The 2021 Antarctic Total Solar Eclipse:
Waves in the Ionosphere-Magnetosphere System

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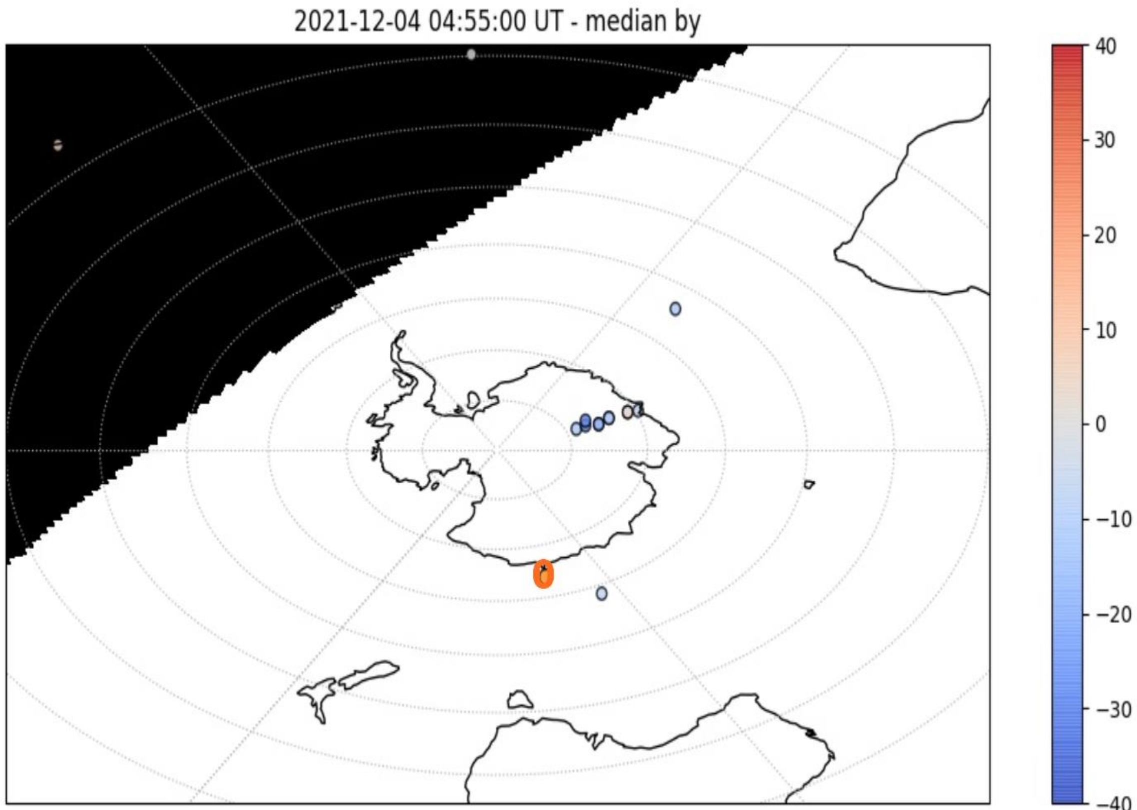
26 June 2023

Ionospheric Electrodynamics – Antarctic Total Solar Eclipse

Background

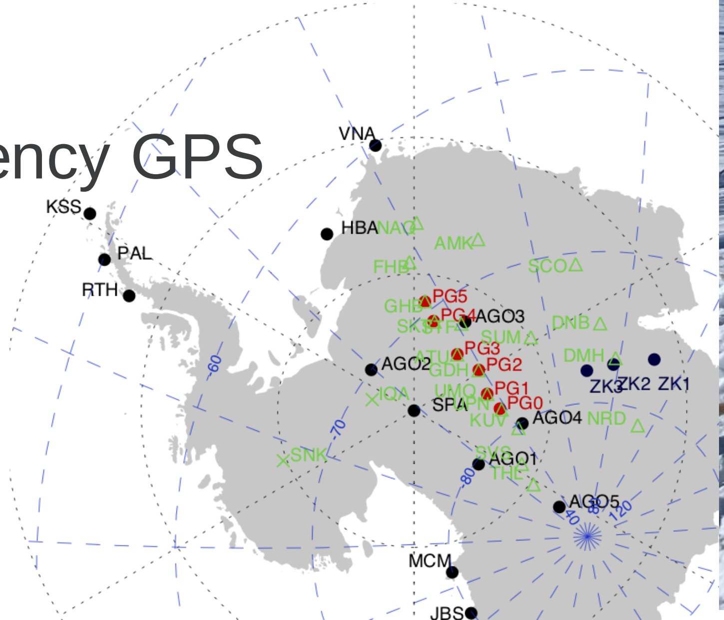
- Total Solar Eclipse occurred December 04, 2021
- Ionospheric parameters of eclipses are well studied
  - Chen et al.,2021; Dang et al., 2018
- Previous studies inconclusive WRT magnetic “eclipse effect”
  - Some see decrease in B_{n-s}
    Momani et al., 2011
  - Others see increase in B_{e-w}
    Kim et al., 2018
  - Some report both
    Stening et al., 1971
  - Some find nothing at all
    Korte et al., 2001
- Antarctic Eclipses are rare
  - 18 year period

