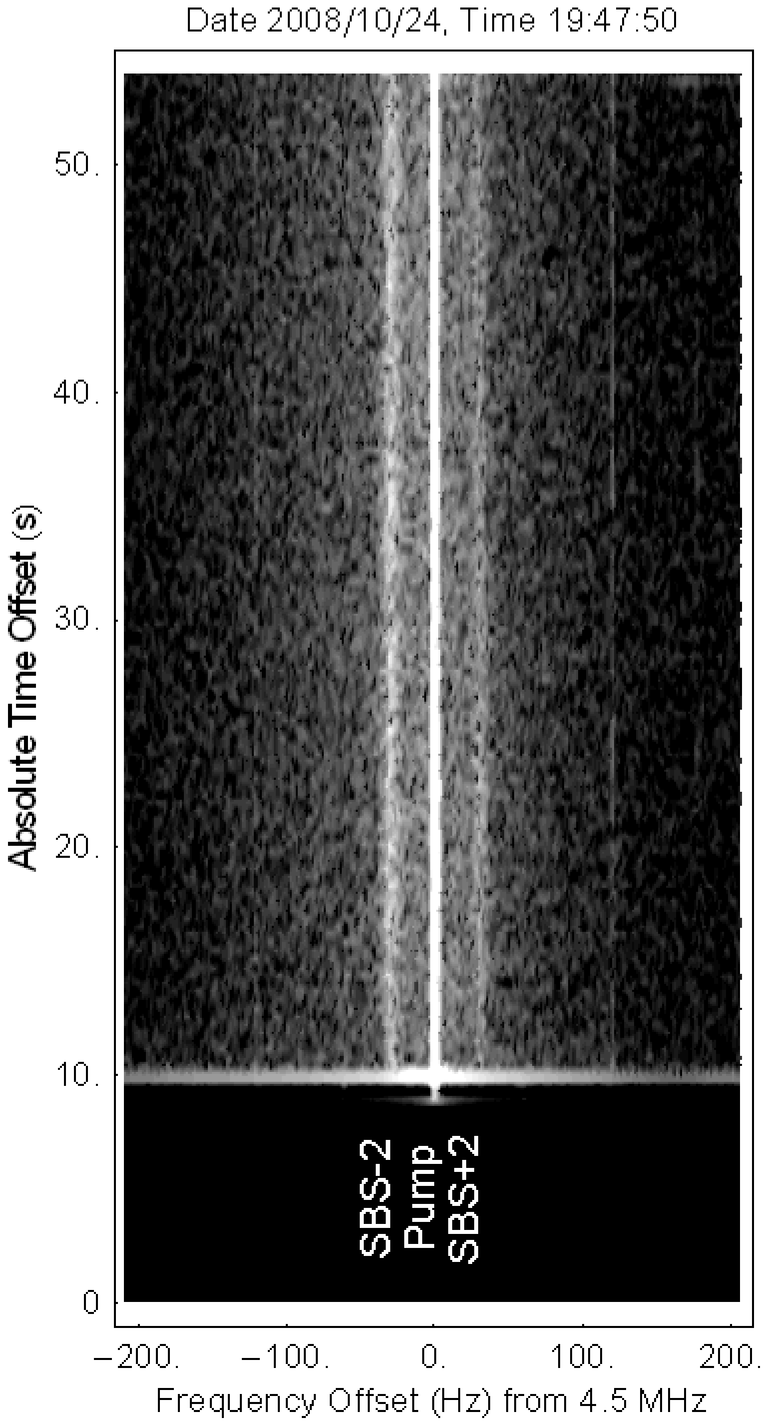
Stimulated Electromagnetic Emissions Measurements Near HAARP with Vertical Beam



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







SBS Matching Condition Theory

- Manley-Rowe Equations

$$\omega_0 = \omega_S + \omega_{IA}$$

$$\mathbf{k}_0 = \mathbf{k}_S + \mathbf{k}_{IA}$$

Ion Sound Speed

$$\boxed{c_{IA}^2 = \frac{\gamma_e K_B T_e + \gamma_i K_B T_i}{m_i}}$$

- Ion Acoustic/Electrostatic Ion Cyclotron Wave Dispersion

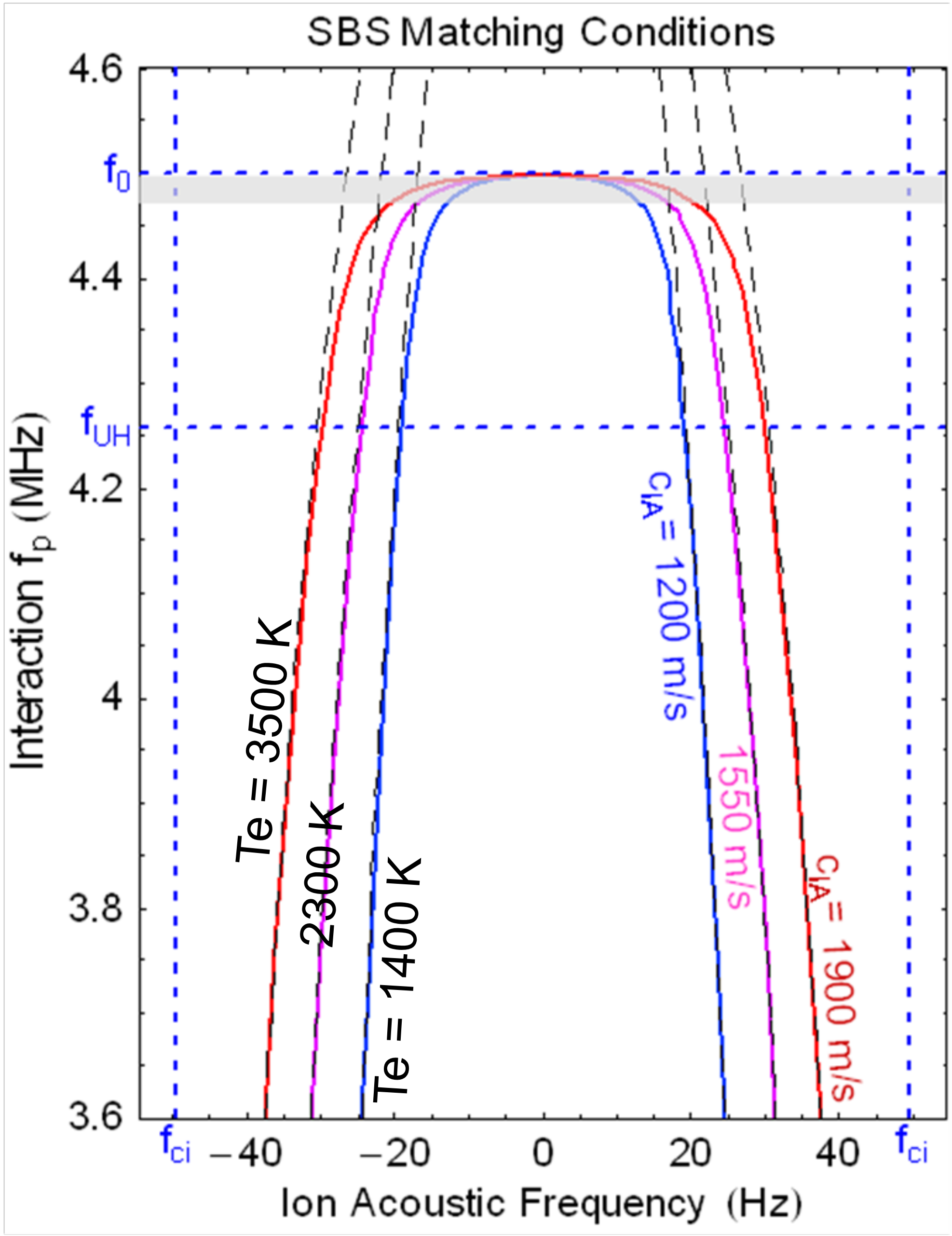
$$\omega_{IA}^4 - (\Omega_i^2 + k_{IA}^2 c_{IA}^2)\omega_{IA}^2 + \Omega_i^2 k_{IA}^2 c_{IA}^2 Cos^2\theta = 0$$

