Swarm-E Radio Receiver Instrument Observations of High Power VLF Waves in the Ionosphere for Rapid Radiation Belt Remediation

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Man Hua[4], Jacob Bortnik[4], Qianli Ma[4], Pekka T. Verronen[5], Andrew Howarth[6]
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[5]Sodankylä Geophysical Observatory, Univ. Oulu, Sodankylä, Finland
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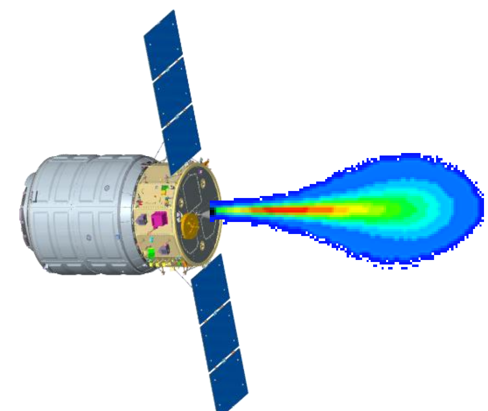
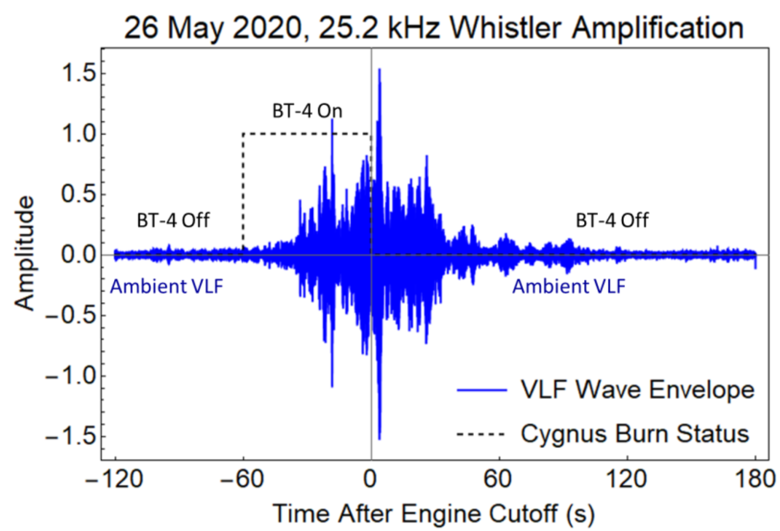
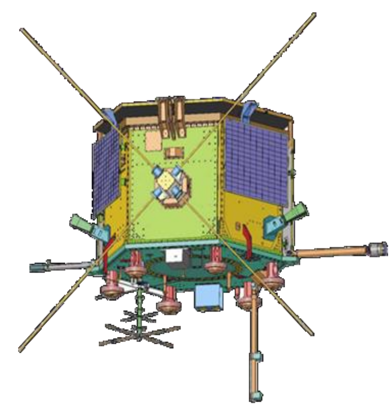


Northrop Grumman
Cygnus Rocket Burn



Amplified VLF Signal



Swarm-E e-POP
Electric Field Sensor

Amplification of VLF Waves in Space

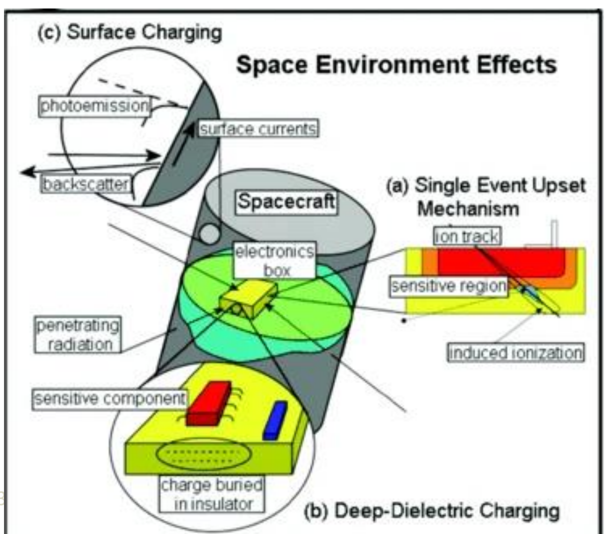
Presentation Outline

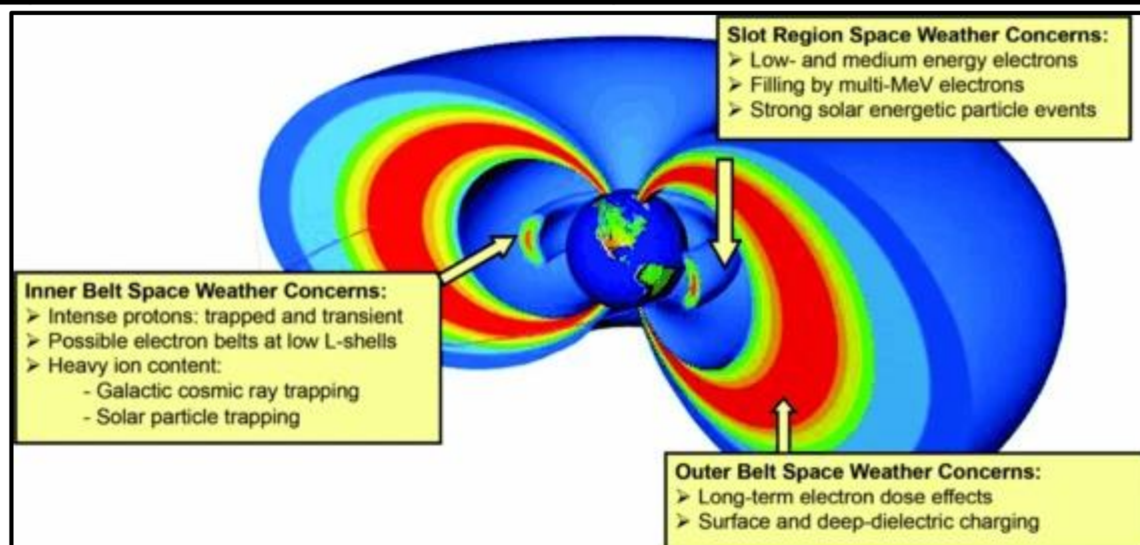
- Problem: Energetic Electrons in the Radiation Belts
  - Bad for Satellites – Destroys Spacecraft Electrons
  - Good Source of Energy for Ionospheric Modification Experiments
    - Artificial Energetic Electron Precipitation with VLF Whistler-Mode Waves
    - Localized Production of Optical Emissions, Enhanced D-Region Densities and X-Rays
- Generation of Intense Whistler Mode Waves in Space
  - VLF Signal Exciters on the Ground or on Satellites
  - New Concept: Directional Amplification of Whistler Waves in Space
- F-Region Directional Amplification Experiments in Space
  - Rocket Motor Burns Generate Lower Hybrid Waves over Ground VLF Transmitters
  - Simultaneous VLF and Lower-Hybrid Wave Excitation with HAARP High Power HF
- F-Region Lower Hybrid Waves Leading to Large VLF Amplification
  - Broadband 30 dB Amplification of Low Frequency EM Waves from Earth Sources
  - Transmitted VLF Signals Also Amplified by Strong Radiation Belt Interactions
- Electrical Engineering Tools for Solving the Radiation Belt Problem
  - System Design Engineering (Building a VLF Transmitter Out of the Ionosphere)
  - Signal Processing (Detecting the Source and Received VLF Waves)
  - Electromagnetic Theory (Radiation and Propagation of the HF and VLF Waves)

Impacts of Enhanced and Natural Belts on Satellites

Gombosi et al., Anthropogenic Space Weather, Space Sci. Rev. 212, 985–1039 (2017).

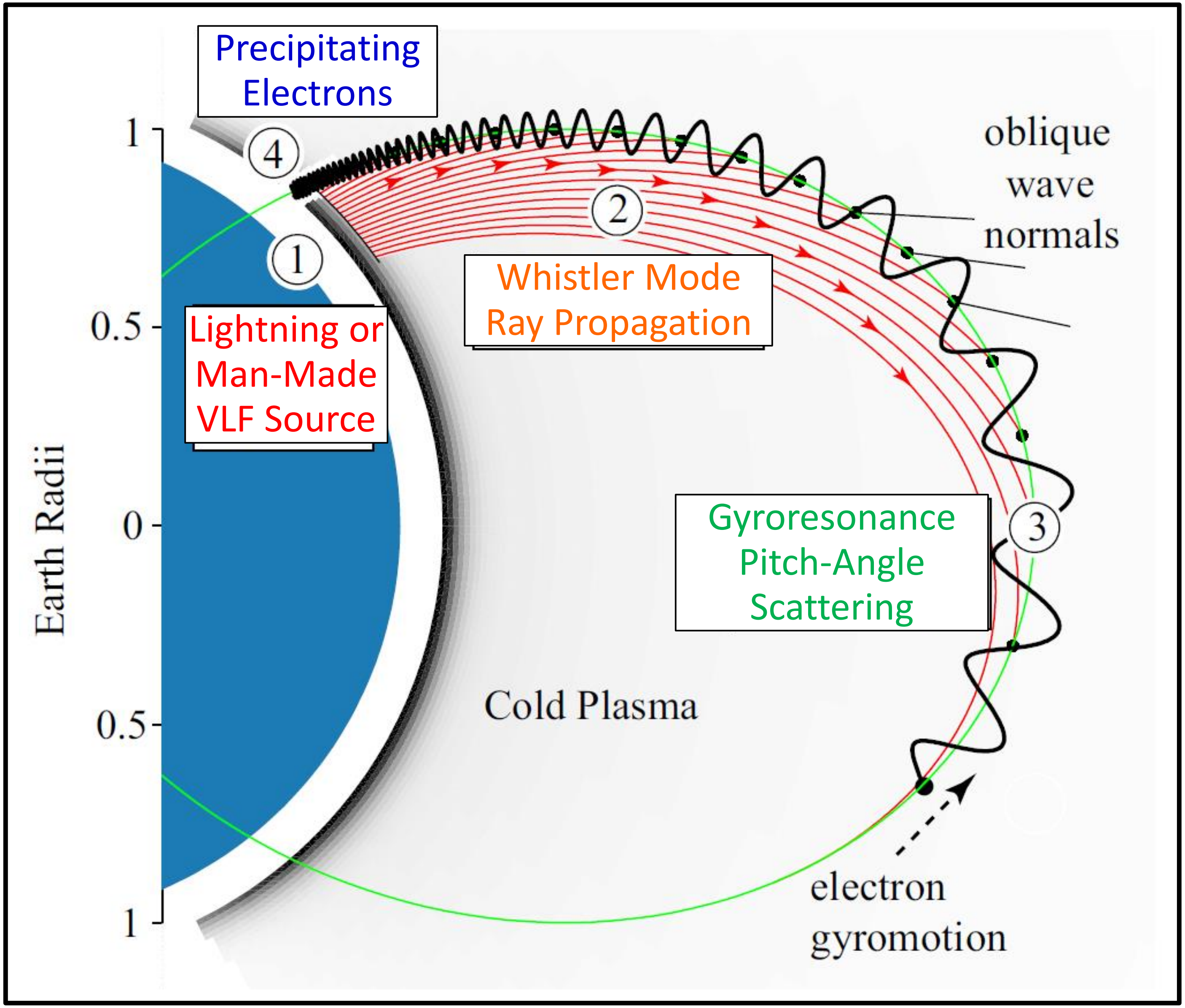
Satellite	Launch	End	Damage history	Comments
Injun I	Jun 1961	Mar 1963	Solar cell and transmitters	Solar cell reduced power
TRAAC	Nov 1961	Aug 1962	**Solar cell Radiation Damage**	Failure of the power system
Transit-4B	Nov 1961	Aug 1962	**Solar cell Radiation Damage**	Test circuits diagnose failure
OSO-1	Mar 1962	May 1964	Solar cell damage	Recorder failure in May 1962
Ariel-1	Apr 1962	Aug 1962	**Solar cell Radiation Damage**	
Kosmos-5	May 1962	May 1963	Reported damage by Starfish.	
Telstar-1	Jul 1962	Feb 1963	**Transistor radiation damage**	Instrumented to measure
Alouette-1	Sep 1962	Jan 1968	No adverse effects by Starfish	Conservative power design
Explorer XIV	Oct 1962	Aug 1963	Encoder Intermittent failures	
Explorer XV	Oct 1962	Jan 1963	**Under-voltage Failure**	
ANNA-1B	Oct 1962	?	**Solar cell Deterioration**	Flew the first GaAs solar cells





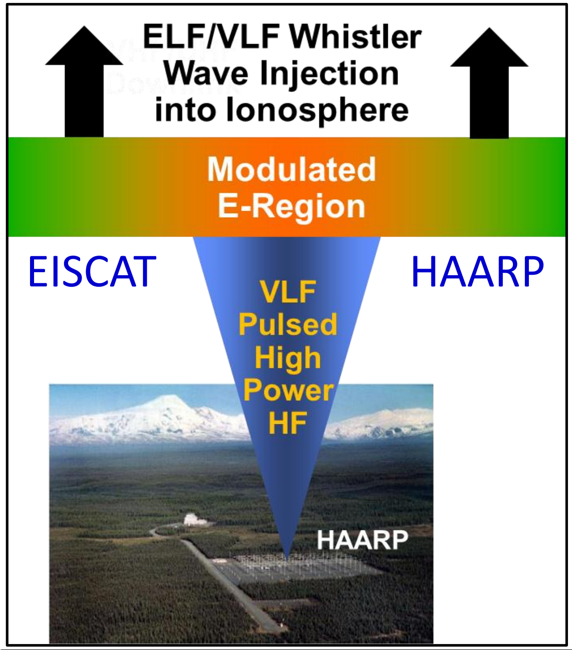
Solution: Whistler Resonance Scattering of Energetic Electrons

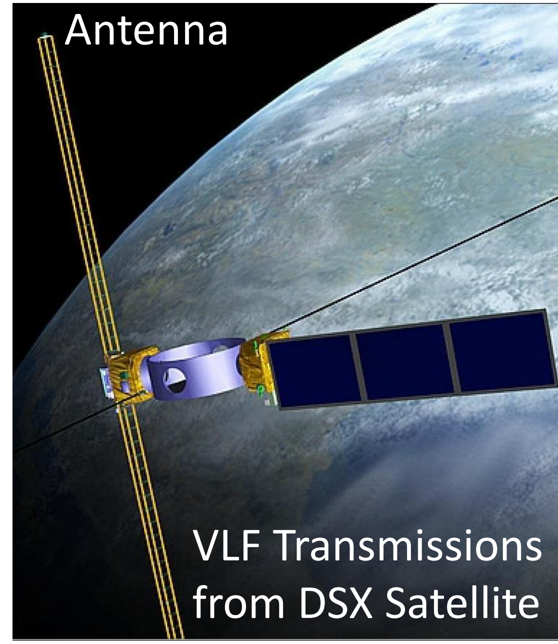
Lauben et al., Precipitation of Electrons by Oblique Whistlers, 2001

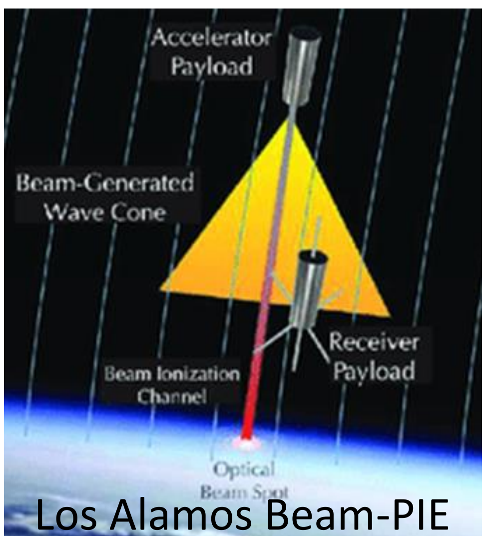


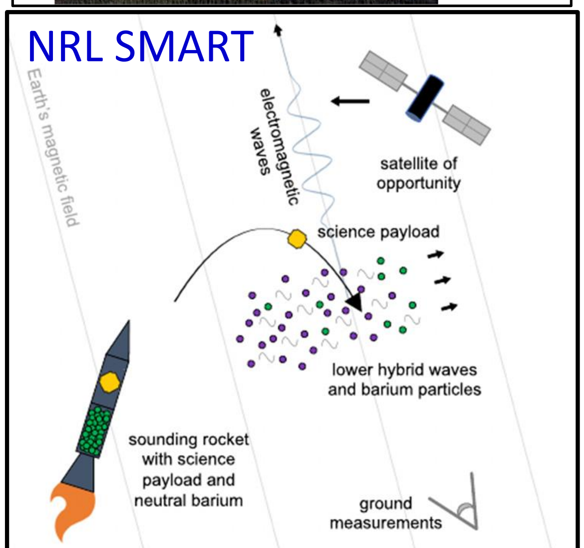
Need for Directional Amplification of VLF Waves in Space

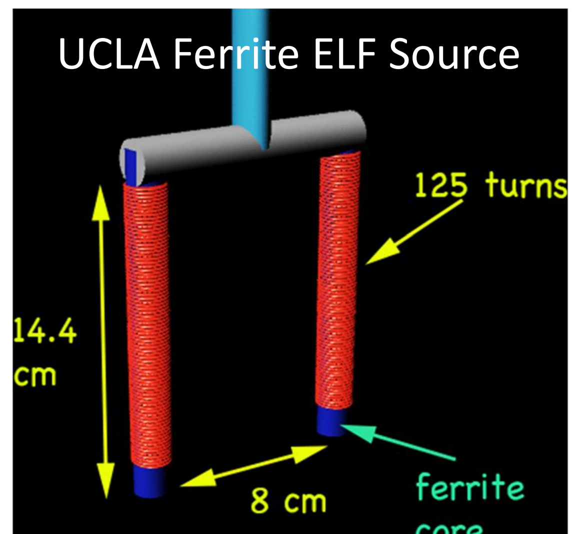
Devices Designed to Generate ELF/VLF Waves for RBR











Rocket Exhaust Driven Amplification of VLF Waves in Space

Comparison of Amplification With ELF/VLF Wave Excitation

Whistler Wave ELF/VLF-Signal Exciters → 8 pT → Whistler Wave Signal Detectors

1. Ground Sources
   a) **Lightning**
   b) **Global VLF Transmitters**
2. **High Power HF Ionospheric Modification**
   a) **EISCAT, HAARP, Arecibo Modulated Electro Jets**
   b) **Nonlinear Interactions**
3. Satellite Sources Briefed to Flight
   a) Large Antenna/Powerful VLF transmitter on **AFRL DSX**
   b) **Ferrite Antennae** for Shear Alfven (EMIC) Waves
   c) Modulated Electron Beams of **LANL Beam-PIE**
   d) High Speed Ion Injections with **NRL SMART**

