Doppler perturbations of satellite observations by VHF ST radar

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Why use VHF radar for satellite observations?

The number of satellites in Low Earth Orbit (LEO) is exponentially increasing.

Proposed corporate mega constellations mean that there may be an additional 100,000 satellites in LEO, compared to 4871 in 2021.

Increased the risk of Kessler Syndrome events.

VHF radar provides a low-cost alternative to traditional satellite detection methods.

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Buckland Park Stratosphere Troposphere (BPST) VHF radar.

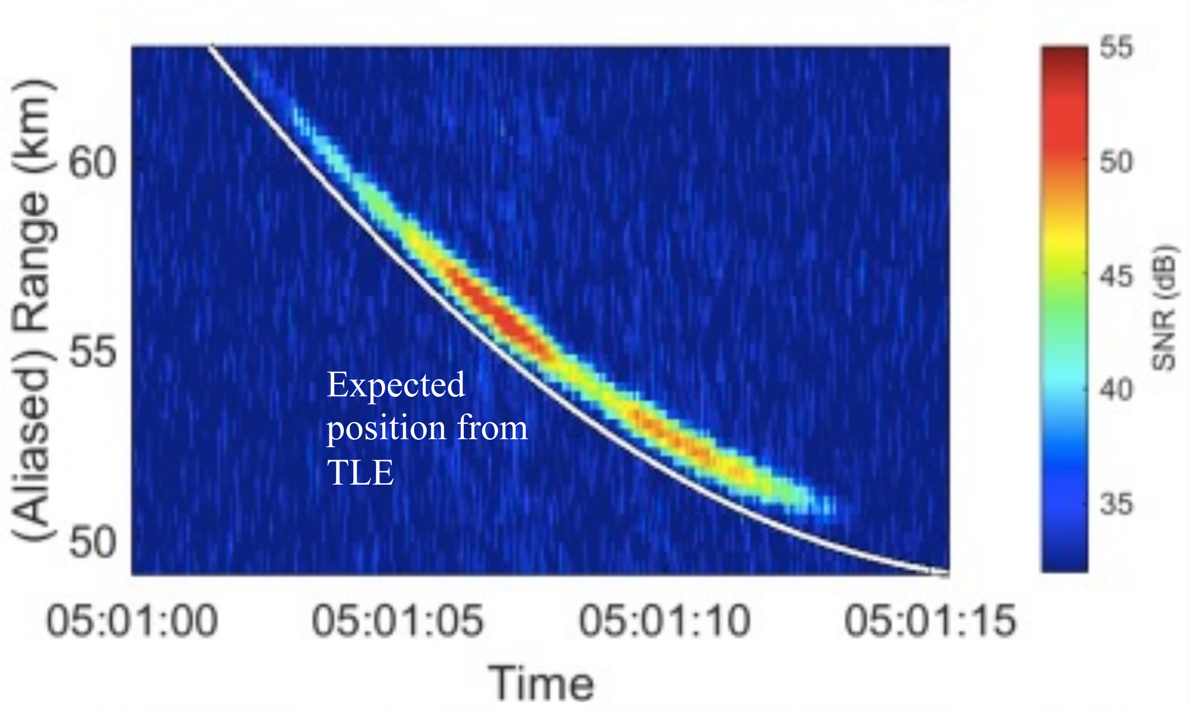
Located ~35 km north of Adelaide.

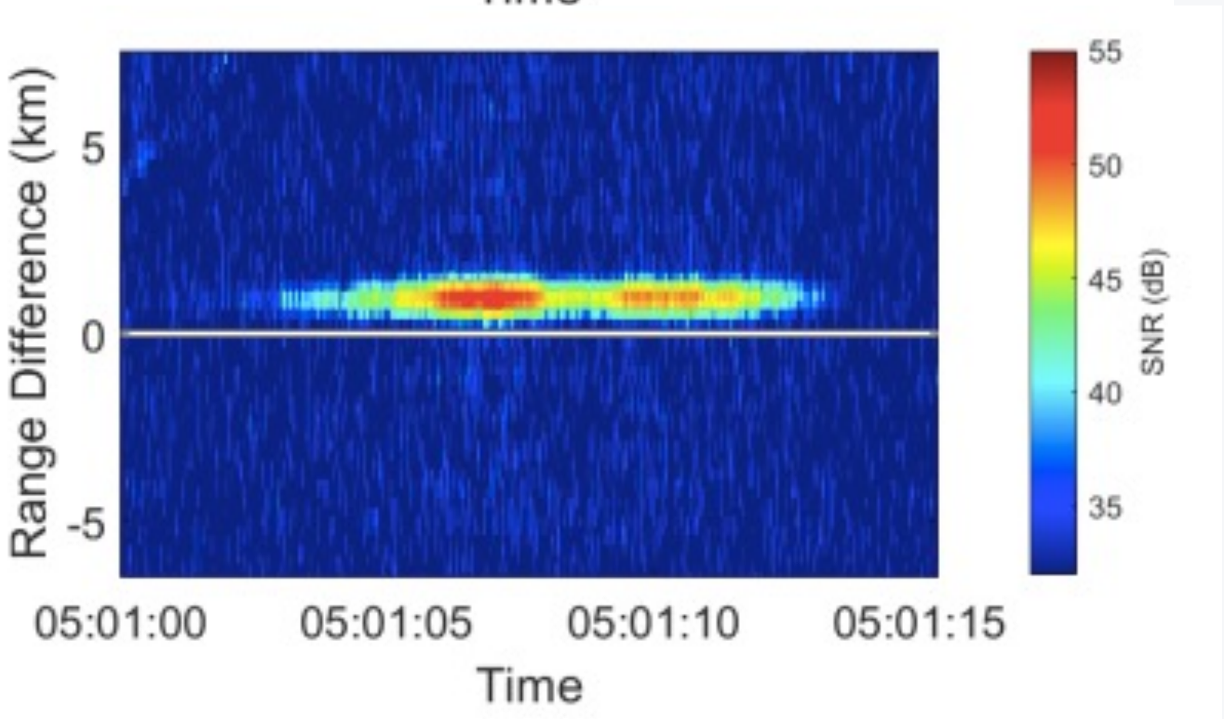
Operates at 55 MHz at 40 kW.

12x12 array of Yagi antennas

- -5 beam directions with 6° beam width:
  - - Vertical
  - - NESW (15° off Zenith)

Can detect objects with a radar cross section of $1m^2$ at a range of 1000





Courtesy of: Heading et. Al (2022)

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Buckland Park Stratosphere Troposphere (BPST) VHF r

Located ~35

Operates at

12x12 array

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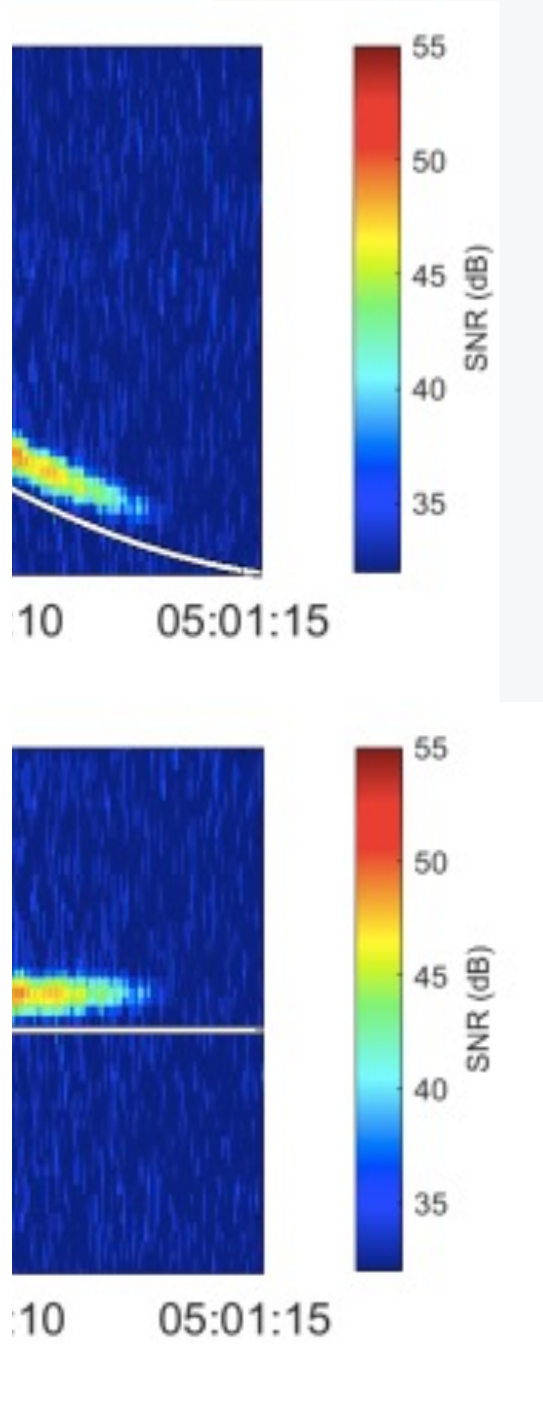
Can detect o



Courtesy of: Heading et. Al (2022)

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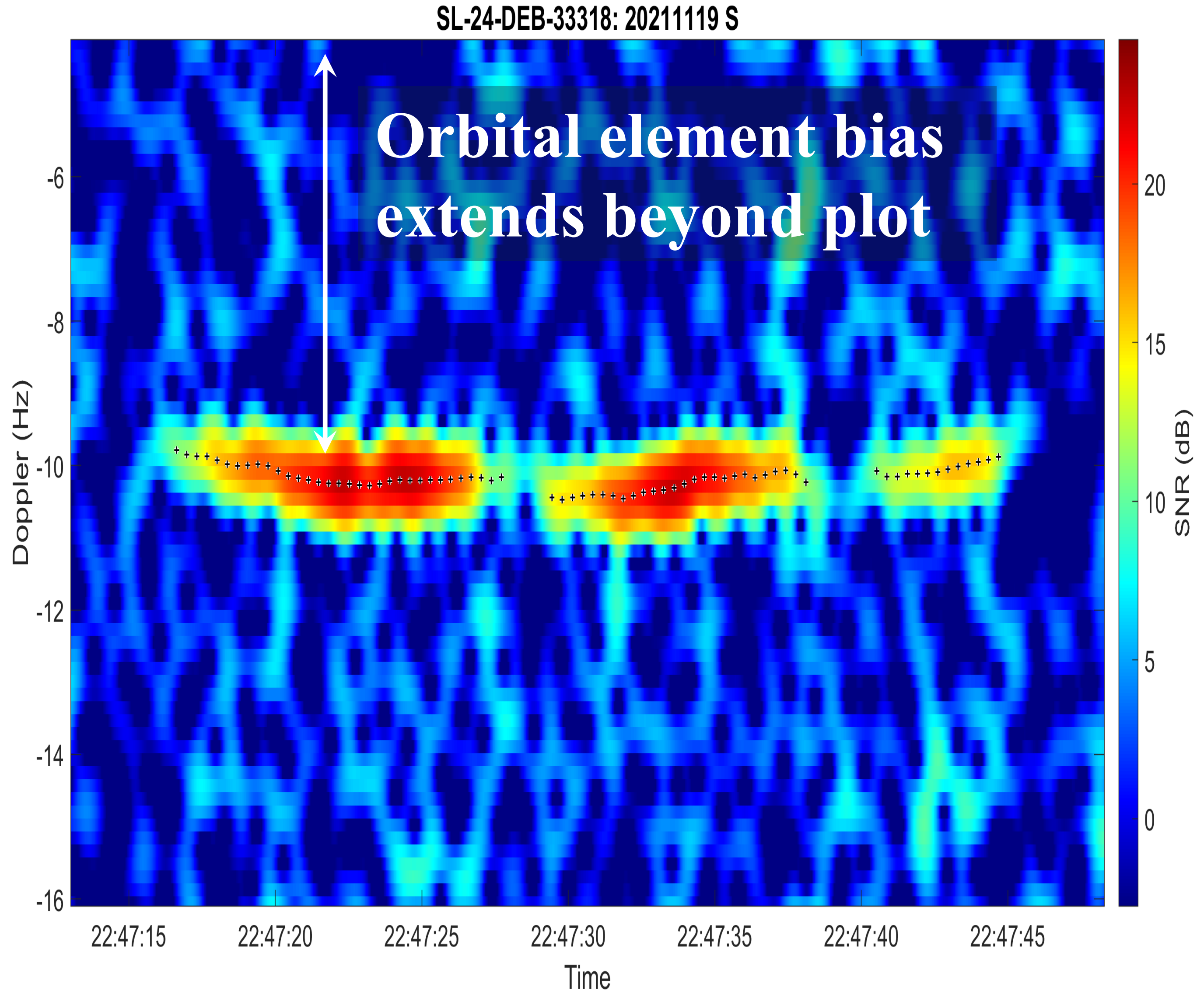
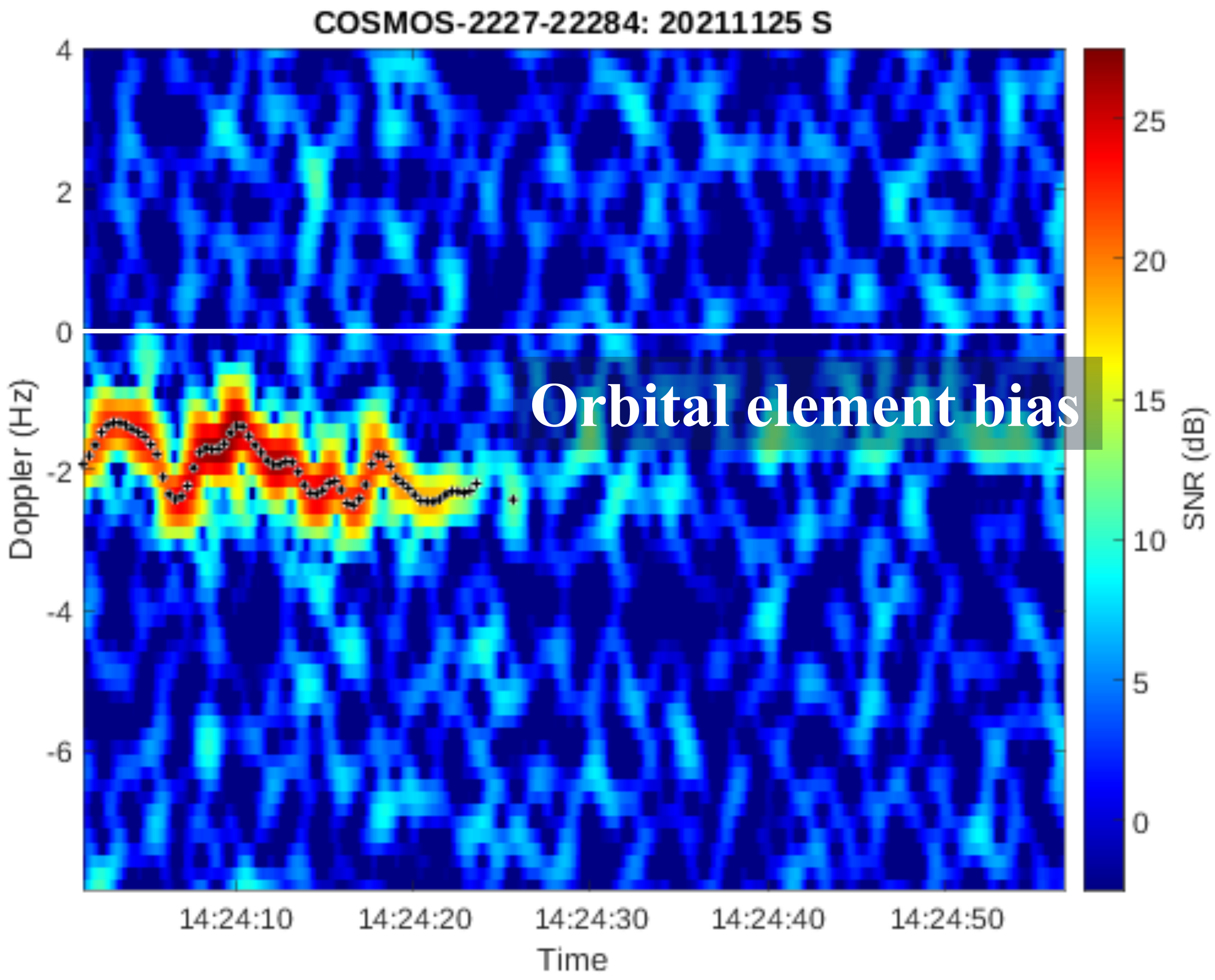
Doppler measurements from BPST