- Electromagnetic Wave Dispersion

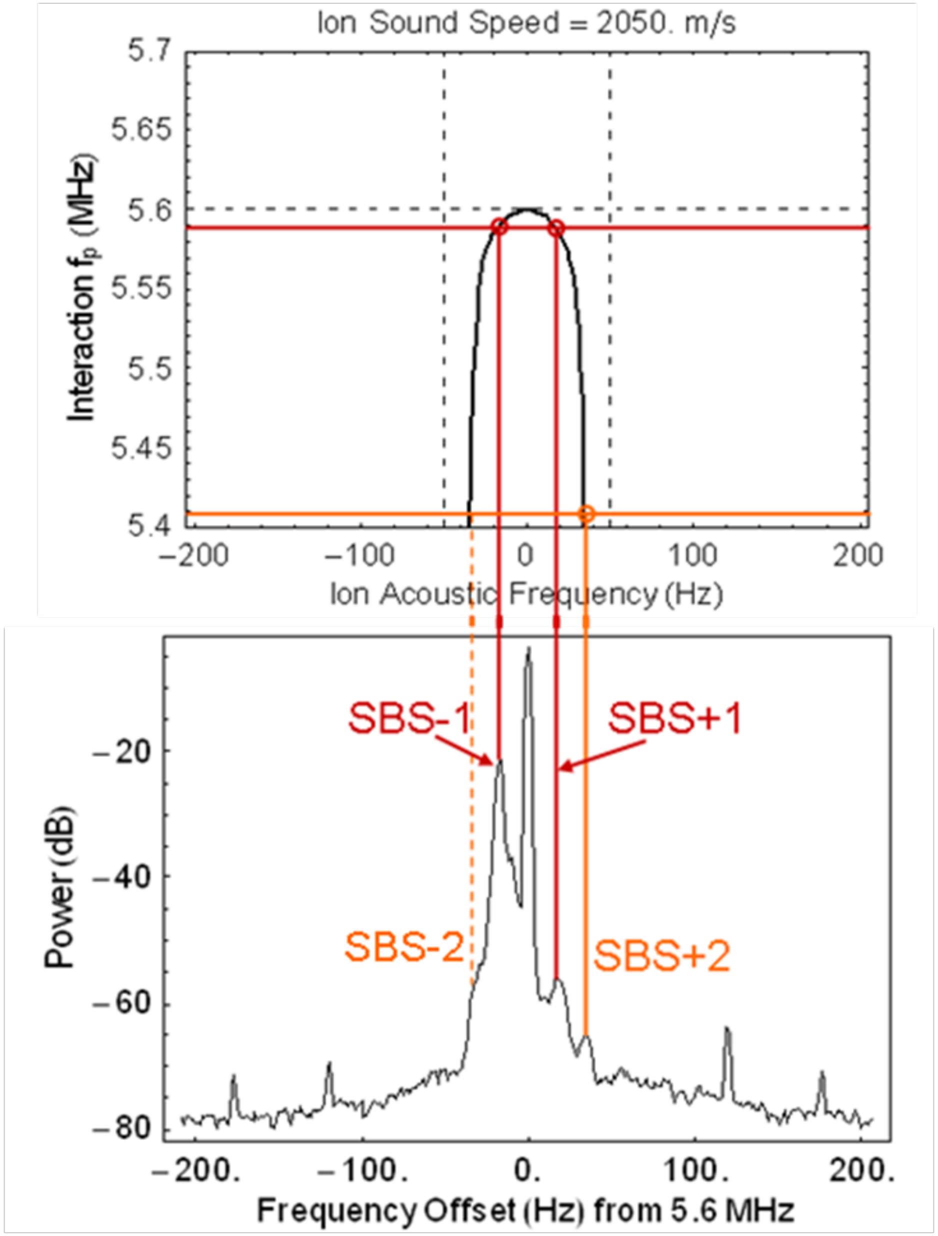
(+ for O-Mode, – for X-Mode)

$$\frac{2(\omega_{0,S}^2 - \omega_p^2)\omega_p^2}{\omega_{0,S}^2 - k_{0,S}^2 c^2} = \left(2(\omega_{0,s}^2 - \omega_p^2) - \Omega_e^2 Sin^2\theta \pm \sqrt{\frac{4(\omega_{0,S}^2 - \omega_p^2)^2 \Omega_e^2 Cos^2\theta}{\omega_{0,S}^2} + \Omega_e^4 Sin^4\theta} \right)$$

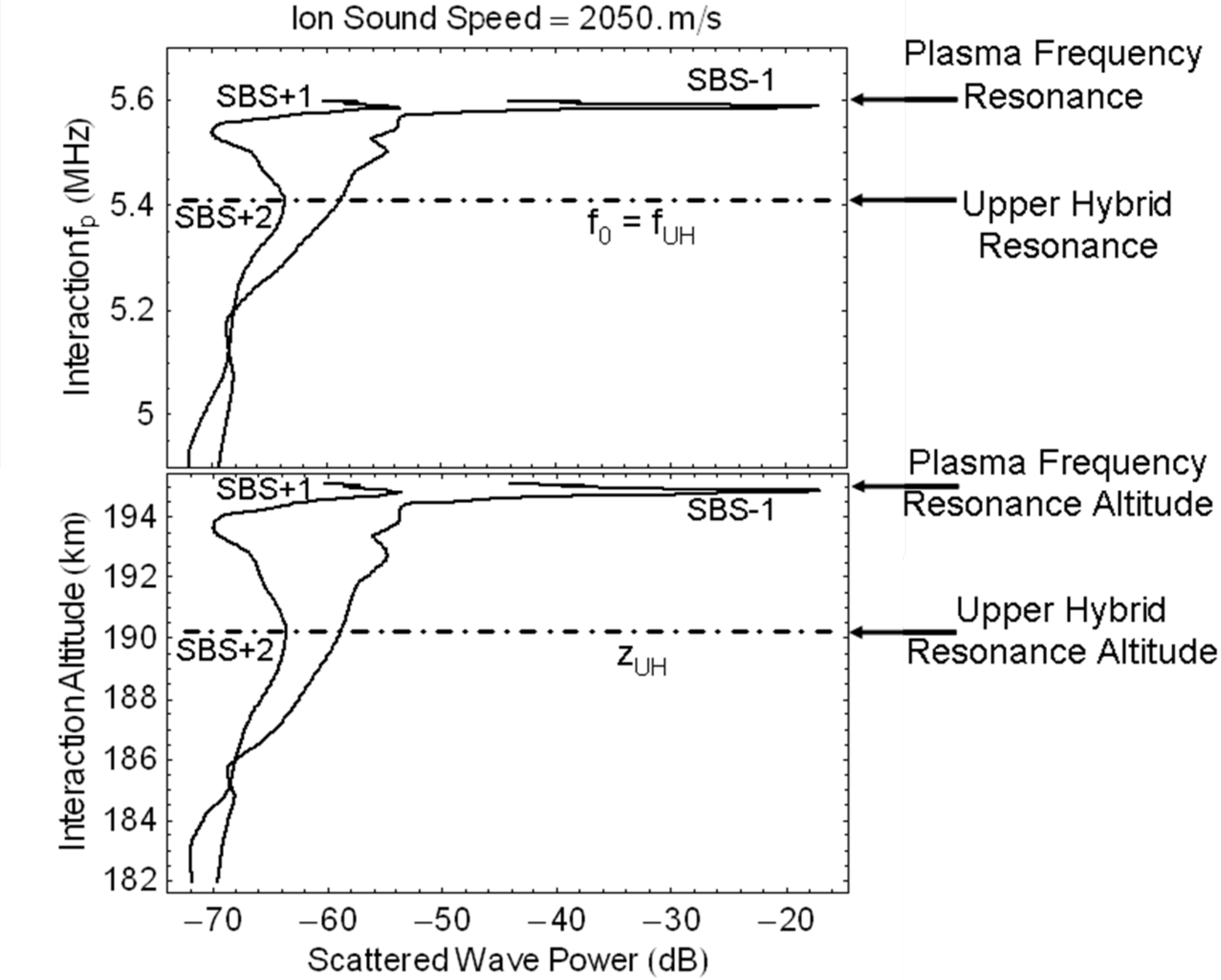
SBS Matching Conditions for O-Mode HF Waves at 4.5 MHz and Ion Acoustic Waves



Mapping of the SBS EM Scatter Lines to the Source Altitude for the 5.6 MHz SEE Signal

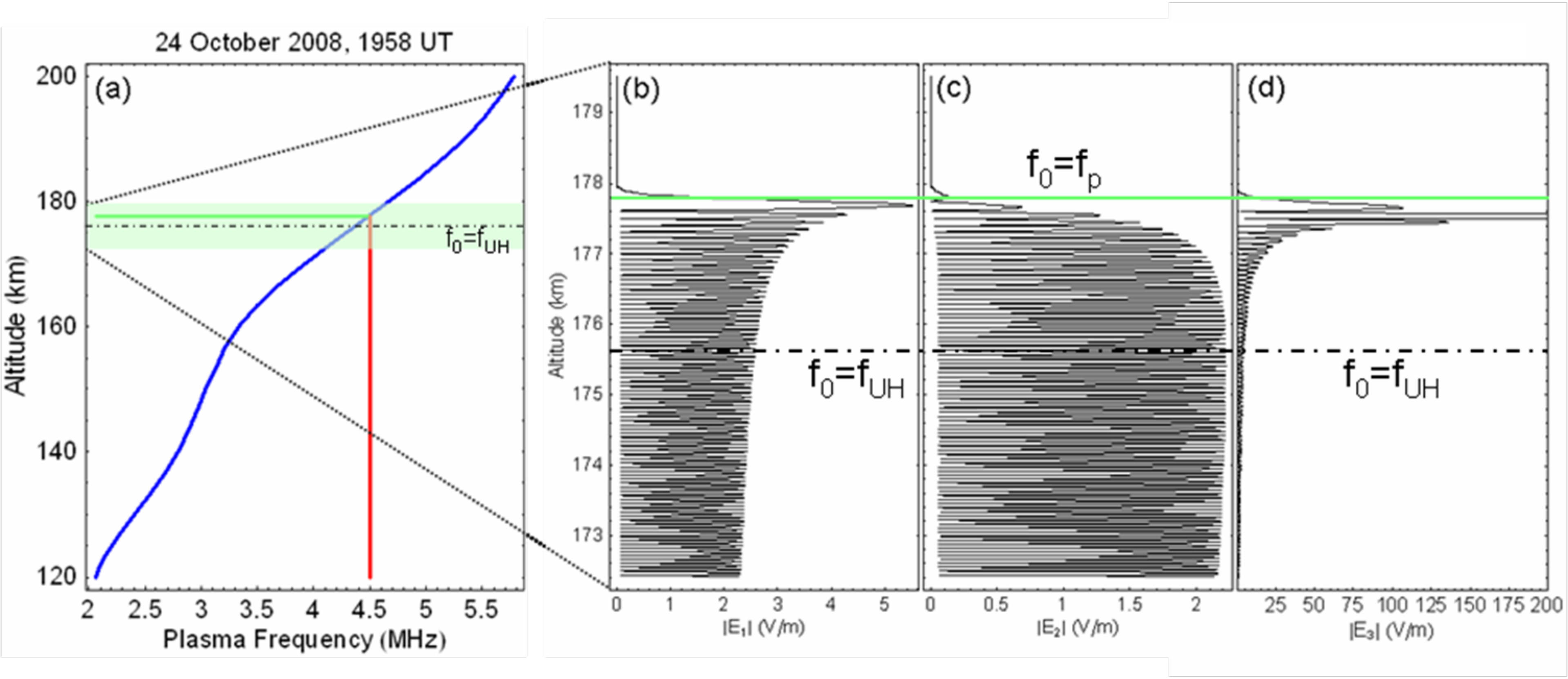


Scattered SBS EM Wave Profile for 5.6 MHz Pump at the Magnetic Zenith with 3.6 MW Transmitter Power (1.66 GW ERP)



