Space and Laboratory Experiments Using Plasma Waves to Detect Satellites in Low Earth Orbit

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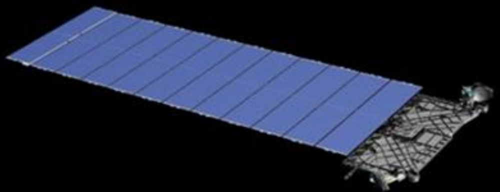
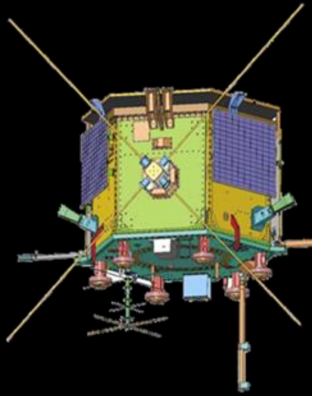
Iridium



Starlink

Waves

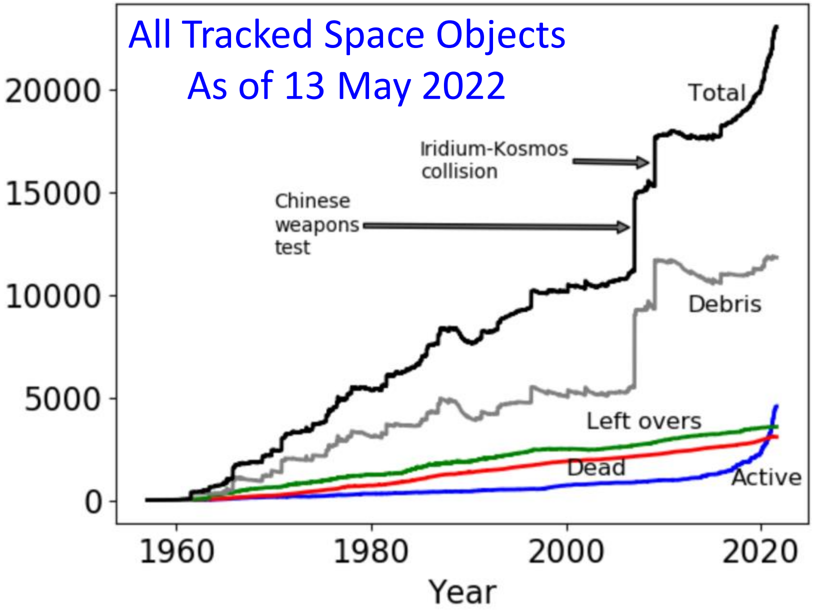


e-POP

Potential Hazards

In Situ Hazard Detection

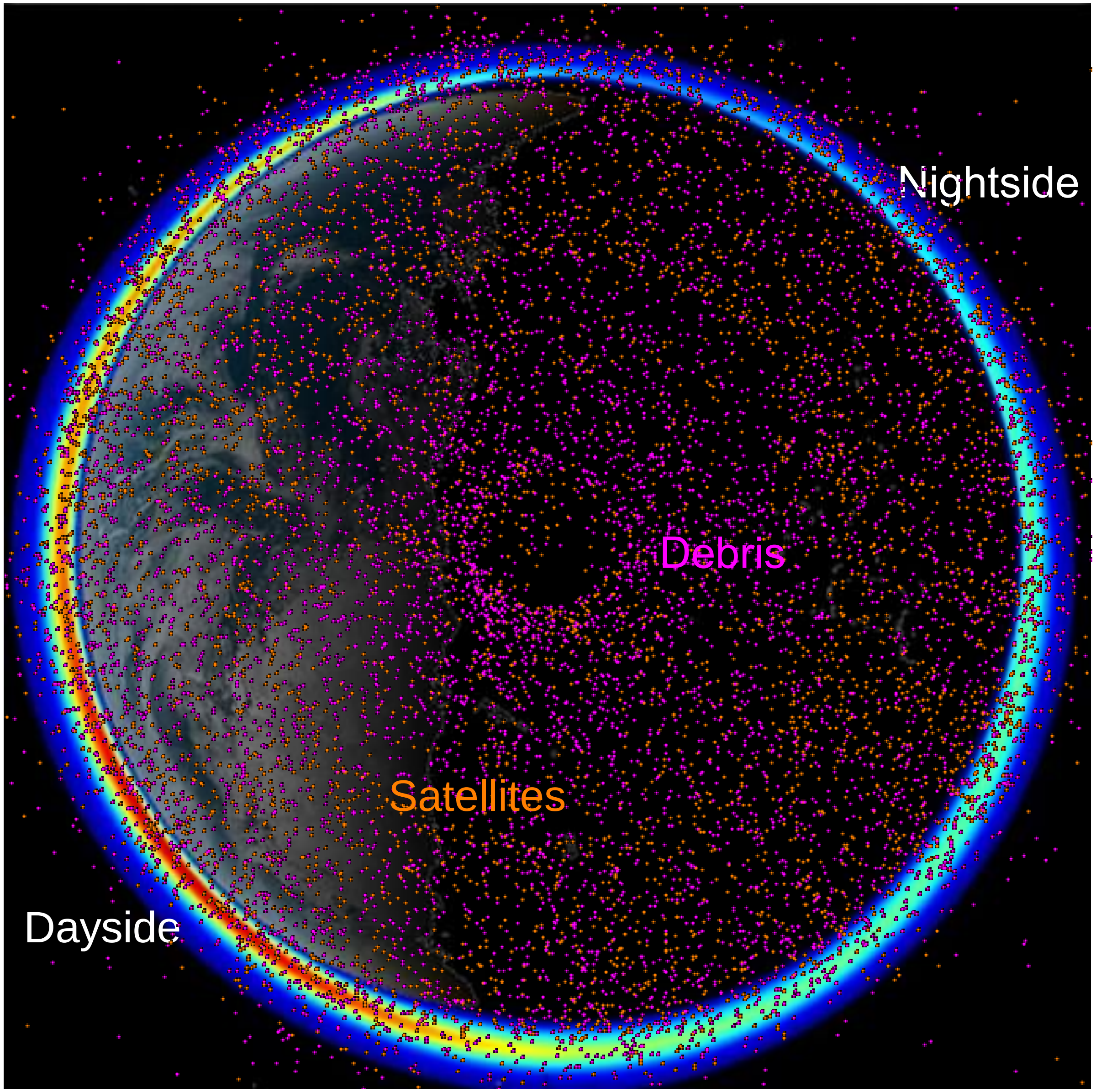
Space Object Hazards from Collisions


All Tracked Space Objects
As of 13 May 2022

- **Space Debris Sources and Hazards**
  - Satellites and Space Debris
  - Orbital Motion in Magnetized Plasma
- **Debris Detection for Collision Avoidance**
  - Optical Sensors with Scattered Light
  - Radar Scatter of EM (Radio) Waves
  - **Wave Generation by Charged Objects**
  - **In Situ Detection of Plasma Waves**
  - **Remote Detection of Scatter from Debris Waves**
- **SOIMOW Deep Dive in Experiment and Theory**
  - Charging, Wave Generation and Measurement
  - Experiments with Target Space Objects and Host Sensors
    - Unique FLASH Signature of Space Debris During Conjunctions
    - 20 dB Signal to Noise at ~ 60 km Range between Host Sensor and 10 cm Target
  - Whistler and Magnetosonic Wave Propagation Characteristics
    - Guidance of Whistler Waves in a 19.5° Half Angle Cone Aligned with **B**.
    - Guidance of Compressional Alfven Waves in a Cylinder Around **B**.

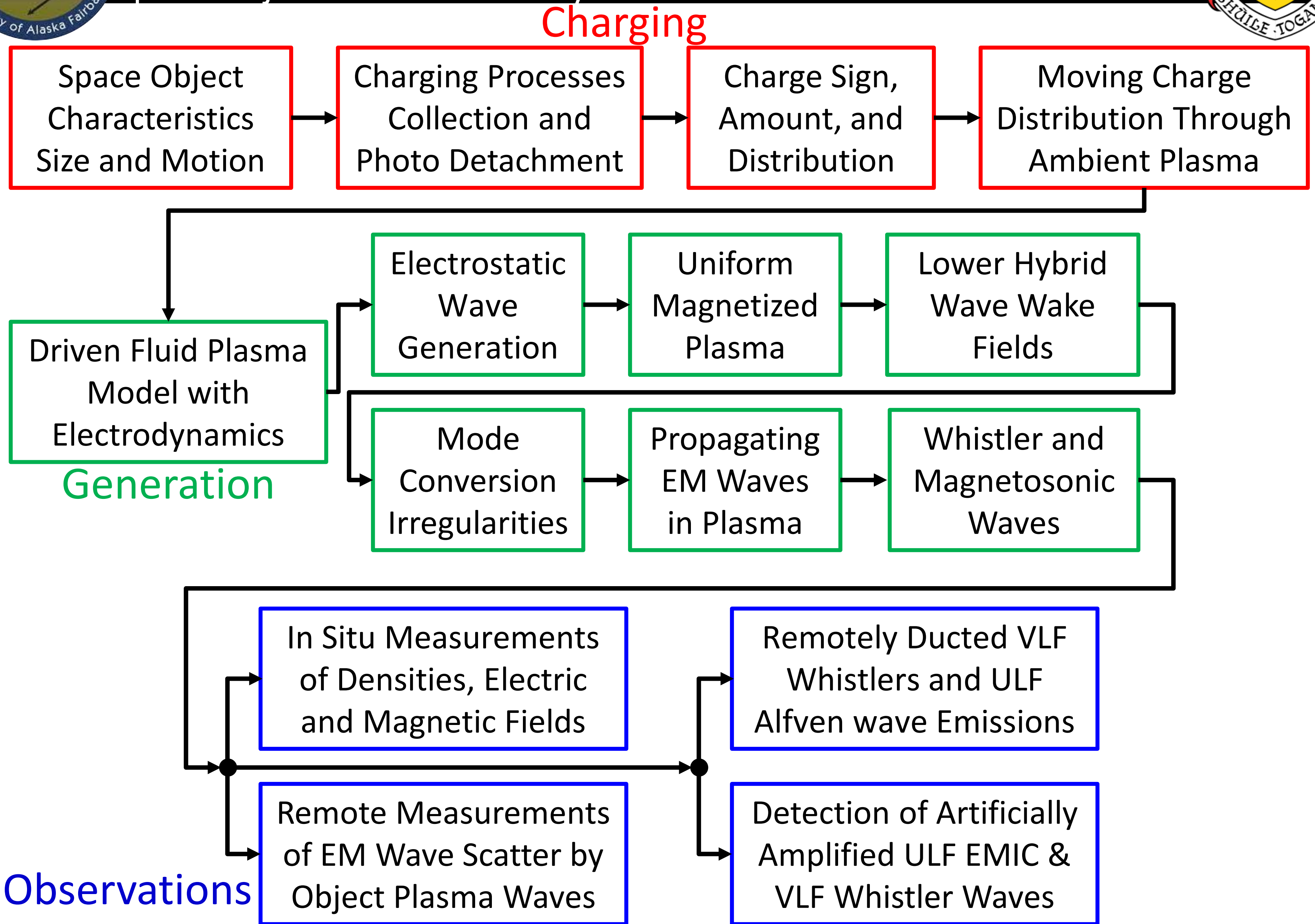
Space Objects Orbit the Earth in a Magnetized Plasma

The Ionosphere at the Earth's Limb is Described by SAMI3 Model



Plasma Waves from Charged Objects in Hypersonic Orbits - SOIMOW

Space Object Identification by Measurements of Orbit Driven Waves



Charging

Space Object Characteristics Size and Motion → Charging Processes Collection and Photo Detachment → Charge Sign, Amount, and Distribution → Moving Charge Distribution Through Ambient Plasma

Generation

Driven Fluid Plasma Model with Electrodynamics

Electrostatic Wave Generation → Uniform Magnetized Plasma → Lower Hybrid Wave Wake Fields

Mode Conversion Irregularities → Propagating EM Waves in Plasma → Whistler and Magnetosonic Waves

Observations

In Situ Measurements of Densities, Electric and Magnetic Fields

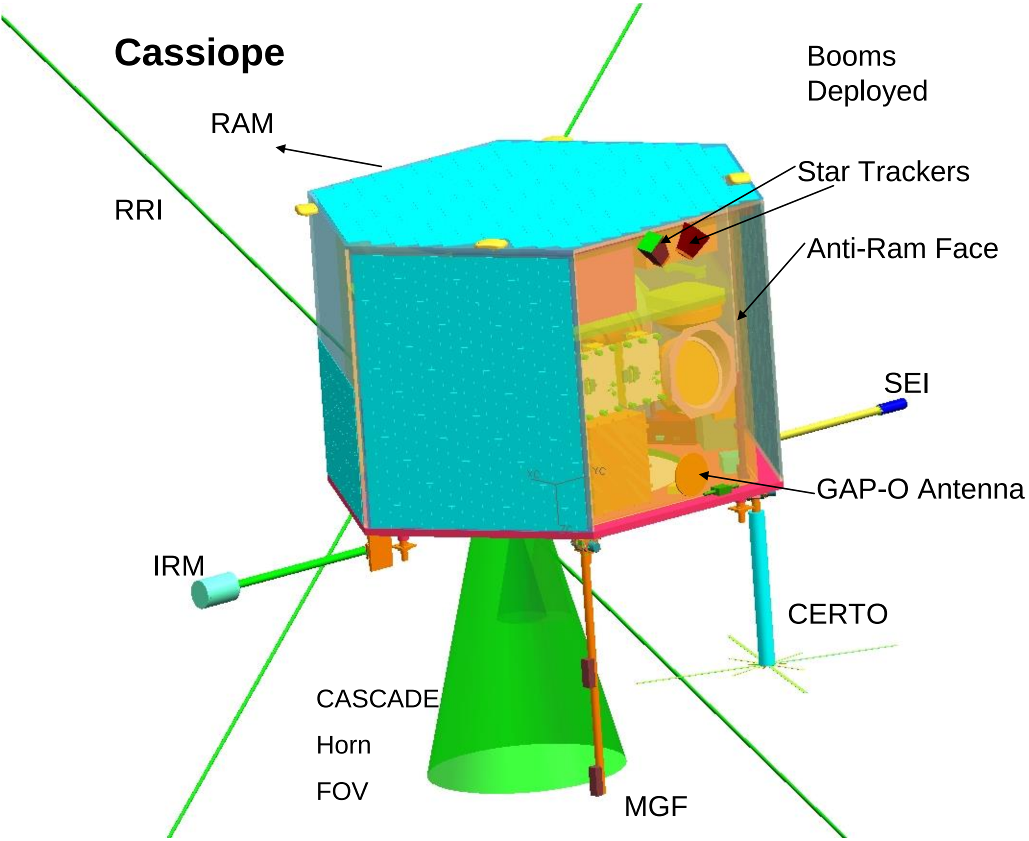
Remote Measurements of EM Wave Scatter by Object Plasma Waves