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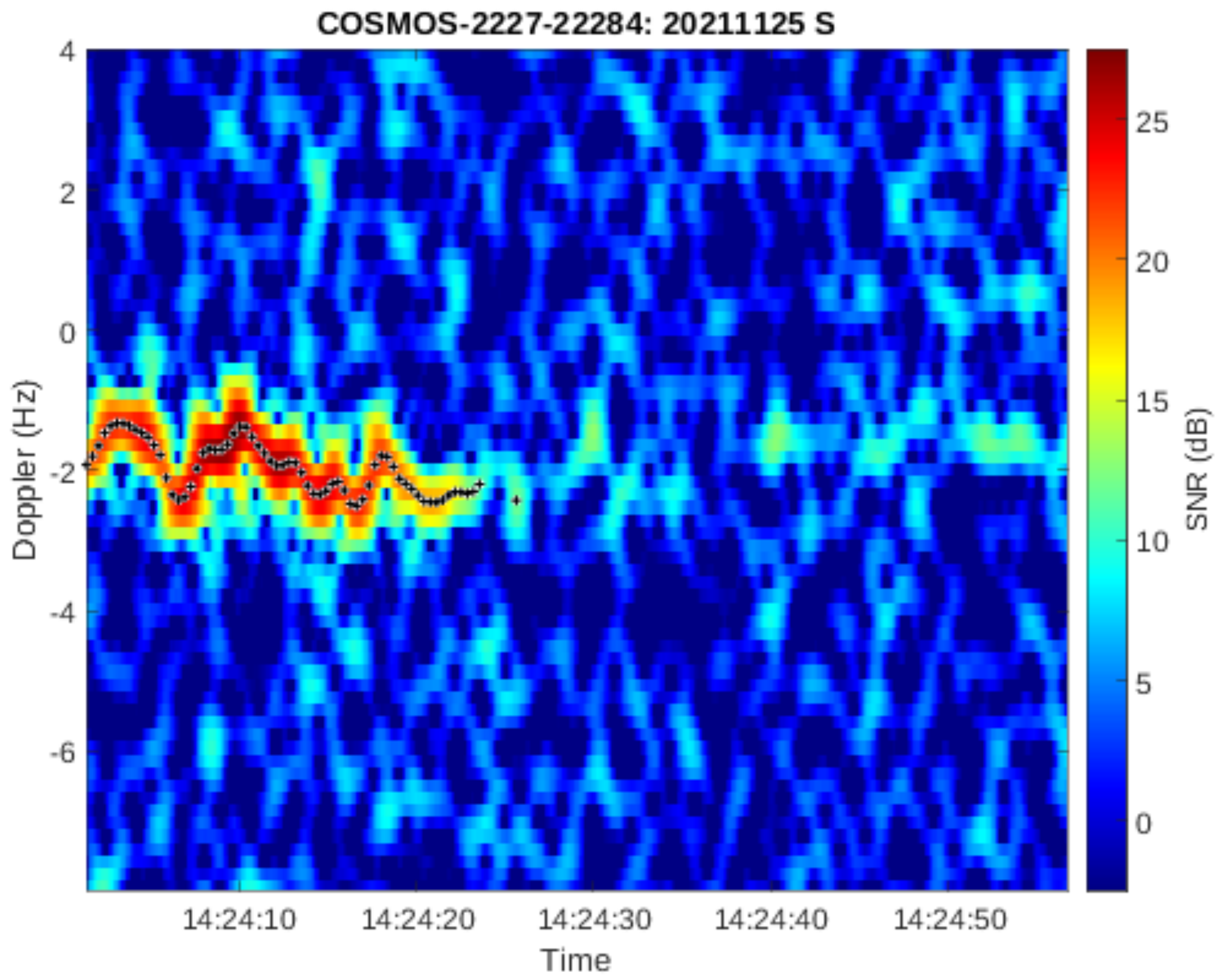
Potential causes for observed perturbations

Variation in Doppler due to translational motion has been mostly removed.

Our hypothesis is the Doppler variation is due to an ionospheric effect caused by the radio wave moving through areas of varying electron density.



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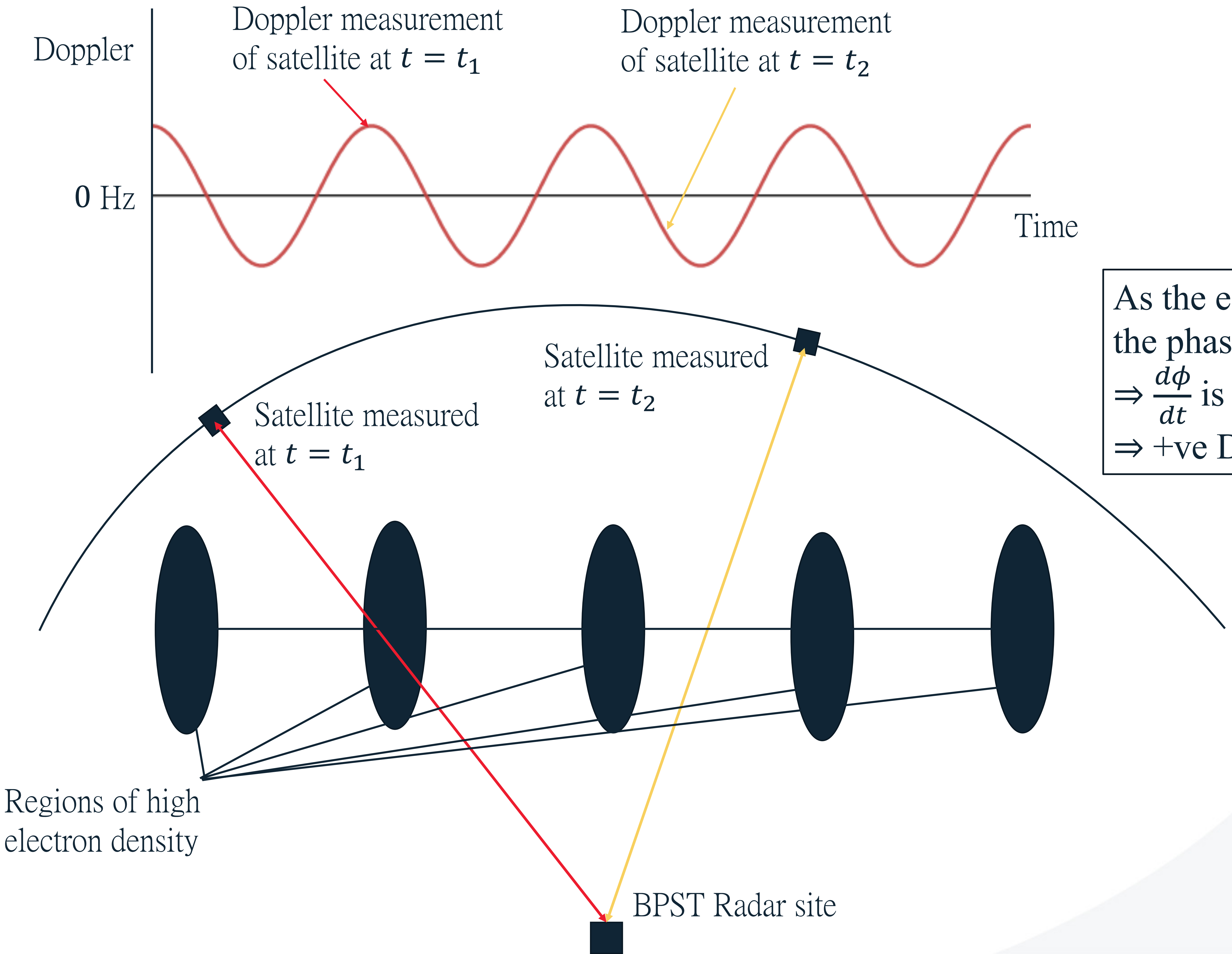

As the electron density increases the phase path decreases

$\Rightarrow \frac{d\phi}{dt}$ is negative

$\Rightarrow$ +ve Doppler shift

Potential causes for the ionospheric disturbances

- Atmospheric Gravity Wave (AGW) generated ionospheric disturbances.

  - AGWs are disturbances in the neutral atmosphere, created by many sources.

- Plasma waves generated in the magnetosphere which propagate along geomagnetic field lines to the Earth.

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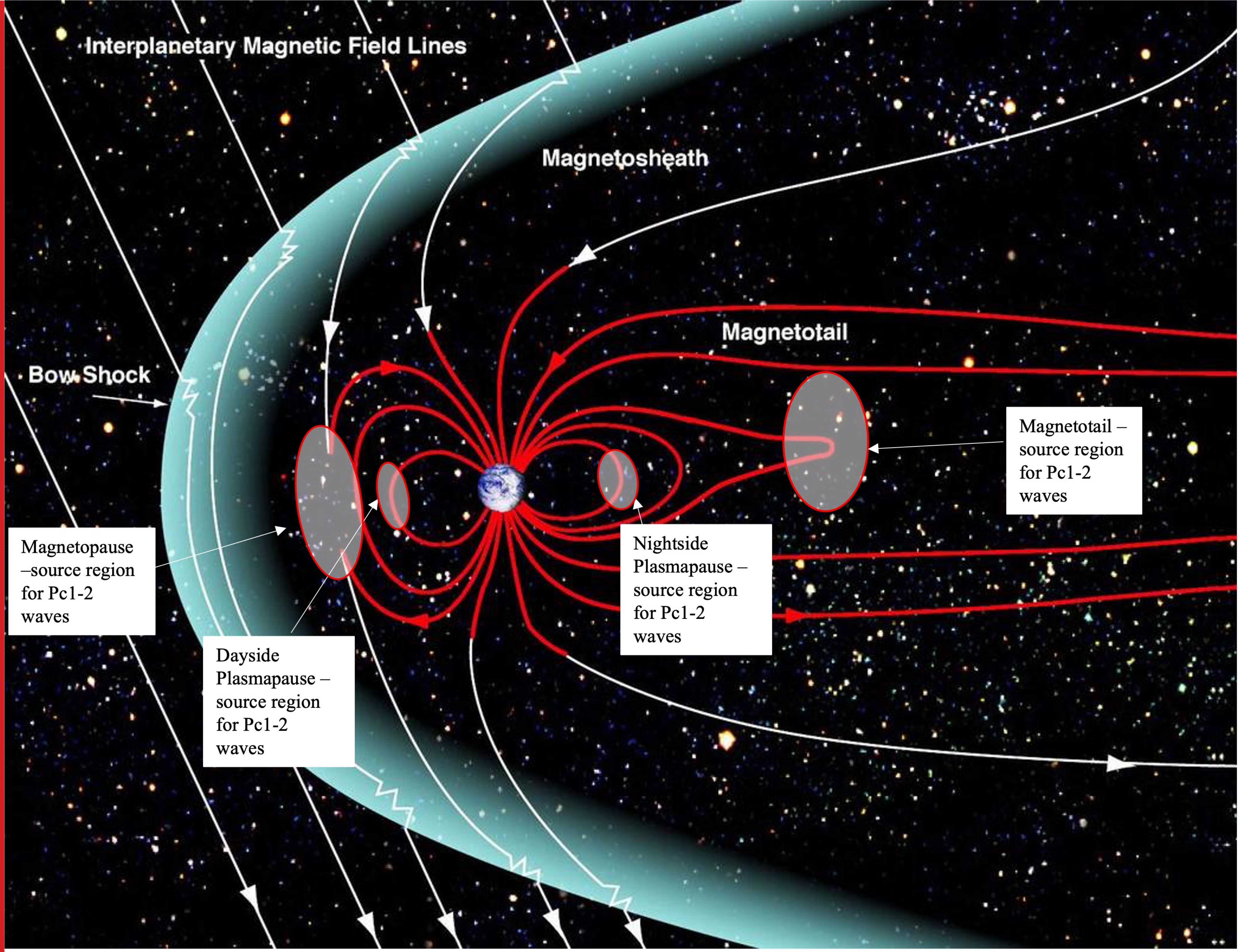
Plasma wave generation regions



Field line diagram after Zell, 2017

Four generation regions of interest:

Magnetopause – occurrence rate expect to peak at 10:00 and 14:00 MLT.