Full Wave Solution for EM Pump Wave at 4.5 MHz in the Ionosphere Over HAARP

Maximum Value for |E3| = 2145 V/m



Determination of Electron Temperature at UH Resonance Altitude

- Assumptions

  $T_e \cong 3\ T_i$

  $\Omega_e,\ \Omega_i$ known

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

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
Te (K)	3506	3506	3176	2866

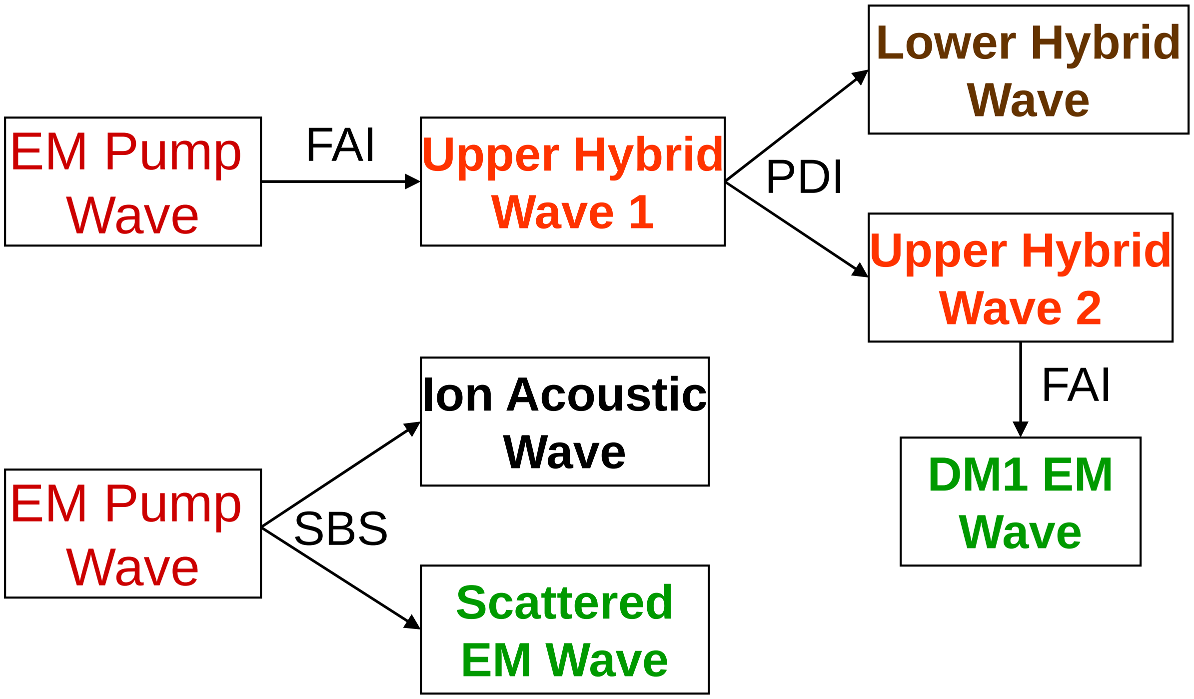
- Ion Acoustic Speed

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

- QL Solution

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

Competing Processes for Generation of Downshifted Stimulated Electromagnetic Emissions