1. **VLF Receivers** in Space and on Ground (Arase, DSX, SWARM-E)
2. **Electron Precipitation** into the Lower Atmosphere (cep)
3. **Earth-Ionosphere Waveguide Modification** for EM Wave Propagation
4. **Enhanced D-Region** for HF Absorption Indication of Electron Precipitation

Rocket Exhaust Driven Amplification of VLF Waves in Space

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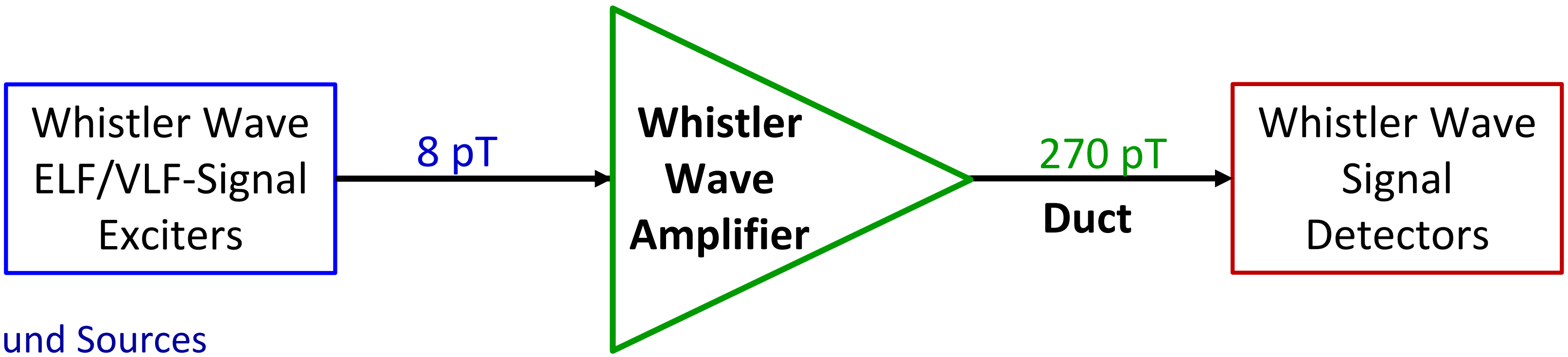

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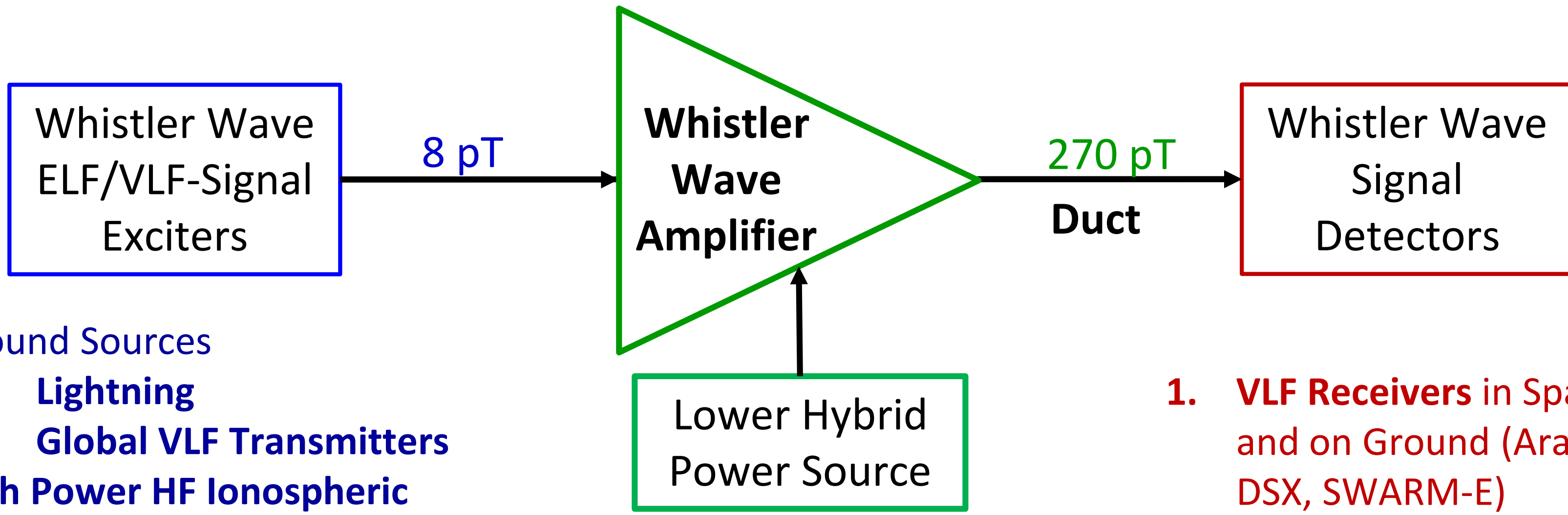

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1. **Rocket Exhaust Driven Amplification (REDA)** Using Wave-Wave Interactions (WTWPA)
2. **High Power HF Stimulated Amplification (HFSA)** Using Wave-Wave Interactions (WTWPA)

1. **VLF Receivers** in Space and on Ground (Arase, DSX, SWARM-E)
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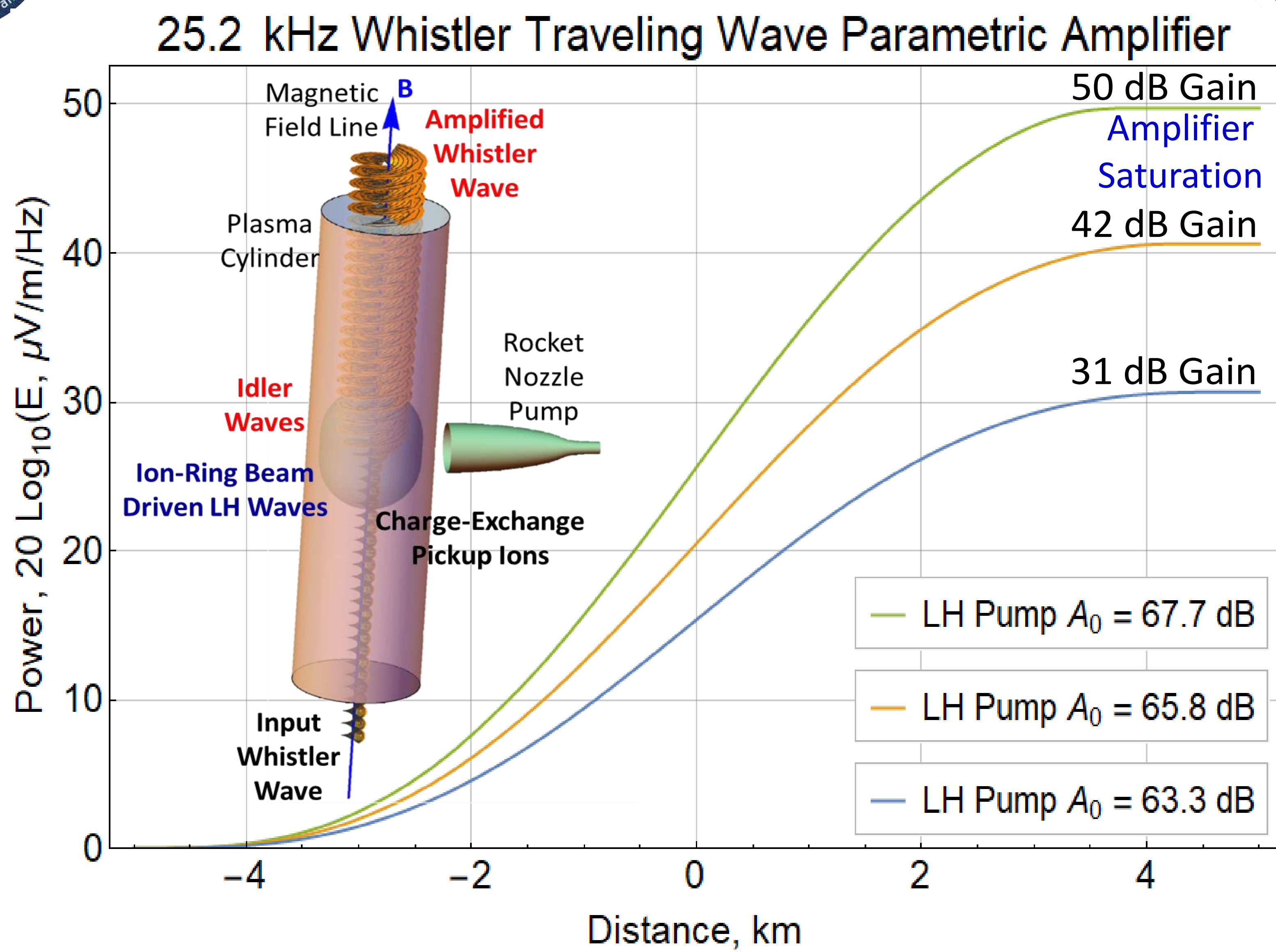
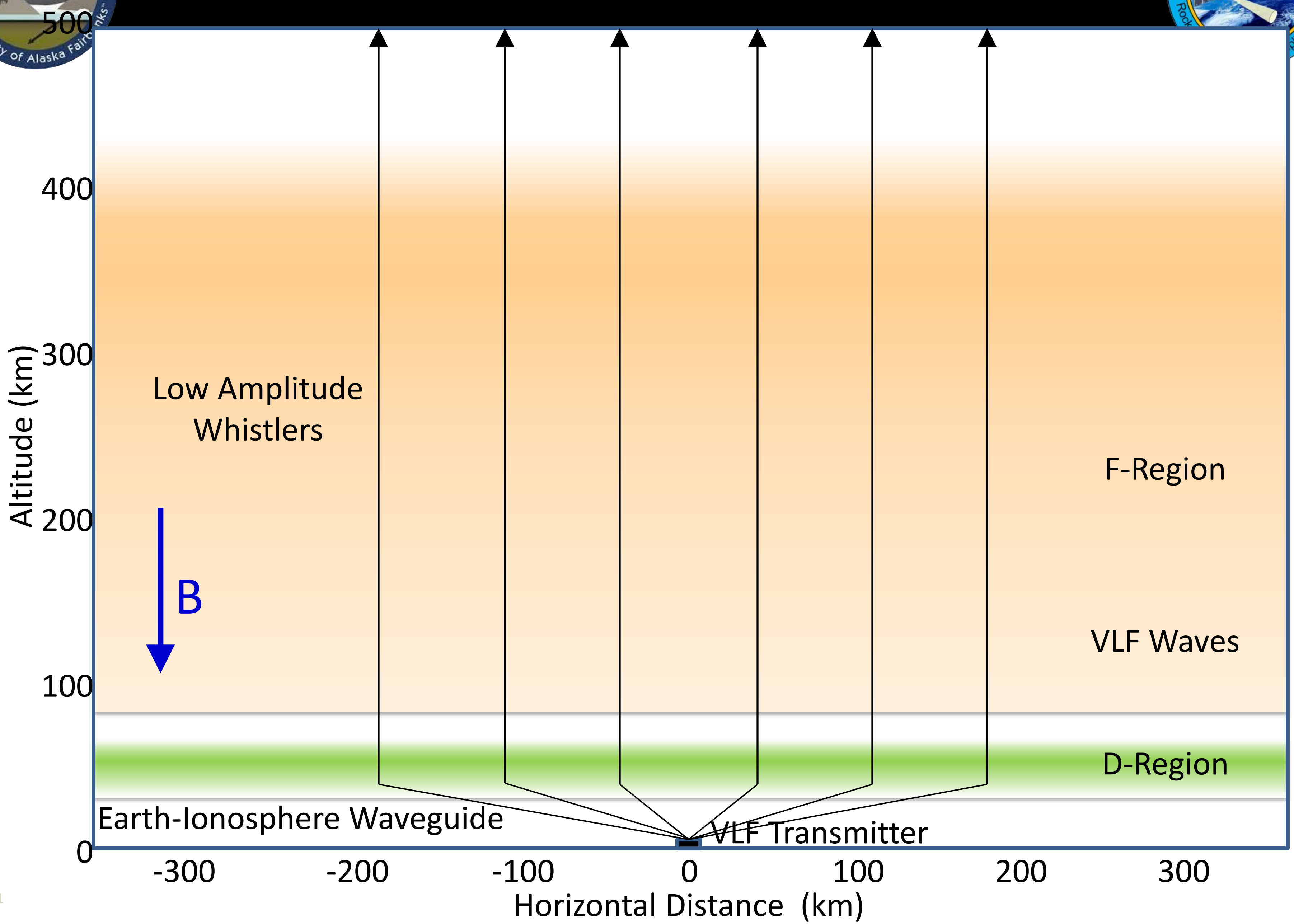
Whistler Traveling Wave Parametric Amplifier (WTWPA)

LH Pump Wave Potential A_{0M} Determines Amplifier Gain



Bernhardt, Whistler Traveling Wave Parametric Amplifier, IEEE Trans. on Plasma Sci., 49, 2021

Method 1: Rocket Exhaust Driven Amplification of VLF



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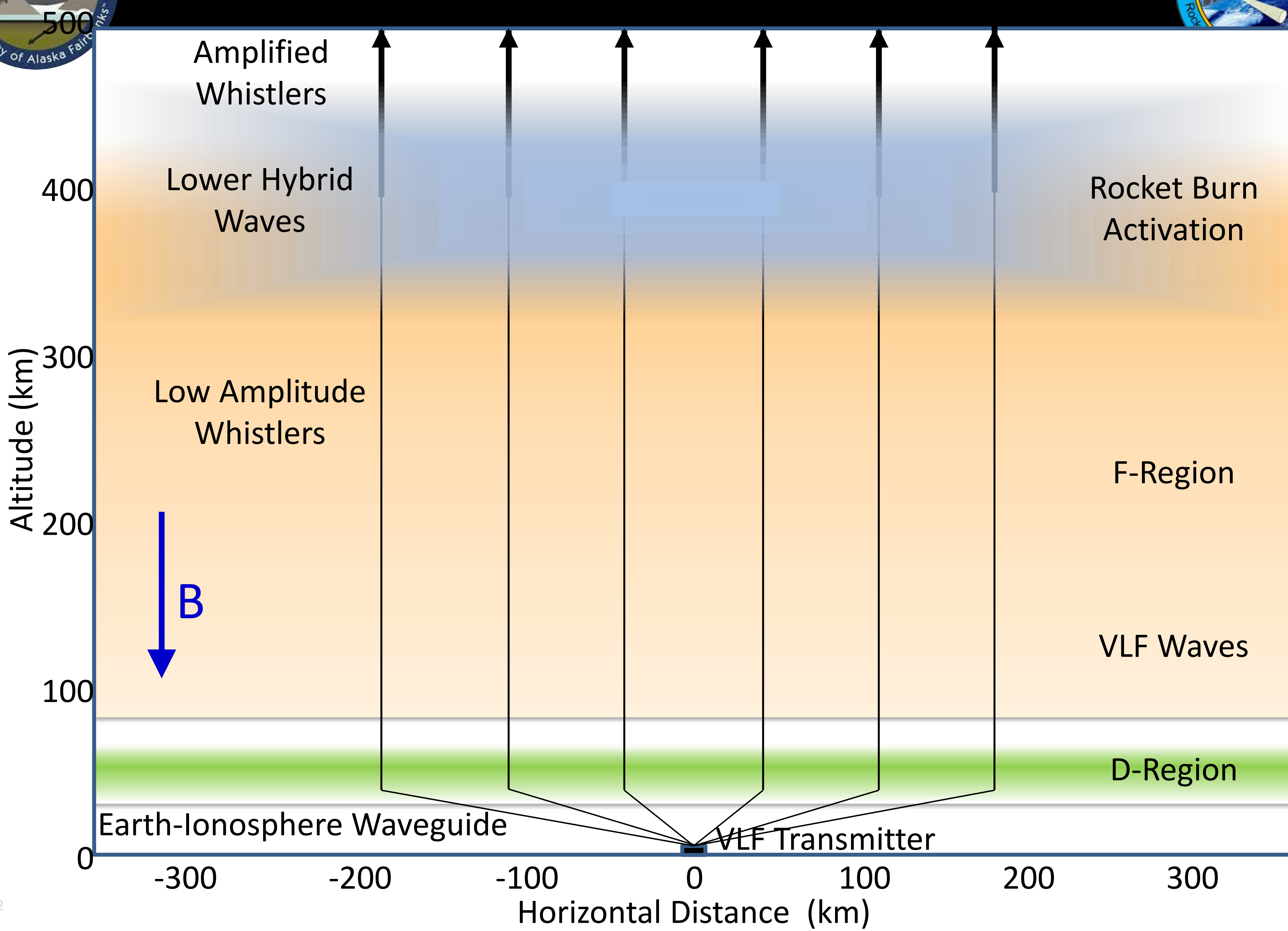