Remotely Ducted VLF Whistlers and ULF Alfven wave Emissions

Detection of Artificially Amplified ULF EMIC & VLF Whistler Waves

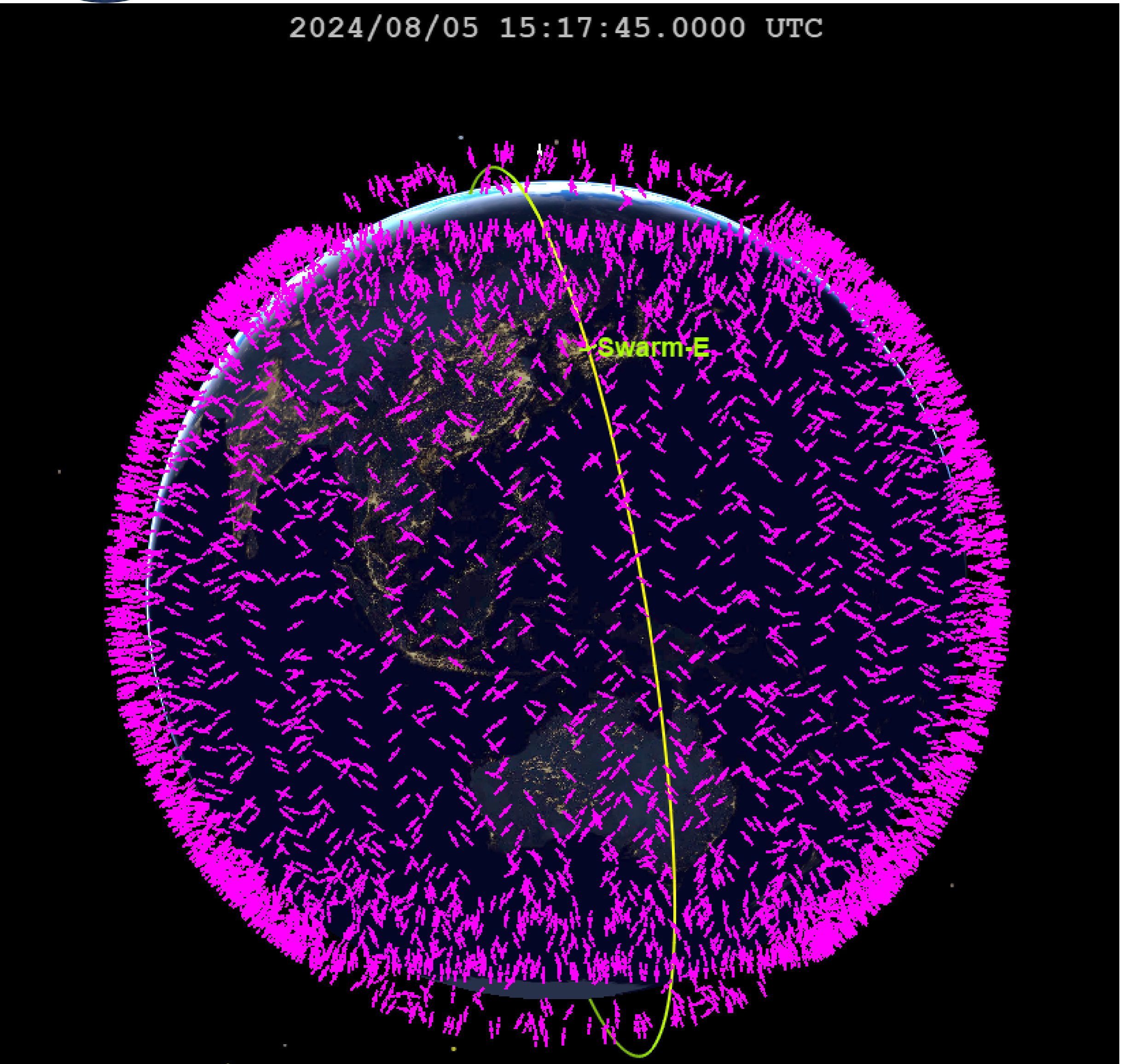
Space Object Instrumentation on Swarm-E (CASSIOPE) Micro-Satellite

The Satellite was Launched on 29 September 2013

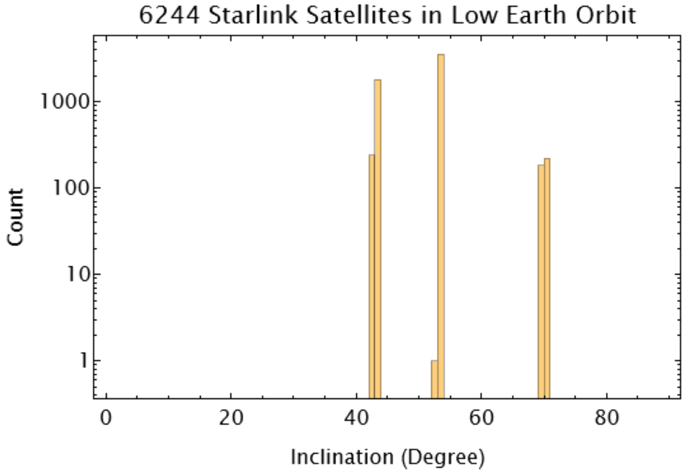


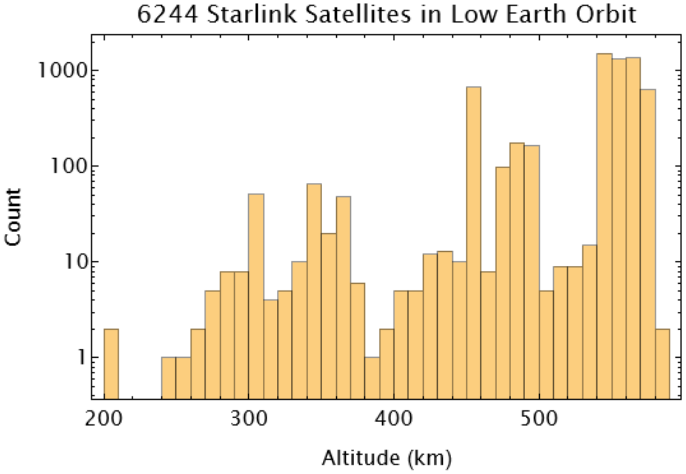
- *Imaging particle instruments*
  - IRM: Imaging rapid ion mass spectrometer
  - SEI: Suprathermal electron imager
  - NMS: Neutral mass and velocity spectrometer
- *Imager and wave receivers-transmitter*
  - FAI: Fast auroral imager
  - CERTO: Radio tomography
  - RRI: E-Field receiver
  - MGF: Magnetometer
  - GAP: Differential GPS

LEO Satellites Pass Near the Swarm-E e-POP RRI Sensor using Relatively Frequent Satellite Conjunctions with Starlink Satellites



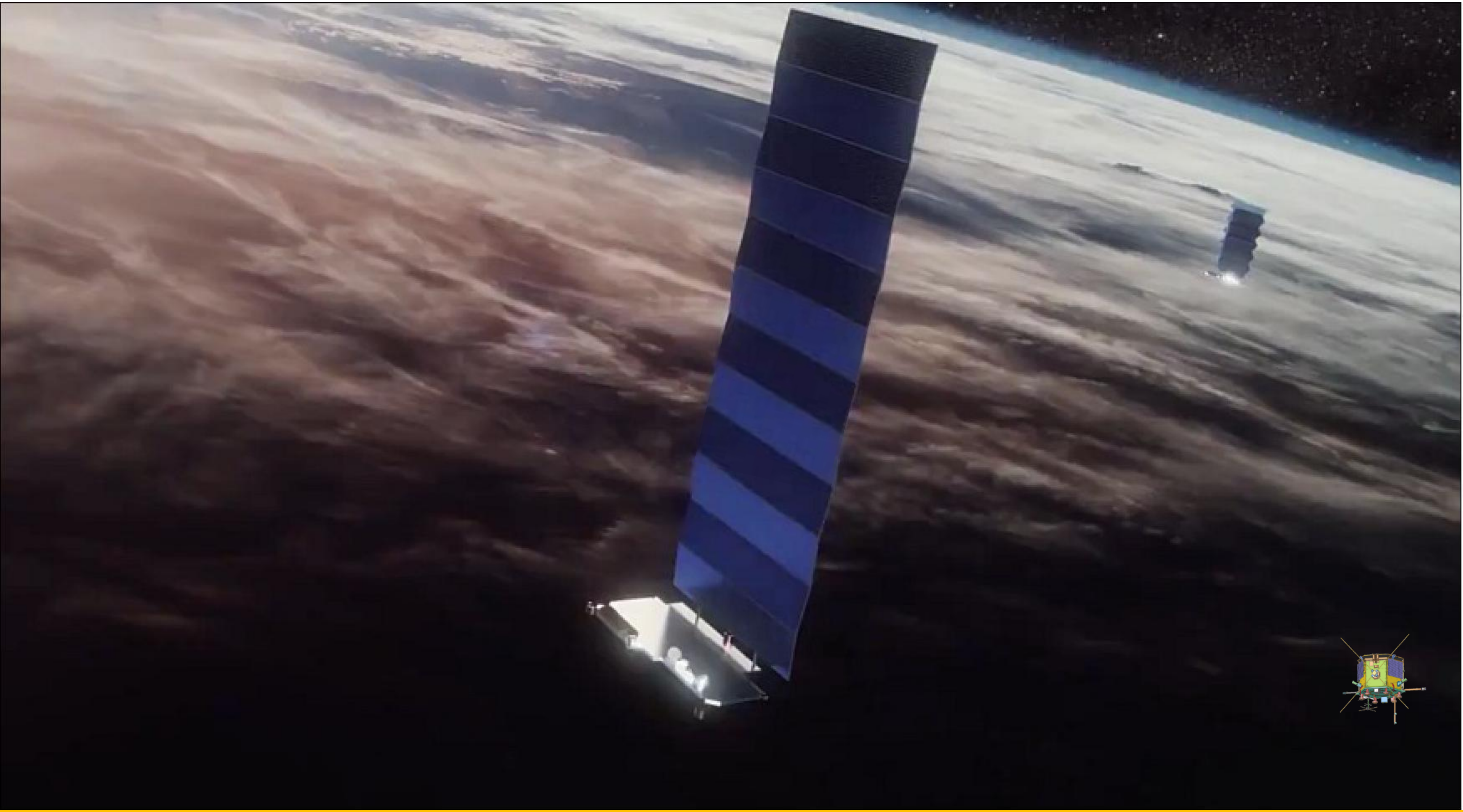
SWARM-E/e-POP Orbit Between 325 and 1250 km Altitude