EM Pump Wave

FAI

Upper Hybrid Wave 1

PDI

Lower Hybrid Wave

Upper Hybrid Wave 2

FAI

DM1 EM Wave

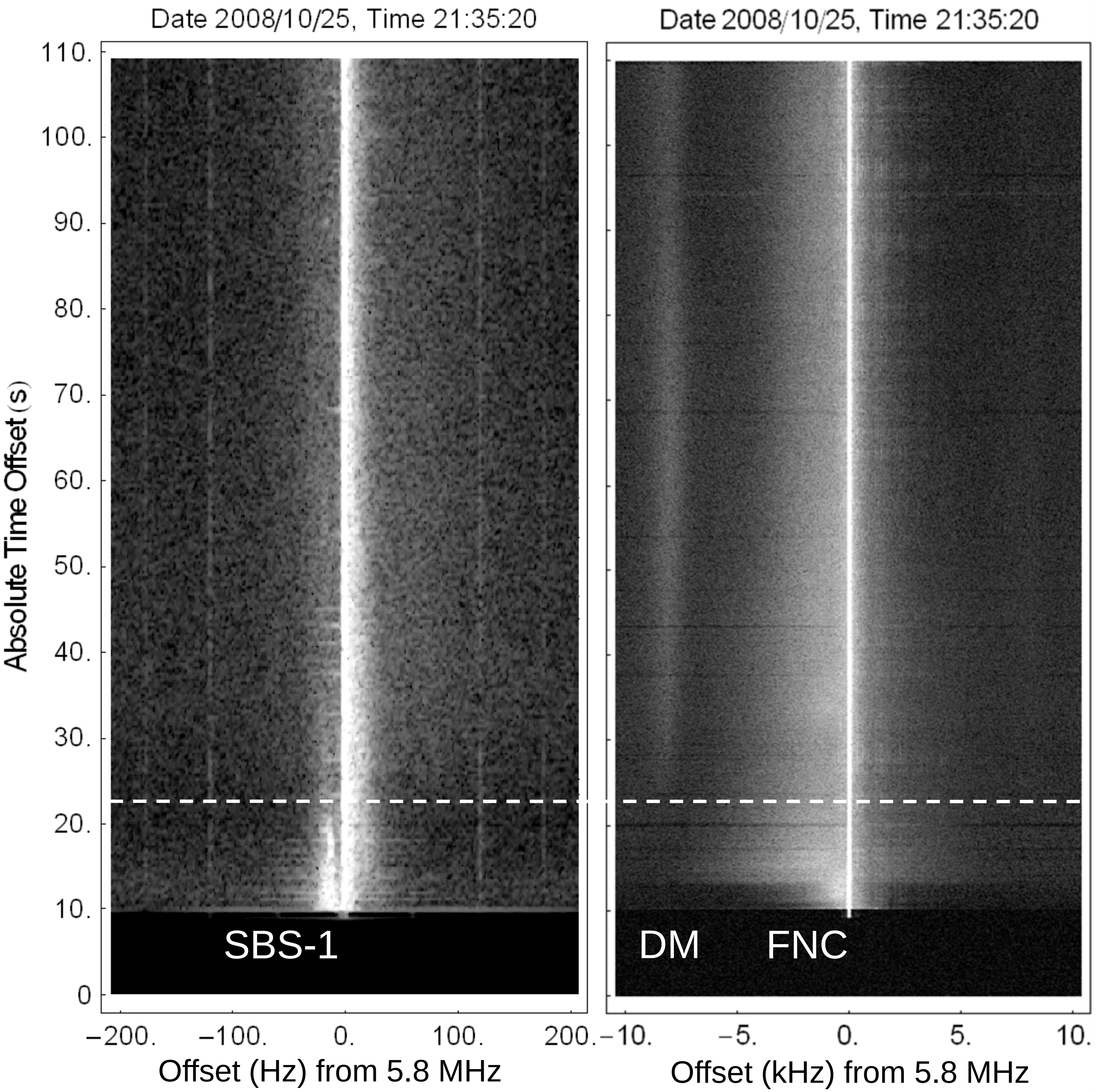
EM Pump Wave

SBS

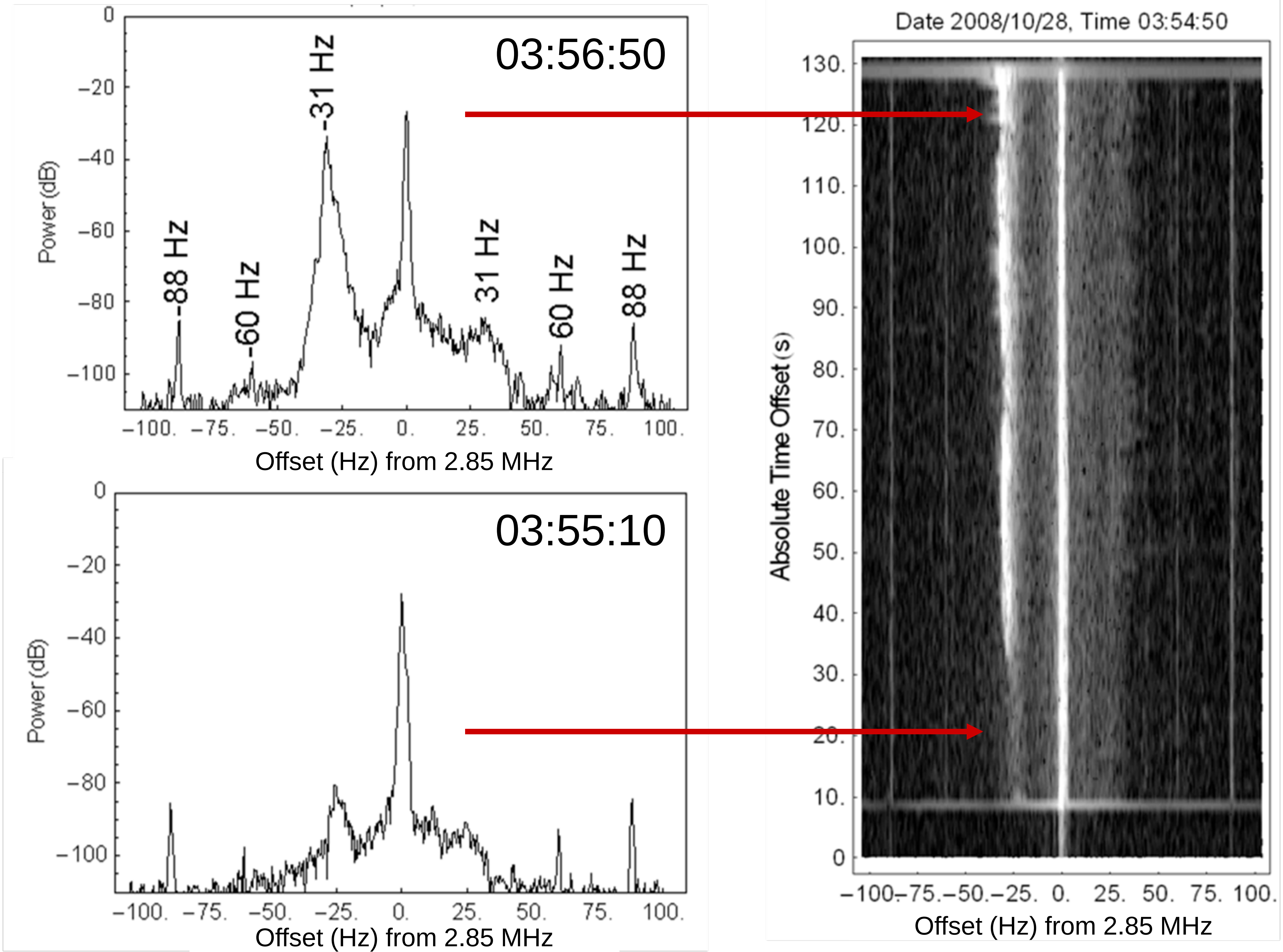
Ion Acoustic Wave

Scattered EM Wave

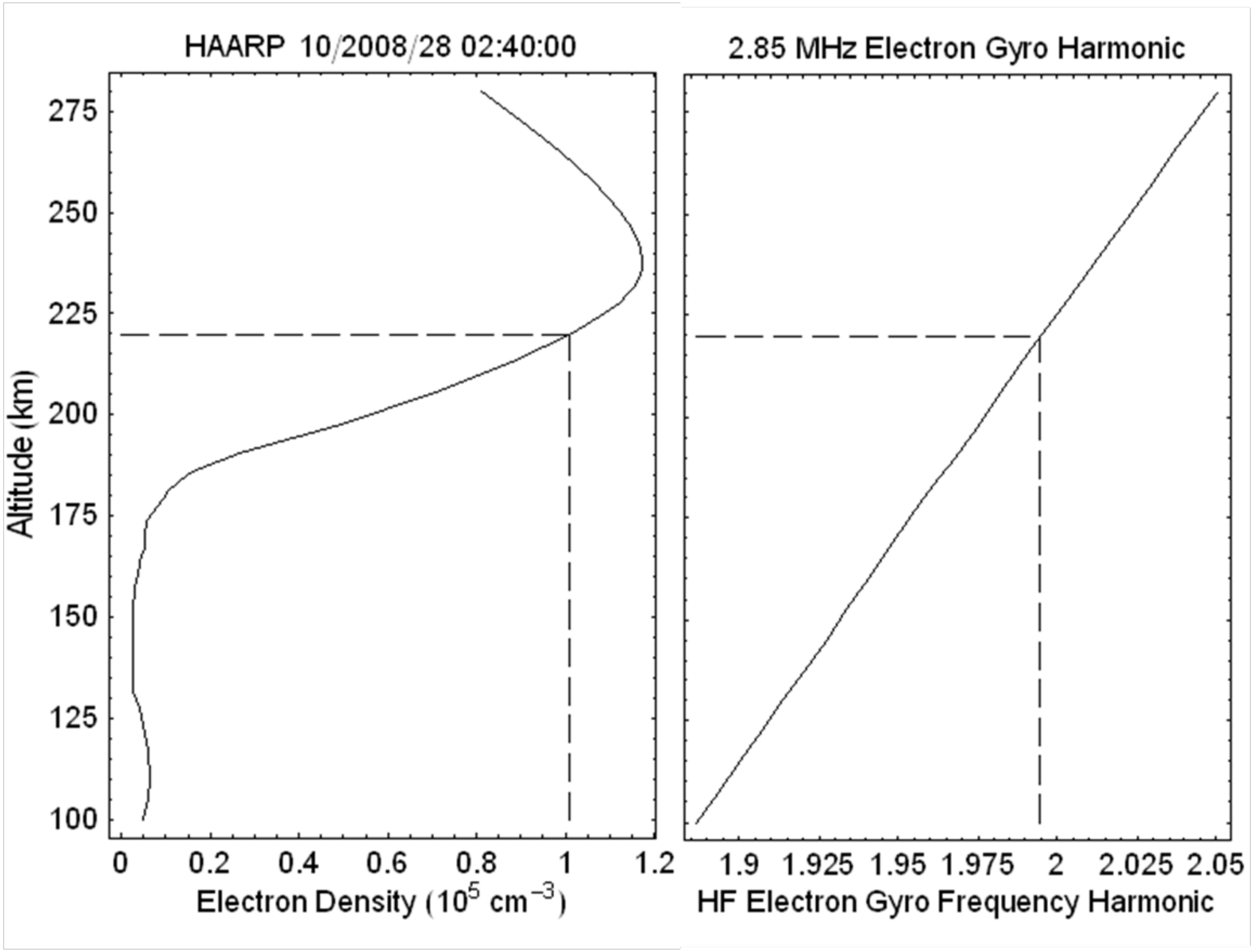
Transition Between Stimulated Brillouin Scatter Near the Reflection Altitude and Mode Coupling on Field Aligned Irregularities at Upper Hybrid Wave Region



SBS at UH Level for Underdense HF



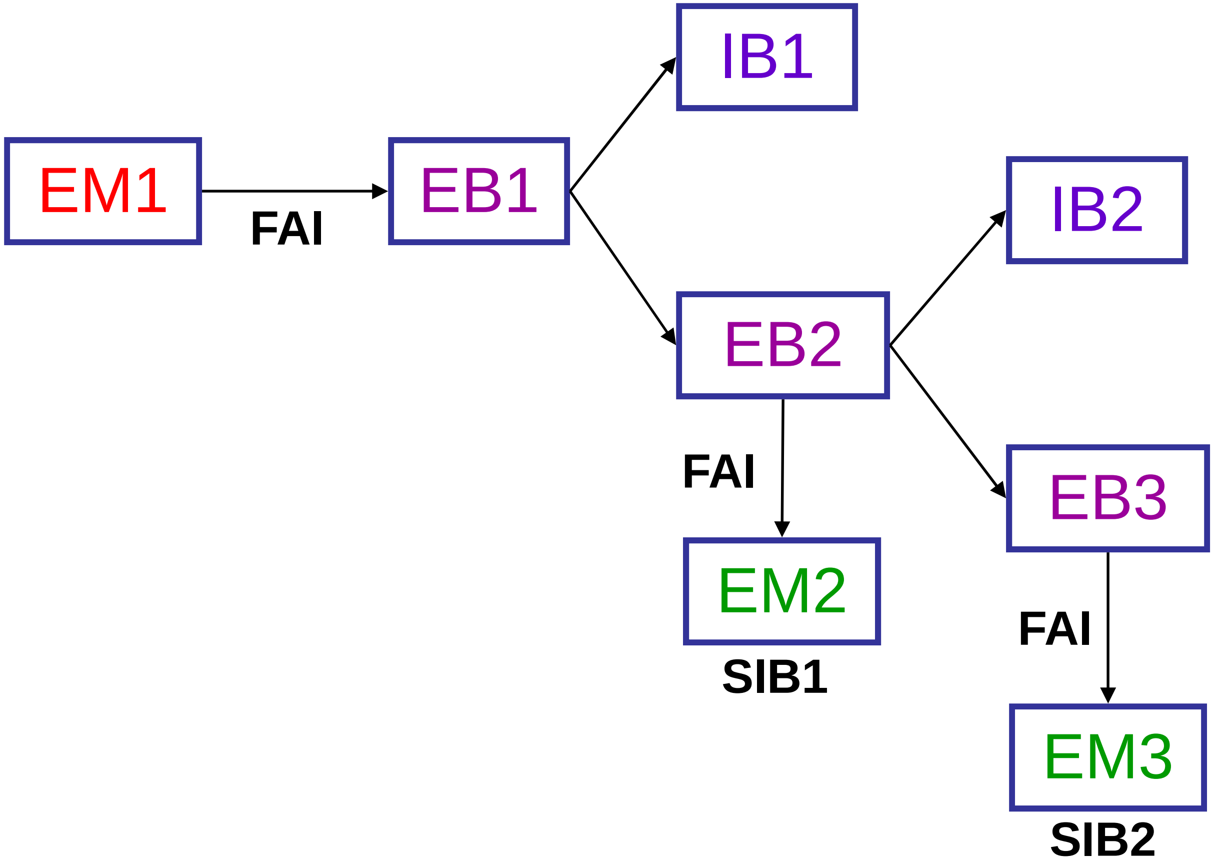
HF Interactions Near the Seconds Electron Cyclotron Harmonic
Electron Density Profile for 28 October 2008



Parametric Decay Instabilities Observed by Stimulated EM Emissions

Parent Wave 0	Daughter Wave 1	Daughter Wave 2	Instability Name	Observed for HF
Electron Bernstein Wave	Electron Bernstein Wave	Ion Bernstein Wave	Electron Bernstein Decay Instability	Yes SEE