Magnetotail – occurrence rate expected to peak at 00:00 MLT.

Dayside plasmapause – occurrence rate expected to peak at 12:00 MLT.

Nightside plasmapause – occurrence rate expected to peak at 00:00 MLT.

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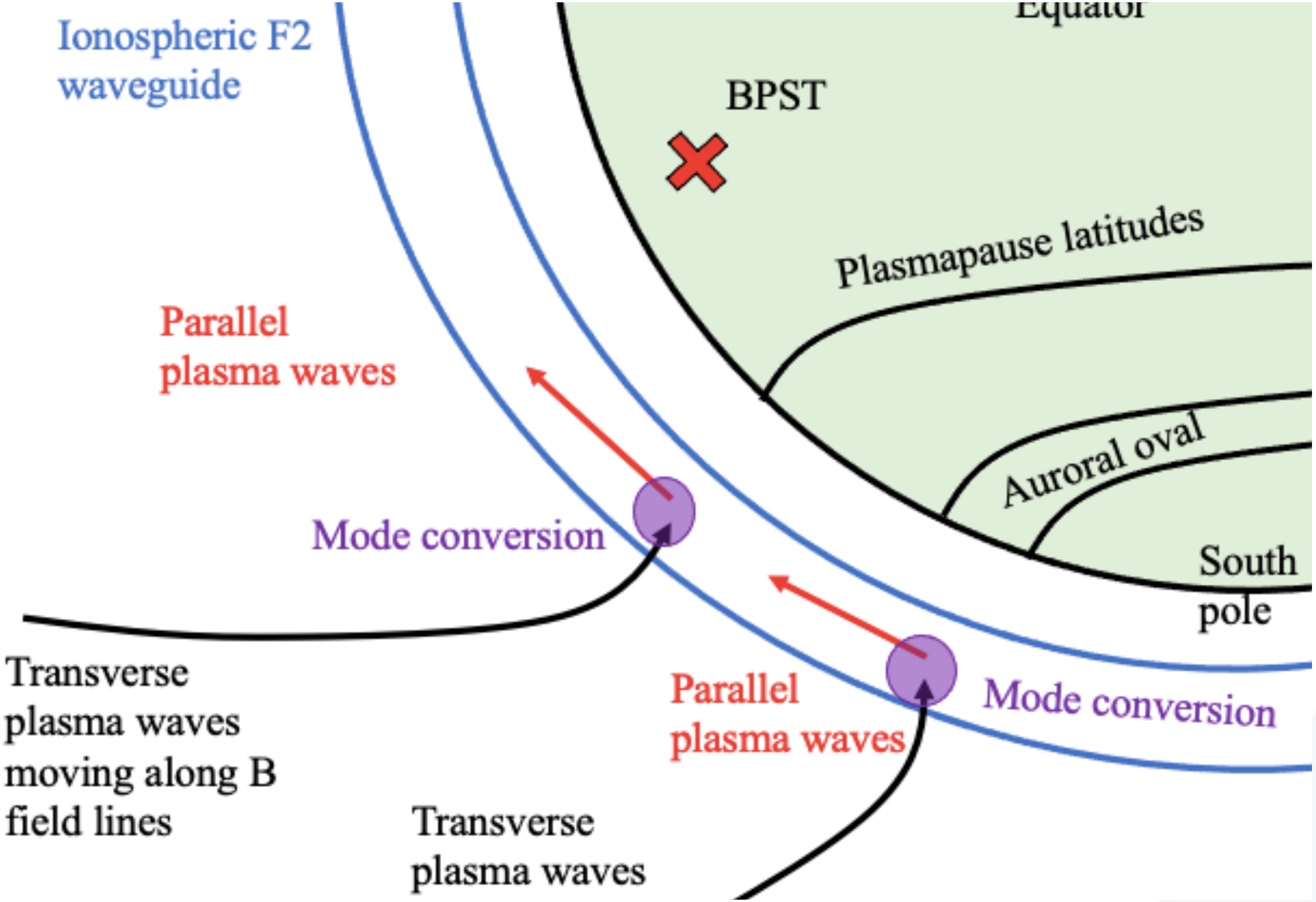
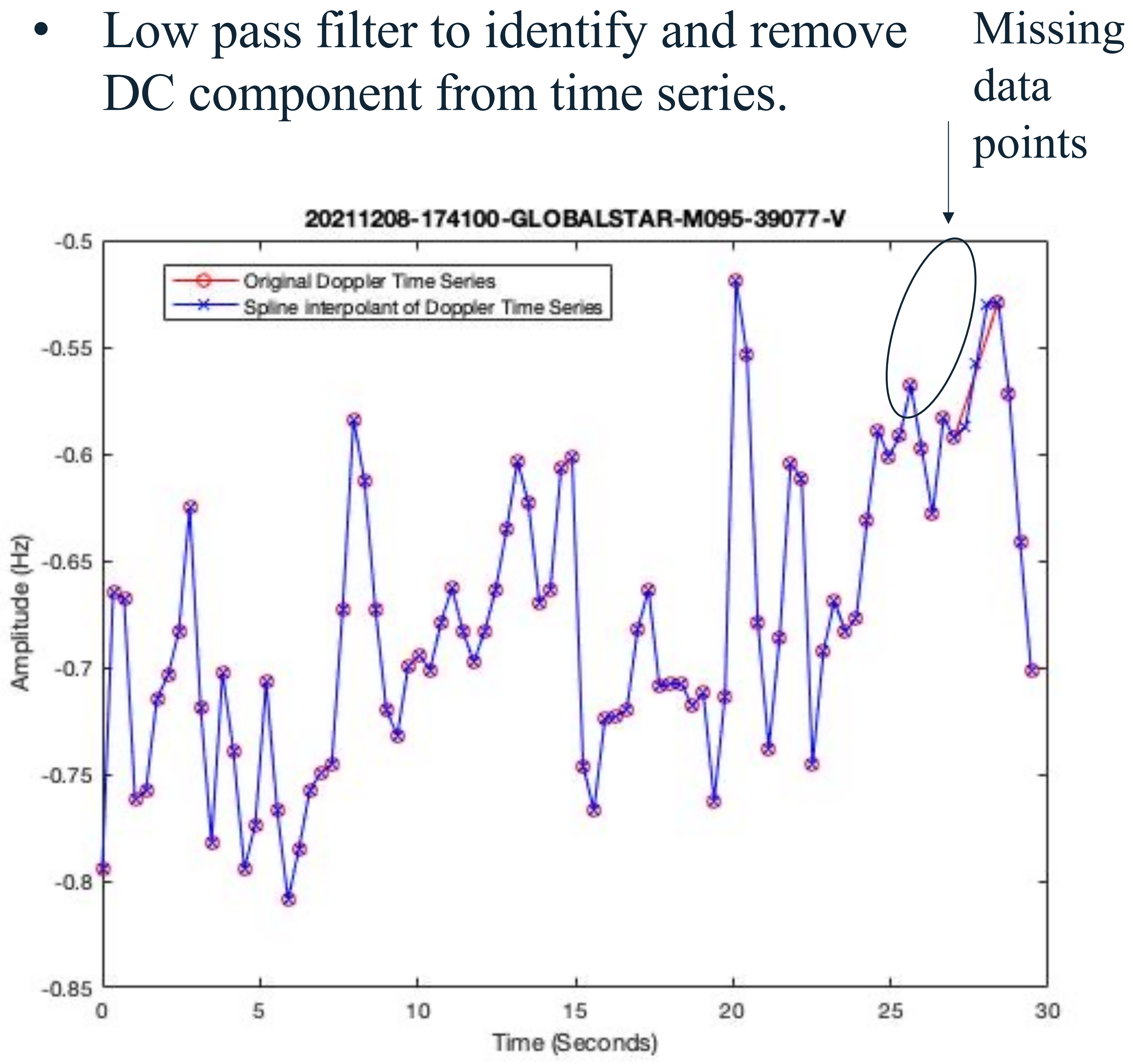


- The plasma waves propagate as transverse waves in the Pc1-2 frequency range until they reach the ionosphere.
- They then mode convert into compressional plasma waves moving in the ionosphere F2 waveguide.

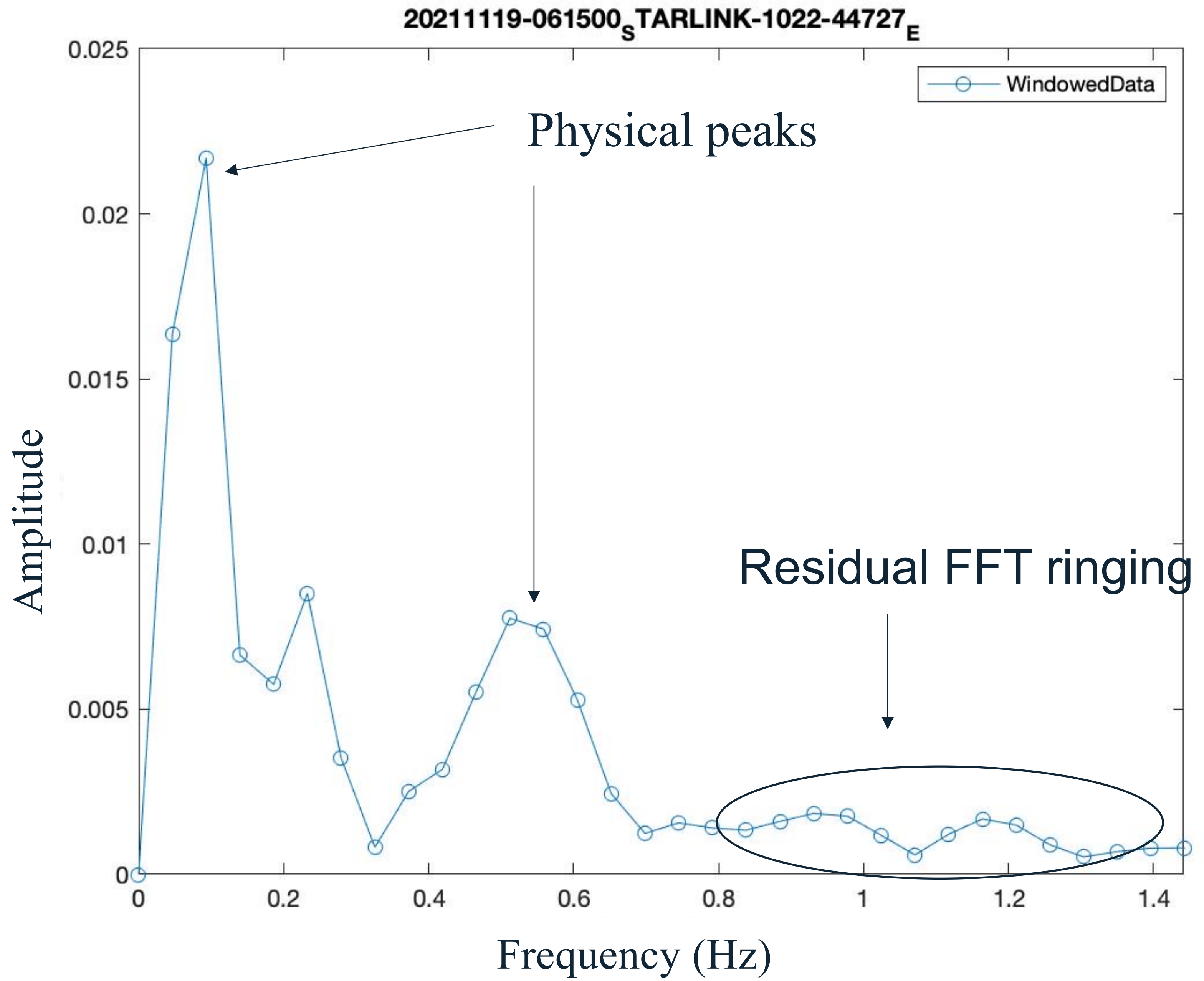
Spectral Peak Detection

- Cubic spline to resample time series.
- Low pass filter to identify and remove DC component from time series.