6244 Starlink Satellites in Low Earth Orbit


6244 Starlink Satellites in Low Earth Orbit

CASSIOPE Micro-Satellite: Instrument Payload

Starlink Satellite Targets for the SWARM-E e-POP/RRI Host

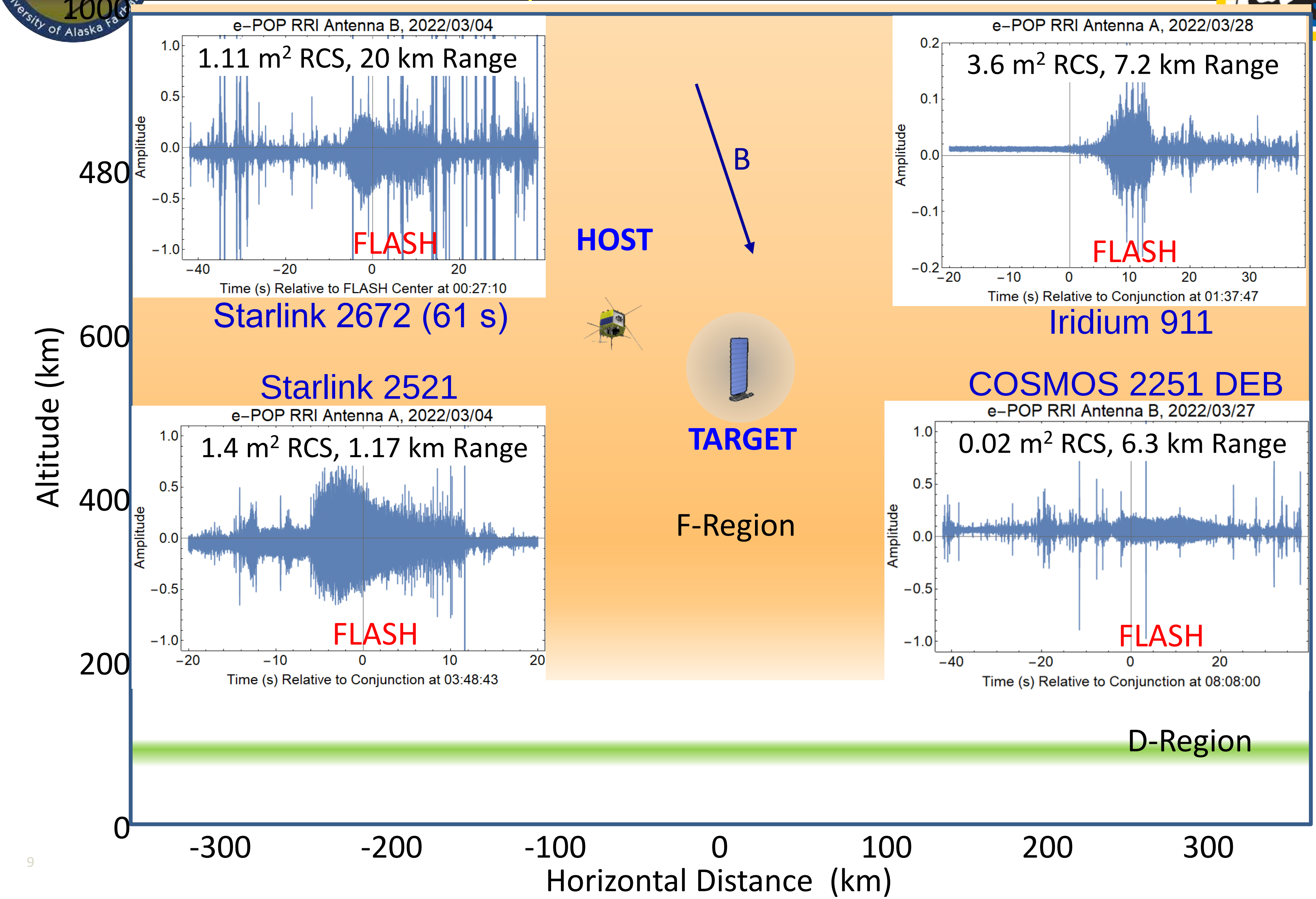


Electric Fields Measured Made with Swarm-E/RRI for 2 to 10 Minutes at a 62.5 kHz Sample Rate In Burst Mode 1-4 Times per Day During Close Proximity with Space Debris and Other Objects

Key Features of Low and Medium Frequency Plasma Waves for Space Debris Identification and Tracking (SINTRA)

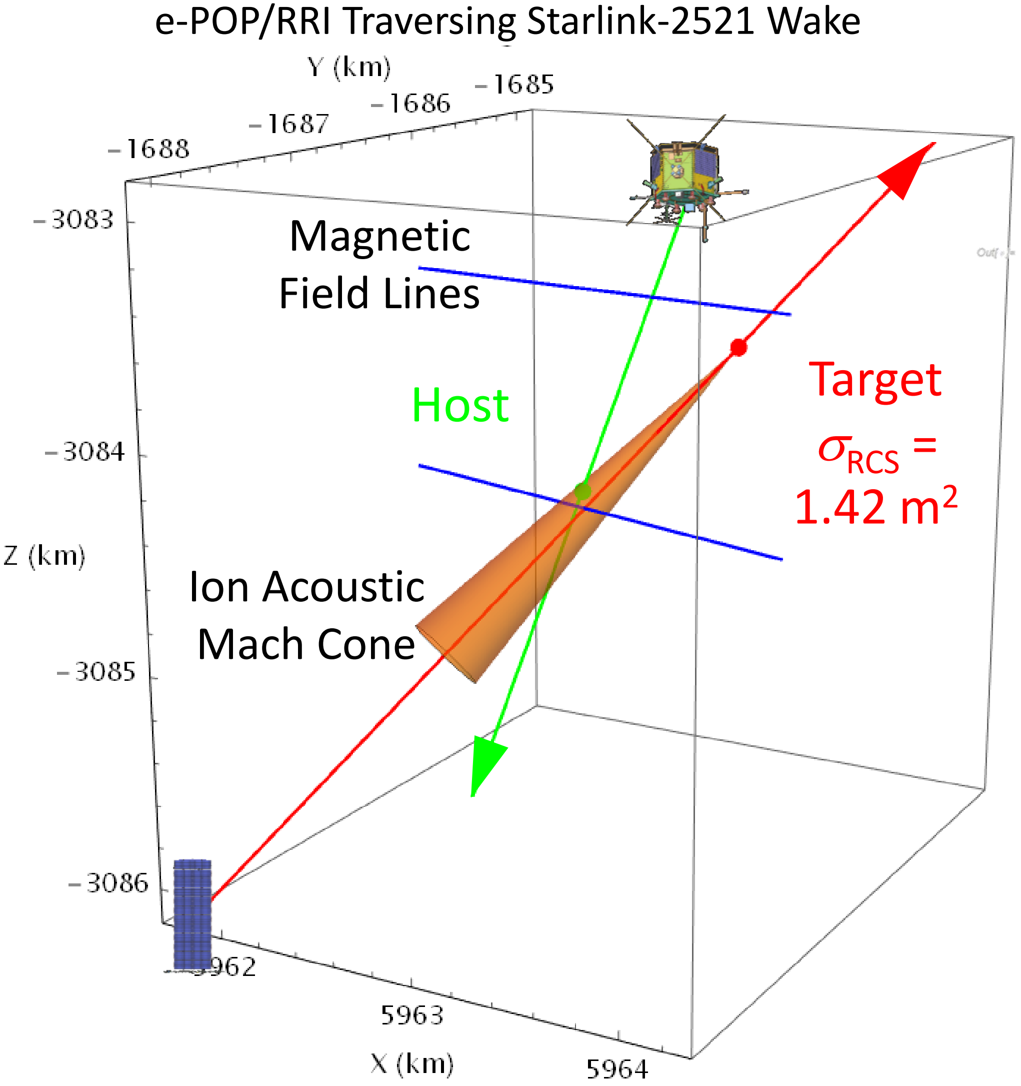
Mode	Alias	Frequency Range	Theory	In Situ Data	Property
Fast Magnetosonic	Compressional Alfven Wave	Low Frequency $0 < \omega < \Omega_i$ or ω_{LH}	e-MHD	FLASH Below LH Frequency	**Isotropic Around B**
Alfven	Shear Alfven Wave	Low Frequency $0 < \omega < \Omega_i$	Cherenkov	None	**Along B**
Slow Magnetosonic	Magnetized Ion Acoustic Wave	Low Frequency $0 < \omega < \Omega_i \cos\theta$	MKdV	None	**Along B**
Whistler	Electron Whistler, Helicon Wave	Medium Frequency $\Omega_i < \omega < \Omega_e \cos\theta$	e-MHD	FLASH Above LH Frequency	**19° Cone Around B**
Electrostatic Ion Cyclotron	First Ion Cyclotron	Low Frequency $\omega^2 = \Omega_i^2$	Single Fluid	None	**E || k**
EM Ion Cyclotron	Second Ion Cyclotron	Low Frequency $\omega^2 = \Omega_i^2\cos^2\theta$	Hall MHD	FLASH Below IC Frequency	**Narrow Cone Around B**
Ion Acoustic	Unmagnetized Ion Sound Waves	Medium Frequency $\Omega_i < \omega < \omega_{pi}$	KdV	None	**ES with Debye Lengths**
Lower Hybrid	Finite-k_z Lower Hybrid Waves	Low Frequency Fixed $\omega_{LH}^2 = \dfrac{\Omega_i\Omega_e + \Omega_e^2\cot^2\theta}{1+\Omega_e^2/\omega_{pe}^2}$	e-MHD	In situ on Host	**Fan Perpendicular to B**

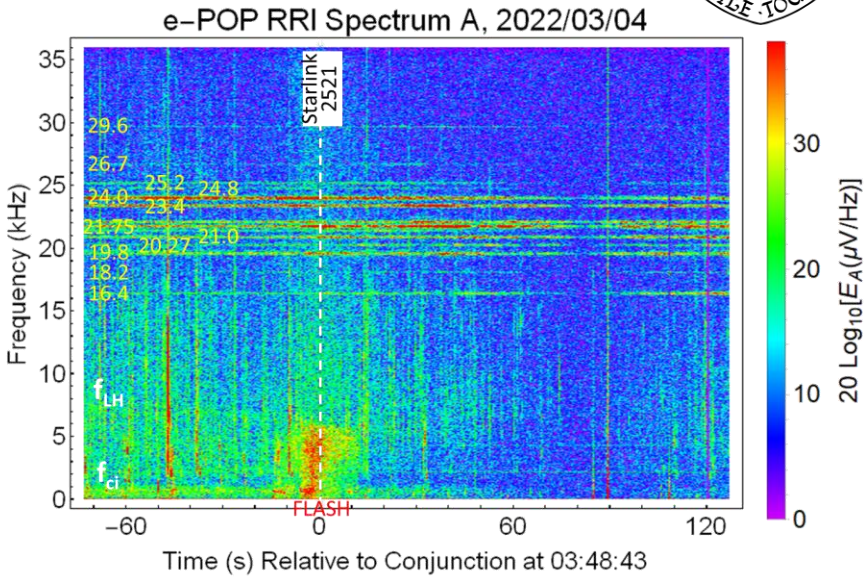
Satellite Detection of EM Wave Generation During SOIMOW Experiments with SWARM-E RRI



Space Object Identification with Measurements of Orbit Driven Waves

Satellite Wake and Wave Generation Experiments


e-POP/RRI Traversing Starlink-2521 Wake



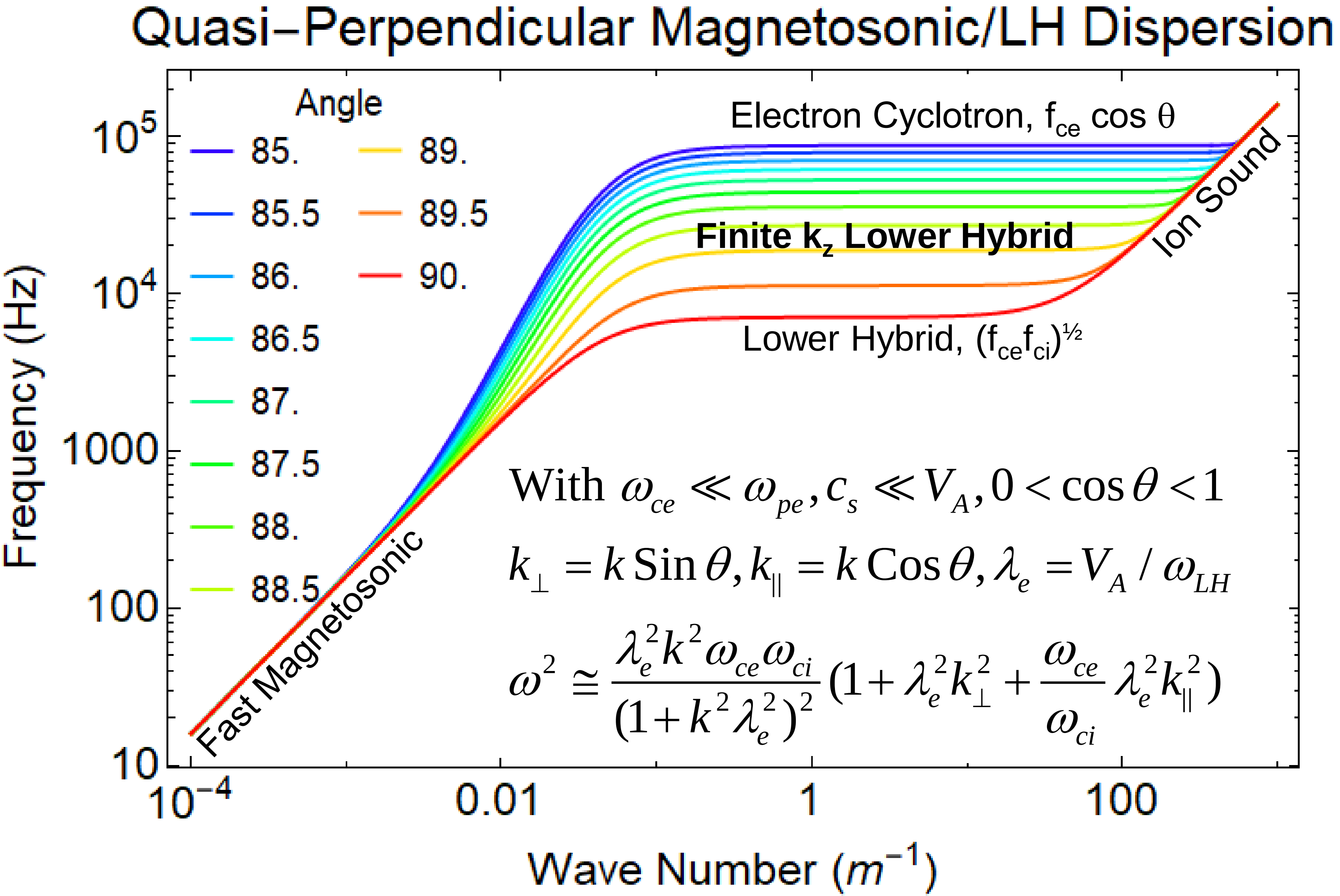
- Unusual Observations
  - **Starlink 2521 Encounter with Kr HED OFF**
  - Electric Field “Flash” 20 dB Above Ambient
  - Time and Frequency Limited Spectrum
  - Time Centered on Encounter
  - Ion Cyclotron and Lower Hybrid Limits
  - **1200 mm Object Size**
  - **50 km Detection Range for Plasma Cloud**
- Interpretation
  - Plasma Waves Driven by Target Motion
  - Strong Magnetosonic Waves
  - Weak Whistler Waves
  - In Situ Ion Acoustic and Lower Hybrid Waves