Stimulated Ion Bernstein (SIB) Generation



EM1

FAI

EB1

IB1

EB2

IB2

FAI

EB3

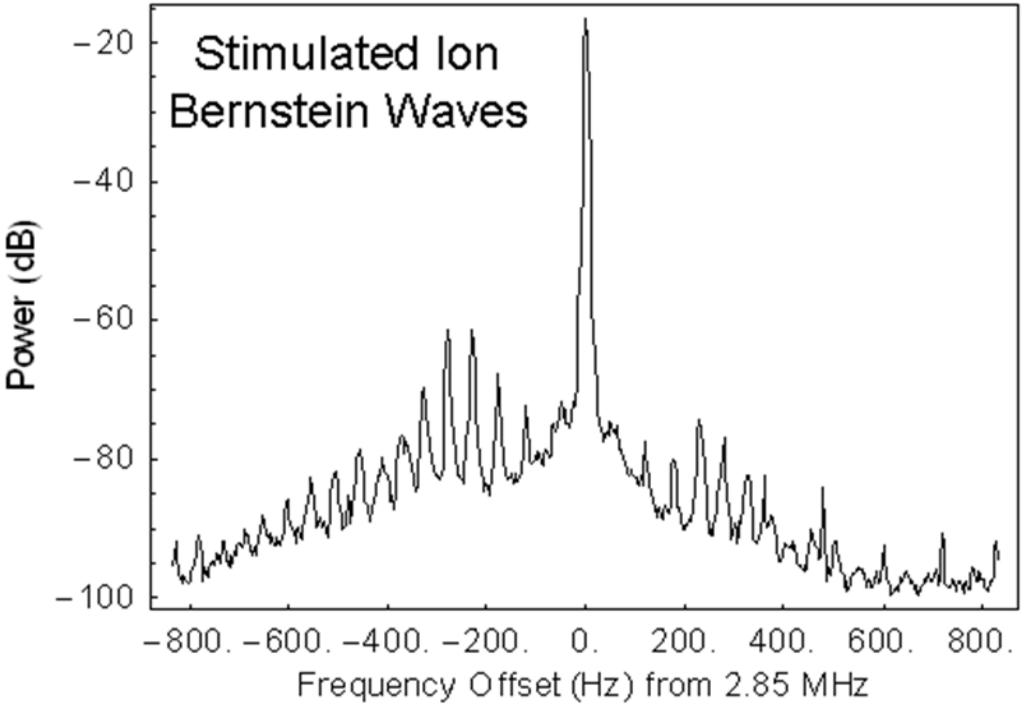
EM2

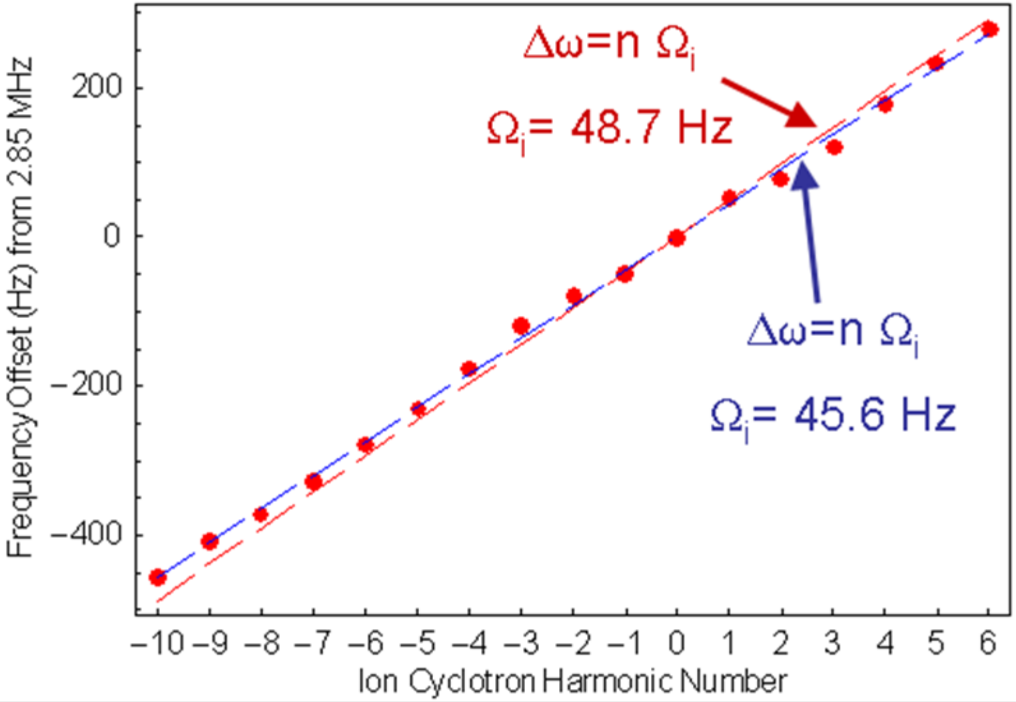
SIB1

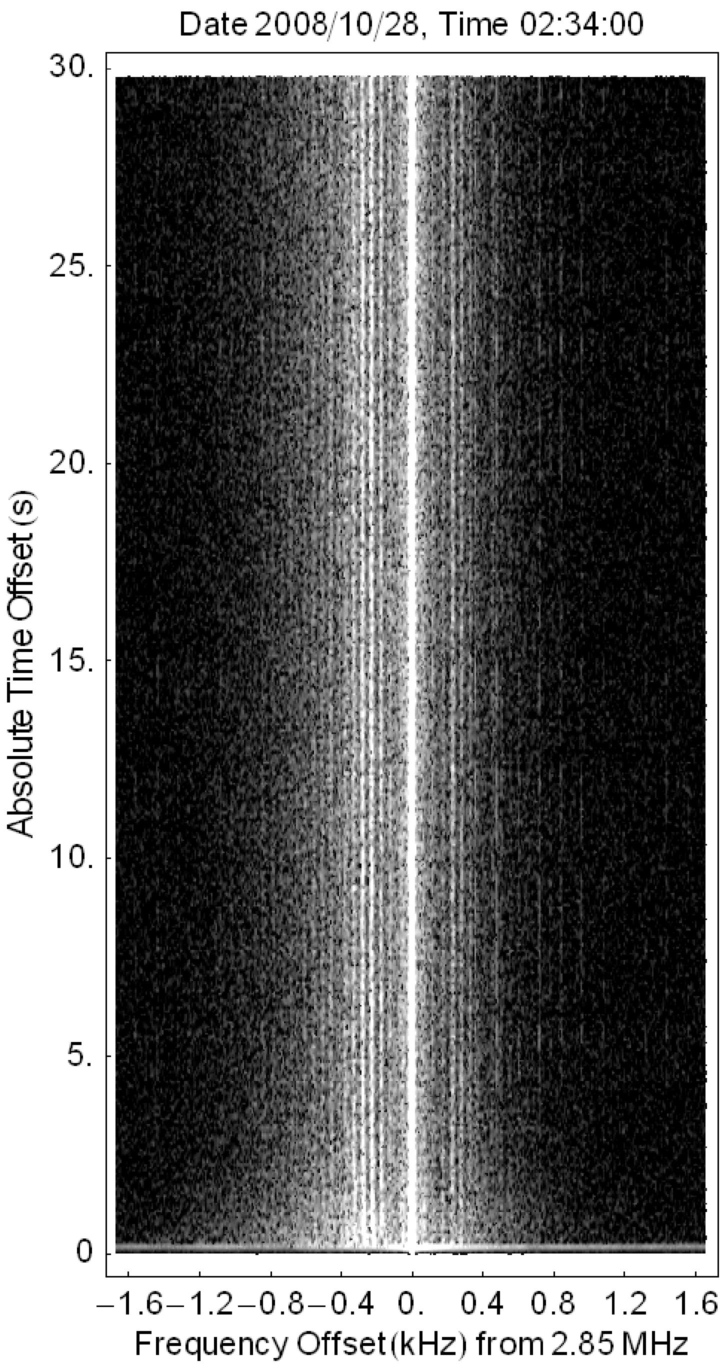
FAI

EM3

SIB2


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

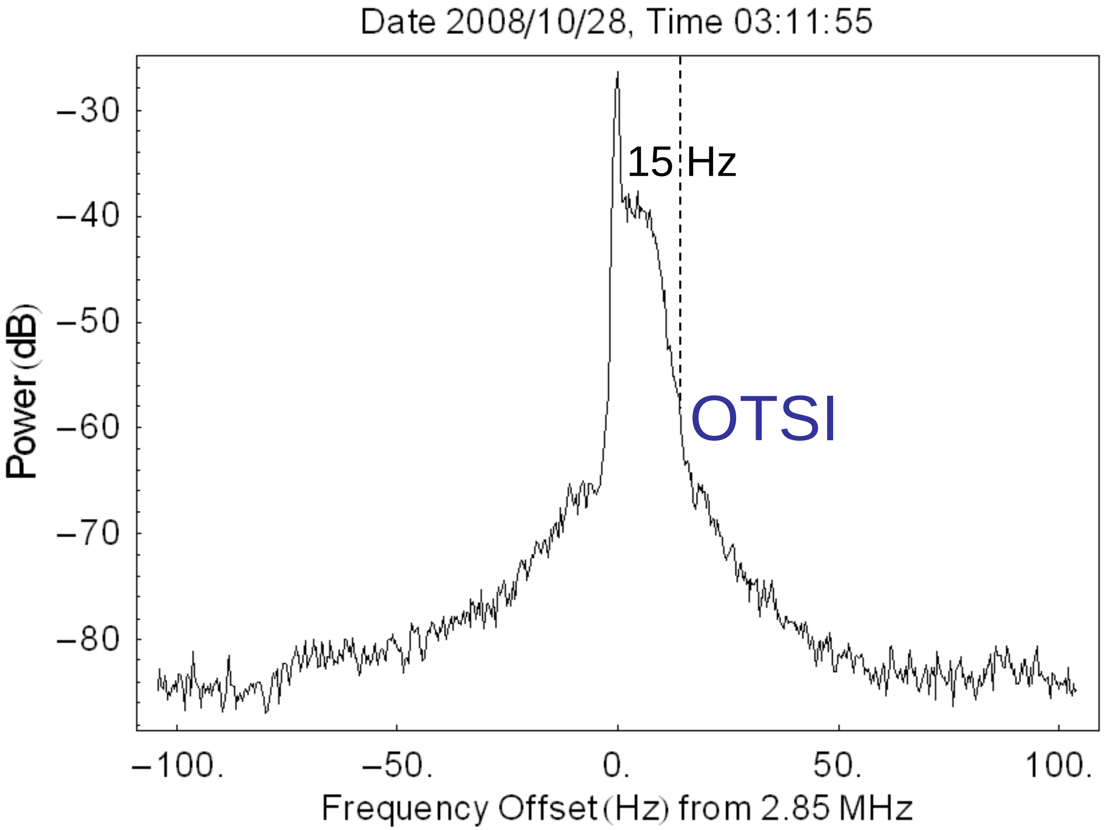

Δω=n Ω_i
Ω_i= 48.7 Hz
Δω=n Ω_i
Ω_i= 45.6 Hz
Frequency Offset (Hz) from 2.85 MHz
200
0
−200
−400
−10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6
Ion Cyclotron Harmonic Number