Peak detection criteria

Criterion	Value
Minimum Peak Width	0.035
Minimum Peak Height	$H_{min} = (\mu_{1/2}(f(8:end)) + \bar{x}(f(8:end)))/2$
Minimum Peak Separation	$f_{sep} = 2.1 * f_{unit}$
Minimum Peak Prominence	0.001



Spectral Peak Detection

The peak detection algorithm:

-Detected 183 peaks.

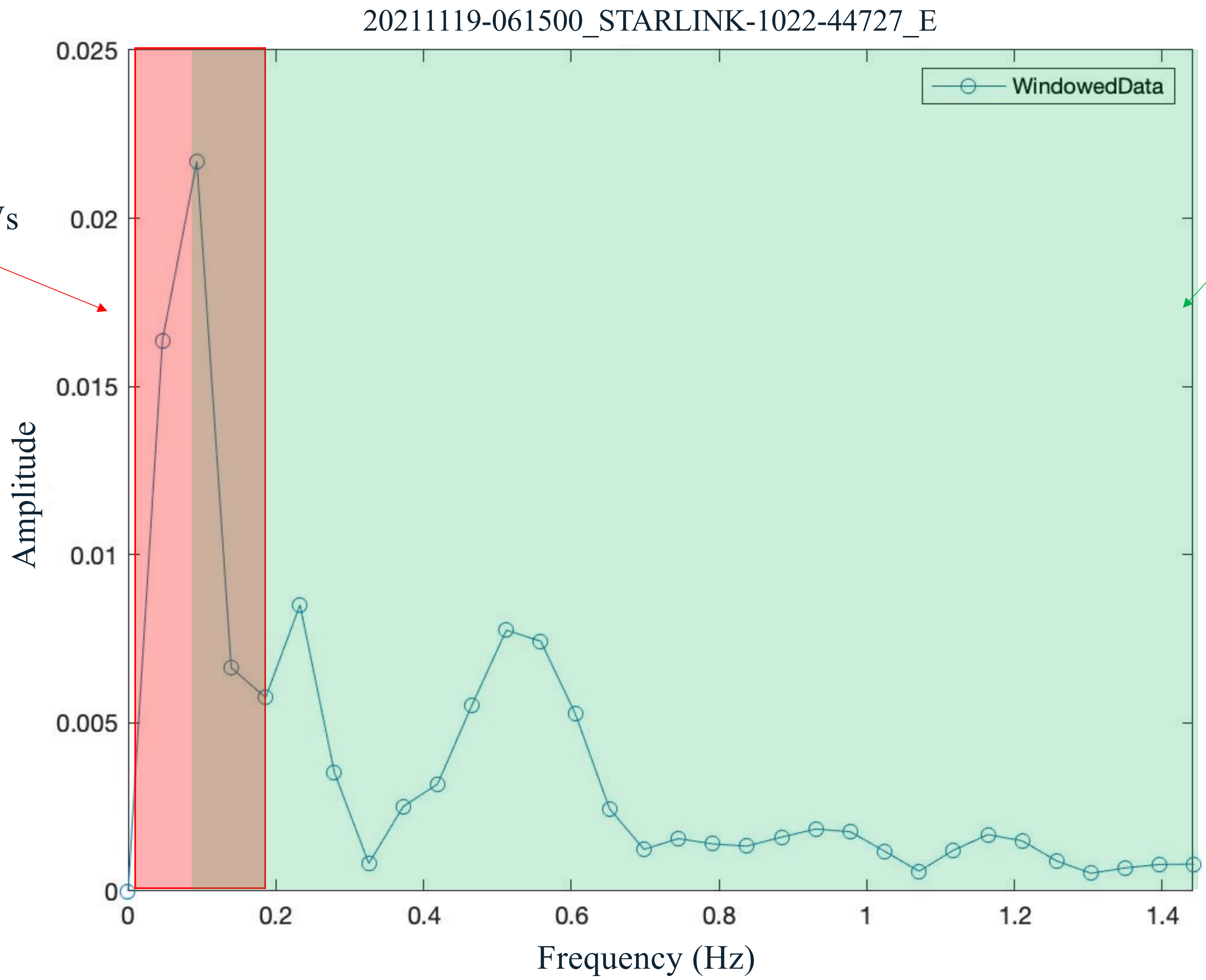
-Failed to identify 12 peaks.

-Incorrectly identified 4 peaks.

The peak detection algorithm had an accuracy of 91.3%.

Expected Frequencies

Expected frequency range of medium scale ionospheric disturbances caused by AGWs



Expected frequency range of the plasma waves

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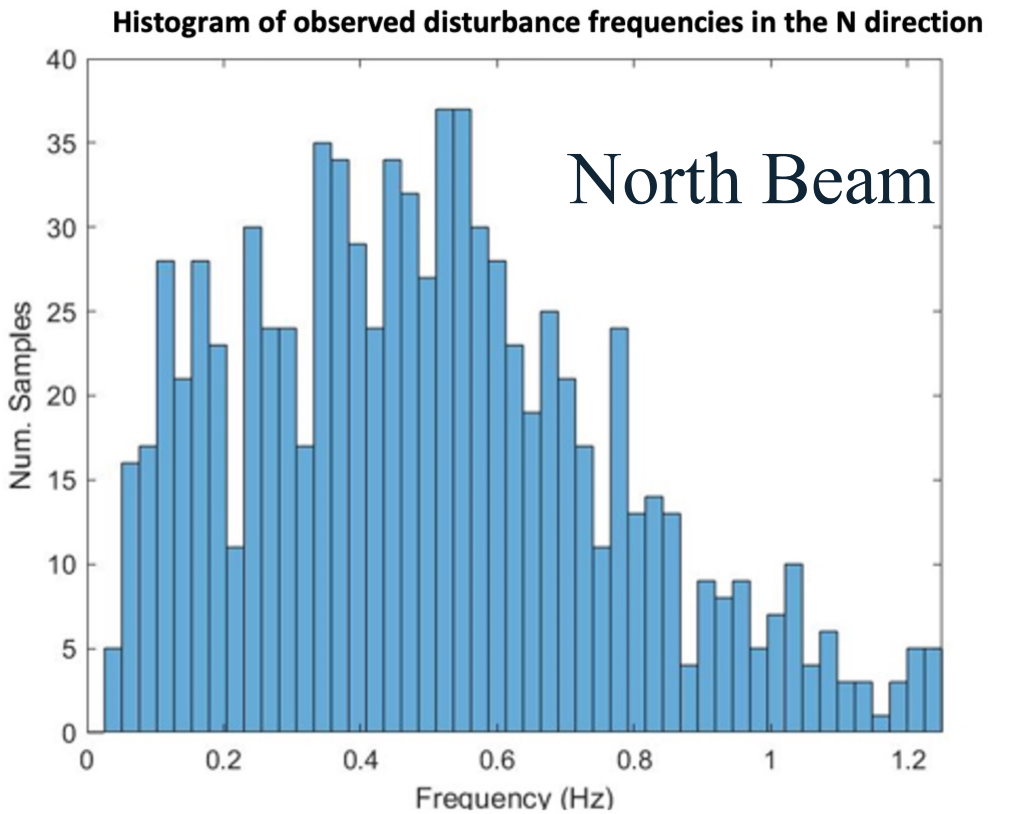
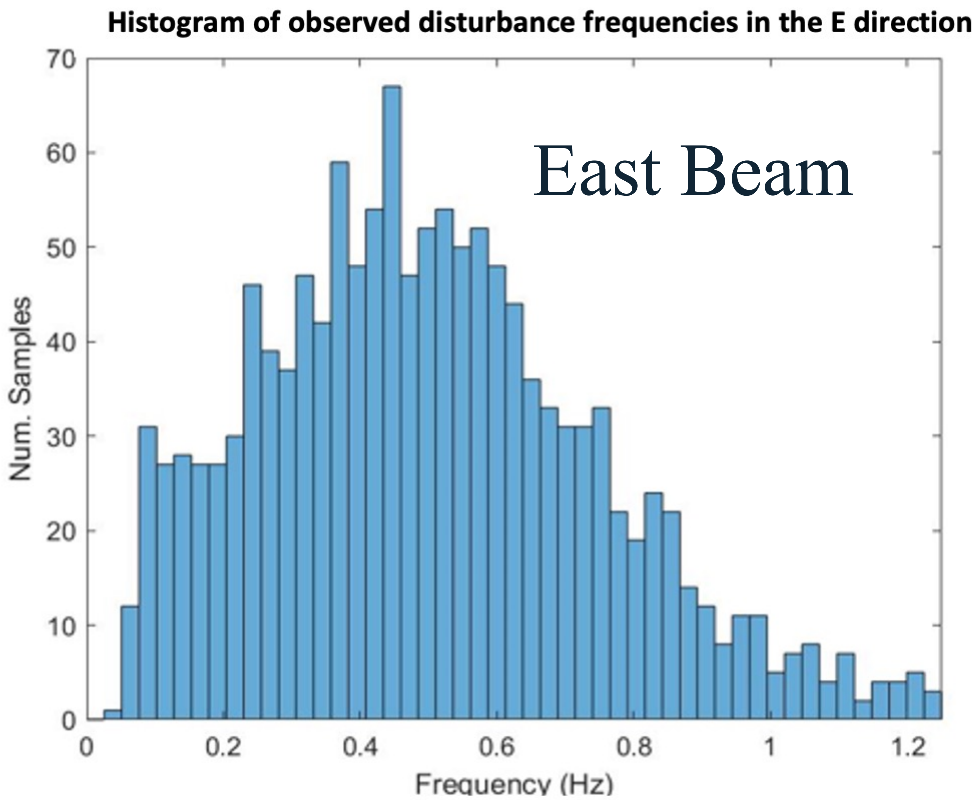
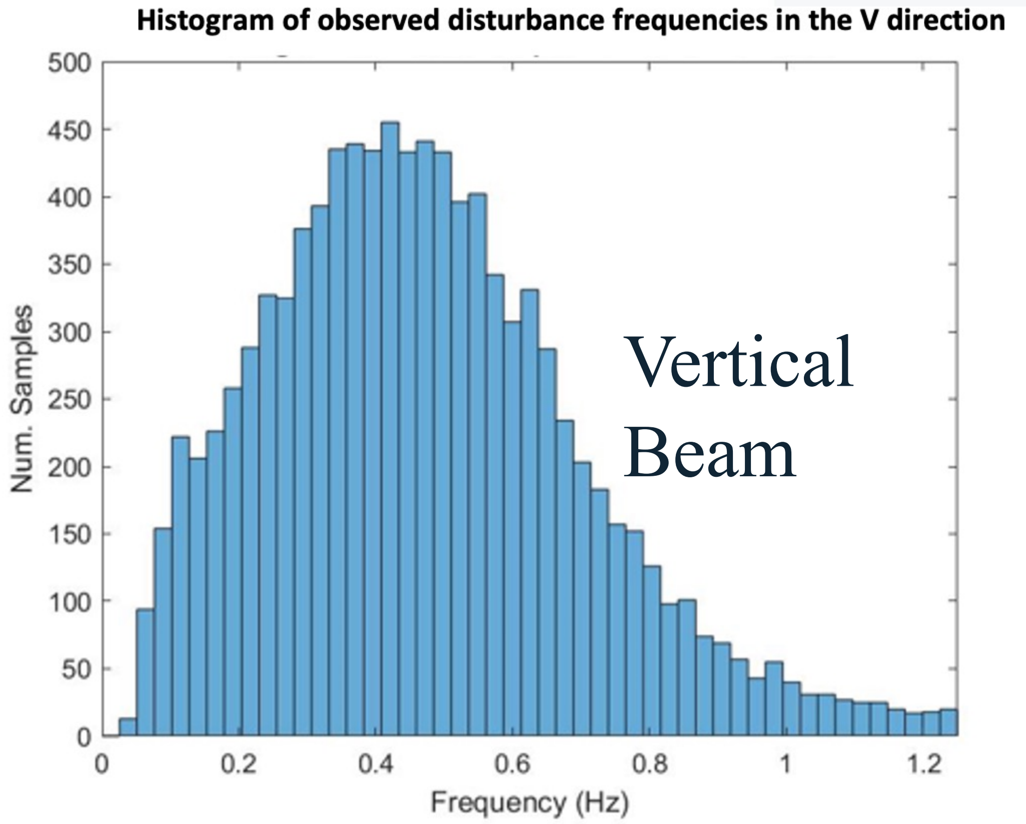
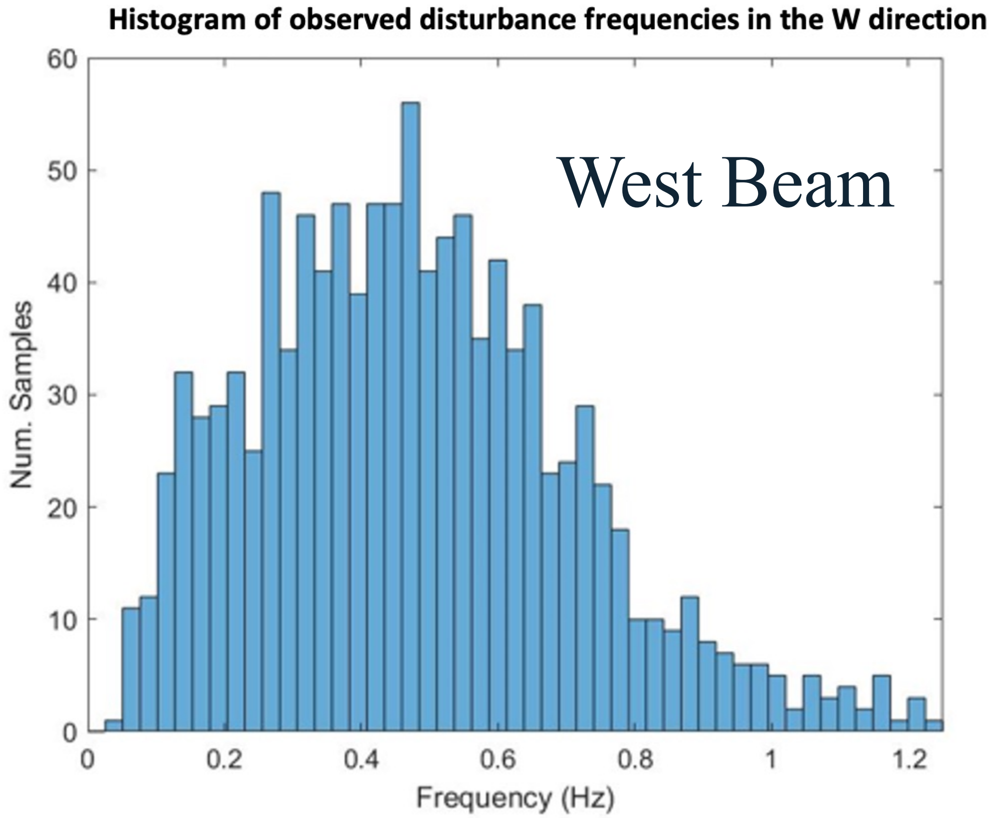
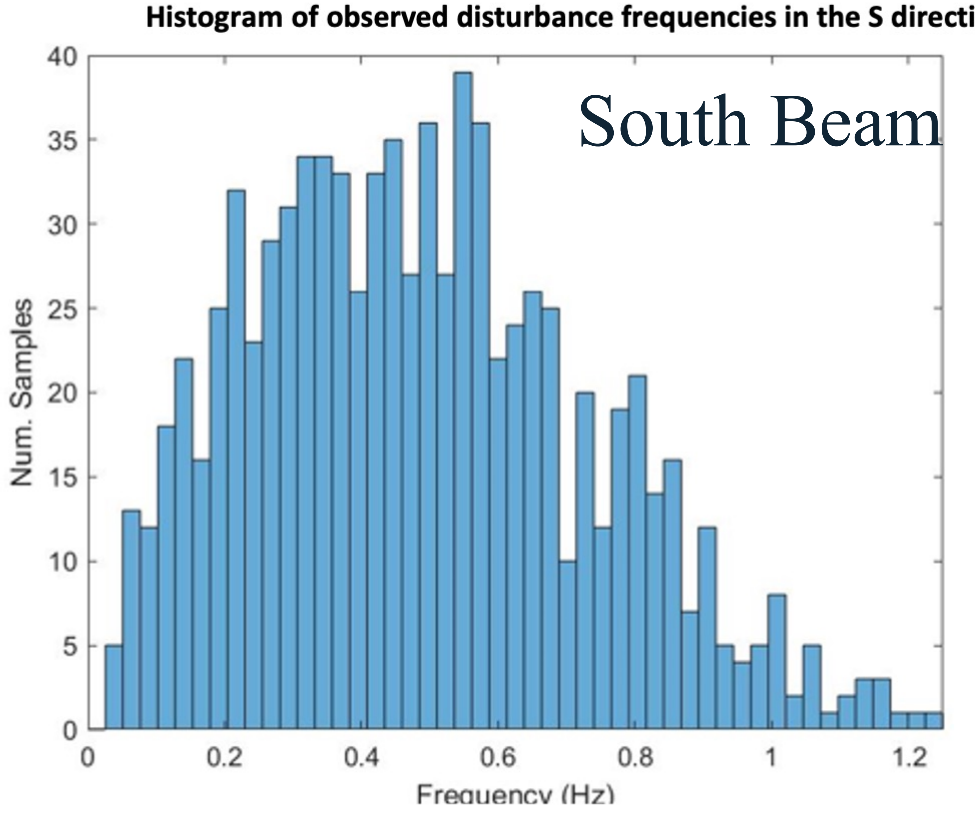
Results - Frequency