Proximity Encounter with No Propulsion

Fluid Plasma Waves for **Nearly Transverse** Propagation

Spontaneous Plasma Wave Emission = Finite k_z LH Wave

$V_A = 10^3$ km/s, $c_S = 10^3$ m/s, $f_{ce} = 10^6$ Hz, $f_{ci} = 50$ Hz, $f_{LH} = 7$ kHz, $\lambda_e = 22.5$ m, $f_{pe} = 2$ MHz



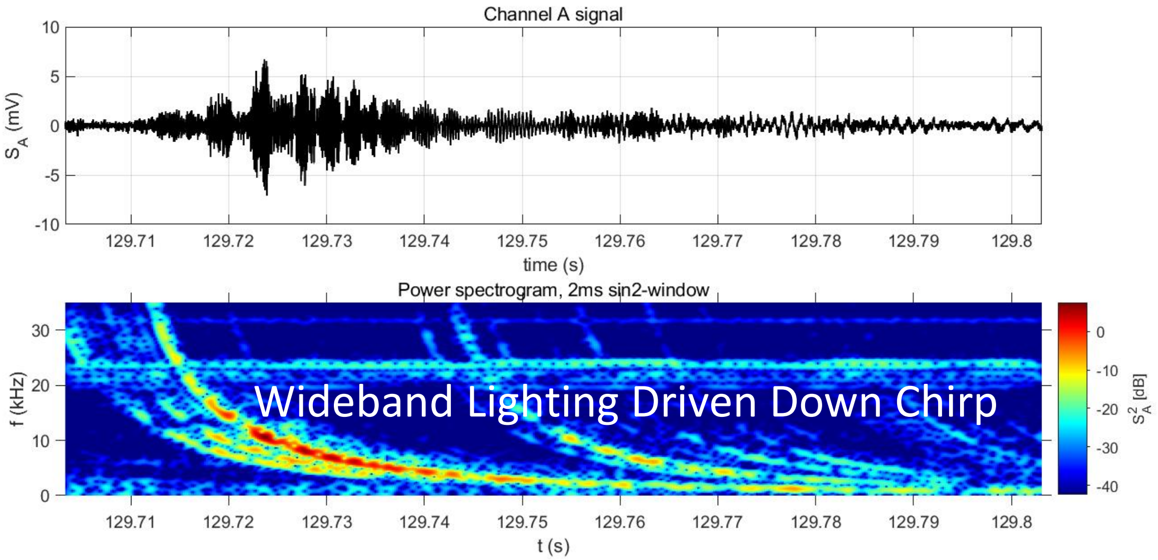
$$\text{With } \omega_{ce} \ll \omega_{pe}, c_s \ll V_A, 0 < \cos\theta < 1$$

$$k_\perp = k\,\mathrm{Sin}\,\theta, k_\parallel = k\,\mathrm{Cos}\,\theta, \lambda_e = V_A / \omega_{LH}$$

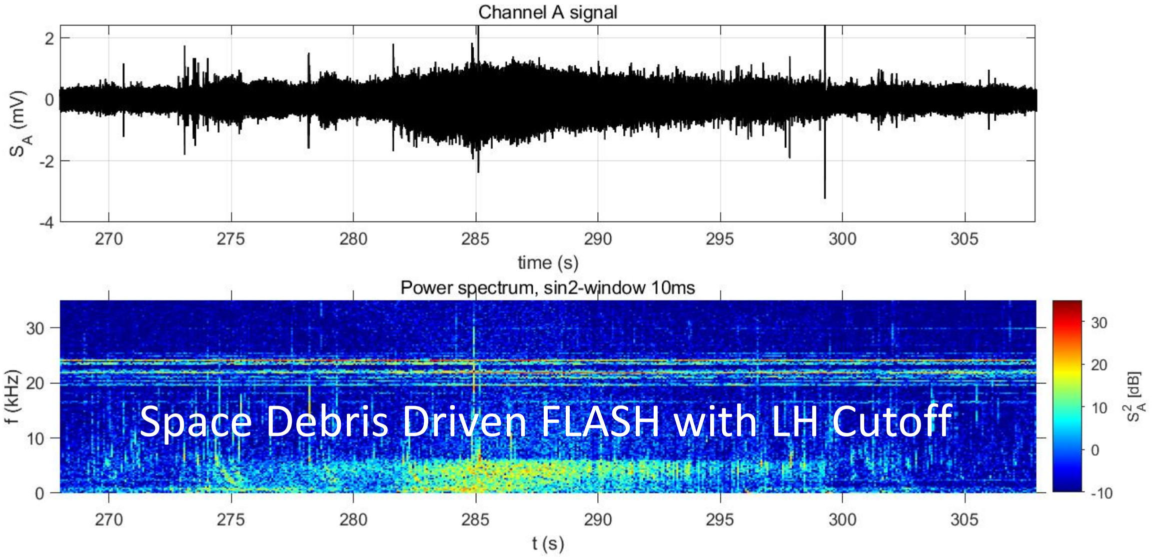
$$\omega^2 \cong \frac{\lambda_e^2 k^2 \omega_{ce}\omega_{ci}}{(1+k^2\lambda_e^2)^2}(1+\lambda_e^2 k_\perp^2 + \frac{\omega_{ce}}{\omega_{ci}}\lambda_e^2 k_\parallel^2)$$

Plasma Wave Detection with Close Encounters

4 March 2022 FLASH Signature of Space Debris

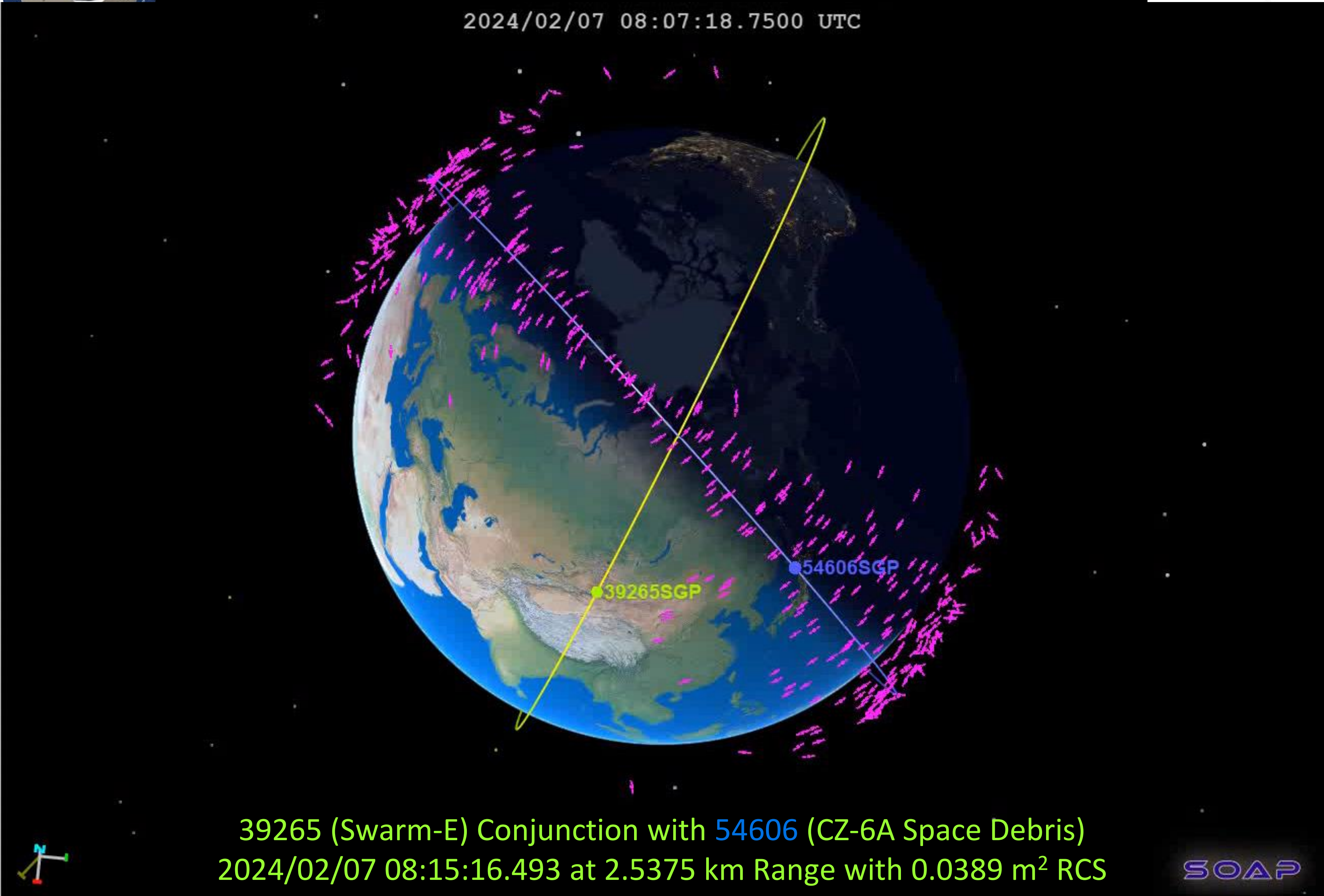


Wideband Lighting Driven Down Chirp



Space Debris Driven FLASH with LH Cutoff

Swarm-E Encounters: Long March 6A Debris Trail on 7 Feb 2024

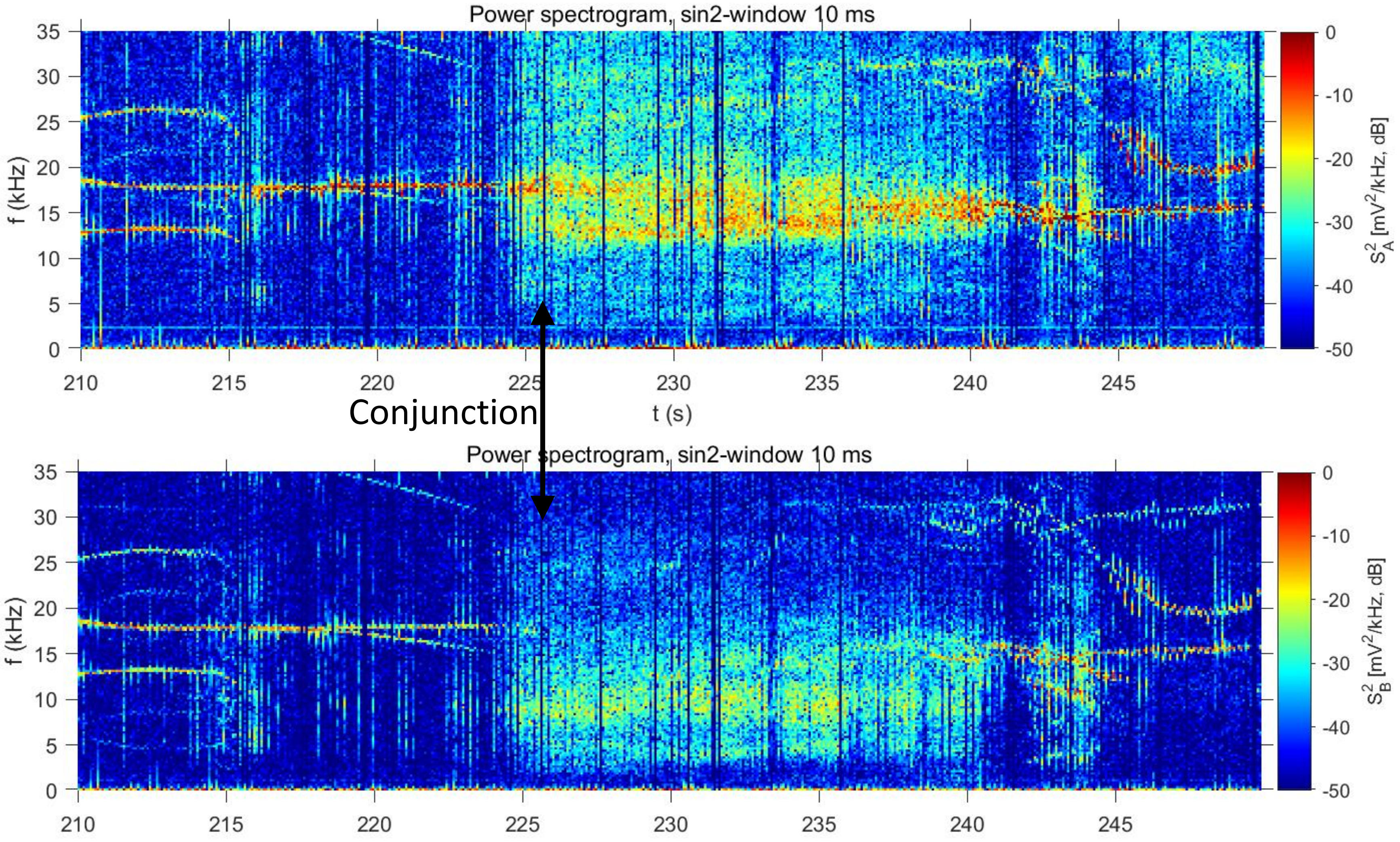


39265 (Swarm-E) Conjunction with 54606 (CZ-6A Space Debris)
2024/02/07 08:15:16.493 at 2.5375 km Range with 0.0389 m^2 RCS