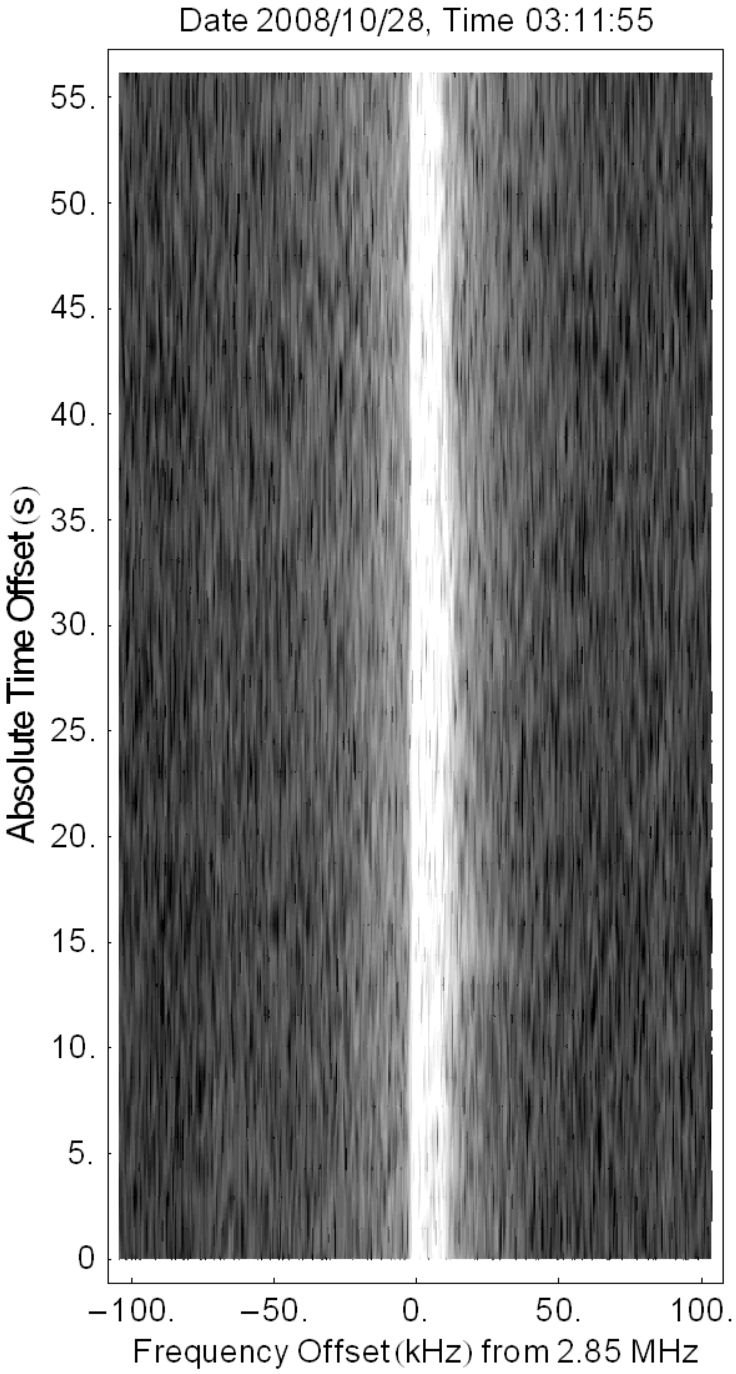

Date 2008/10/28, Time 02:34:00
Absolute Time Offset (s)
30.
25.
20.
15.
10.
5.
0
−1.6 −1.2 −0.8 −0.4 0. 0.4 0.8 1.2 1.6
Frequency Offset (kHz) from 2.85 MHz

Simultaneous Parametric Decay Instabilities Observed by Stimulated EM Emissions

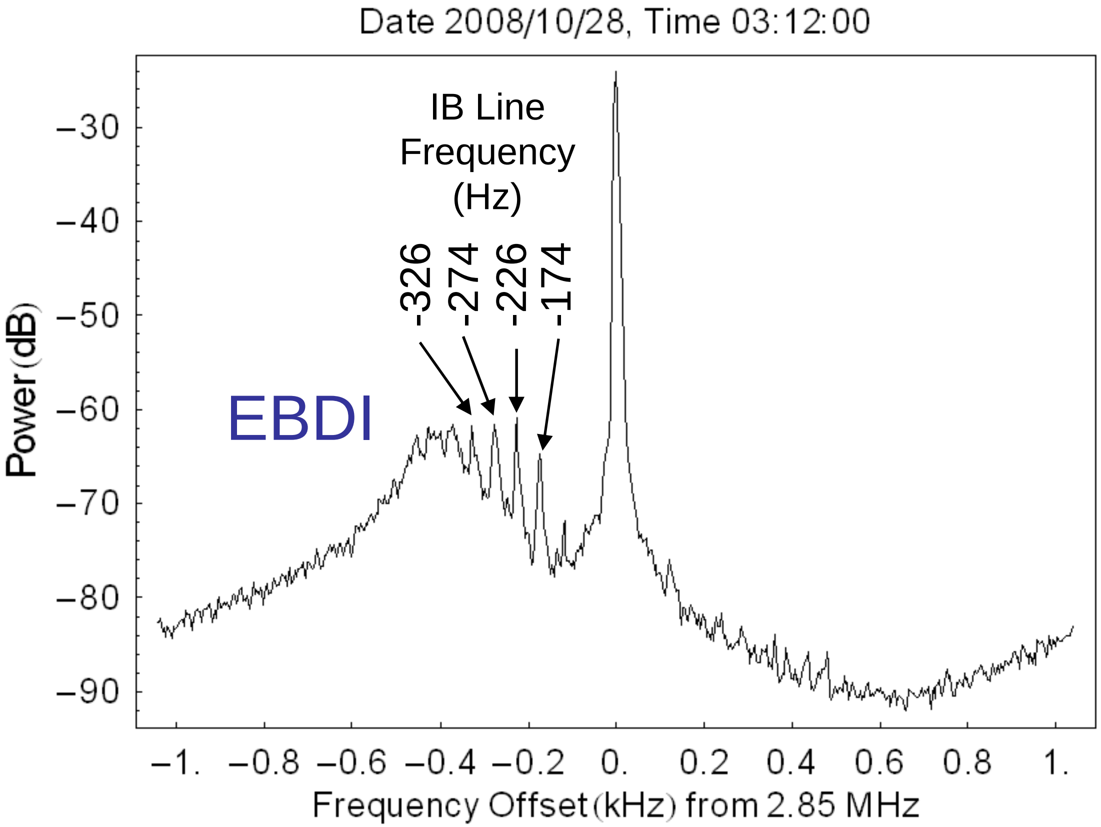
Parent Wave 0	Daughter Wave 1	Daughter Wave 2	Instability Name	Observed for HF
Electromagnetic Wave	Zero Frequency Electron Wave	Zero Frequency Ion Wave	Oscillating Two-Stream Instability	Yes Radar/SEE
Electromagnetic Wave	Electromagnetic Wave	Ion Acoustic Wave	Stimulated Brillouin Scattering Instability	Yes SEE
Upper Hybrid Wave	Upper Hybrid Wave	Lower Hybrid Wave	Lower-Hybrid Decay Instability	Yes SEE
Electron Bernstein Wave	Electron Bernstein Wave	Ion Bernstein Wave	Electron Bernstein Decay Instability	Yes SEE