Mode frequency of ~0.5 Hz. Consistent with plasma waves moving in the Pc1-2 range. Distribution invariant with beam direction.

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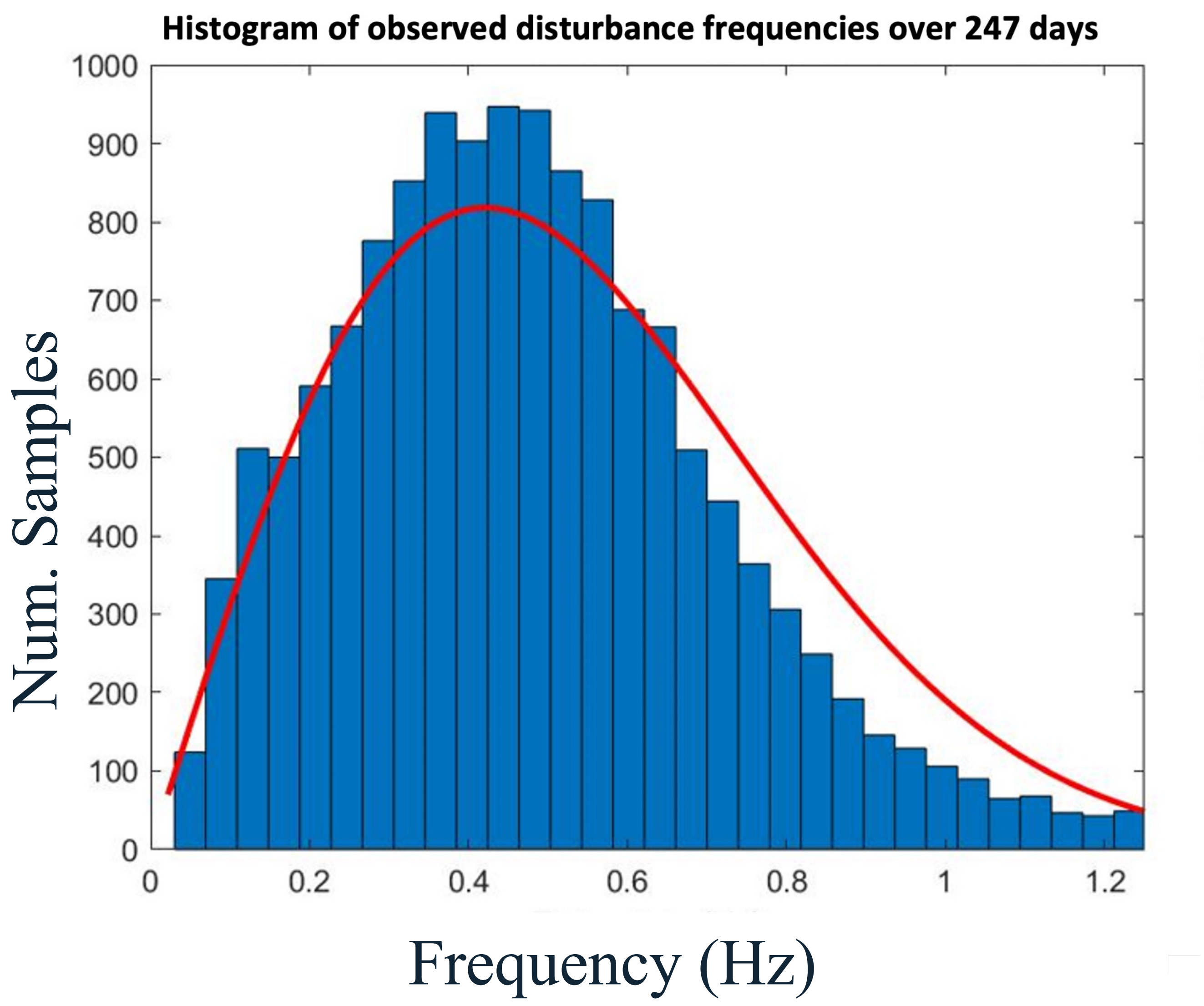
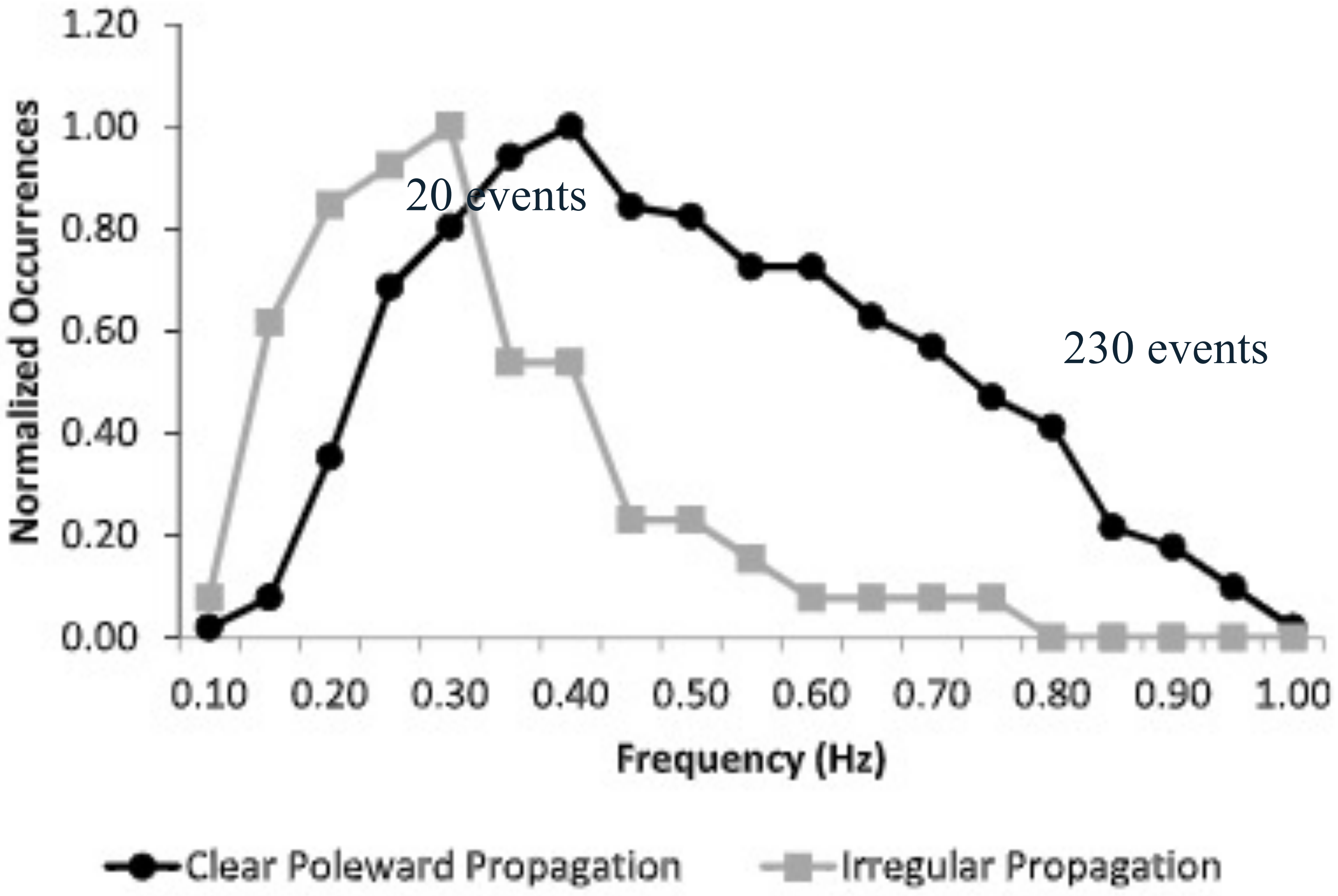
Results - Frequency

Disturbance frequency is the frequency of the ionospheric disturbance.