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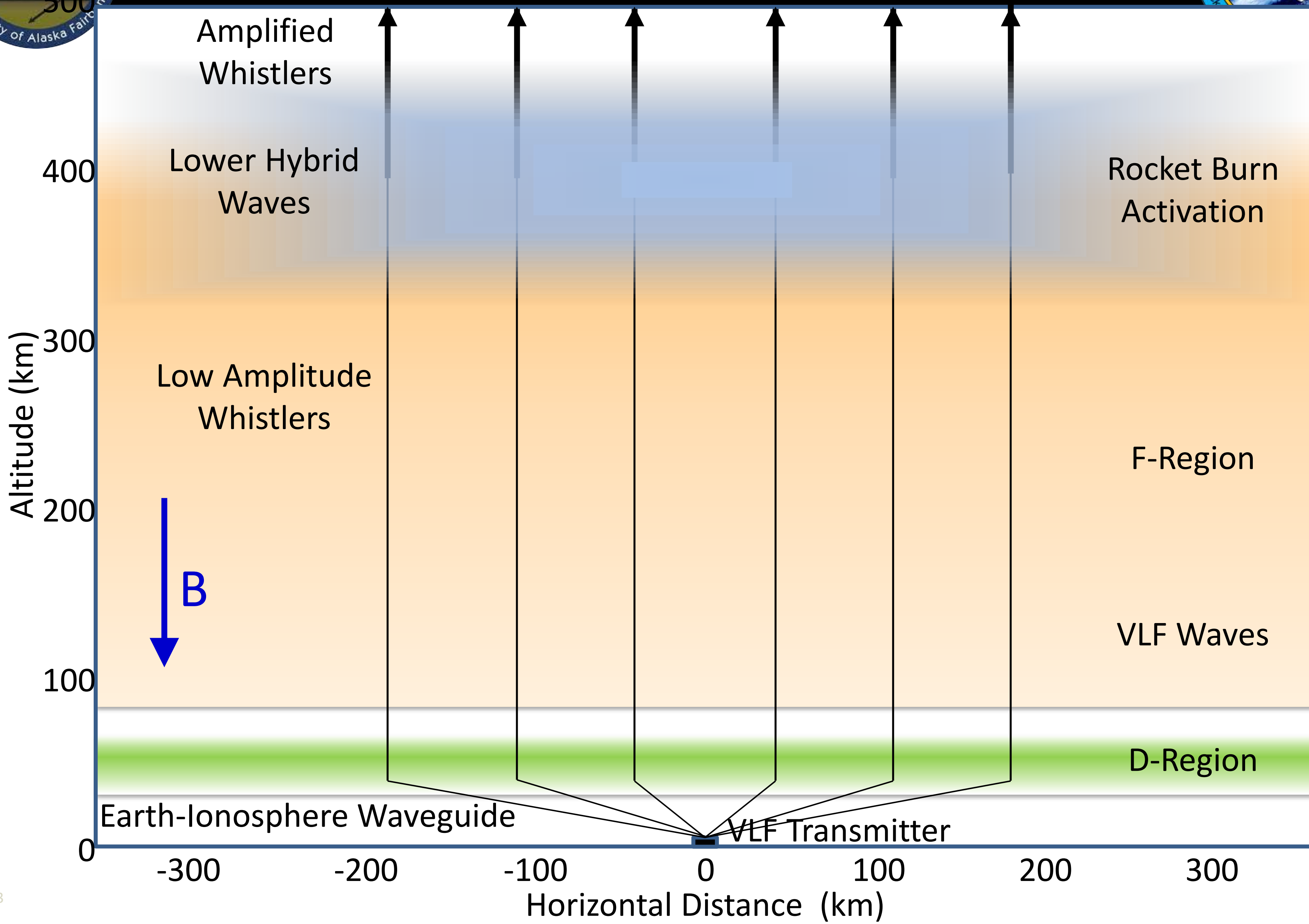
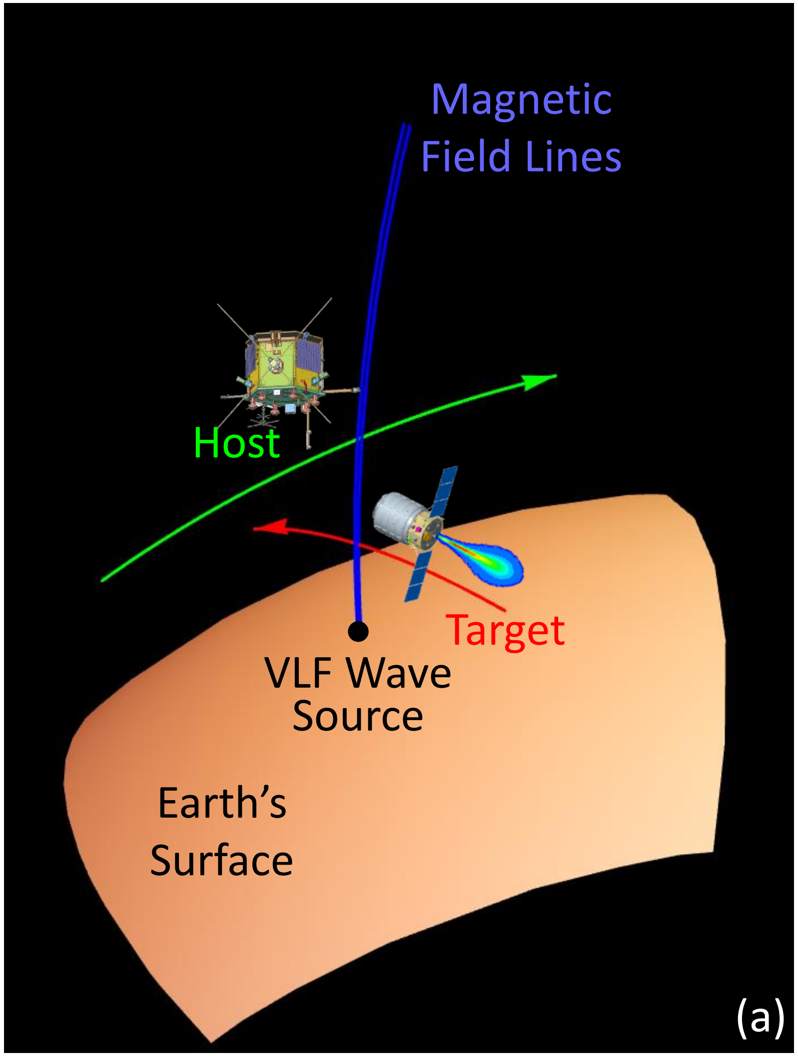
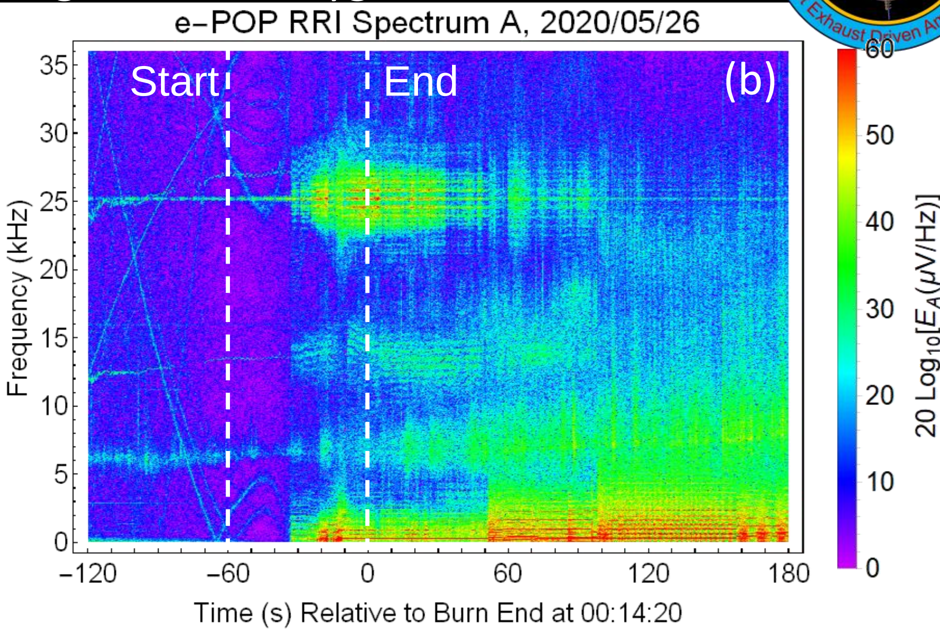


Rocket Exhaust Driven Amplification (REDA) of VLF Waves in Space

Measurements of REDA During the NG-18 Cygnus Mission



Intersection of Whistler Signal with Rocket Exhaust Plume



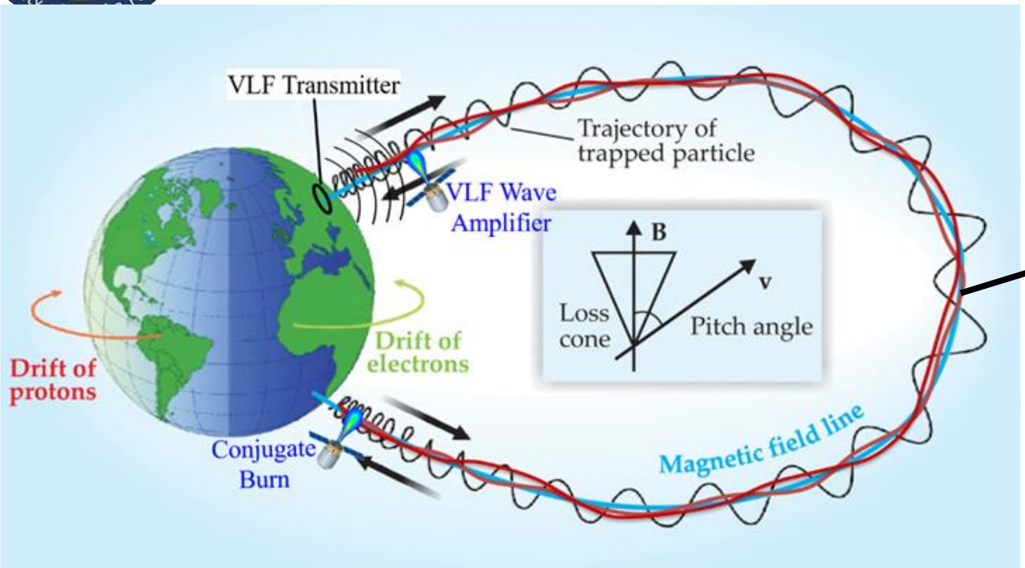
The **Rocket Exhaust Driven Amplification (REDA)** technique **AMPLIFIES** whistler waves from existing ground transmitters rather than trying to **GENERATE** large amplitude whistler waves from ground- or space-based systems.

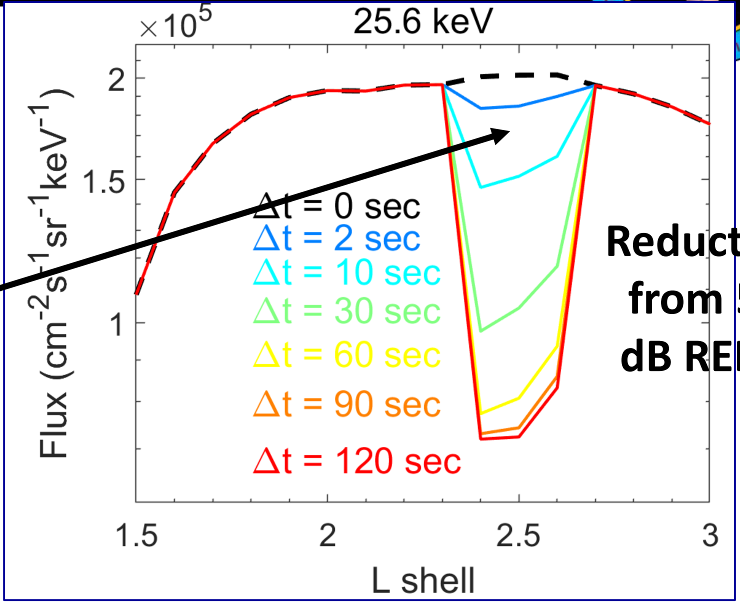
This technique was demonstrated in May 2020 but further tests of REDA are needed to understand and predict the amplification process.

In conjunction with the DOD Space Test Program, ISS reboost burns monitored for REDA application

Why Do We Care? Simulations of Cygnus Burn Experiment

Amplified Whistler Waves Remediate Radiation Belt Electron





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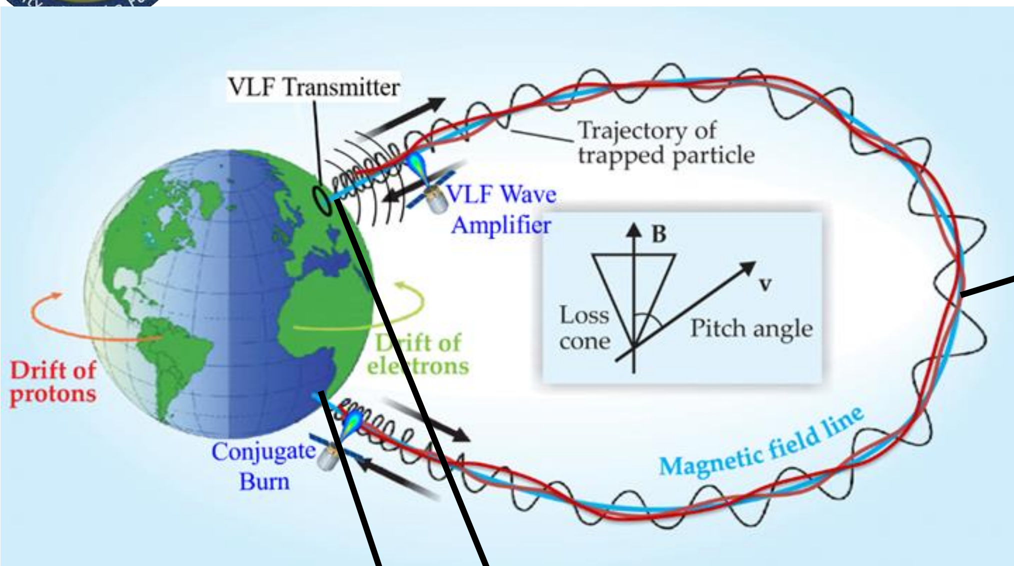
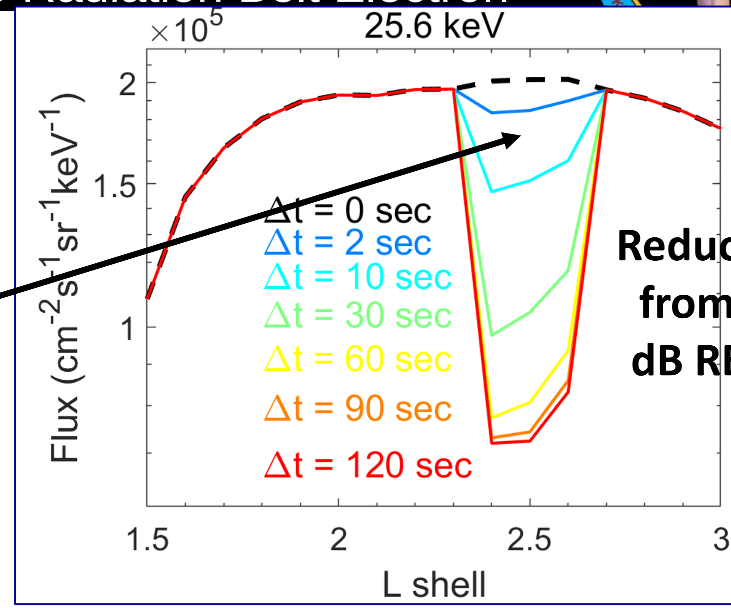
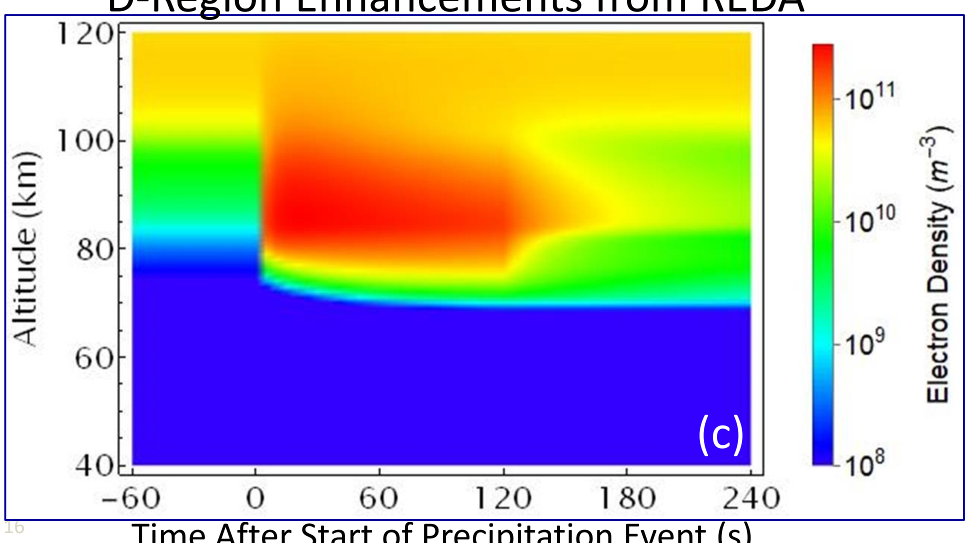




D-Region Enhancements from REDA



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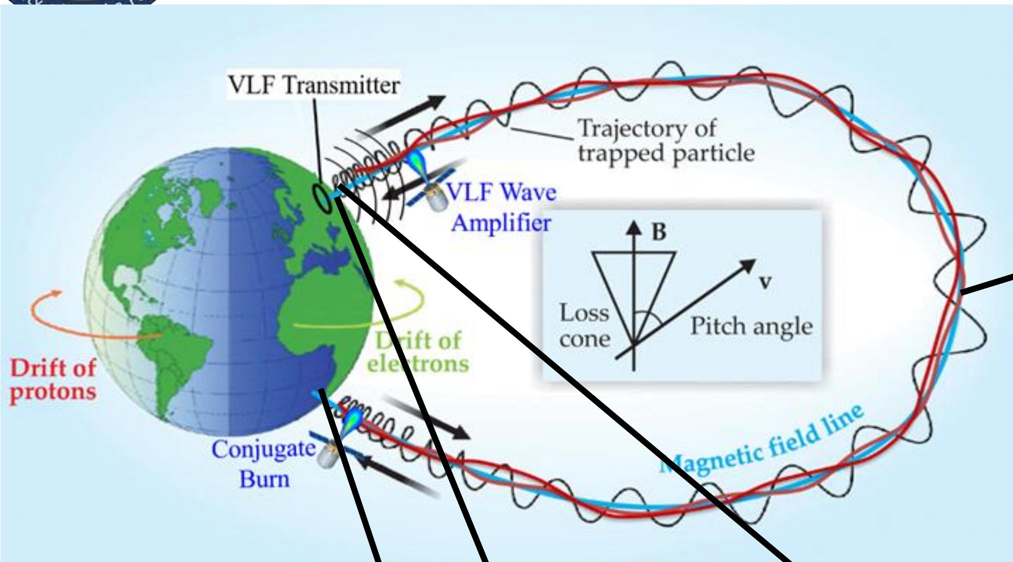
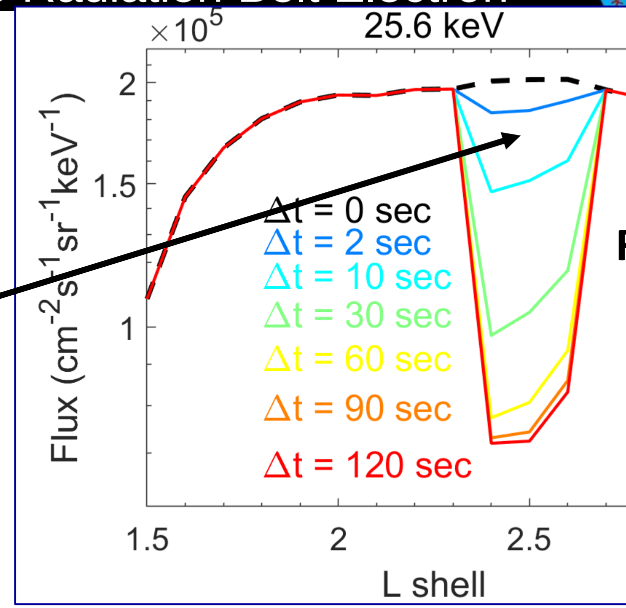
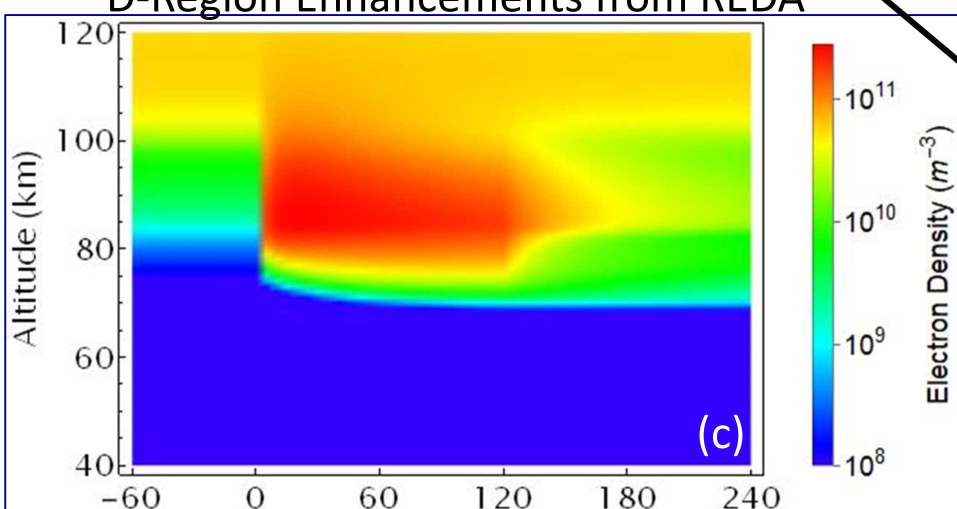
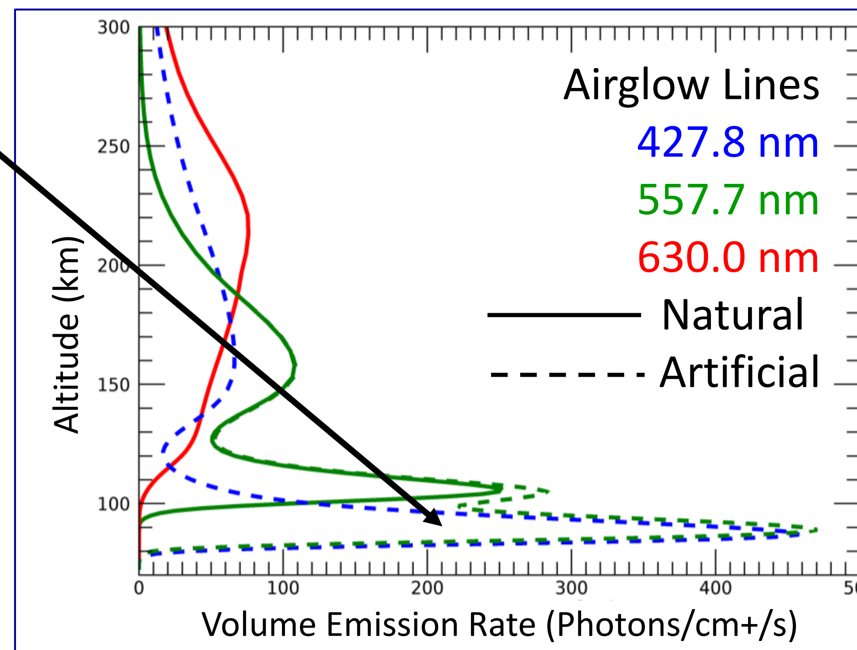