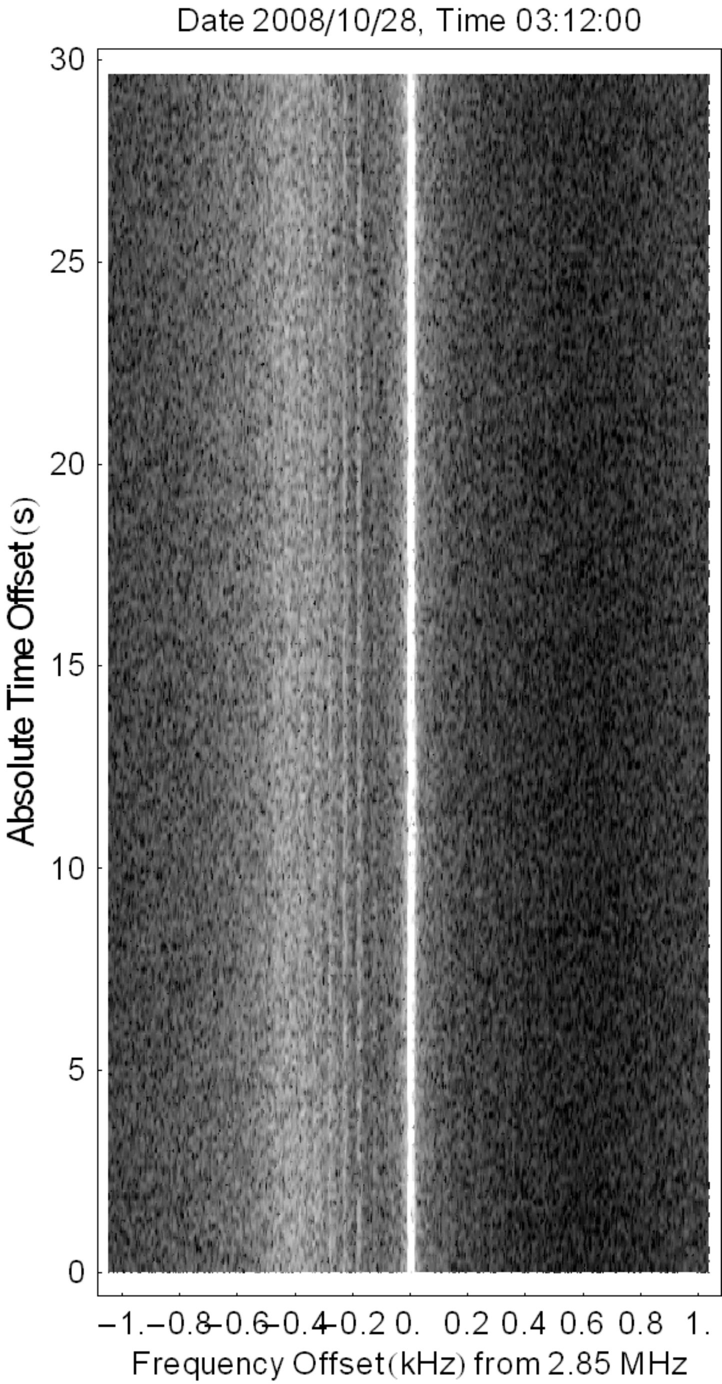
28 October 2008
03:12:00 UT





28 October 2008
03:12:00 UT





28 October 2008
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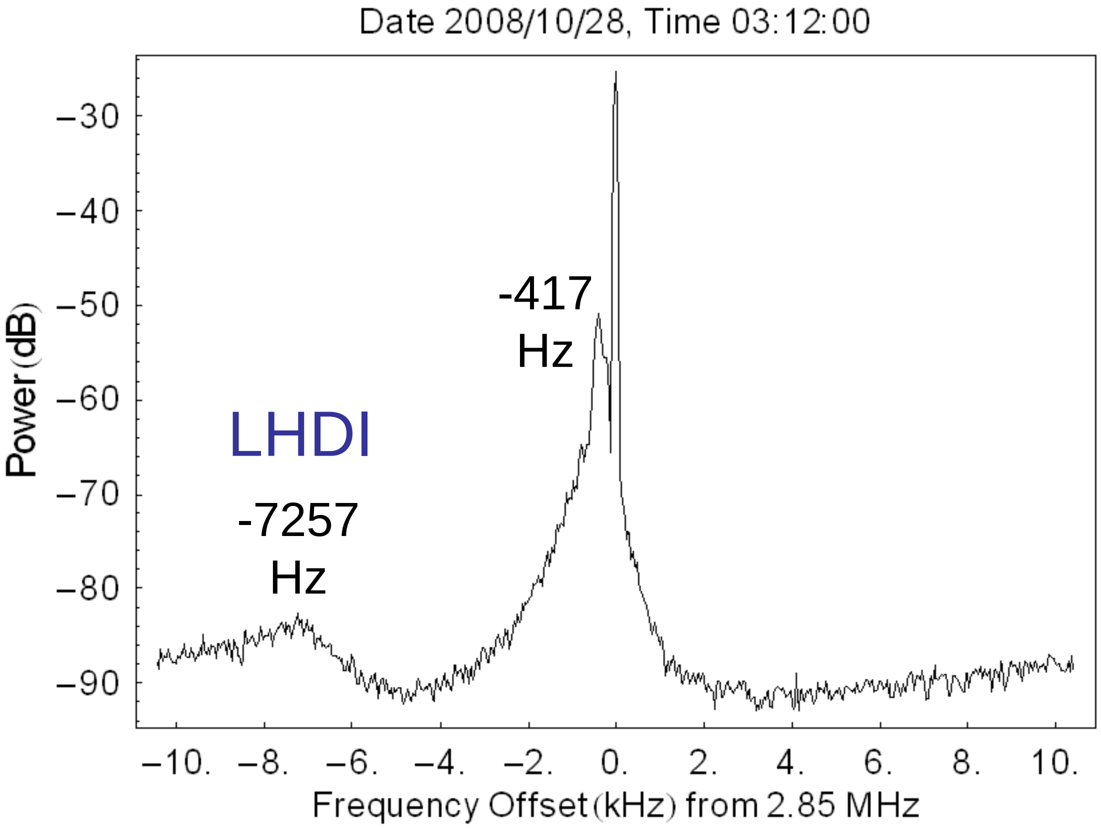
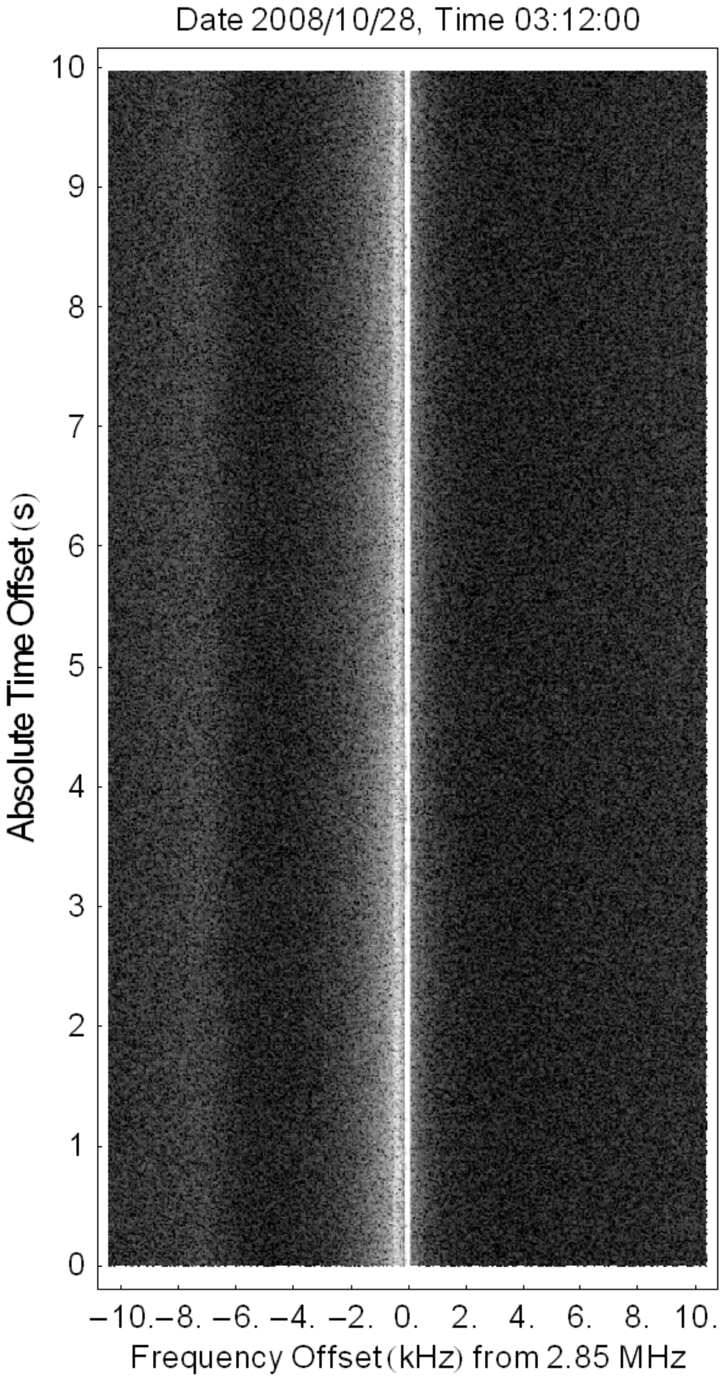