Compressional Alfven Wave Observed by the Swarm-E RRI

75° Latitude, 115° Longitude, 900 km Altitude

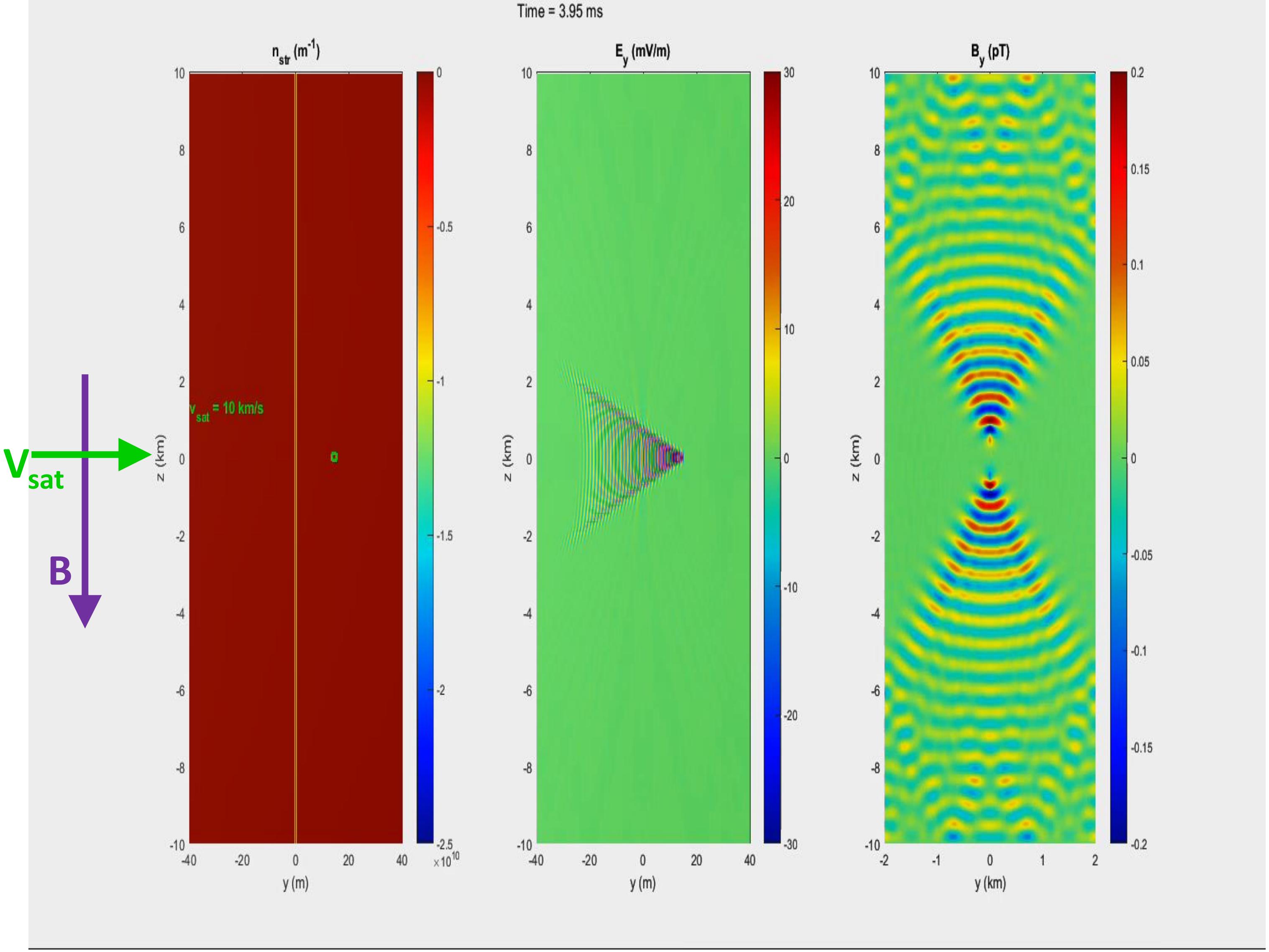
Swarm-E RRI 2024 February 07



Conjunction

Time Relative to 08:11:30 GMT

Narrow striation D_{str}=0.25 m, D_{sat}=0.25 m Movie



Guidance of Whistler Waves by the Earth's Magnetic Field

Storey, Philos. Trans. R. Soc. Ser. A, 246, 113, 1953

Swanson, Plasma Waves, 2003,

- Whistler Dispersion for Wave Normal Angle θ with **B**

$$\omega = (k^2 c^2 \omega_{ce} \cos\theta) / \omega_{pe}^2$$

- Group Velocity Angle α

$$\tan\alpha = \frac{1}{k}\frac{\partial\omega}{\partial k}\bigg|_k \bigg/ \frac{\partial\omega}{\partial k}\bigg|_\theta = -\frac{1}{2}\tan\theta$$

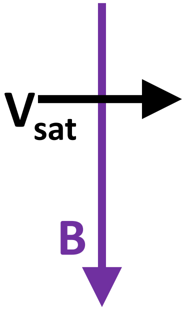
- Maximum Group Velocity Cone Angle of Whistler Wave

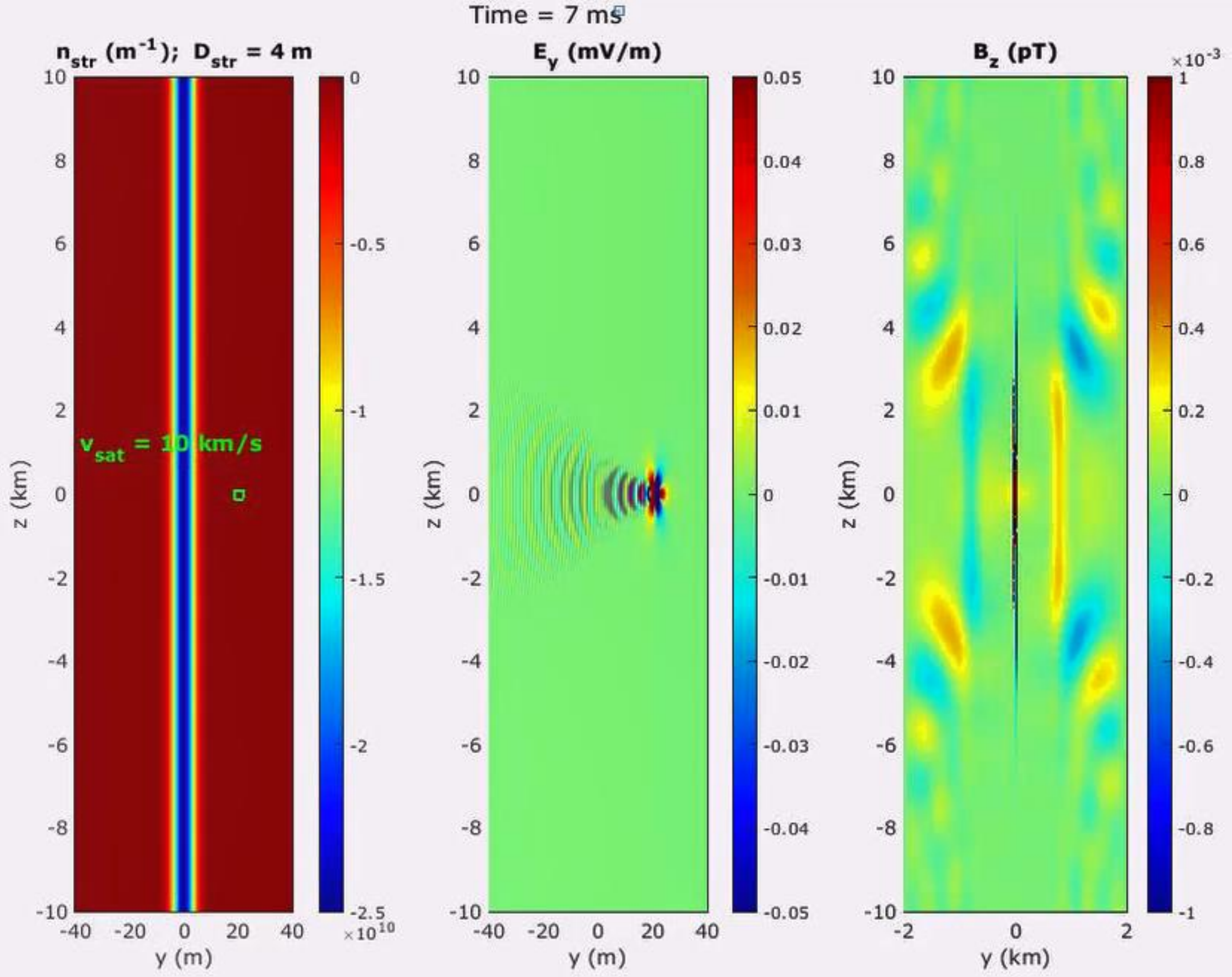
$$\tan(\theta+\alpha) = \frac{\tan\theta}{2+\tan^2\theta}, \frac{\partial\tan(\theta+\alpha)}{\partial\theta} \equiv 0 \Rightarrow \tan^2\theta_{Max} = 2$$

$$\tan(\theta+\alpha)_{Max} = \frac{\sqrt{2}}{2+2} = \frac{1}{\sqrt{8}} \Rightarrow (\theta+\alpha)_{Max} = \tan^{-1}\frac{1}{\sqrt{8}} = 19.4712°$$

- Charged Space Debris Launches Whistler Waves in to a 19.5° Cone Centered on the Magnetic Field Line **B**

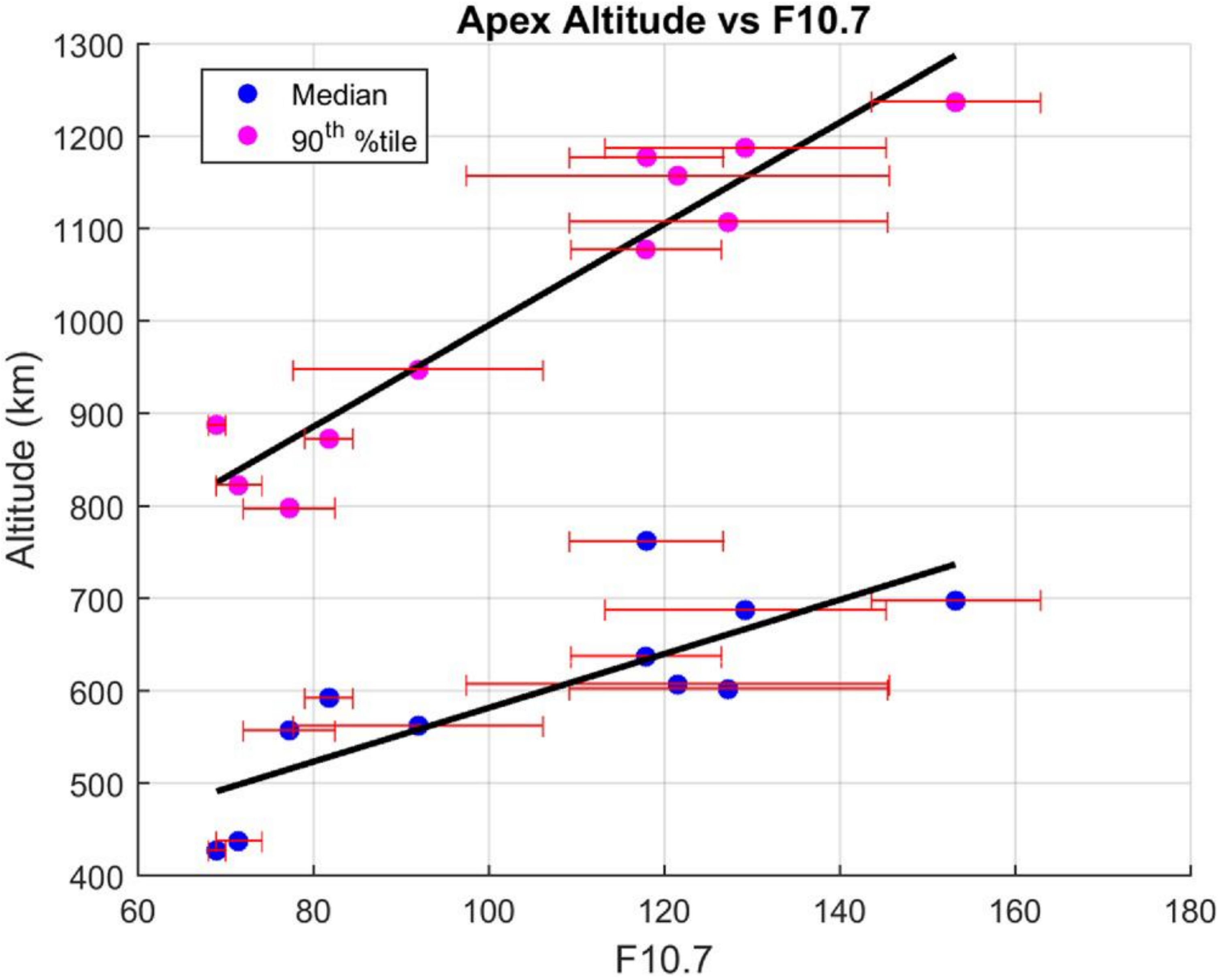
Wide Striation D_{str} = 4 m, D_{sat} = 0.5 m Movie