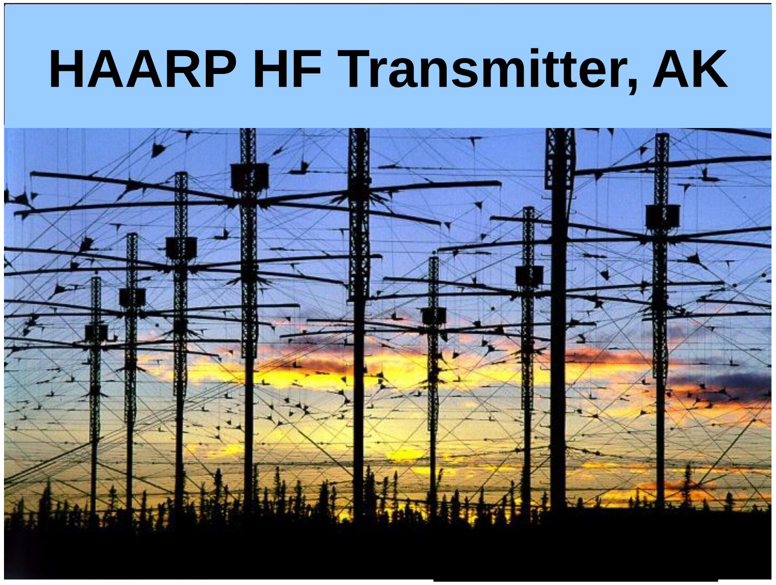
Reduction from 50 dB REDA

D-Region Enhancements from REDA



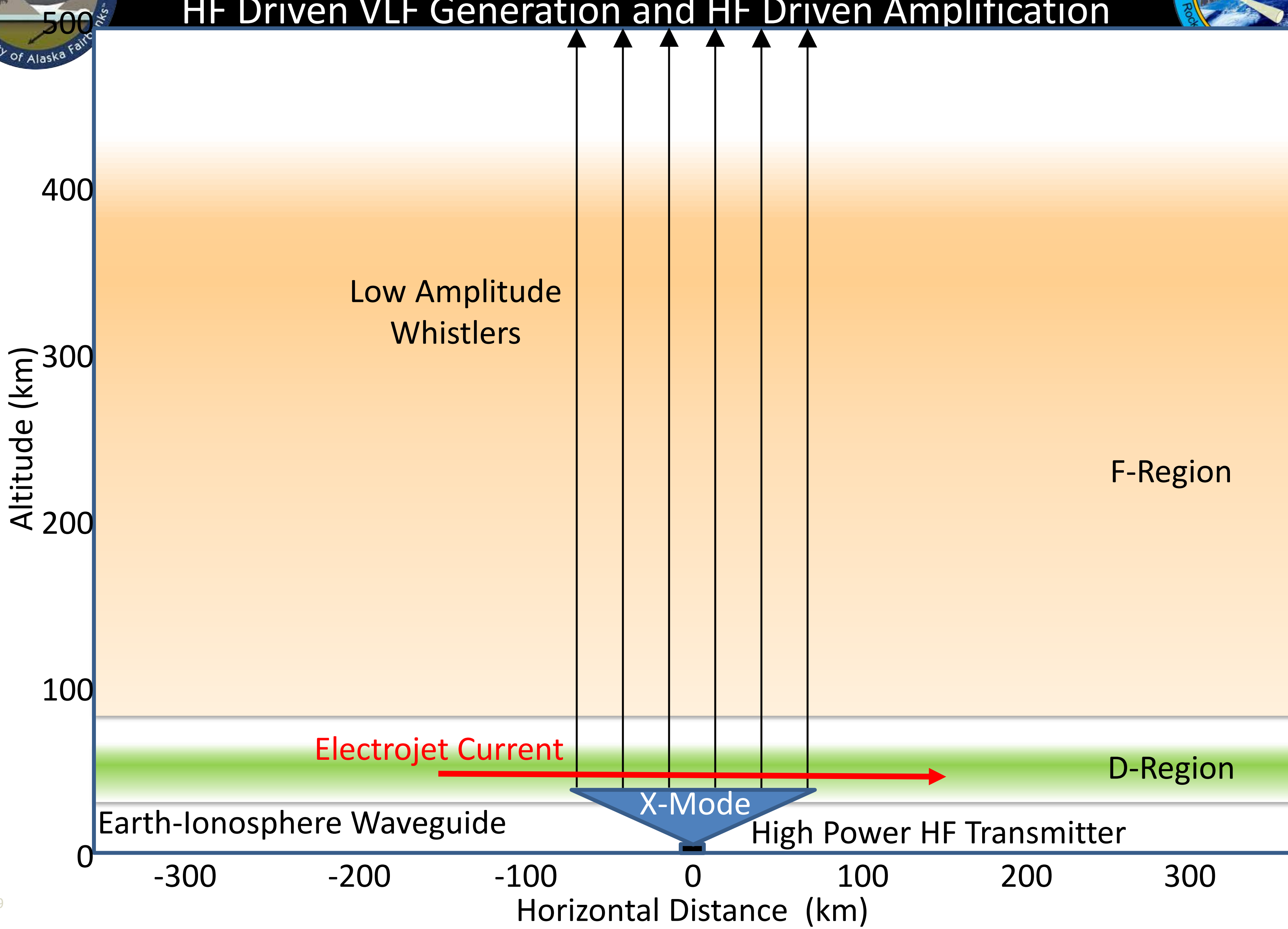


Radio/Radar Based Diagnostics Facilities for HAARP HF Ionospheric Modification



Method 2:

HF Driven VLF Generation and HF Driven Amplification



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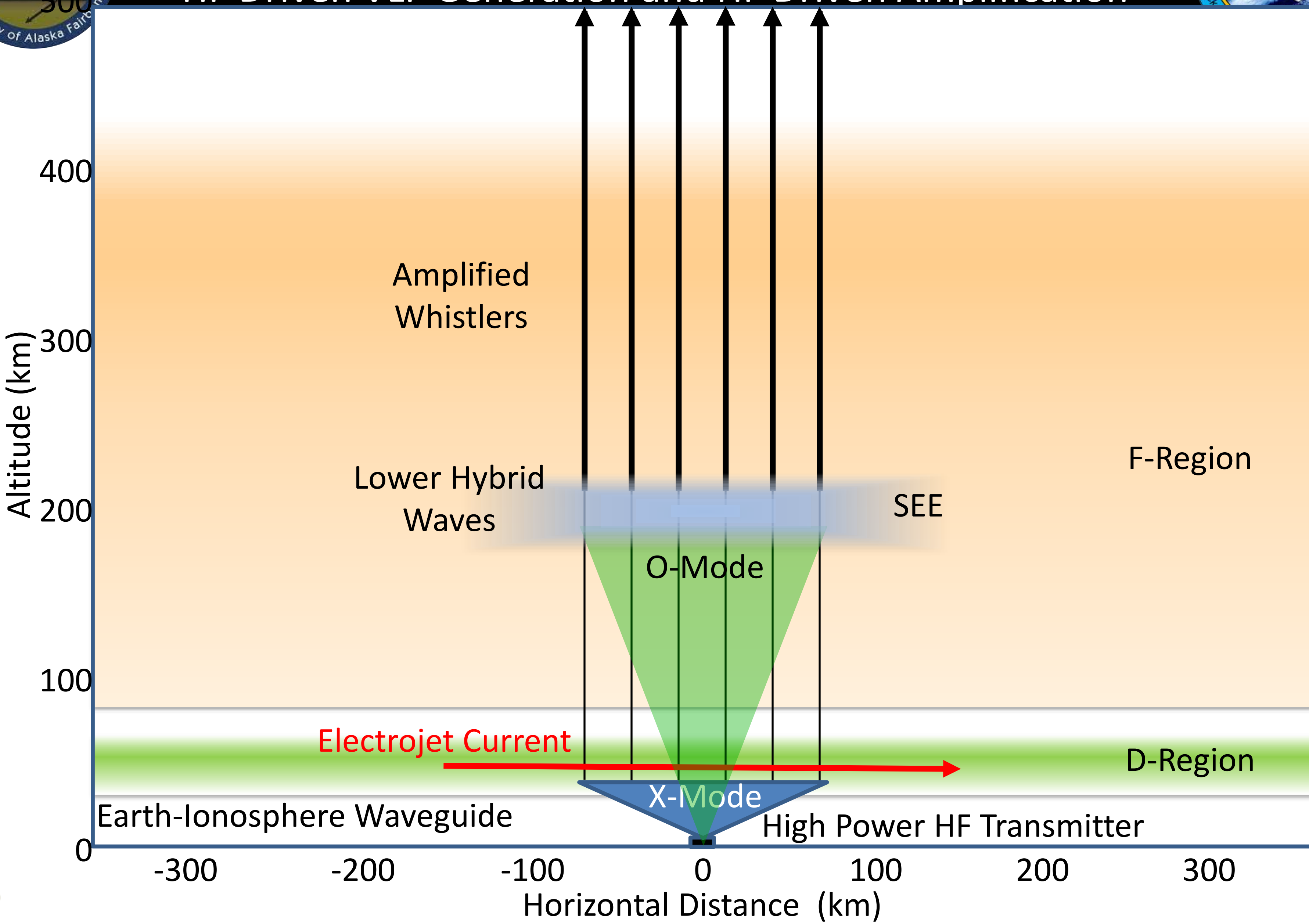

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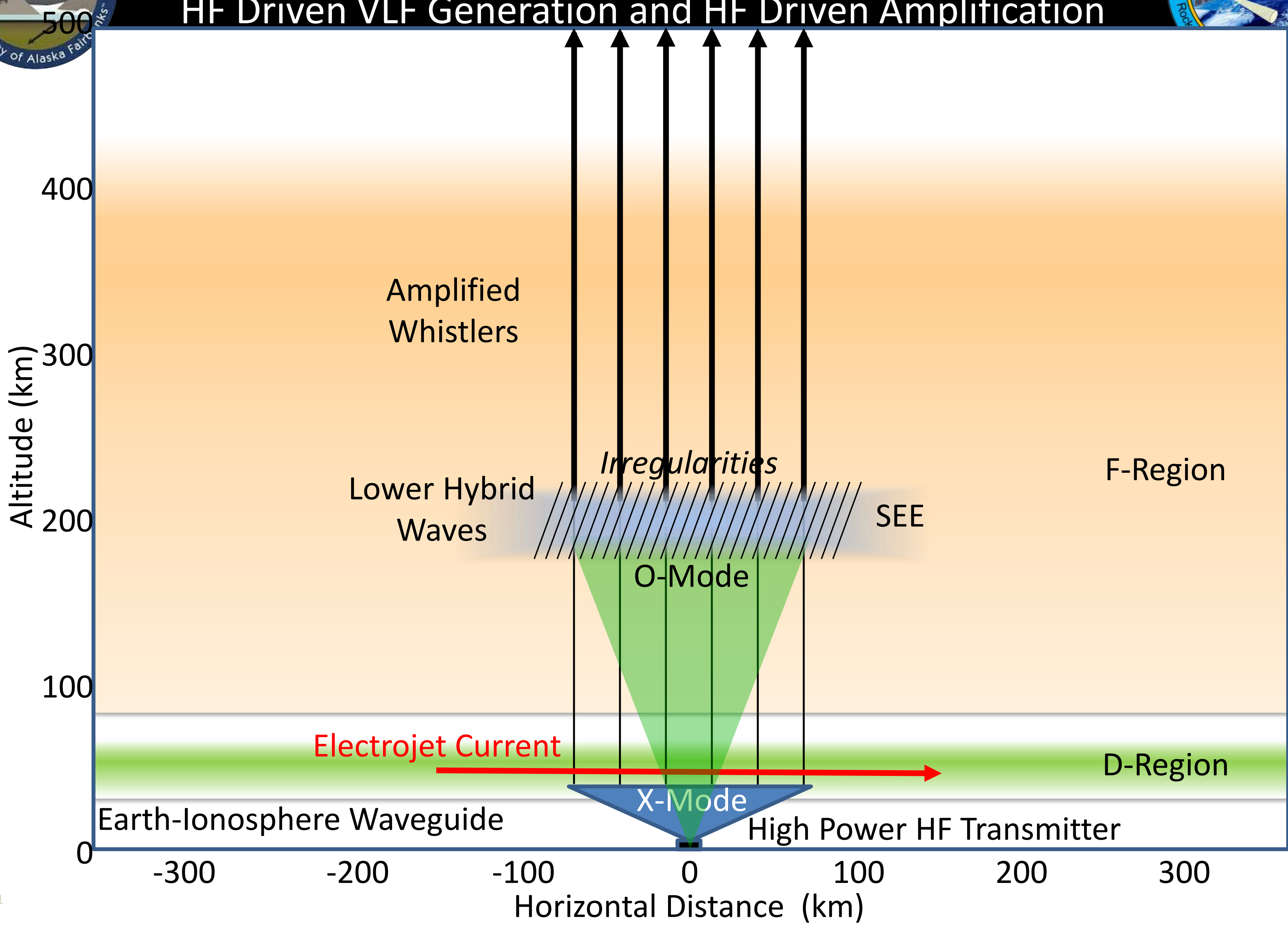