After Kim et. Al (2011); ground-based magnetometers measurements inside the Auroral oval

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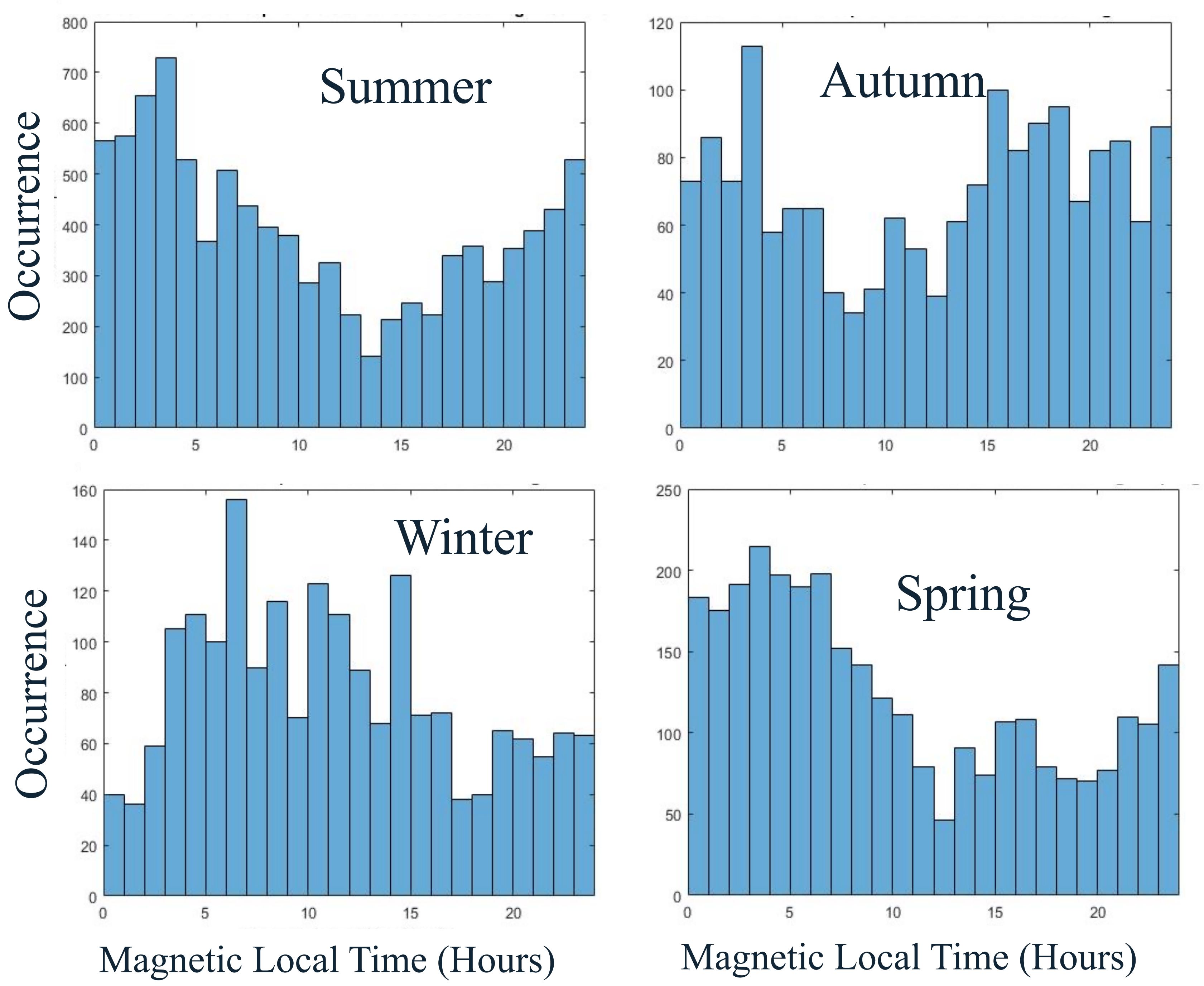
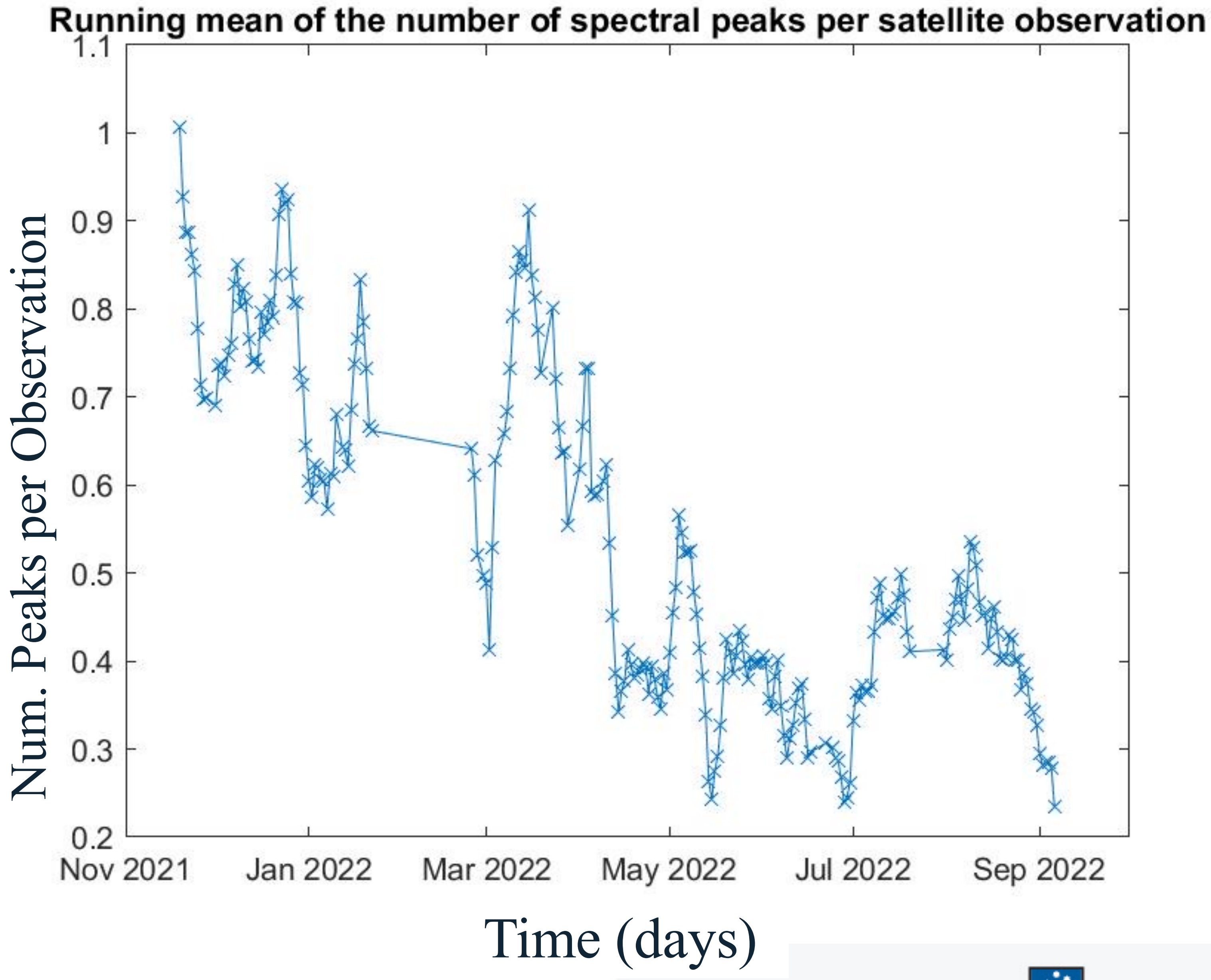
Results – Temporal Variation

Diurnal Variation



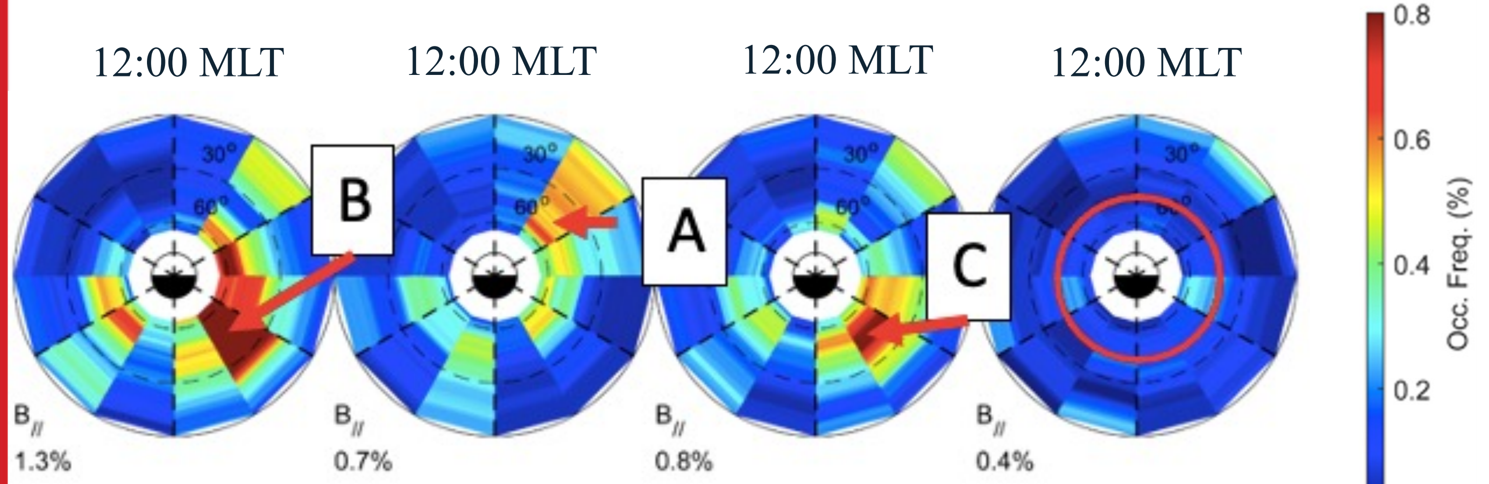
Seasonal Variation



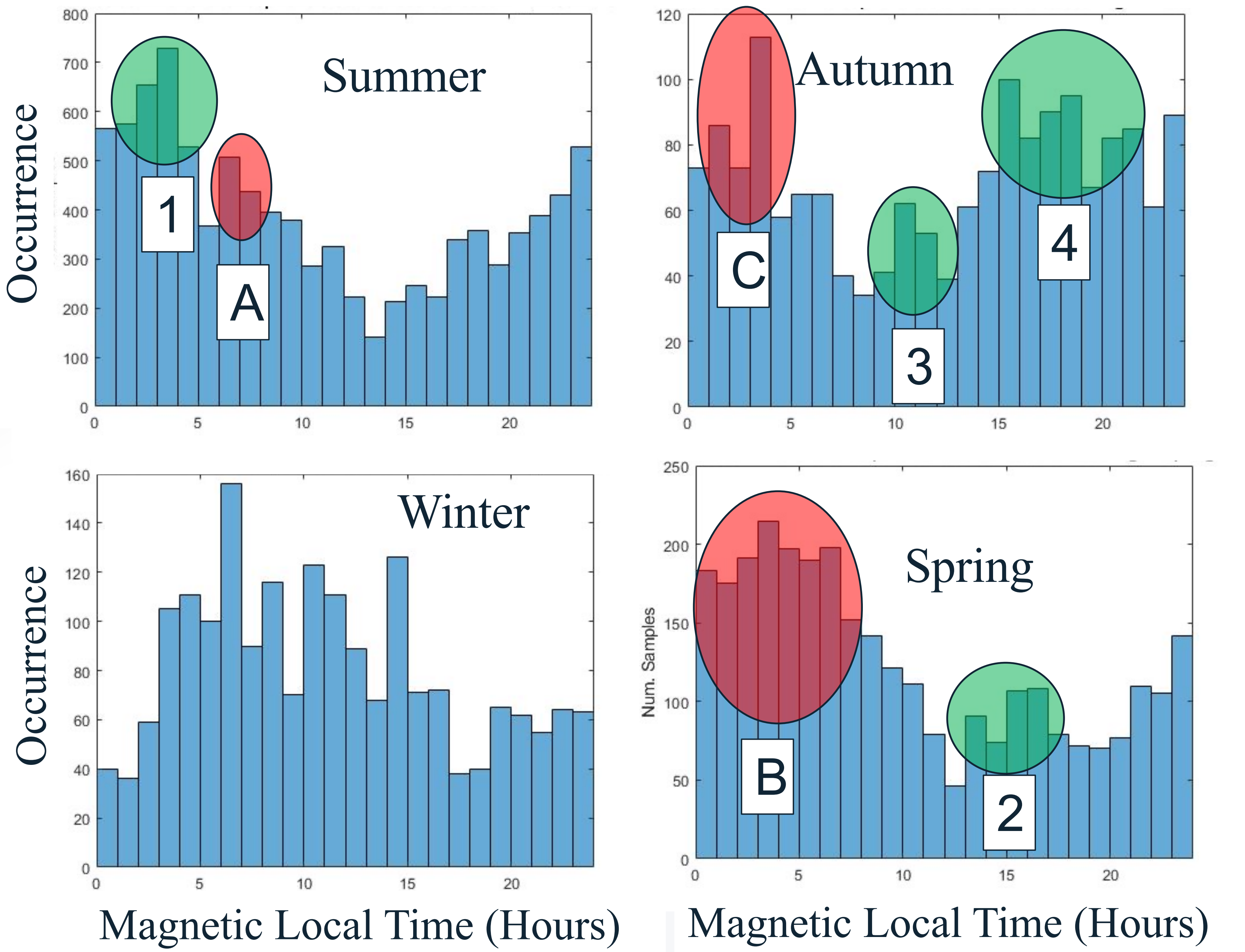
Results – Temporal variation

- Temporal results were compared to Wang et al. 2022 using Swarm satellites.
- BPST observes peaks in the diurnal distributions absent in Wang.
- Wang shows no diurnal distribution during winter
- BPST results show a clear winter diurnal distribution.

• Peaks 1,4, B,C :	nightside plasmapause or magnetotail.
• Peaks A and 2 :	magnetopause.
• Peak 3 :	dayside plasmapause.



Wang et al. (2022);
magnetometers onboard satellites



Attenuation in the F2 waveguide

BPST and Wang show preferred source regions for plasma waves; nightside plasmapause, magnetotail and magnetopause.

Due to attenuation in the F2 waveguide.

Attenuation maximized during low electron density as waveguide boundaries reflect plasma waves less efficiently.

Optimal plasma wave generation times may correspond to large waveguide attenuation.

Less optimal times for plasma wave generation may correspond to times conducive to wave propagation.