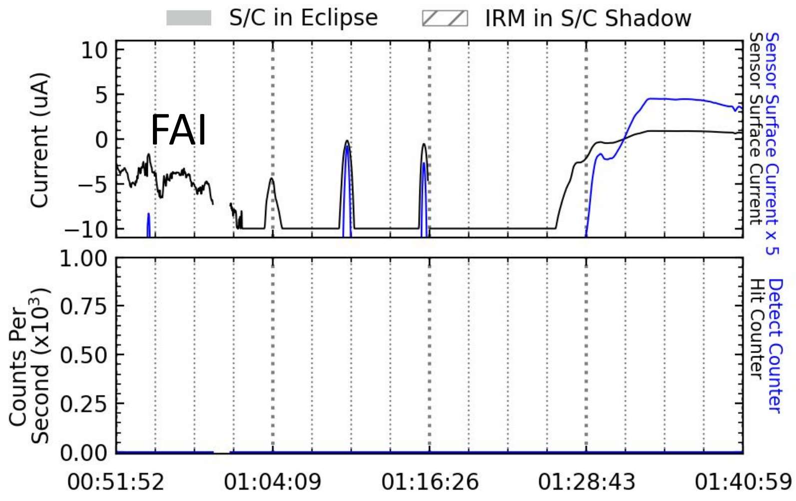


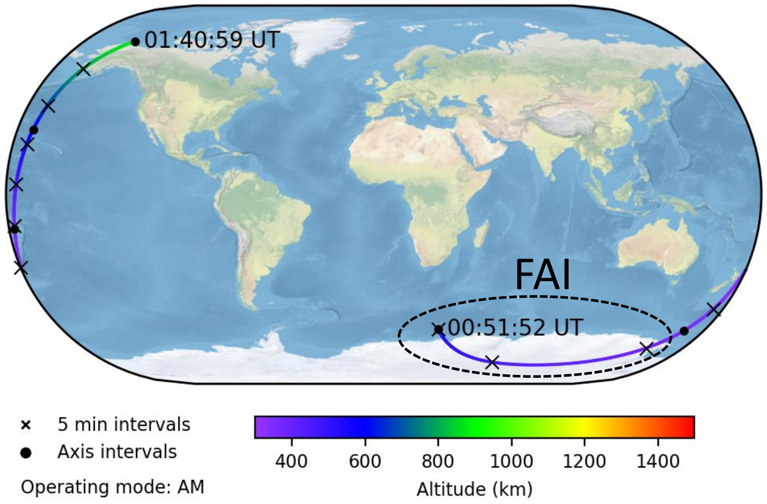
Equatorial Bubble Height Statistics for FAI

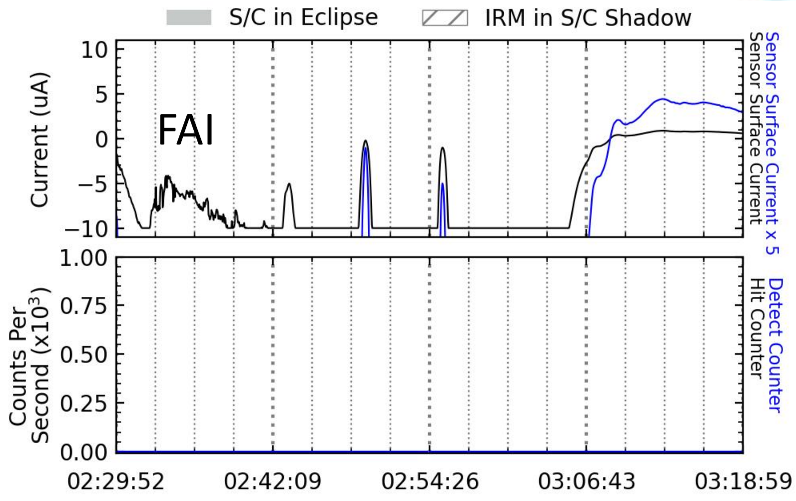
Joshi et al., 2022, J. of Geophysical Research: Space Physics,127

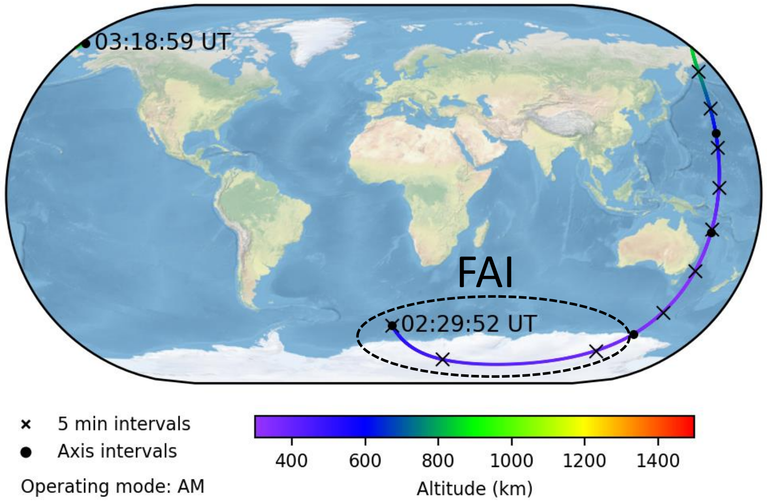


IRM Detection of Auroral FAIs Near 500 km Altitude
Antarctica on 2024 February 07 for Two Successive Passes

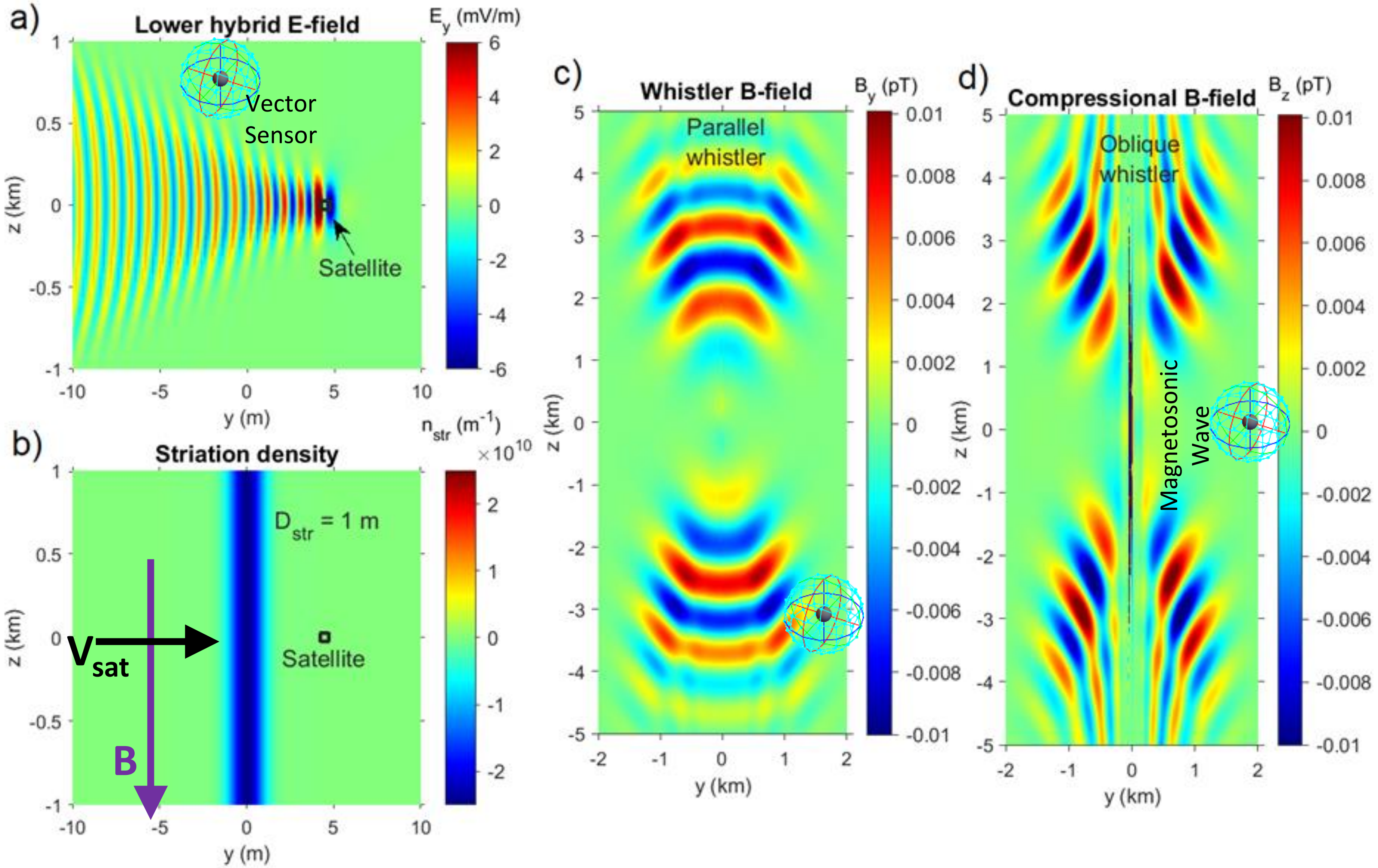








Compressional Alfven, Lower Hybrid, and Oblique Whistler Wave Generation by Satellite and 2-m Plasma Striation

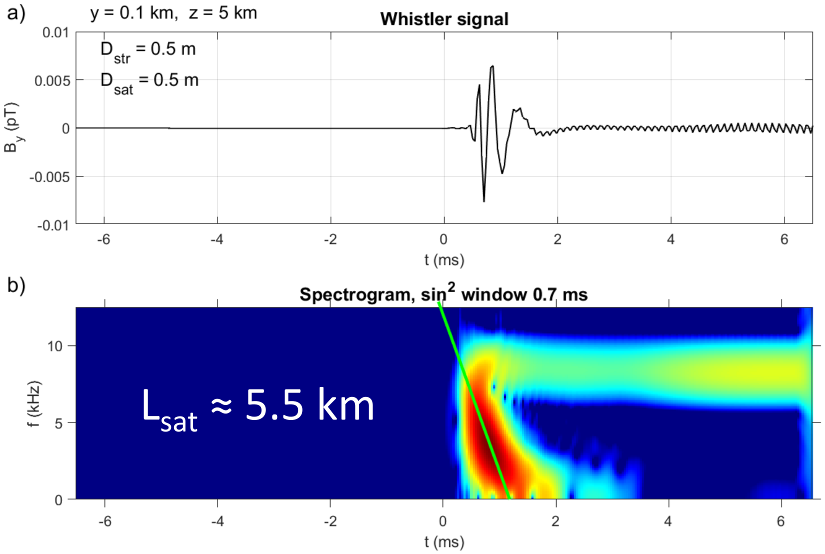


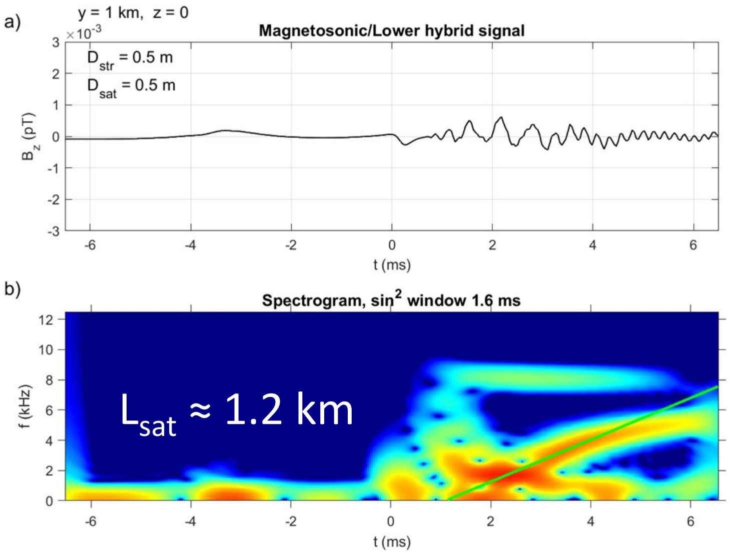
- Locating the Space Debris (or Satellite) After Detection
  - Target Signal is Range Dependent Because of Plasma Dispersion
  - The Wave $E_1 \times B_1$ Poynting Vector Points Away from the Source

Plasma Wave Detection with Close Encounters

Target Properties from Plasma Wave Observations

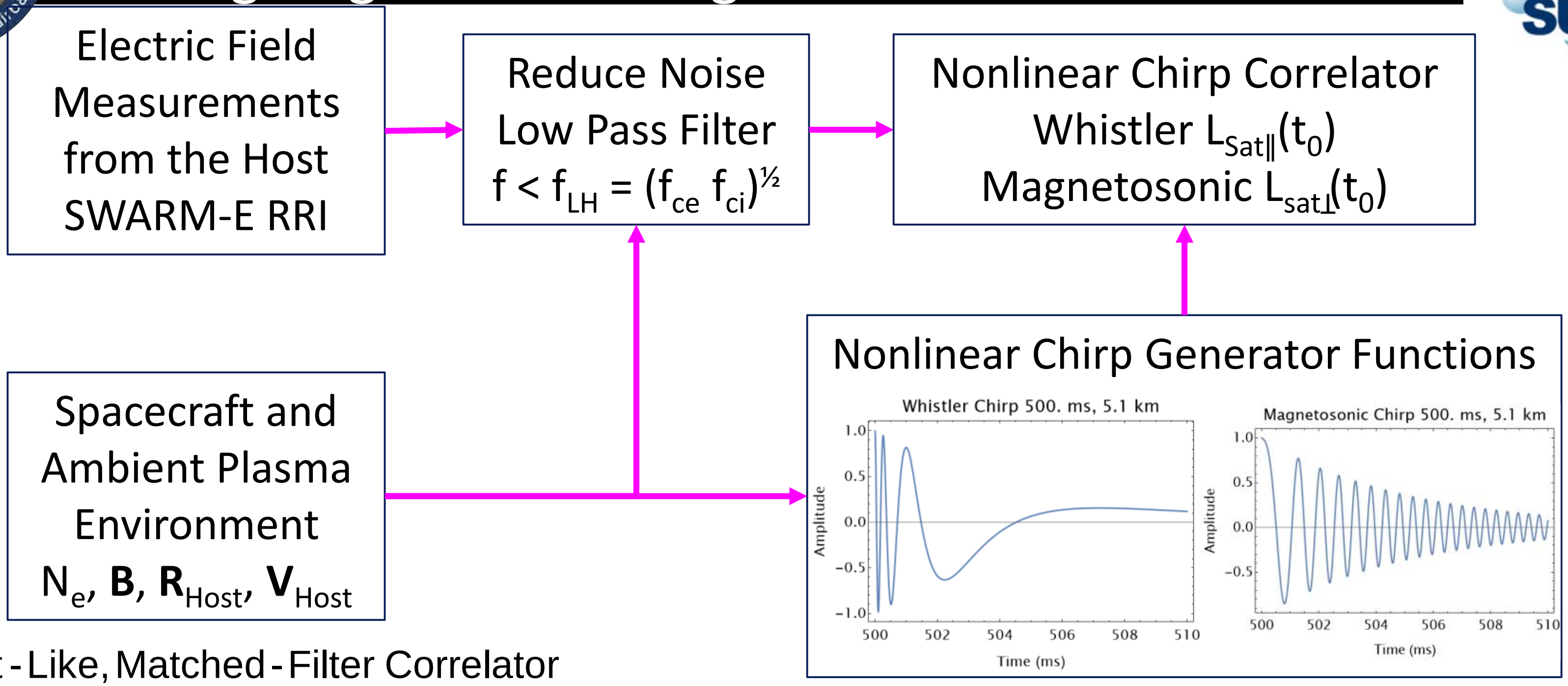
Property	Direction of Target Emission	Along B Distance L to Plasma Wave Emitter	Across B Distance L to Plasma Wave Emitter
Instrument	Low Frequency Vector Sensor	Plasma Wave Receiver	Plasma Wave Receiver
Measurement	Electric and Magnetic Fields	Plasma Wave Complex Fields	Plasma Wave Complex Fields
Derived Quantity	Poynting Flux Vector	Whistler Frequency	Magnetosonic Wave Frequency
Application Formula	$\langle \mathbf{S} \rangle = \frac{1}{2}\mathrm{Re}(\mathbf{E}\times\mathbf{H}^{*})$	$L_{Sat\parallel} = \frac{4\lambda_e\omega_{ce}^{1/2}\omega(t)^{3/2}}{-\partial\omega(t)/\partial t}$	$L_{Sat\perp} = \frac{V_A}{3}\frac{[\omega_{LH}^{2}-\omega(t)^{2}]^{5/2}}{\omega'(t)\omega(t)\omega_{LH}^{3}}$