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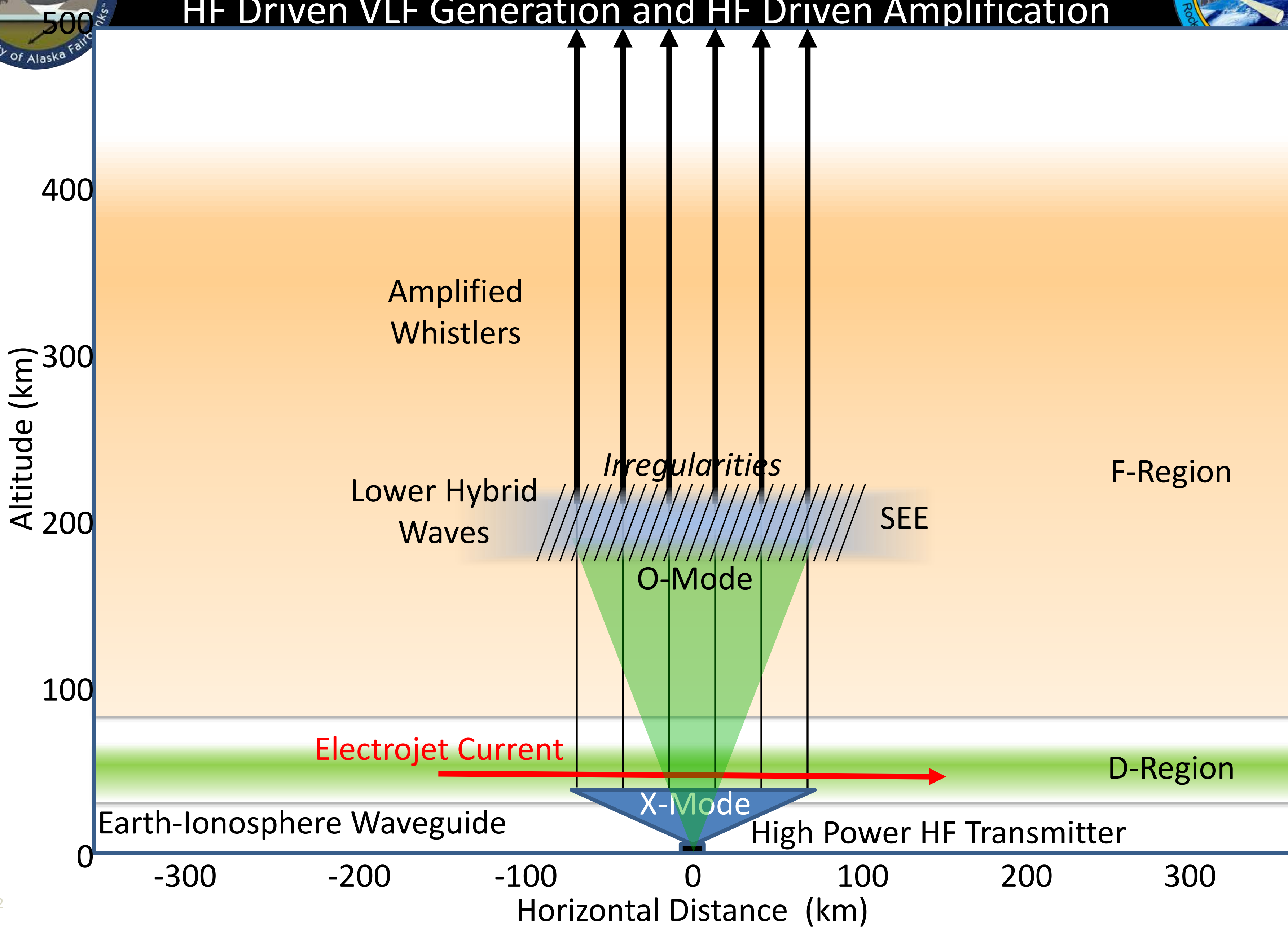
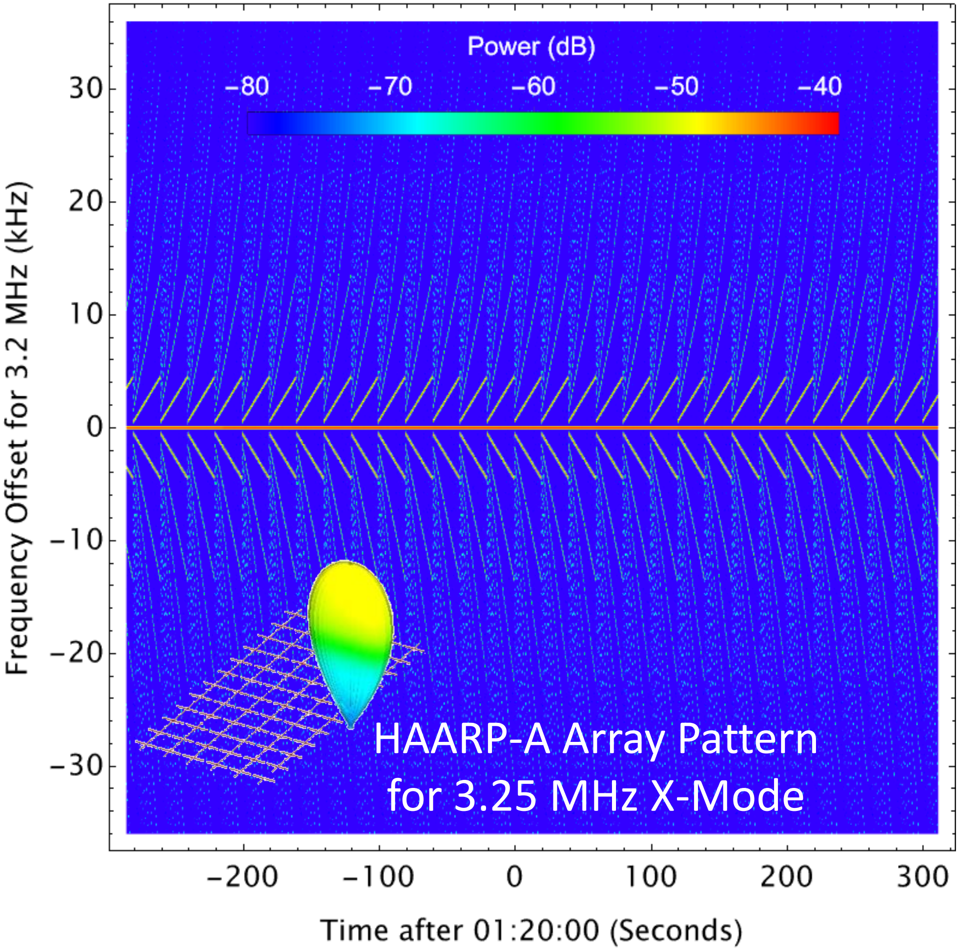


HF Transmissions of 3.25 MHz X-Mode with VLF Chirps
8.1/9.6 MHz O-Mode with Lower Hybrid Wave Stimulations

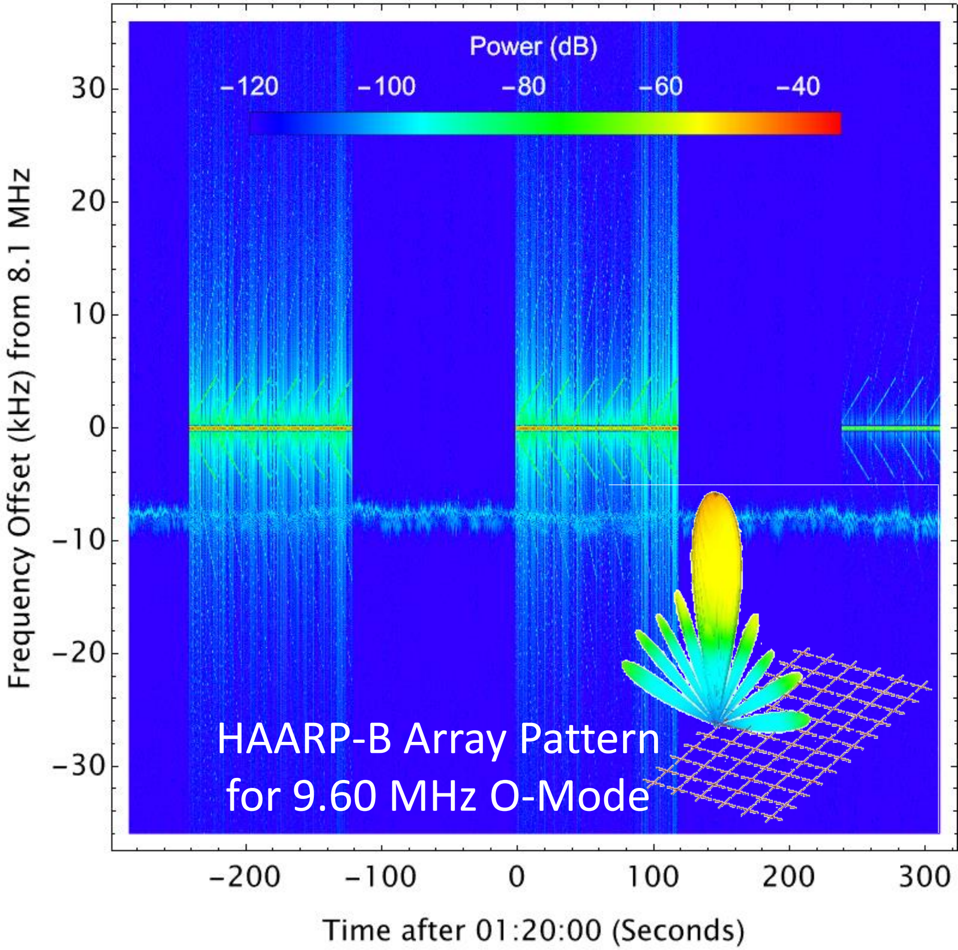
Exciter

HAARP HF Signal A, 7 November 2023

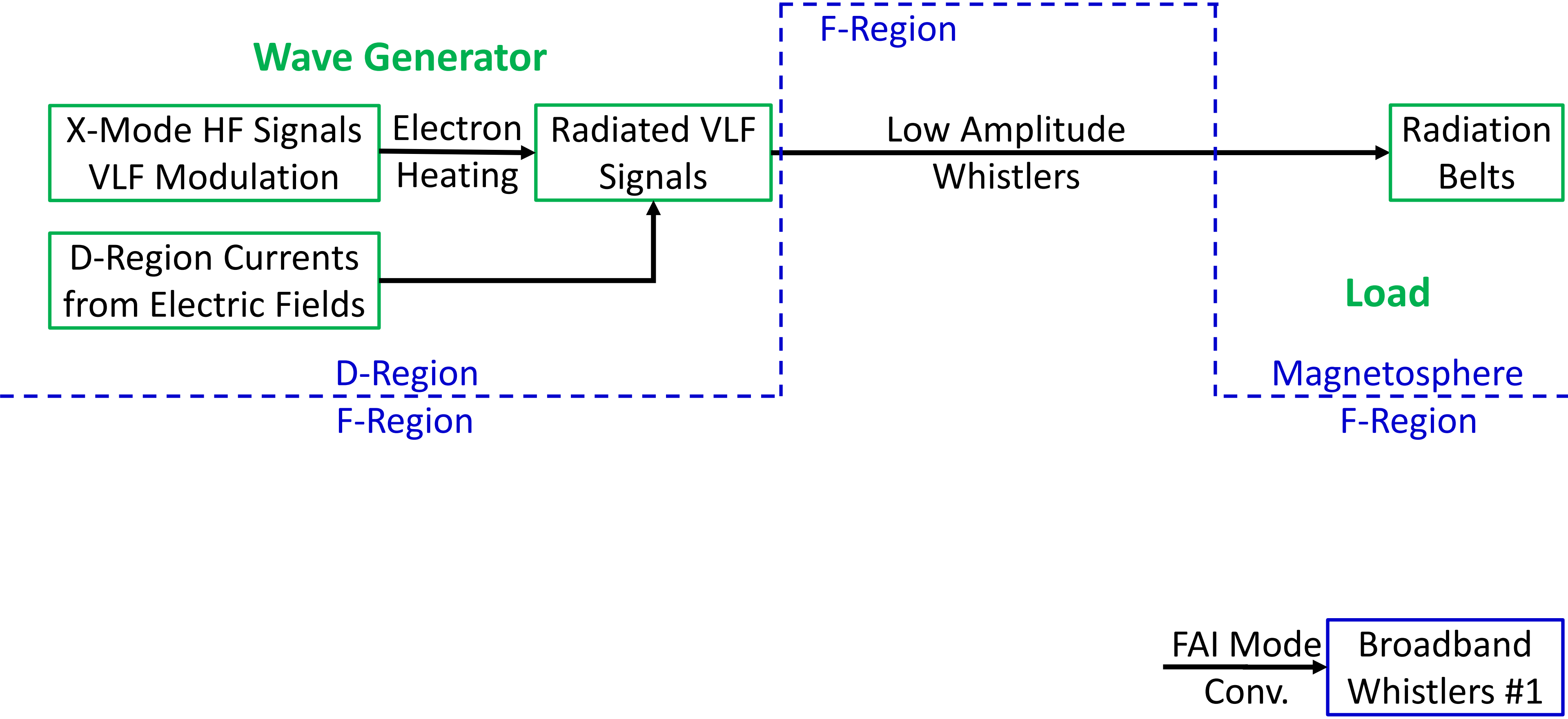


Amplifier

HAARP HF Signal B, 7 November 2023



High Power HF VLF Generation and Amplification Scheme



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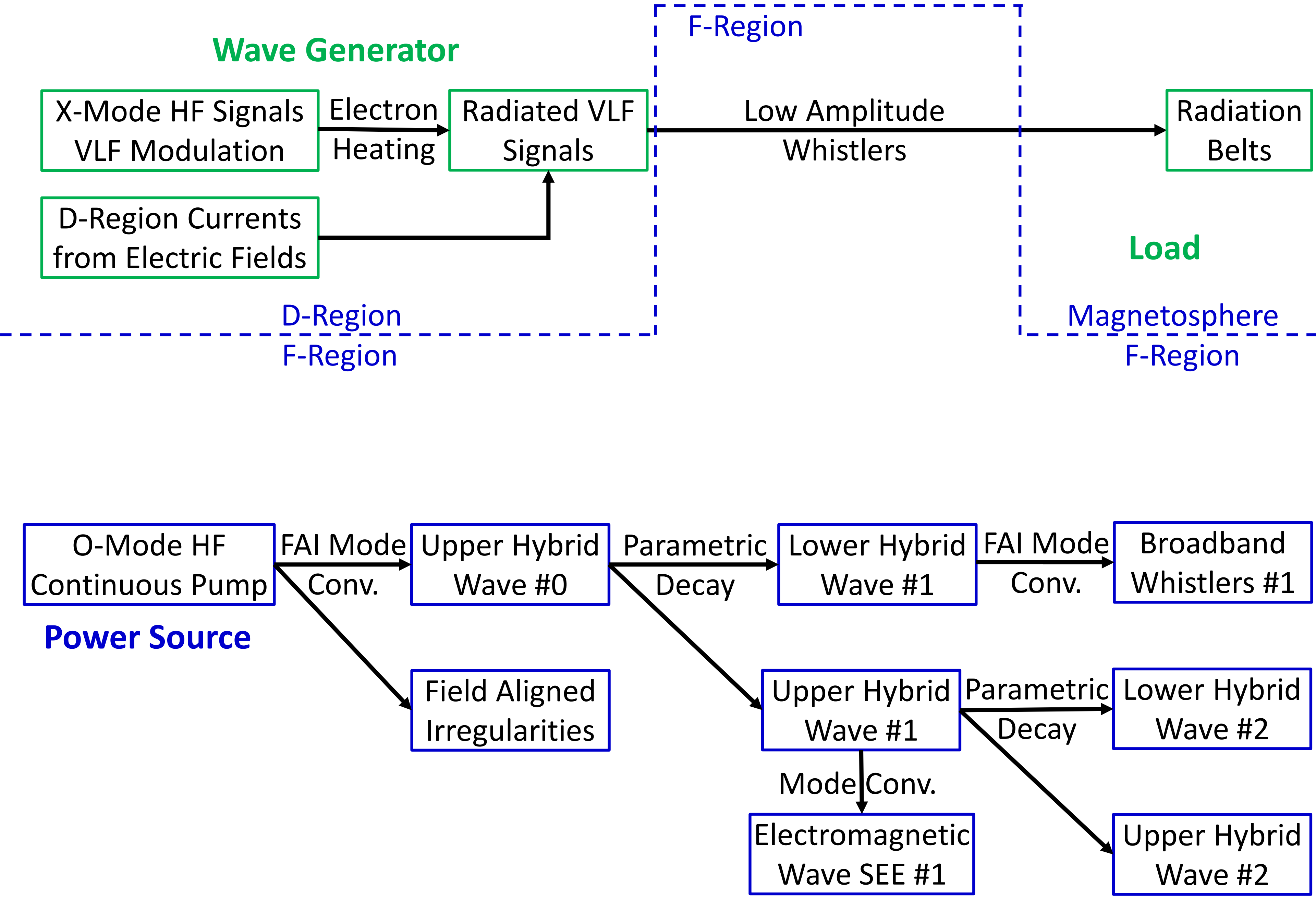

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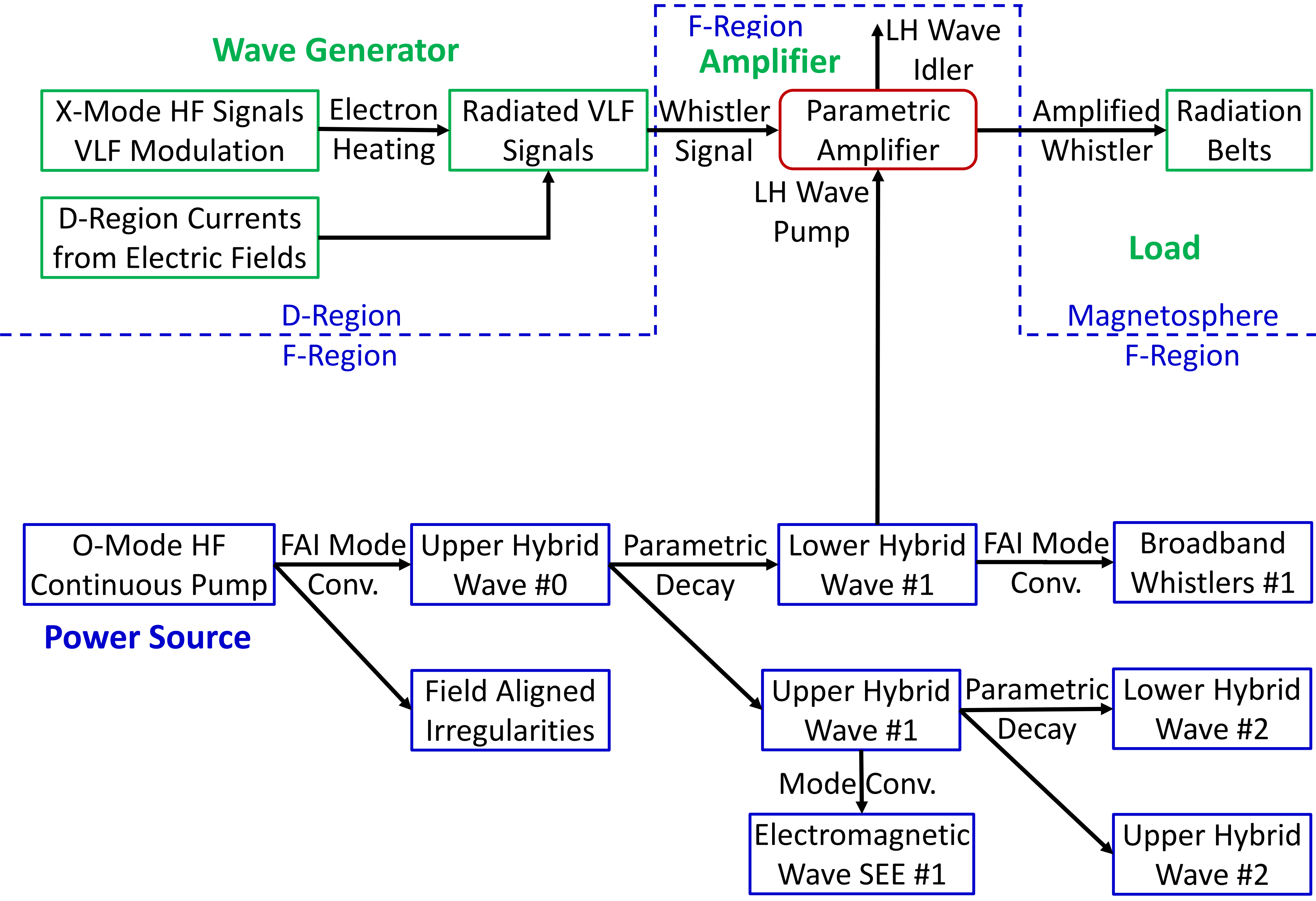
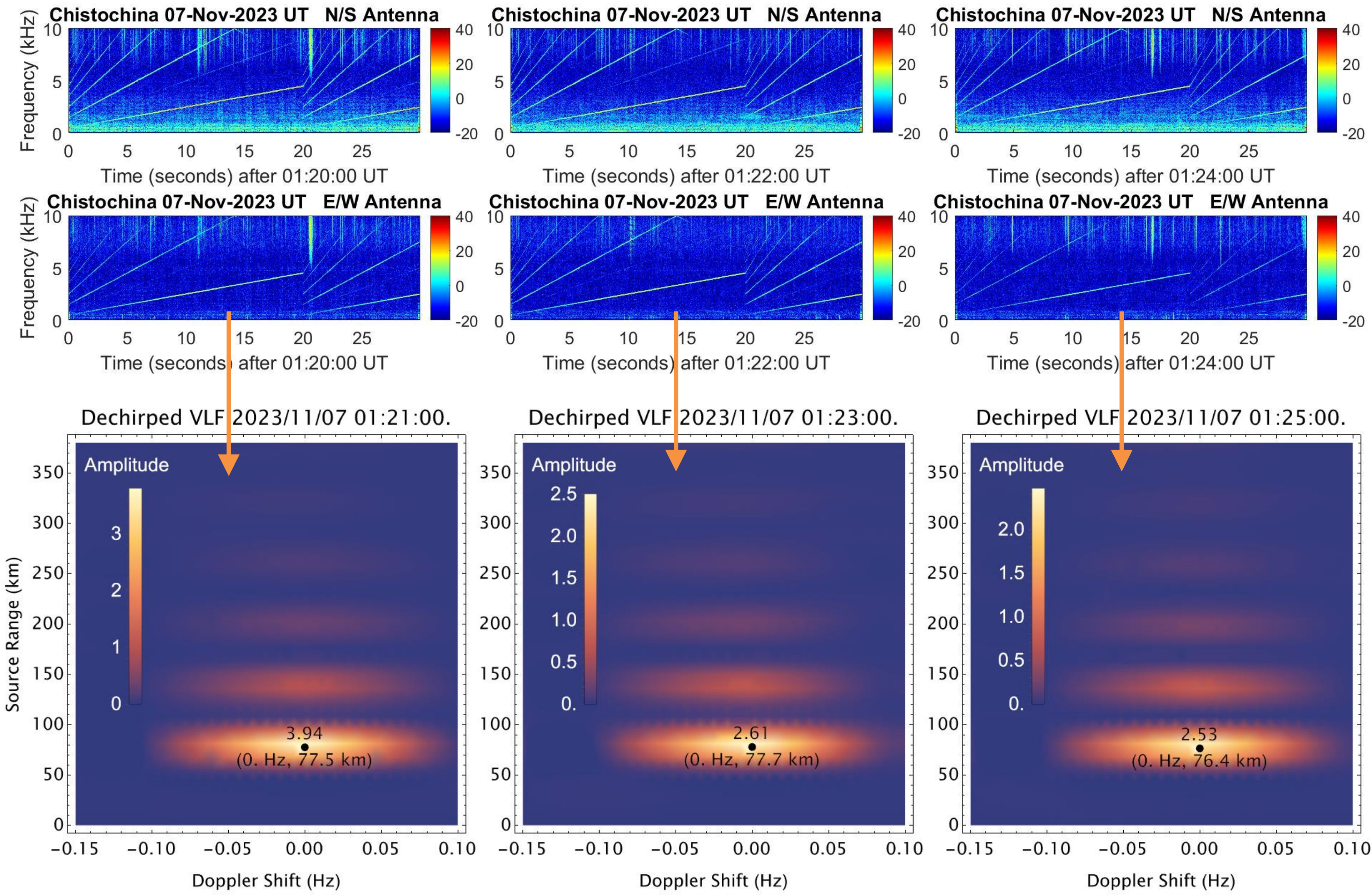