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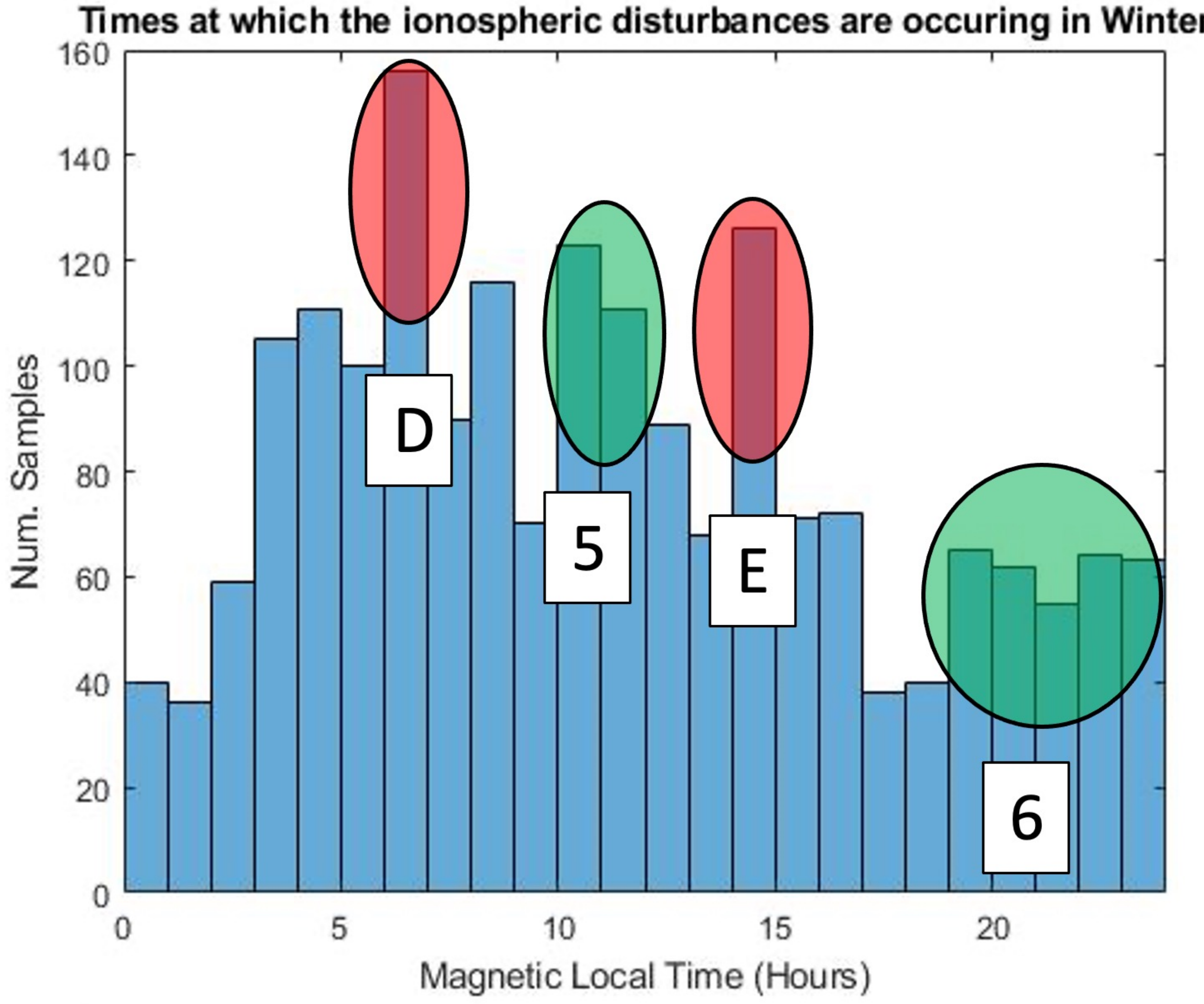
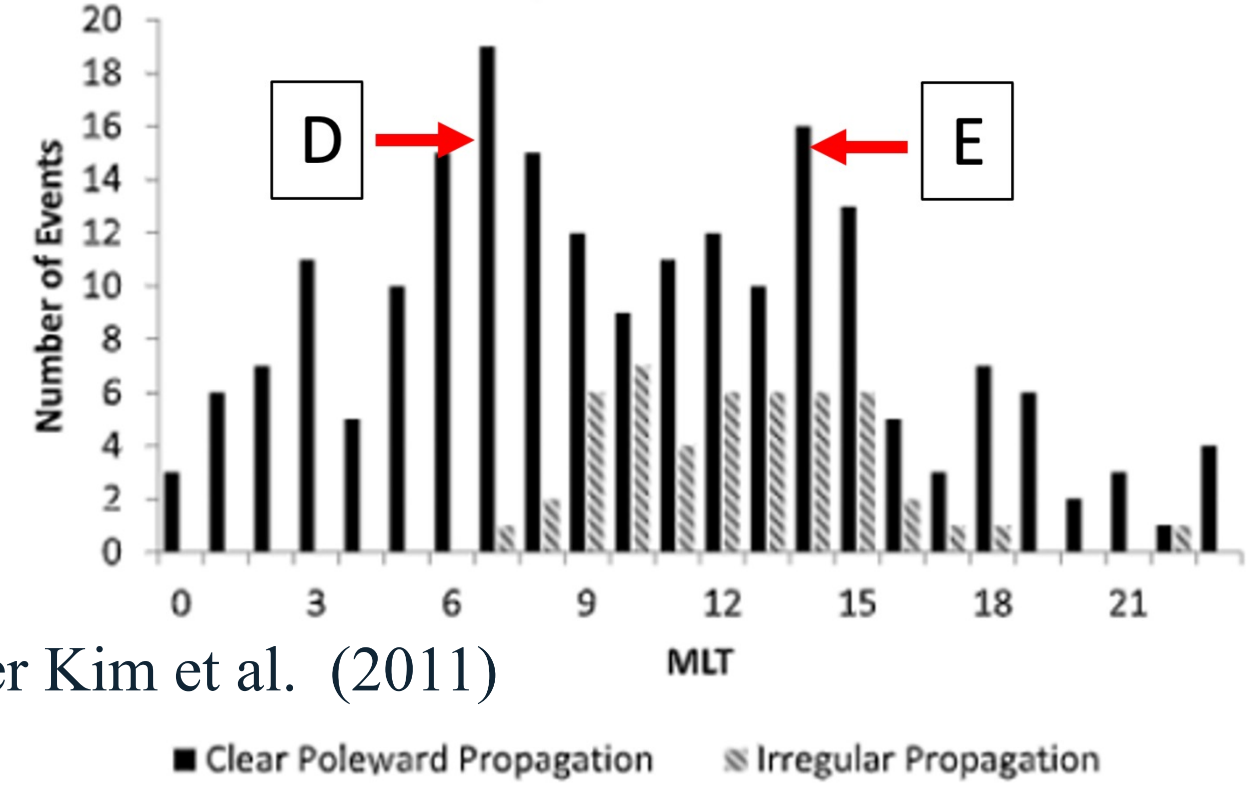
Results – Winter Diurnal variation

- Winter BPST results compared to Kim et al. using ground-based magnetometers inside the auroral ovals (during all seasons).
- BPST observes peaks that are not present in auroral oval results because the plasmapause generated plasma waves cannot propagate through the auroral oval.

Peaks D, E :	The magnetotail.
Peak 5 :	Dayside plasmapause.
Peak 6 :	Nightside plasmapause and the magnetotail.





After Kim et al. (2011)

Summary

Fourier analysis was applied to Doppler satellite observations.

A peak finding algorithm was developed and applied to the amplitude spectra.

The spectral results suggest that plasma waves are causing the observed perturbations.

The preferred source regions for these plasma waves are the nightside plasmapause, magnetopause and magnetotail.

The seasonal and diurnal results suggest that VHF radar is more sensitive to the plasma waves than magnetometers.

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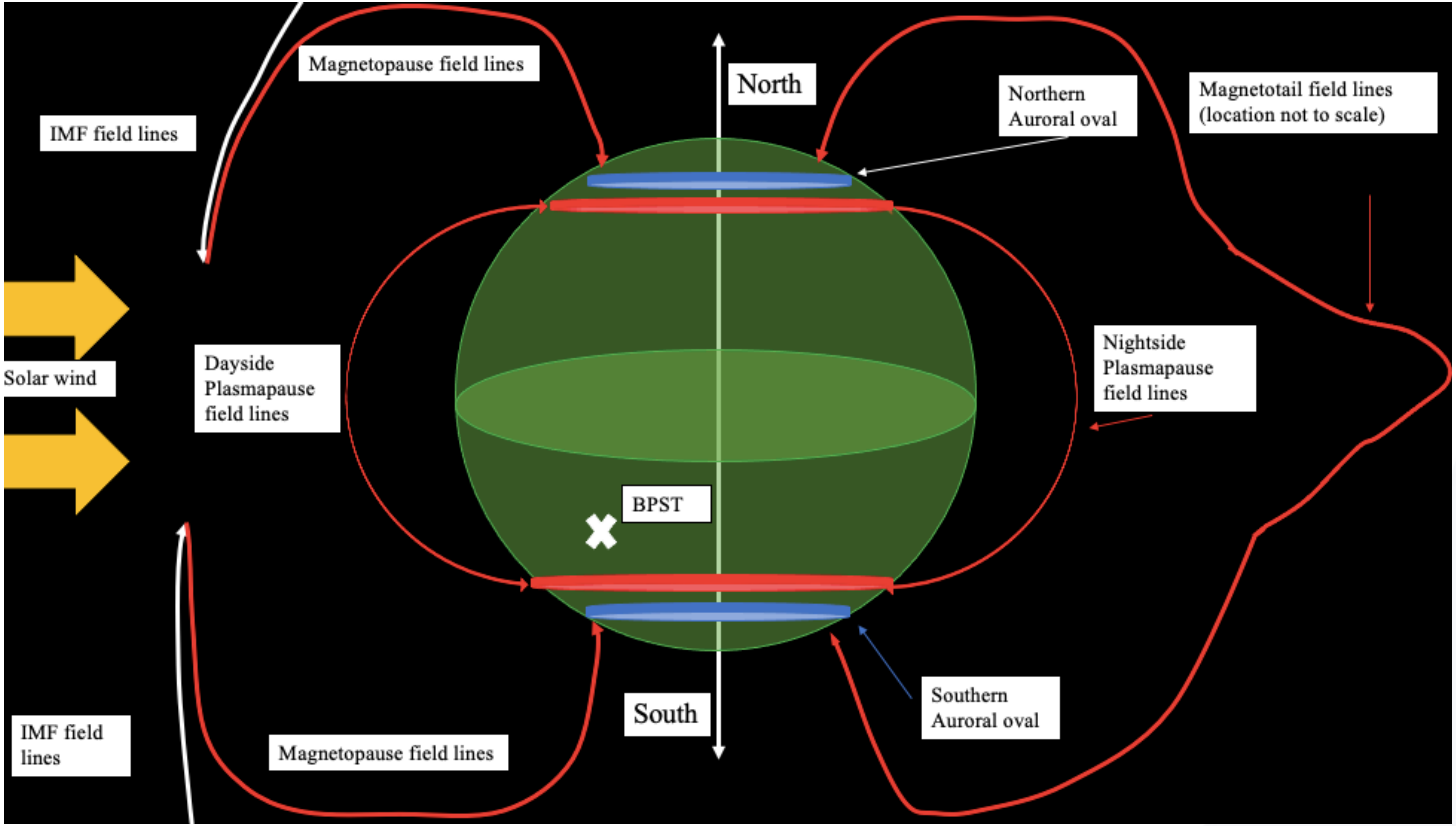