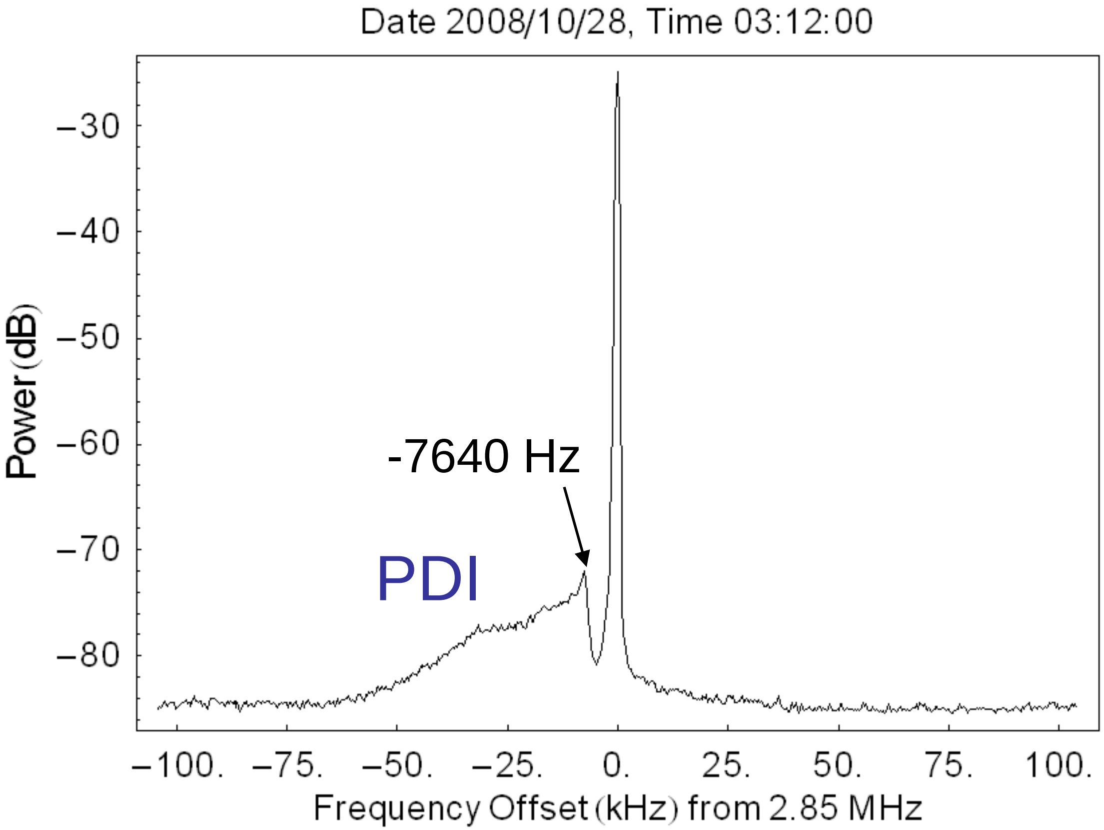
-417 Hz

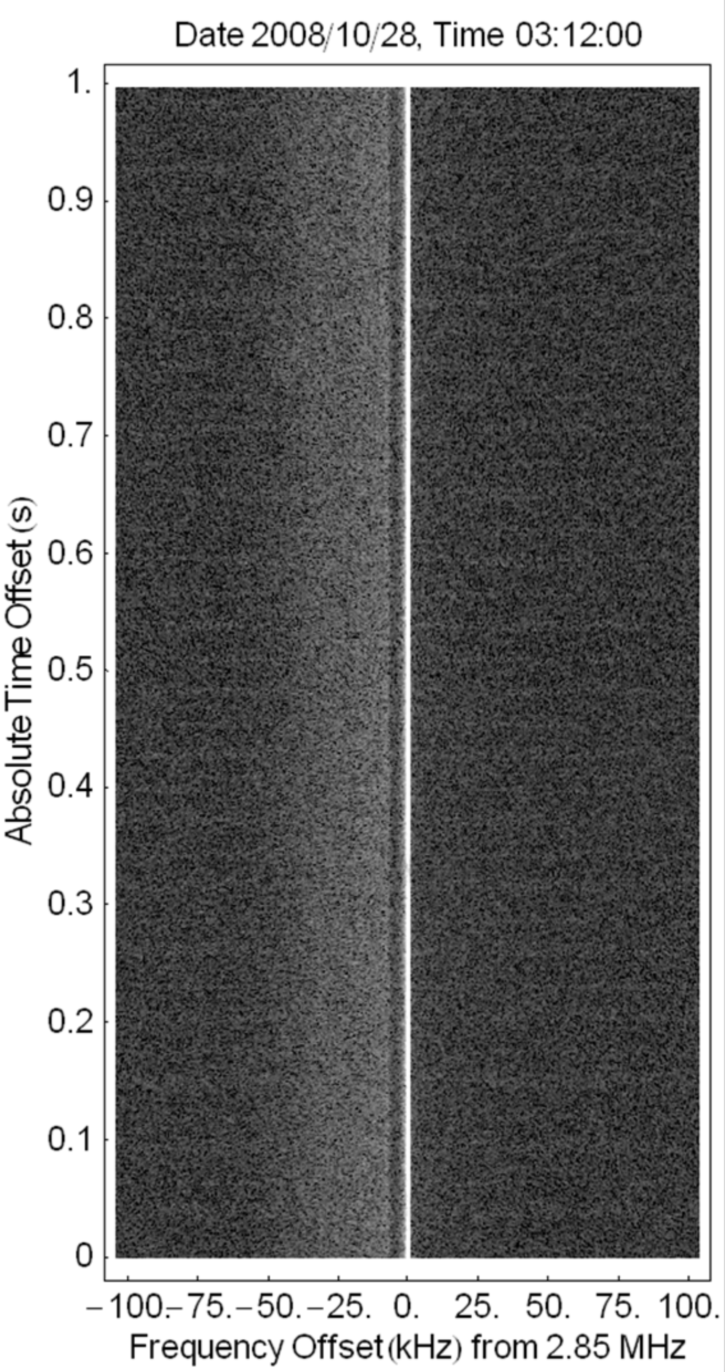
LHDI

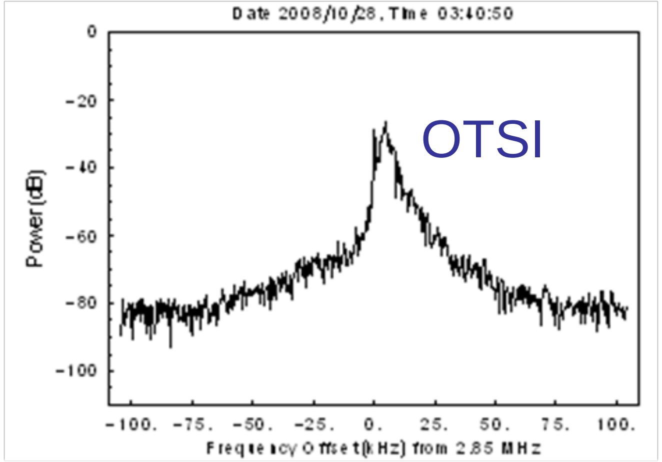
-7257 Hz

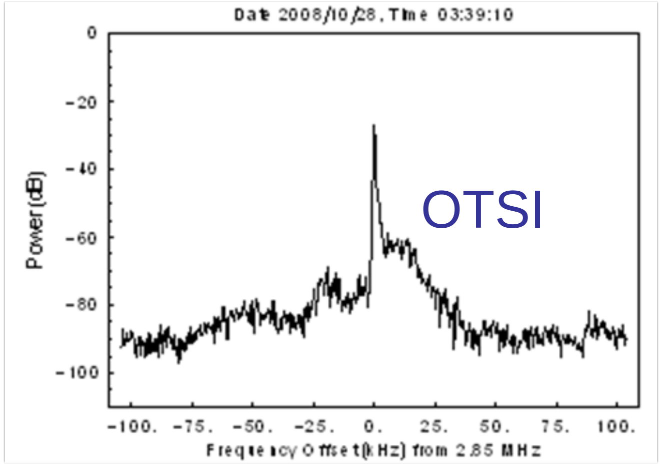


28 October 2008 03:12:00 UT






Date 2008/10/28, Time 03:40:50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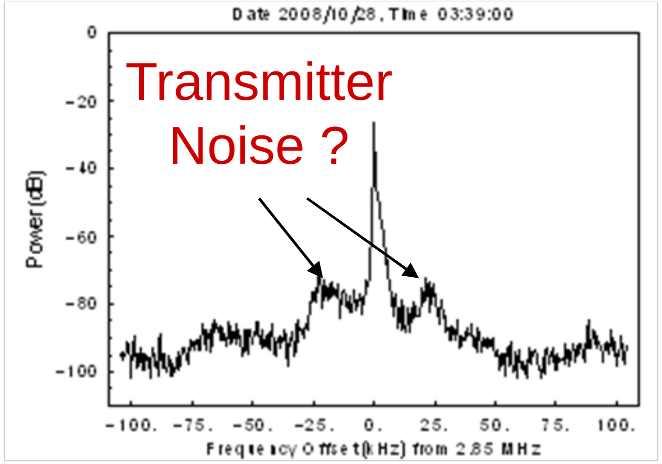
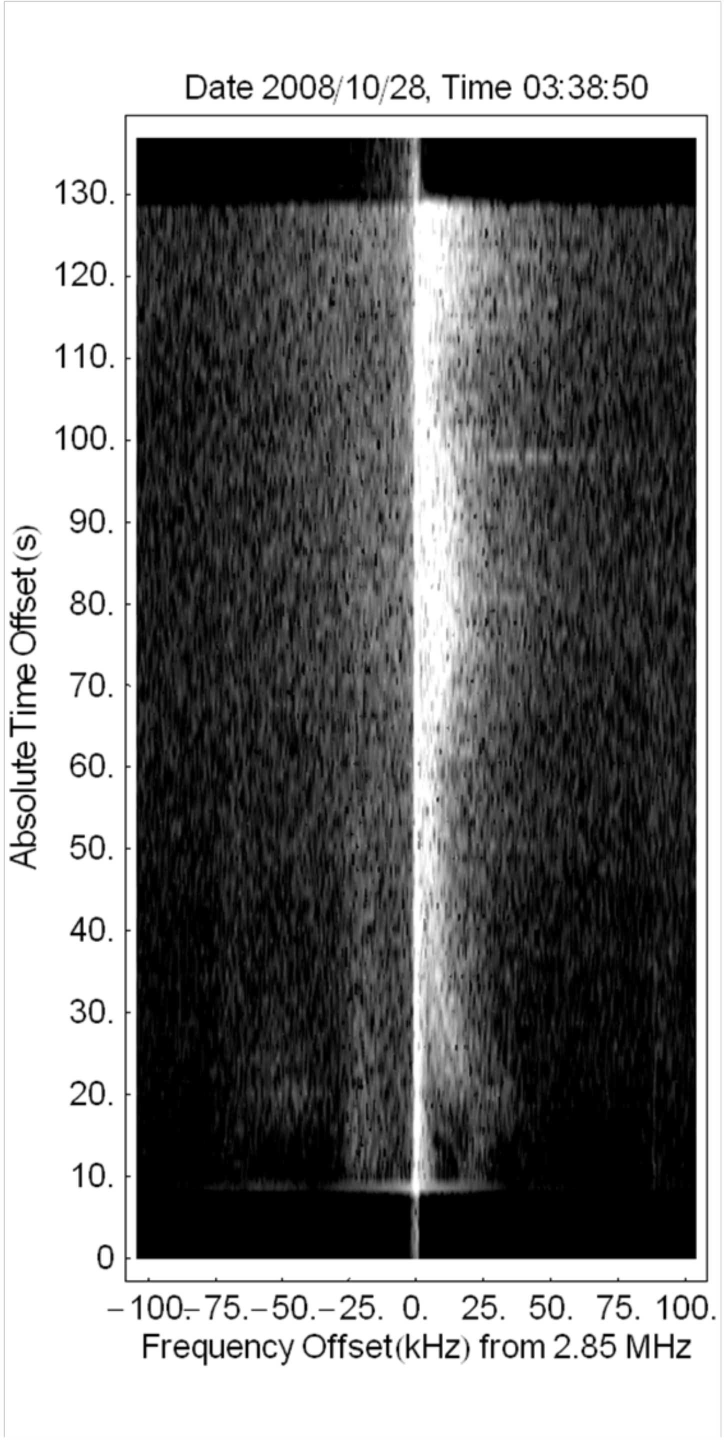

Date 2008/10/28, Time 03:39:00

OTSI

OTSI Growth


Date 2008/10/28, Time 03:38:50

Artificial Electrostatic Waves in the Ionosphere

- Ion Acoustic Waves Generated By Hypersonic Exhaust and High Power Radio Waves When Te >> Ti.
- 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 described by Bernhardt et al., submitted to ***Annales Geophysicae*** , 2009.
  - SBS by Underdense High-Power HF to be Tested in August at HAARP
  - 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
- Stimulated Ion Bernstein Scatter and OTSI Discovery
  - First SEE Observations at HAARP
  - Slight Offsets from Ion Cyclotron Frequency Harmonics