Range Doppler Processing of VLF Linear Chirps from HAARP

VLF Amplitude, Electrojet Altitude and Doppler Motion



HF Transmissions of 3.25 MHz X-Mode with VLF Chirps
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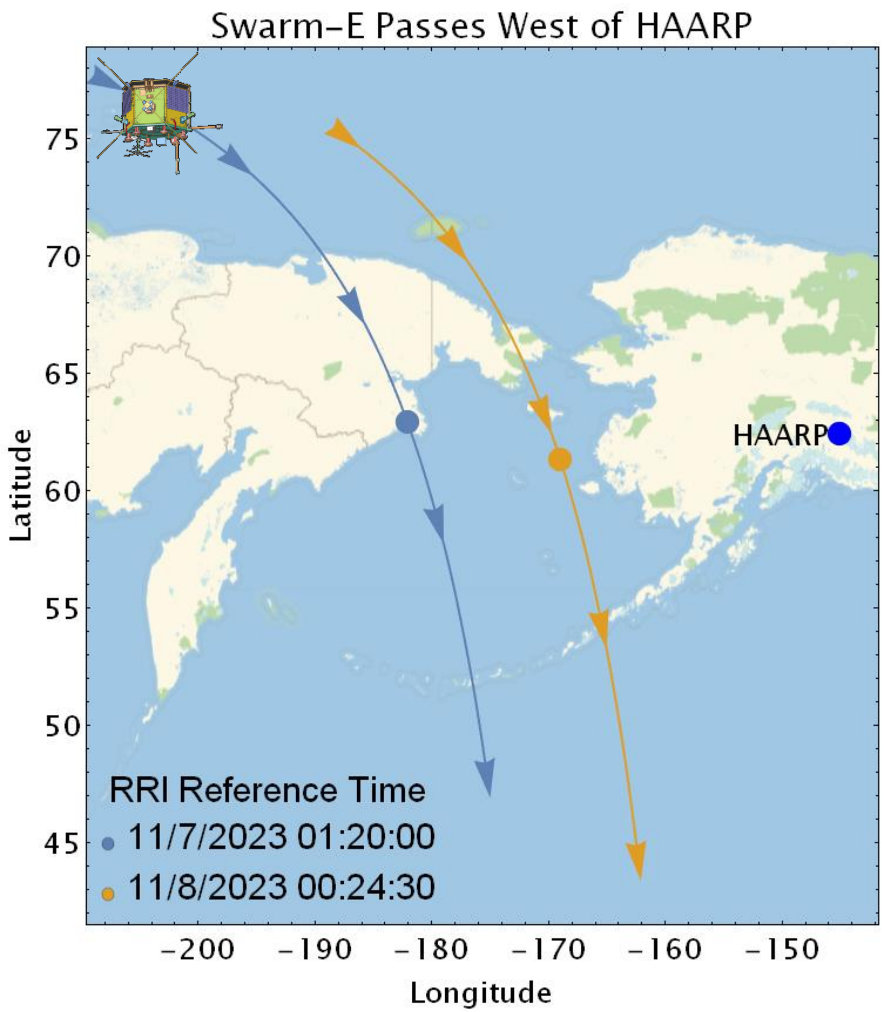

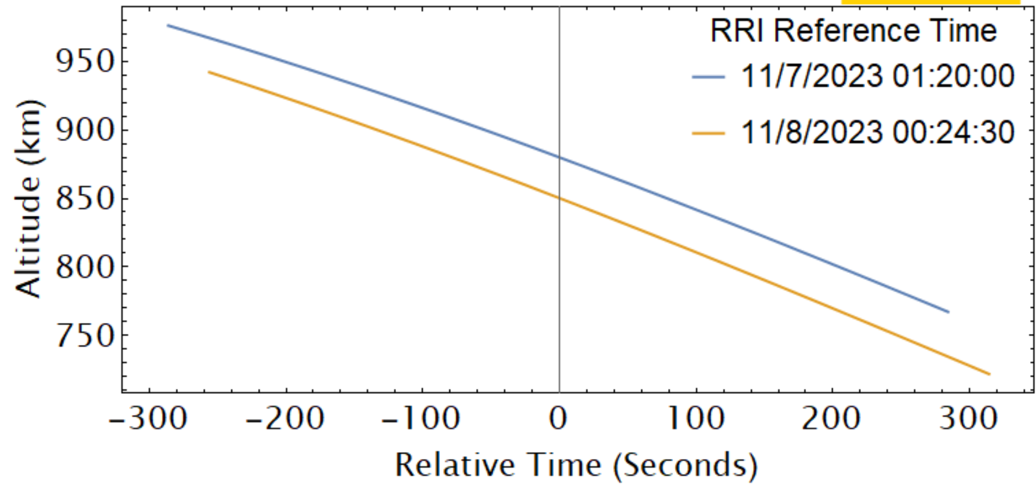

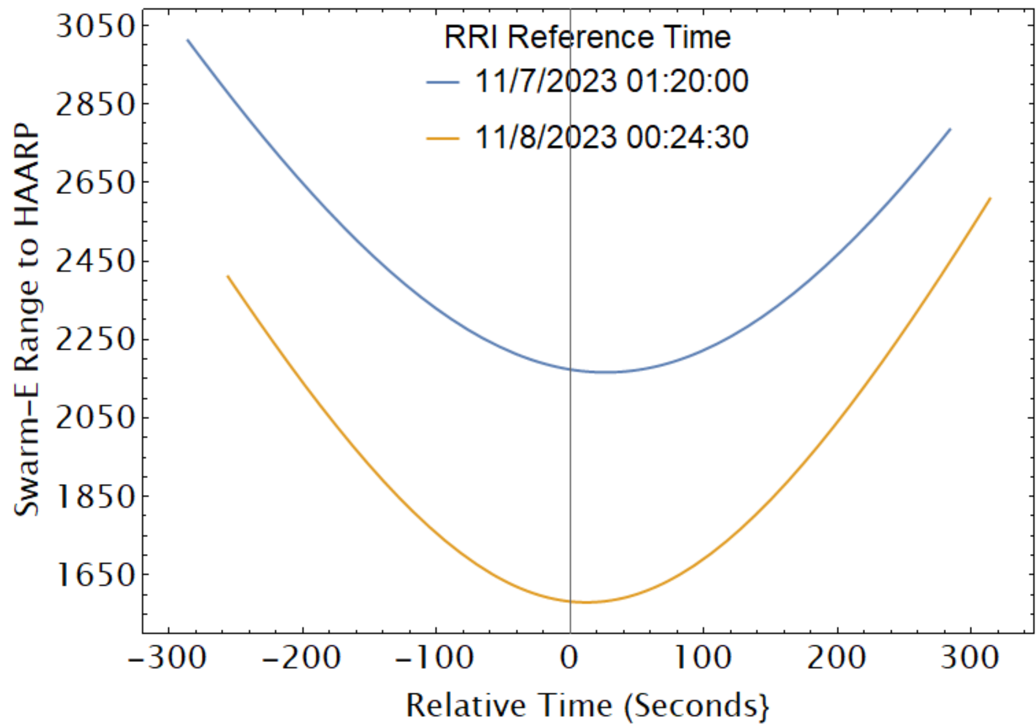

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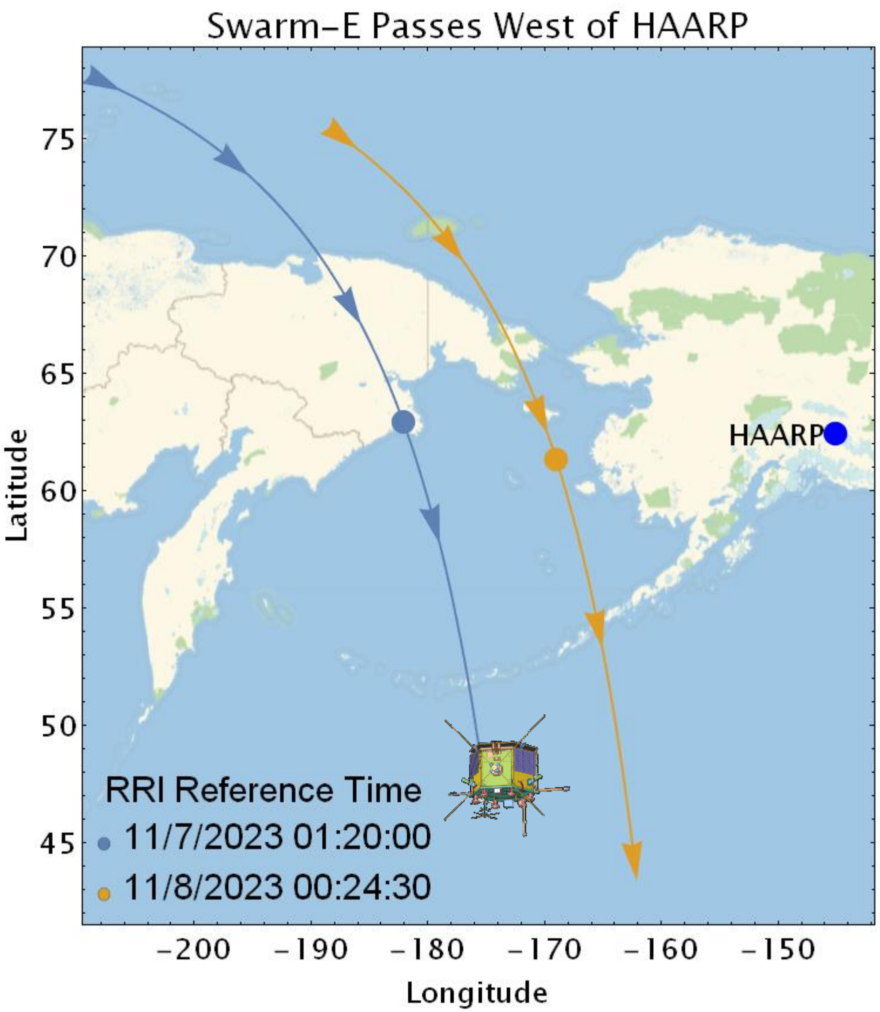
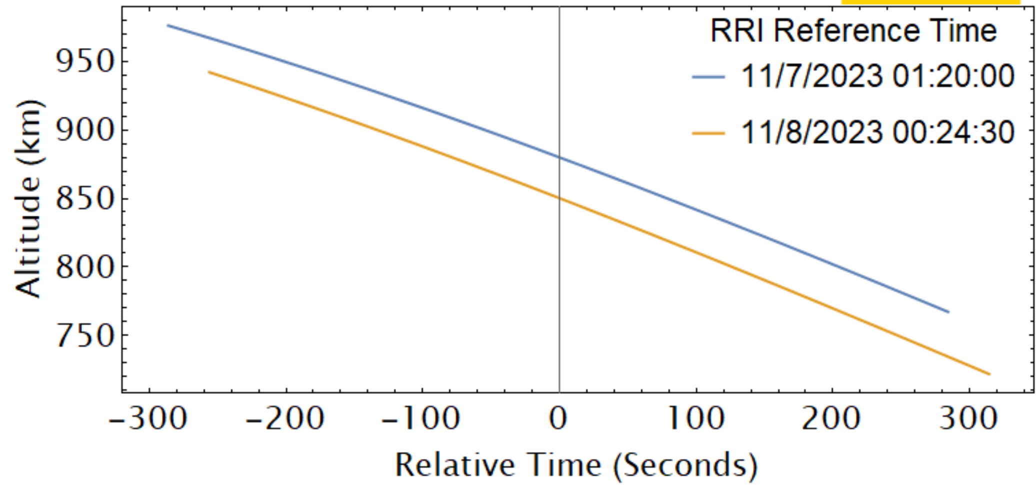
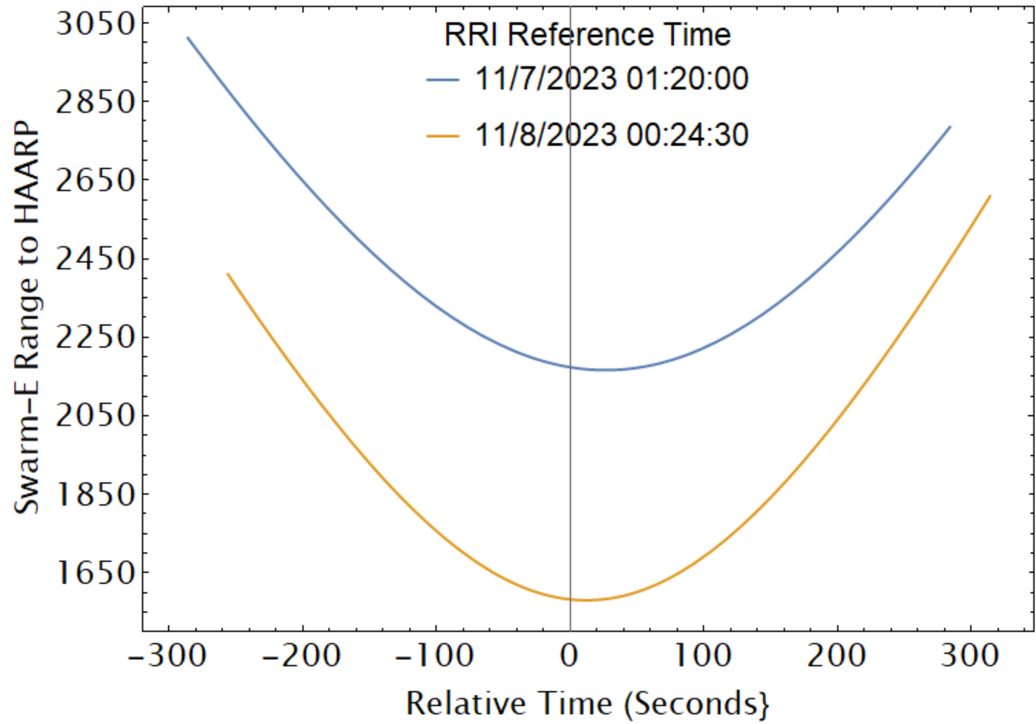
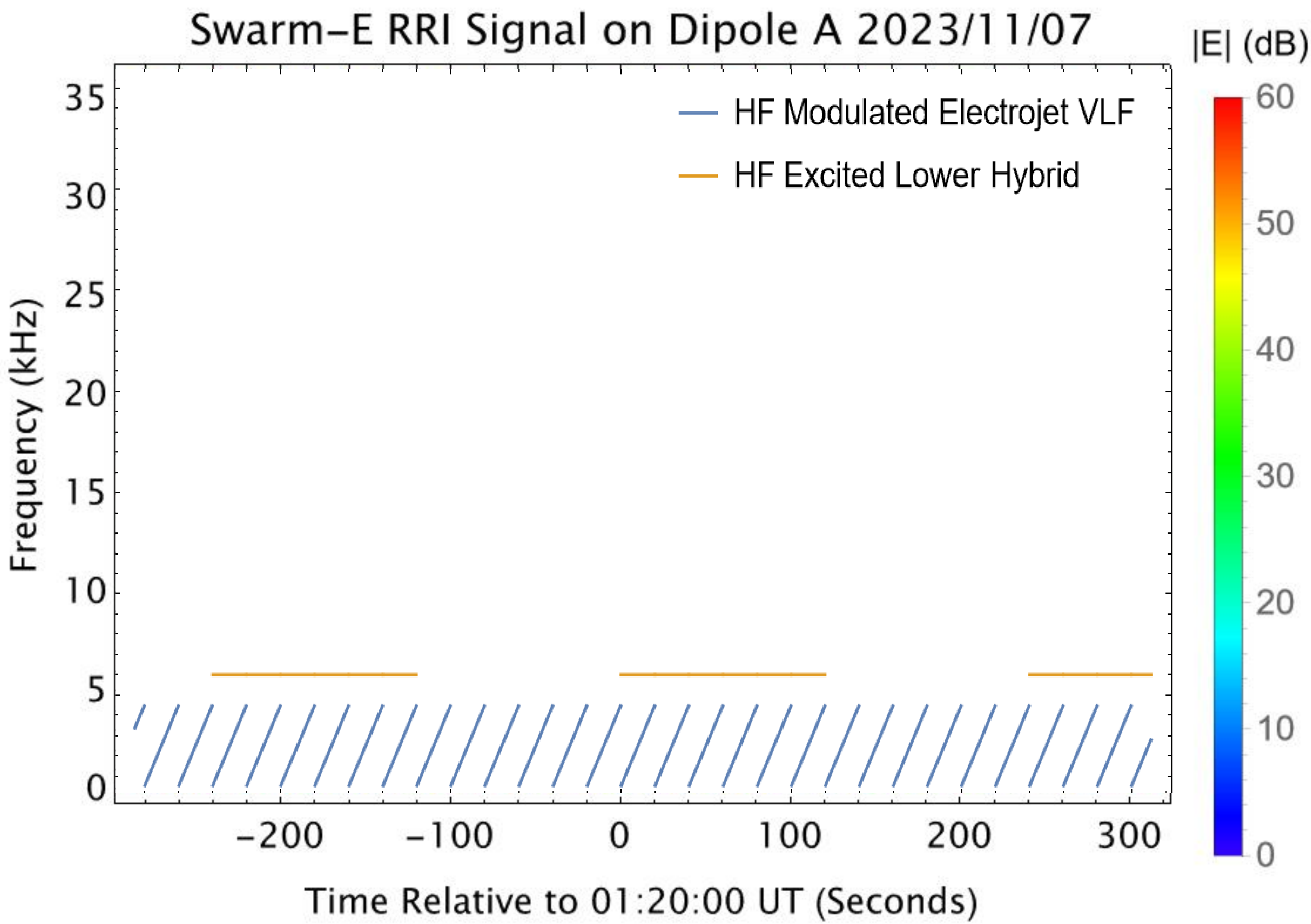
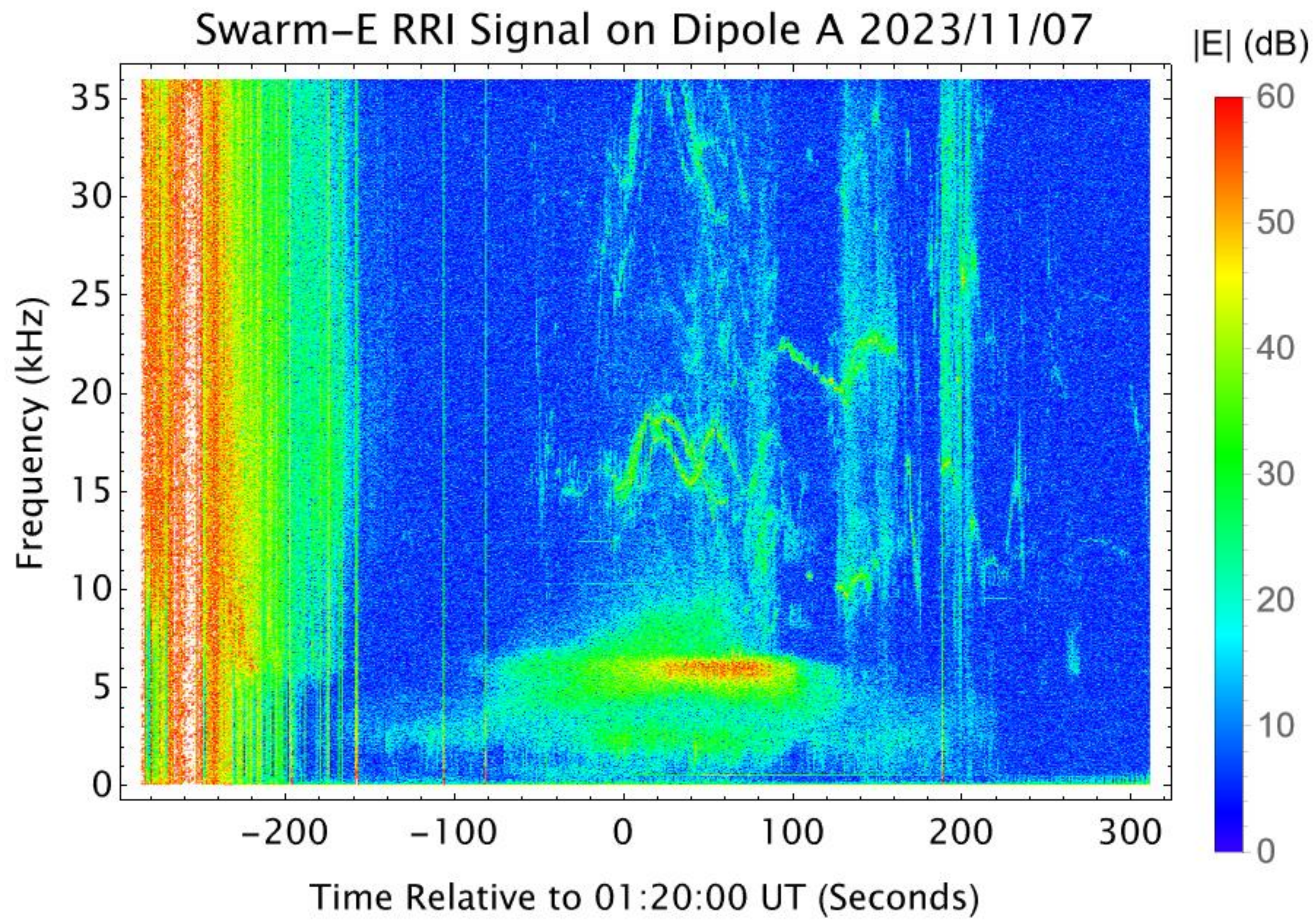