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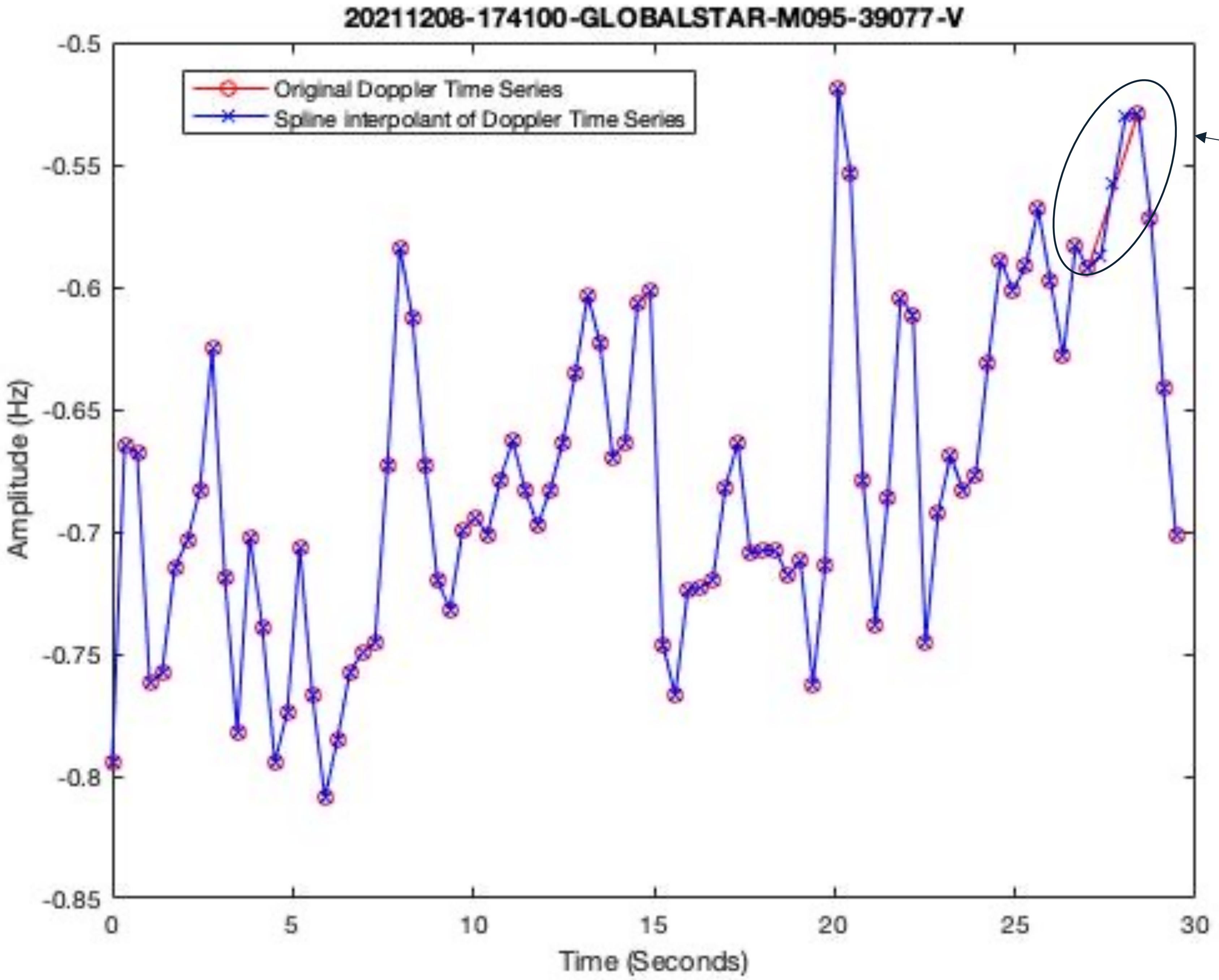
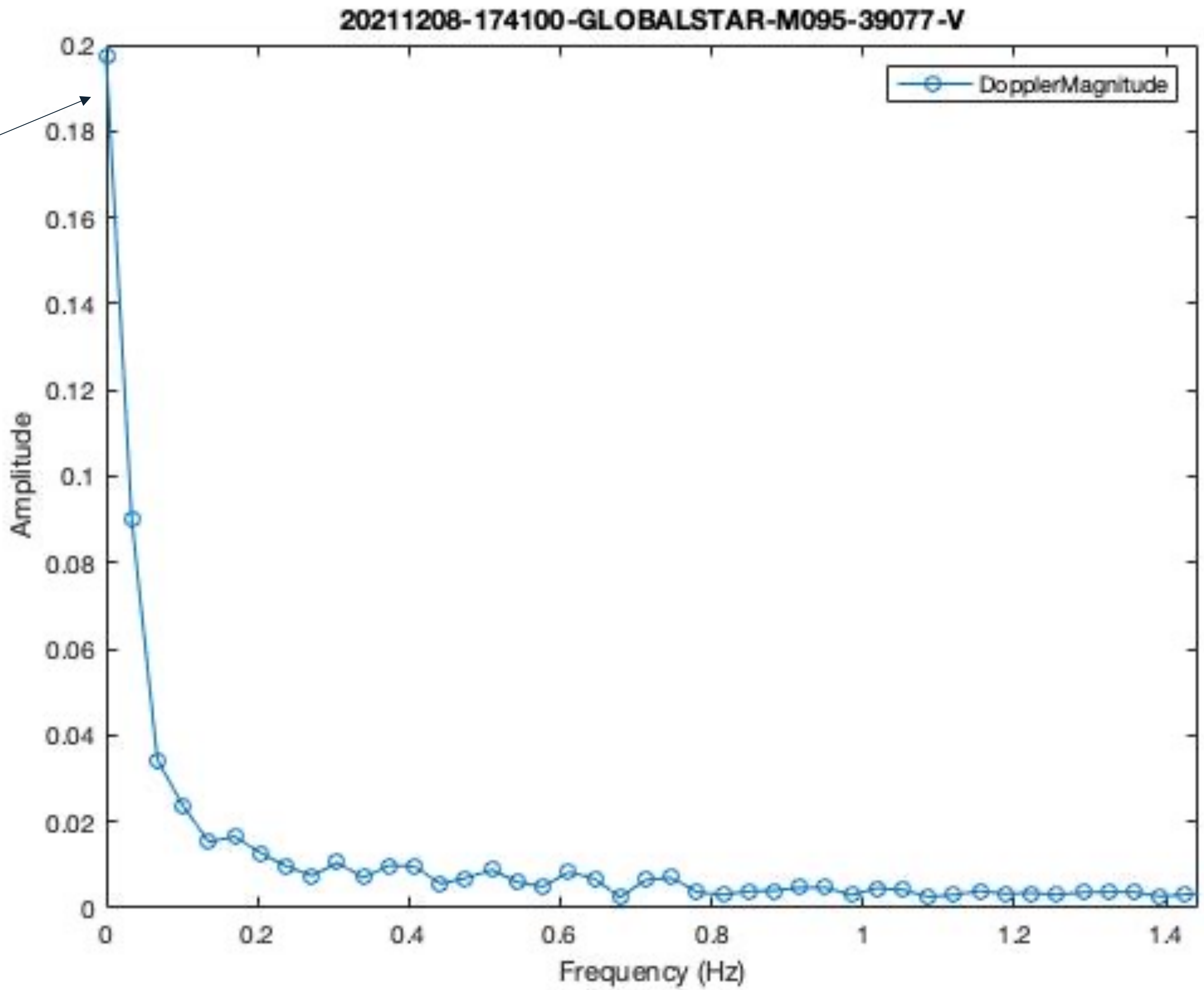
Spectral Analysis of Doppler Peak Data



Missing data p

Spectral Analysis of Doppler Peak Data

Orbital
Element
Bias



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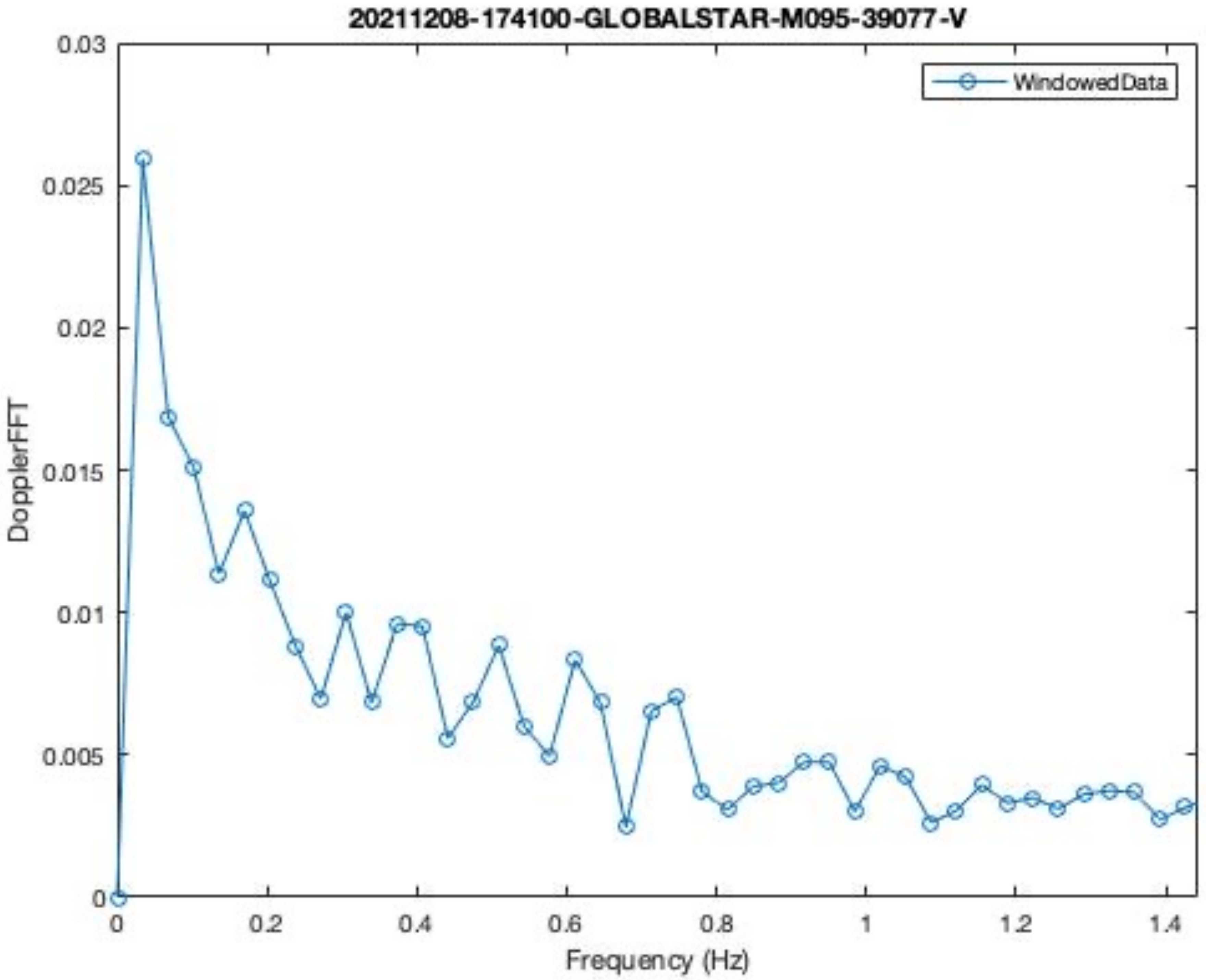
Spectral Analysis of Doppler Peak Data

The low pass filter:

$$y(x) = e^{-10x}$$



Sensitivity of VHF radar to plasma waves

BPST observing peaks unseen by the Swarm or Antarctic results suggests that VHF radar is more sensitive in detecting the plasma waves than the magnetometers used by the Swarm satellites or Antarctic results.

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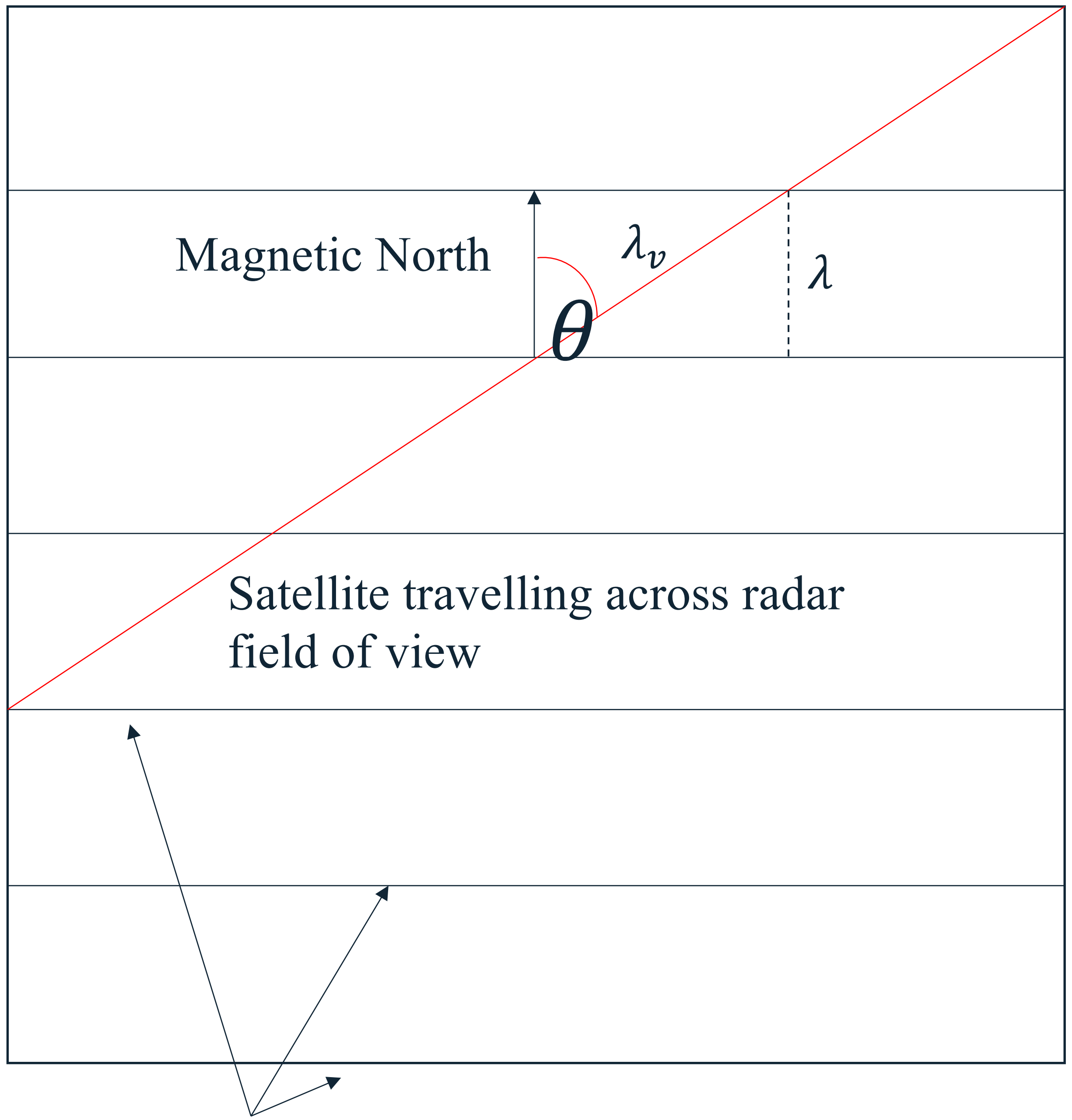
Frequency Correction



Northward propagating wavefronts

λ_v = virtual wavelength.
λ = true wavelength.
θ = direction of travel with respect to magr

Conversion from virtual to true frequency:

$$\lambda_v = \frac{1}{\nu_v}\lambda = \frac{1}{v}\,\frac{\lambda}{\lambda_v} = \cos\theta$$

$$\lambda = \lambda_v \cos\theta$$

$$\frac{1}{\nu} = \frac{1}{\nu_v \nu_v}\cos\theta$$

$$\therefore\ \nu = \frac{\nu_v}{\cos\theta}$$

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