Space Debris Detection and Identification

Range Signal Processing of SOIMOW FLASH Events



Electric Field Measurements from the Host SWARM-E RRI

Reduce Noise
Low Pass Filter
$f < f_{LH} = (f_{ce}\ f_{ci})^{1/2}$

Nonlinear Chirp Correlator
Whistler $L_{Sat\parallel}(t_0)$
Magnetosonic $L_{sat\perp}(t_0)$

Spacecraft and Ambient Plasma Environment
N_e, $\mathbf{B}$, $\mathbf{R}_{Host}$, $\mathbf{V}_{Host}$

Nonlinear Chirp Generator Functions

Wavelet-Like, Matched-Filter Correlator

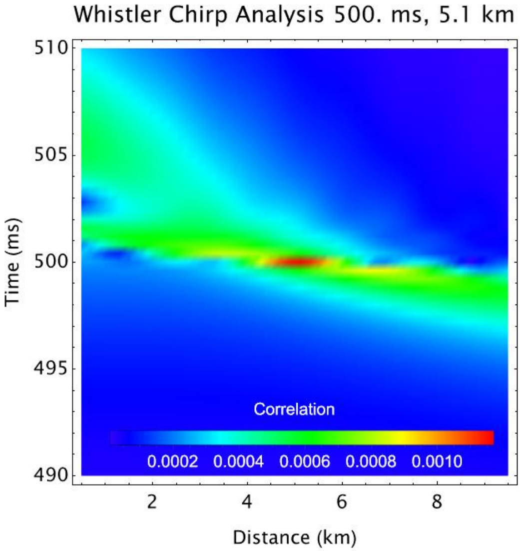
$$\phi_C(t,L) = 2\pi\int_0^t f_C(\tau,L)\,d\tau$$

Chirp Waveform $A_L(t) = e^{i\phi_C(t,L)-\omega_{ci}t}$

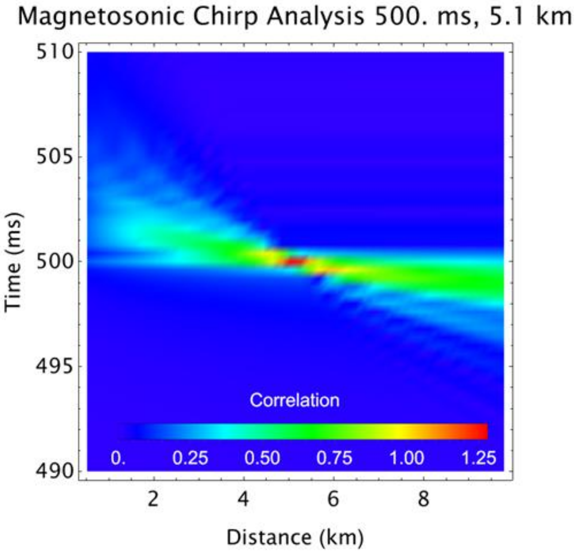
$$u_L(t) = \int_{-\infty}^{\infty} E(\alpha)A_L(t-\alpha)\,d\alpha$$

$$= \int_{-\infty}^{\infty} E(\alpha)\mathrm{e}^{i\phi_C(t-\alpha,D)}\,d\alpha$$

$u_D(t) = \text{Max at } t = t_0$ for distance D



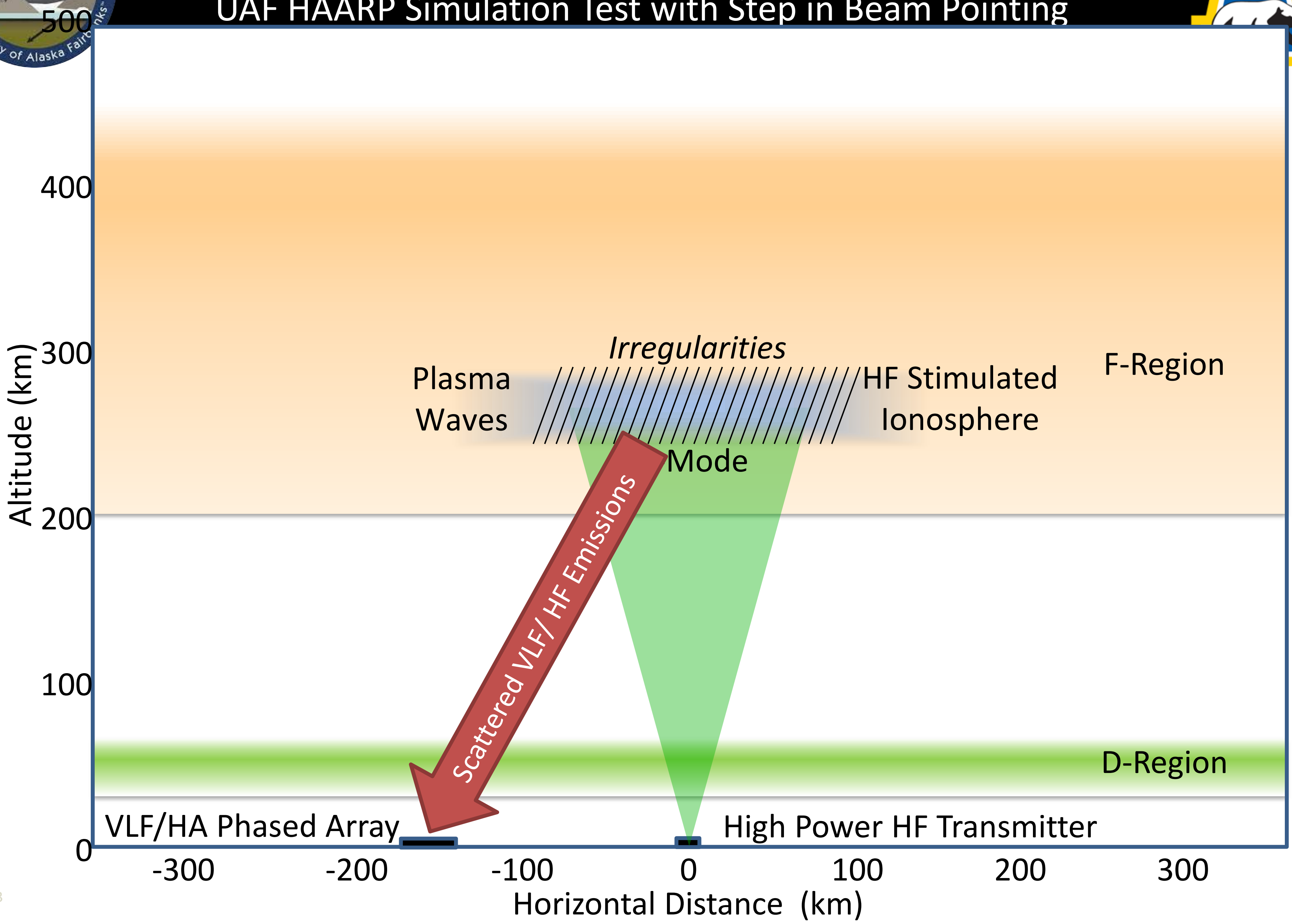
Whistler Chirp Analysis 500. ms, 5.1 km



Magnetosonic Chirp Analysis 500. ms, 5.1 km

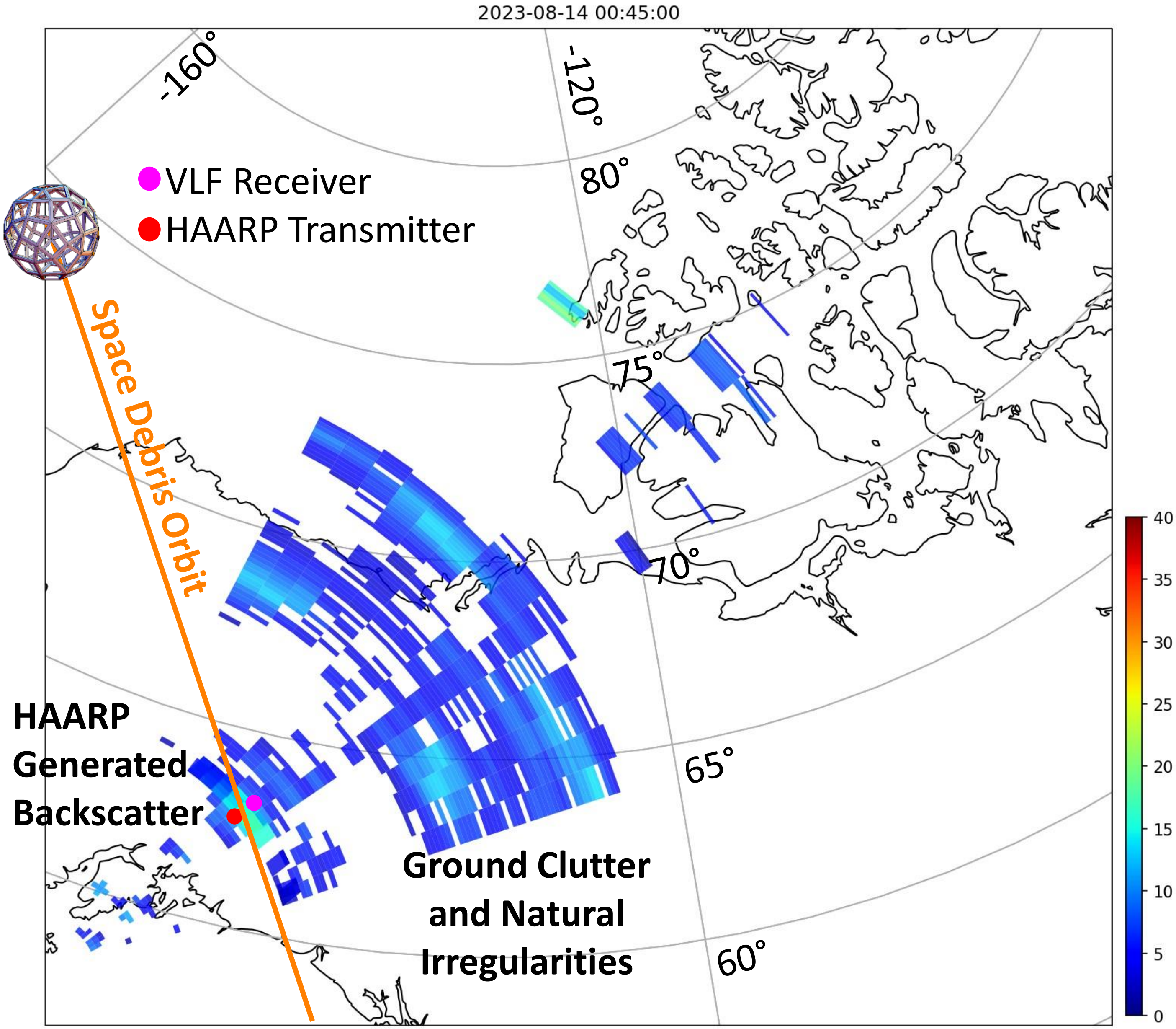
Satellite Passing Through HF Driven Plasma for Wave Diagnostics

UAF HAARP Simulation Test with Step in Beam Pointing



SOIMOW Satellite and Space Debris

Field Aligned Irregularities Generated by HAARP at 5.95 MHz

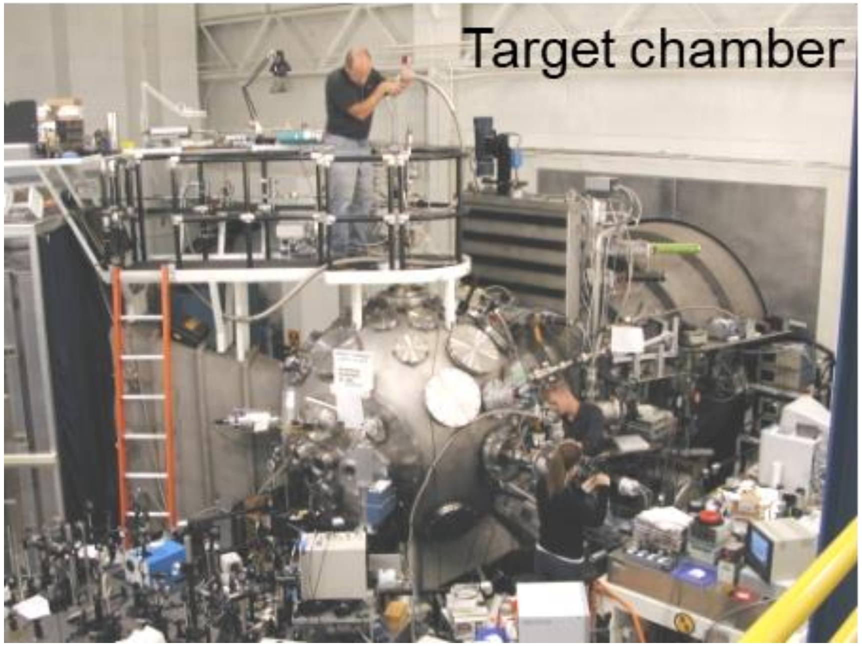


Laboratory Experiment with Debris Injection in Magnetized Plasma
for Measurement of Electromagnetic and Electrostatic Waves