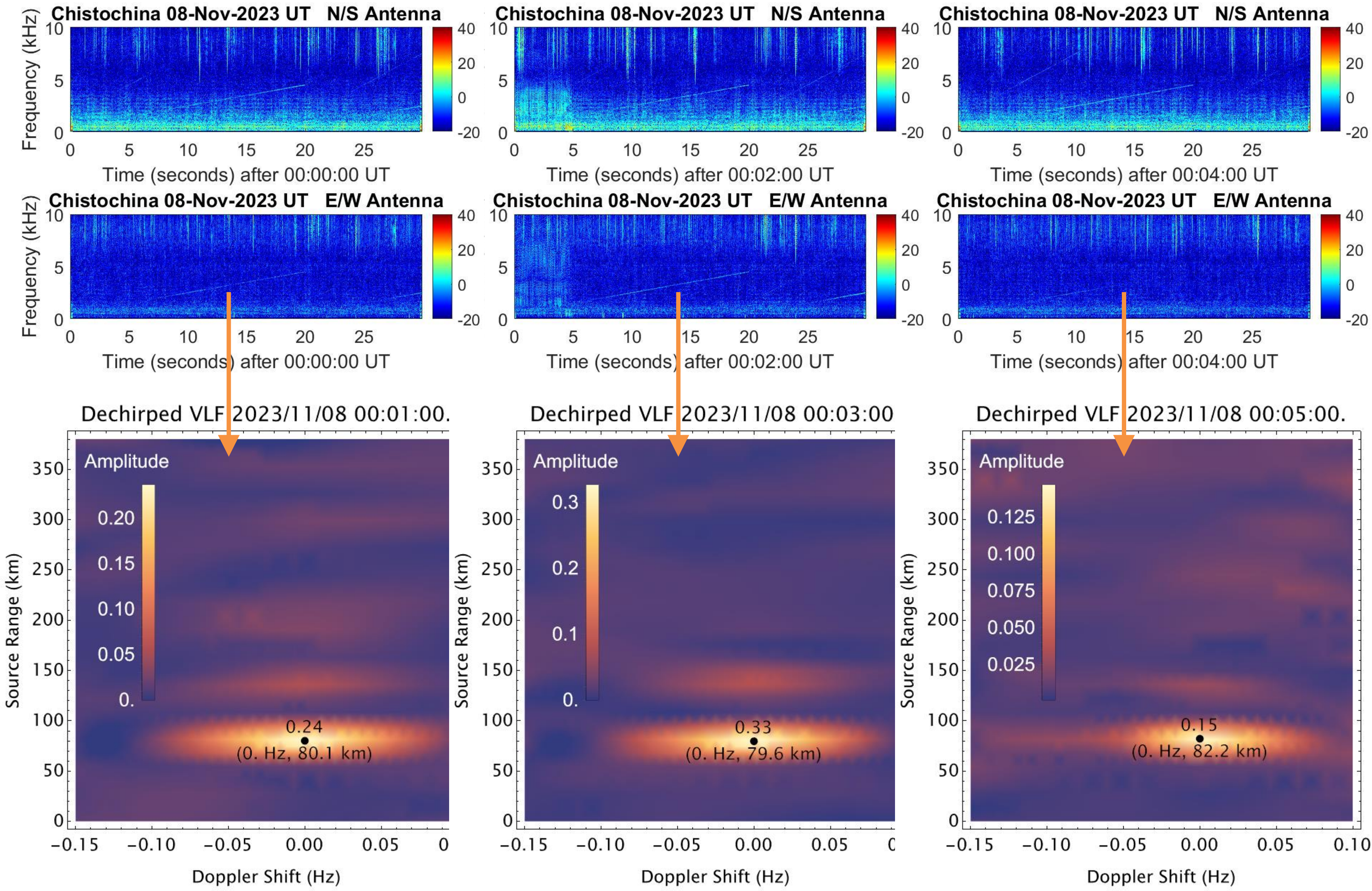




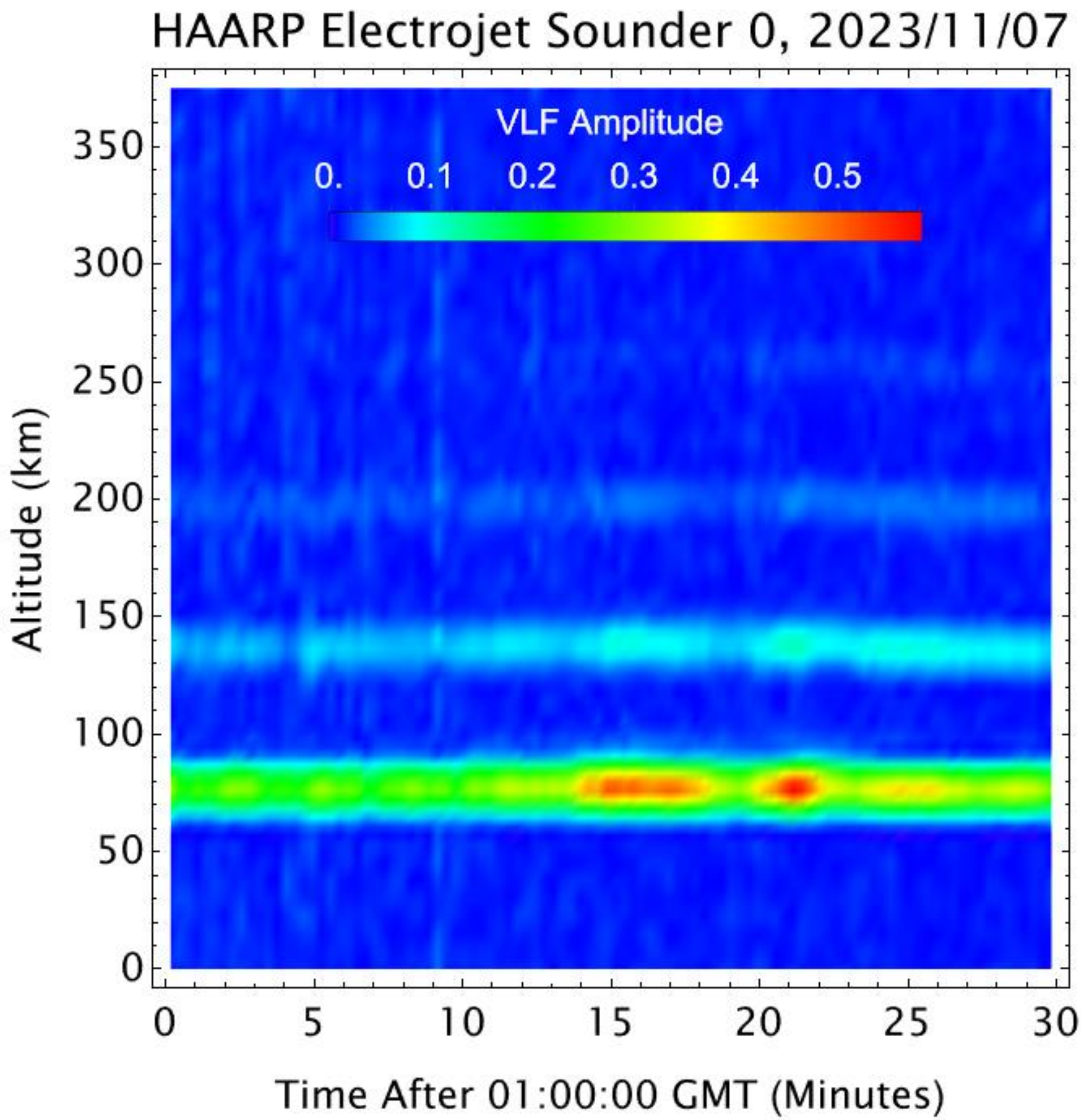
Swarm-E RRI Signal on Dipole A 2023/11/07
HF Modulated Electrojet VLF
HF Excited Lower Hybrid
Frequency (kHz)
35
30
25
20
15
10
5
0
-200
-100
0
100
200
300
Time Relative to 01:20:00 UT (Seconds)
|E| (dB)
60
50
40
30
20
10
0

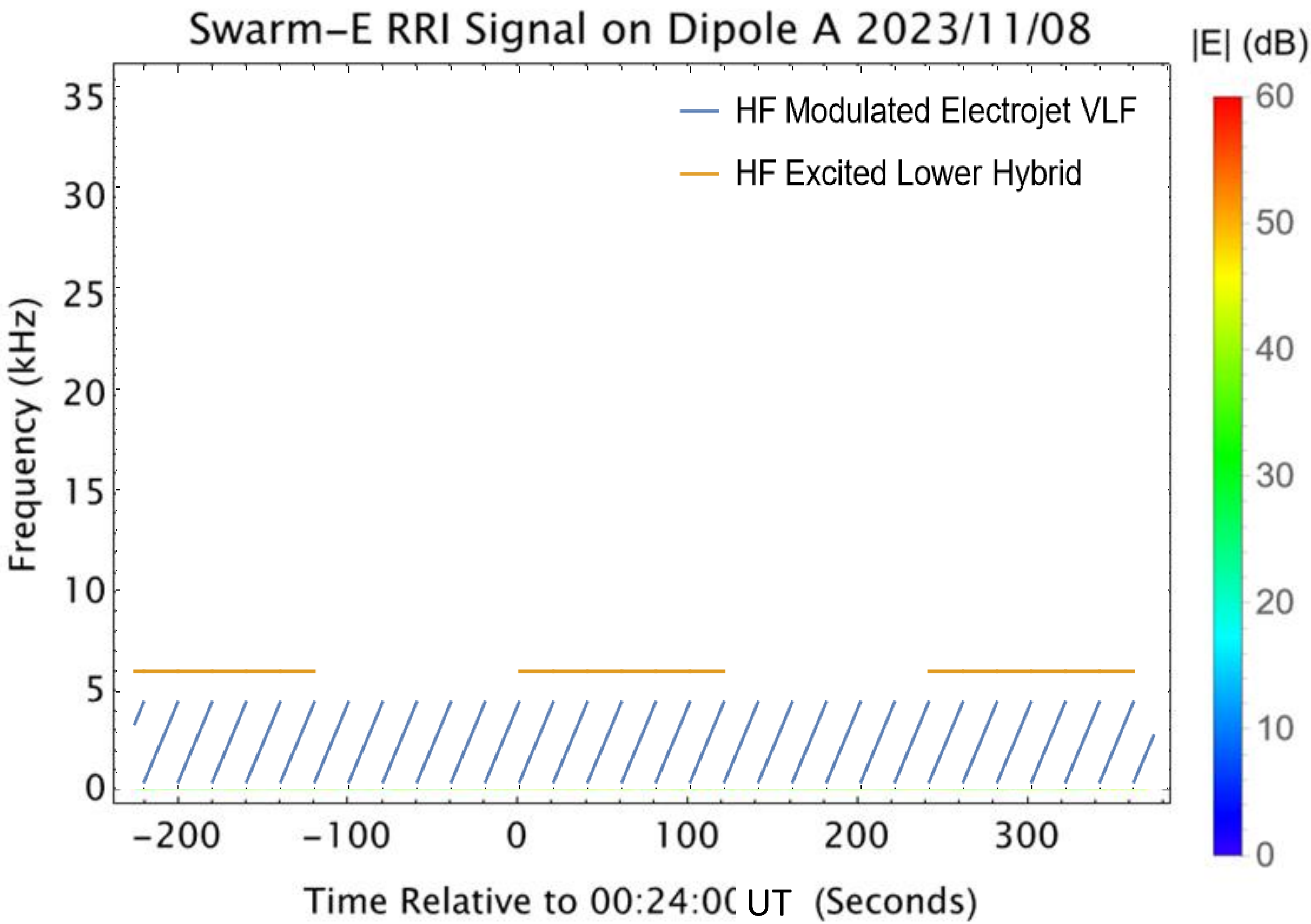

Swarm-E RRI Signal on Dipole A 2023/11/07
|E| (dB)
60
50
40
30
20
10
0
Frequency (kHz)
35
30
25
20
15
10
5
0
-200
-100
0
100
200
300
Time Relative to 01:20:00 UT (Seconds)

HF Transmissions of 3.25 MHz X-Mode with VLF Chirps
12 kHz Spectra and Chirp Compression Correspondences

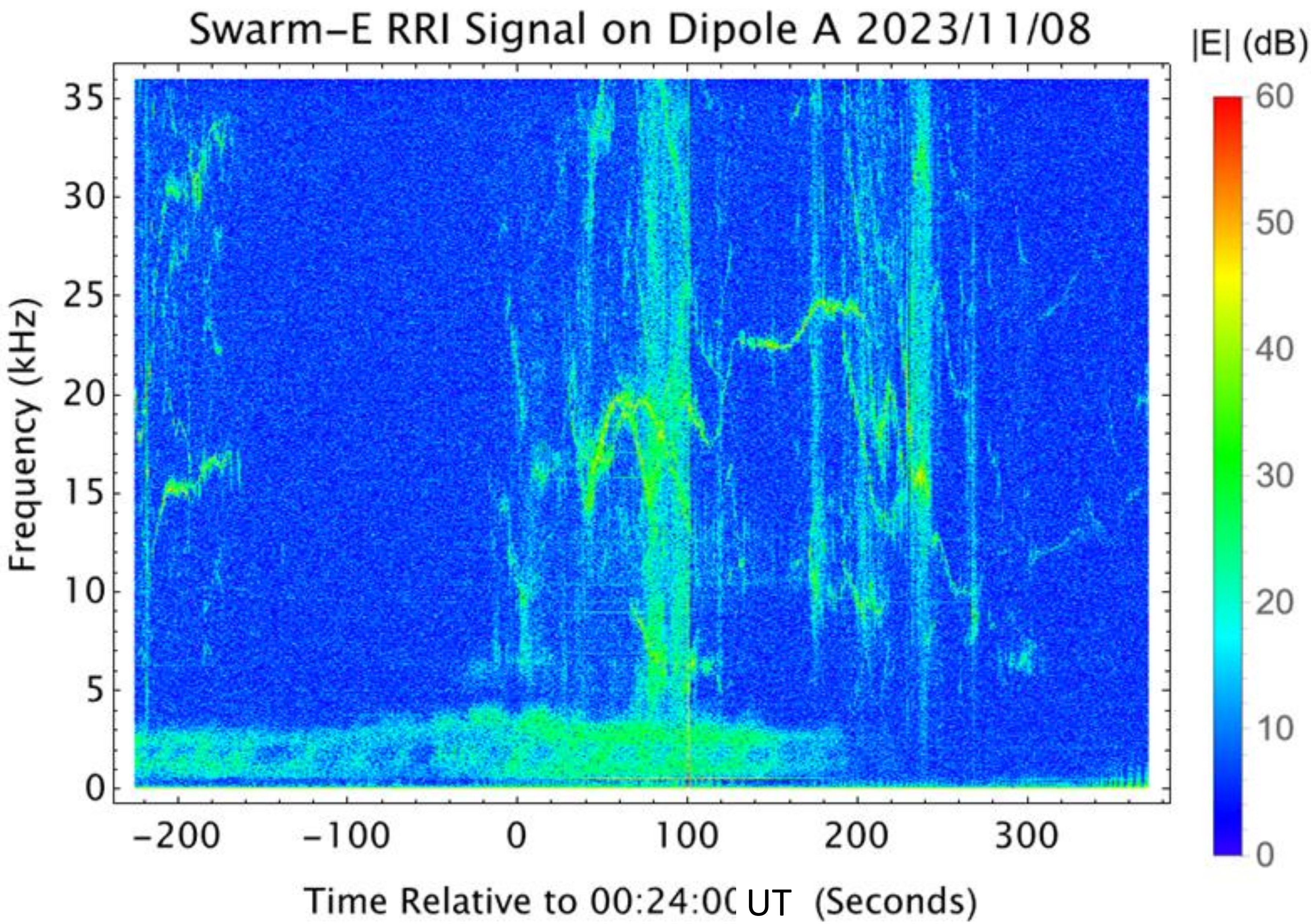


VLF Echo Profiles with 1.5 to 13.5 kHz Chirps for a 7.5 km Spatial Image from a Strong Electrojet





Swarm-E RRI Signal on Dipole A 2023/11/08
|E| (dB)
60
50
40
30
20
10
0
HF Modulated Electrojet VLF
HF Excited Lower Hybrid
Frequency (kHz)
35
30
25
20
15
10
5
0
-200
-100
0
100
200
300
Time Relative to 00:24:0(UT (Seconds)

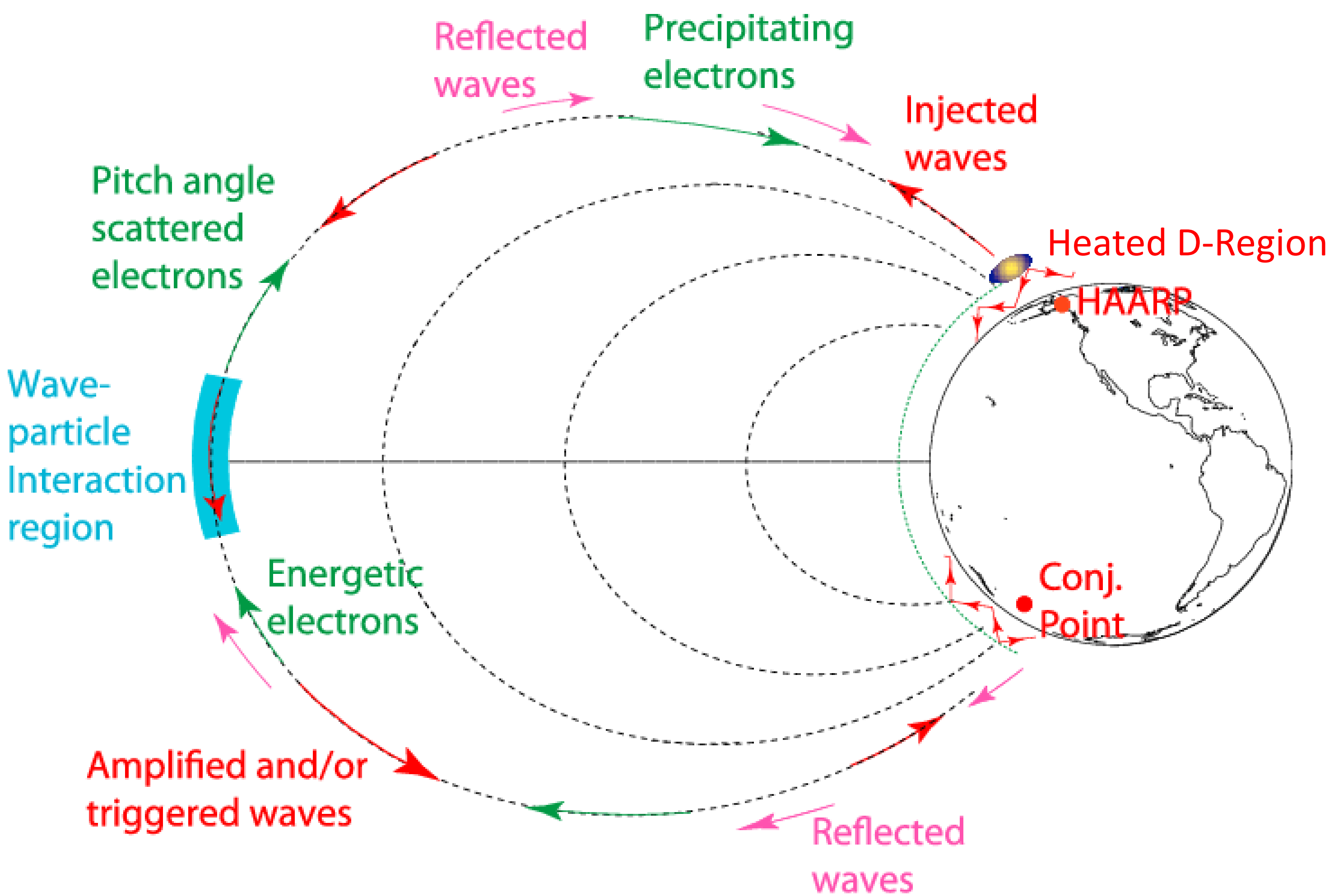


Swarm−E RRI Signal on Dipole A 2023/11/08
|E| (dB)
60
50
40
30
20
10
0
Frequency (kHz)
35
30
25
20
15
10
5
0
−200
−100
0
100
200
300
Time Relative to 00:24:0(UT (Seconds)

Strong VLF Wave Generation Techniques for Space

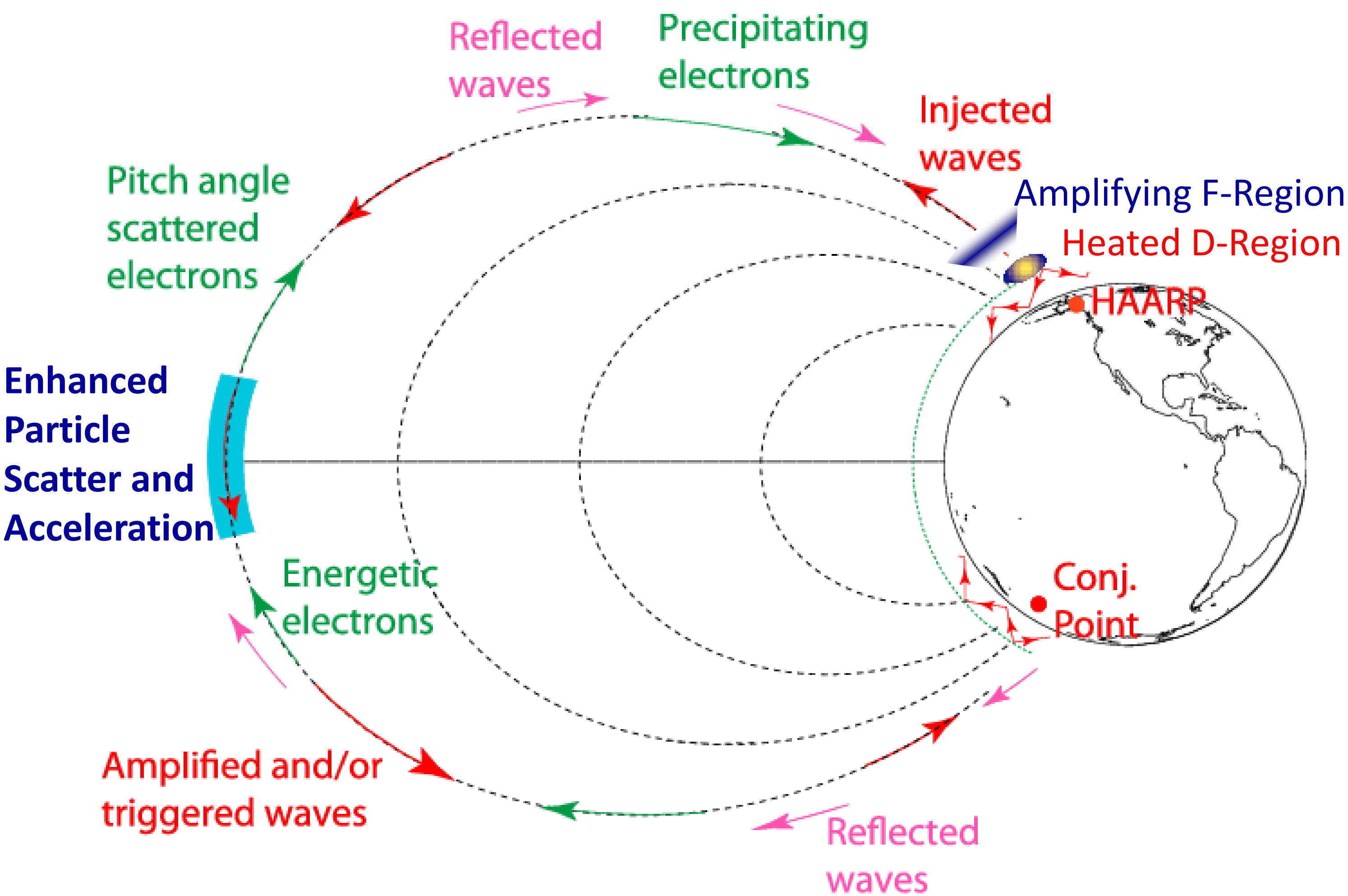
High Power HF Amplification of VLF from Electrojet Modulation

Figure Adapted from Gołkowski, M., et al. J. Geophys. Res., 115, 2010



High Power HF Amplification of VLF from Electrojet Modulation

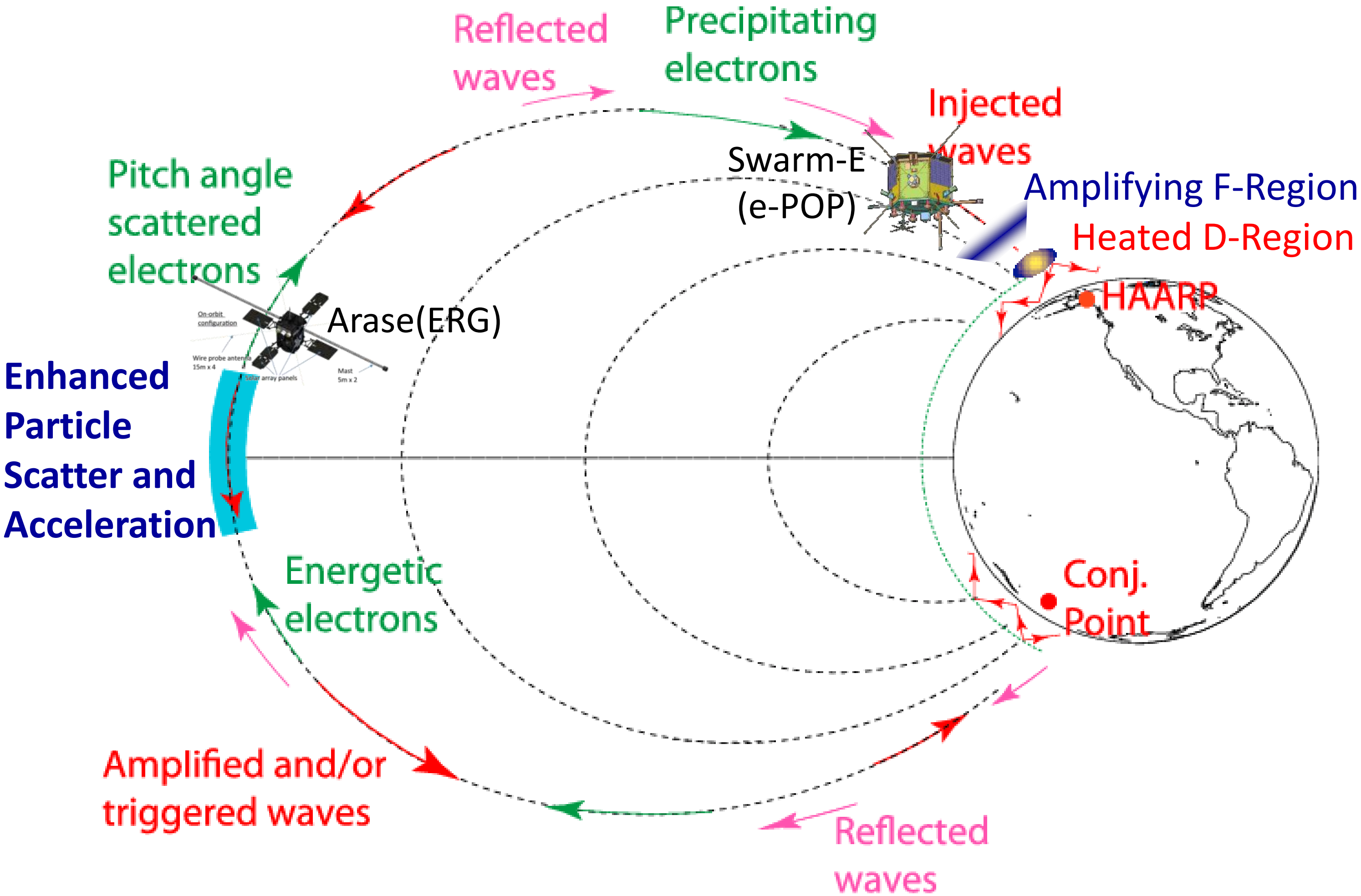
Figure Adapted from Gołkowski, M., et al. J. Geophys. Res., 115, 2010



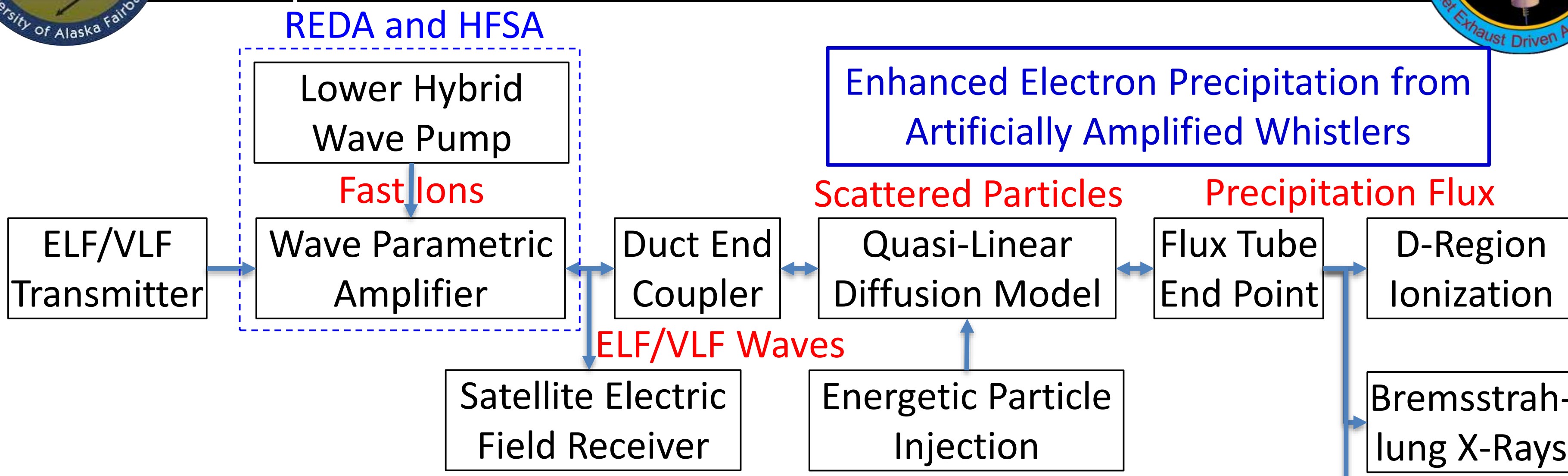
Strong VLF Wave Generation Techniques for Space

High Power HF Amplification of VLF from Electrojet Modulation

Figure Adapted from Gołkowski, M., et al. J. Geophys. Res., 115, 2010



Summary of the Physics and Engineering Needed for Amplified Whistler Waves to Remove Radiation Belt Electrons



- Radiation Belt Electrons are a Hazard to Satellite Electronics
- The Fluxes of Satellite-Killing Electrons Can be Reduced by Amplification of Very Low-Frequency (VLF) Whistler Waves in the F-Region Ionosphere Before They Propagate to the Magnetosphere
- The Rocket Exhaust Driven Amplification (REDA) and High Frequency Stimulated Amplification (HFSA) technique **AMPLIFY** whistler waves from existing ground transmitters rather than trying to **GENERATE** large amplitude whistler waves from ground- or space-based systems
- Both Methods have Been Demonstrated in the Geospace Environment