Naval Research Laboratory Nike for Laser-Driven Acceleration

- Electron beam pumped krypton fluoride (KrF) excimer laser
- 248 nm ultraviolet wavelength
- High Shot Rate: 56-beam, 3 kJ per pulse, 2 shots/hour


Target chamber optics


Target chamber

References:

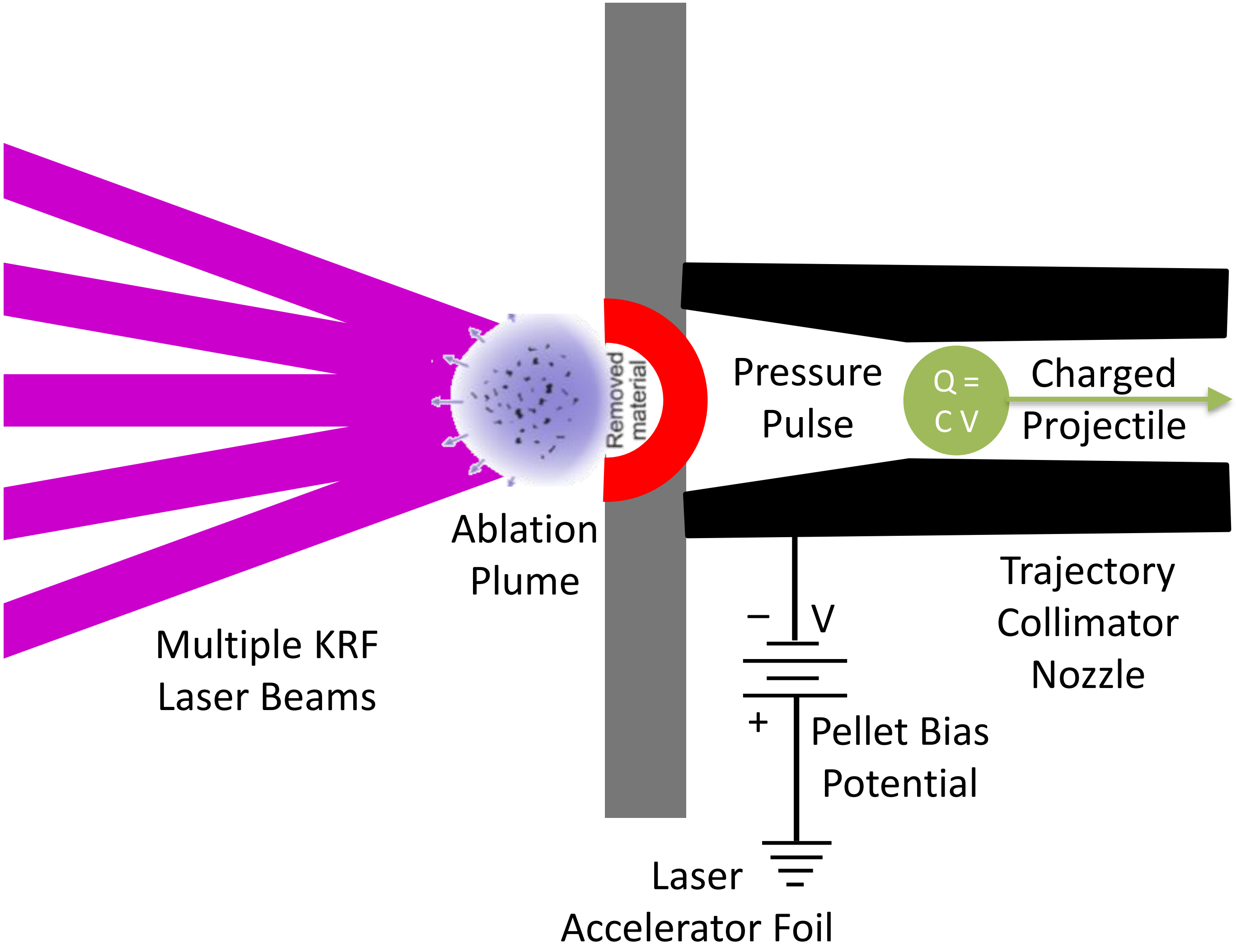
Karasik, M., et al. (2010), Acceleration to high velocities and heating by impact using Nike KrF laser, Phys. Plasmas, 17.

Kadono, T., et al. (2010), Impact experiments with a new technique for acceleration of projectiles to velocities higher than Earth's escape velocity of 11.2 km/s, J. Geophys. Res., 115.

Collaborators, Max Karasik, James Weaver, Plasma Physics Division, NRL, Washington, DC

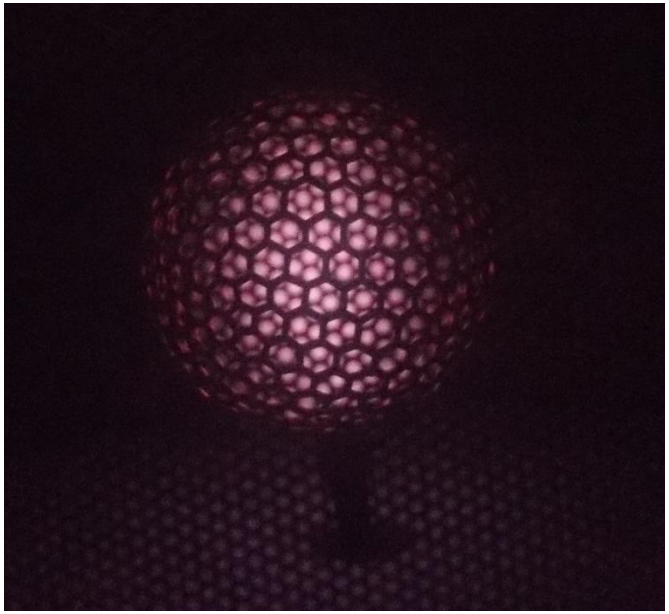
Alternative Laboratory Experiment with Debris Injection Through Plasma

Laser Driven Pellet Accelerator

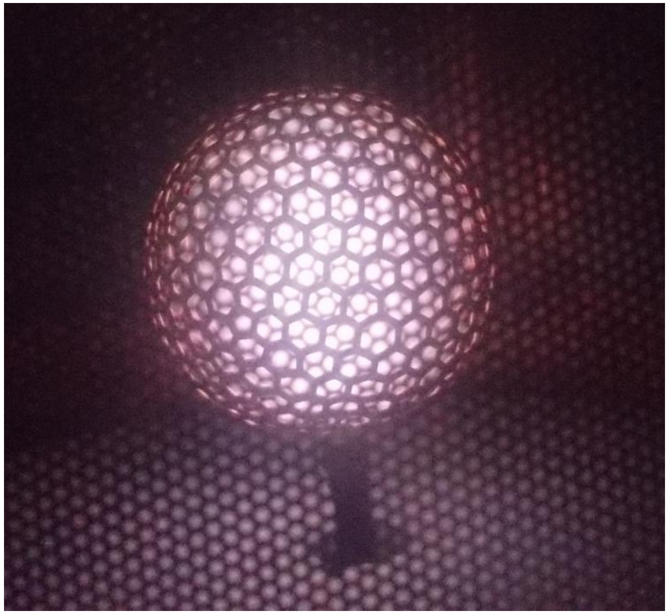


Collaborators, Max Karasik, James Weaver, Plasma Physics Division, NRL, Washington, DC

Low Pressure Air Breakdown Plasma Source with 46 dBm (40 W) RF Drive



2.44 GHz, 150 mTorr Pressure

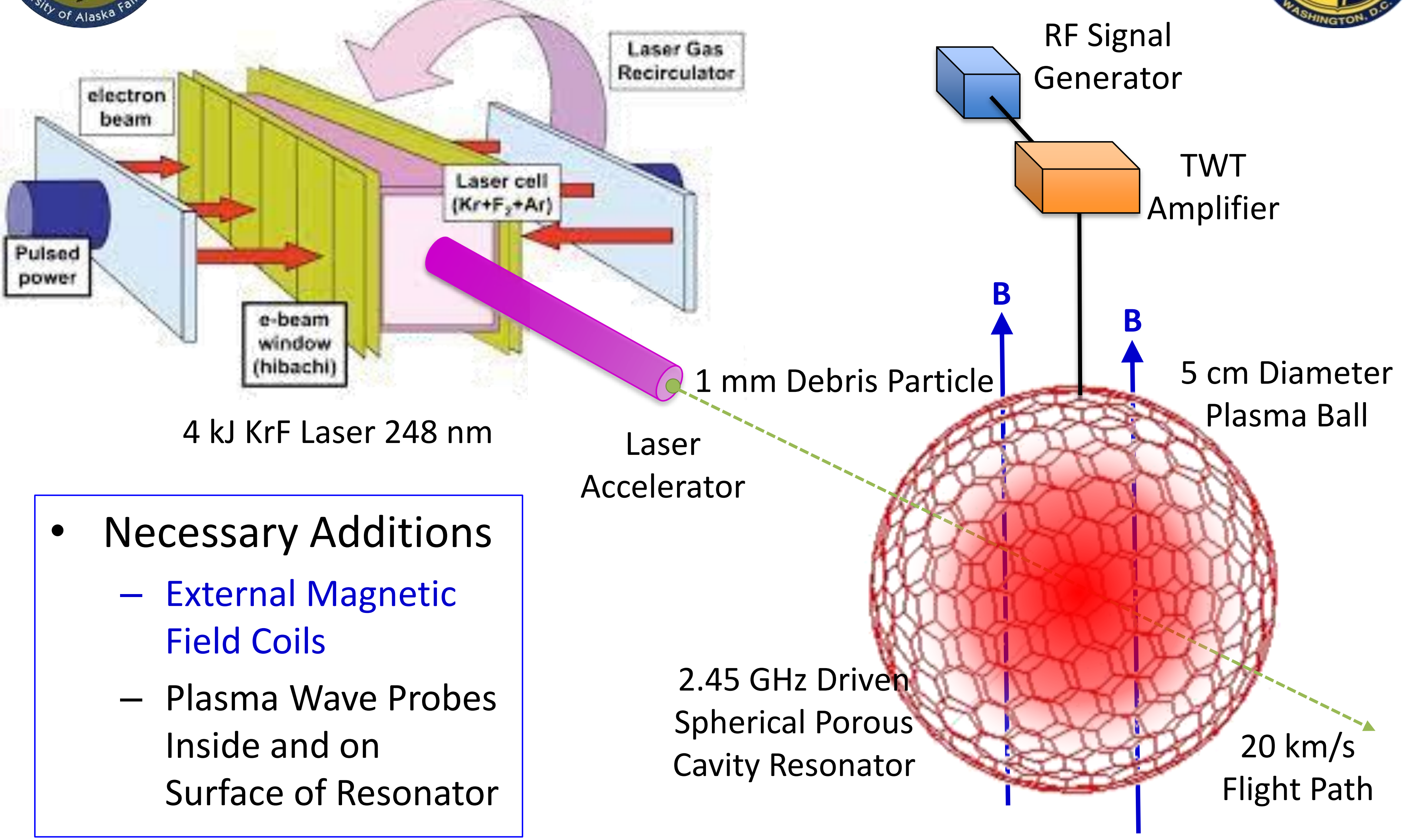


2.44 GHz, 120 mTorr Pressure

Ref.: PA Bernhardt, SJ Briczinski, S-M Han AW Fliflet, CE Crockett, CL Siefring, S Gold
Visible Plasma Clouds With an Externally Excited Spherical Porous Cavity Resonator
IEEE Transactions on Plasma Science, 43, 1911-1918, 2015

Experimental Demonstration of coax-driven resonator Capability.

Alternative Laboratory Experiment with Debris Injection Through Plasma
Excitation of Electrostatic and Electromagnetics Waves in Plasma with B



4 kJ KrF Laser 248 nm

Laser Accelerator

1 mm Debris Particle

RF Signal Generator

TWT Amplifier

5 cm Diameter Plasma Ball

2.45 GHz Driven Spherical Porous Cavity Resonator

20 km/s Flight Path

- Necessary Additions
  - External Magnetic Field Coils
  - Plasma Wave Probes Inside and on Surface of Resonator

Collaborators, Max Karasik, James Weaver, Plasma Physics Division, NRL, Washington, DC

Joint Effort Between NRL NIKE and UAF GI for Validation of Plasma Wave Generation by Space Objects

- Laboratory Measurements of Plasma Waves from Hypersonic Target in a Magnetized Plasma
- Experiment Components:
  - Accelerate 1 mm charged target sphere to > 10 km/s
  - Generate plasma cloud using Spherical Porous Cavity Resonator
  - Excite axial magnetic fields with coils in the NIKE Chamber
  - Detect electric and magnetic fields from moving charged projectiles.
  - Install plasma source and measurement probes in NIKE chamber
  - Compare results with e-MHD Theory and Space Observations
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