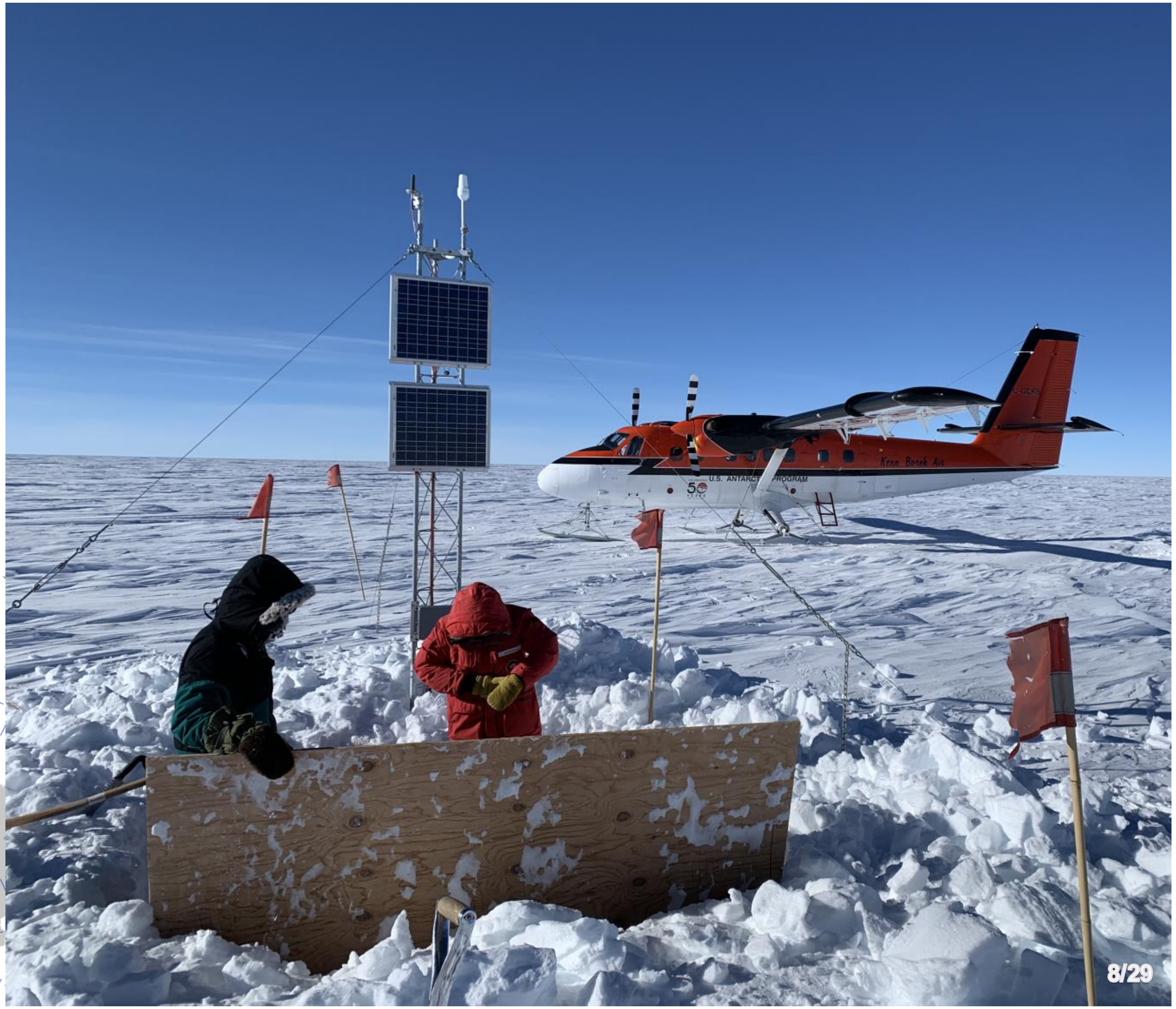


Instrumentation and Data

Autonomous Adaptive Low-Power Instrument Platform (AAL-PIP)

- 6+ stations along the 40 degree magnetic meridian
- Magnetically conjugate to stations in Greenland
- Each station has a fluxgate;
  4 lowest MLAT stations also have:
  - Search-coil
  - Dual Frequency GPS



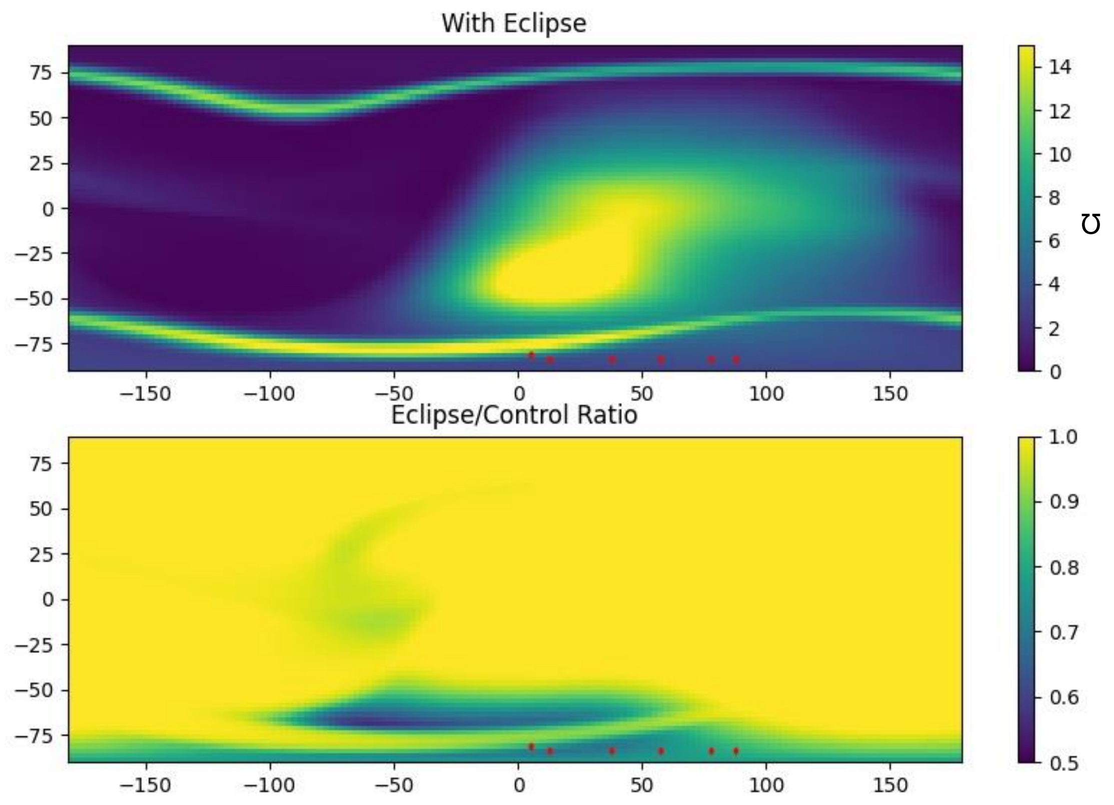


Ionospheric Electrodynamics – Antarctic Total Solar Eclipse

Ionospheric Modeling

- Thermosphere-Ionosphere Electrodynamics General Circulation (TIE-GCM)
- Apparent decrease of ionospheric conductivity by half near totality
- Ray-traced TEC generally agrees until eclipse totality
- Increase in TEC after totality may be explained by thermal upwelling or particle precipitation

Cnossen et al., 2019



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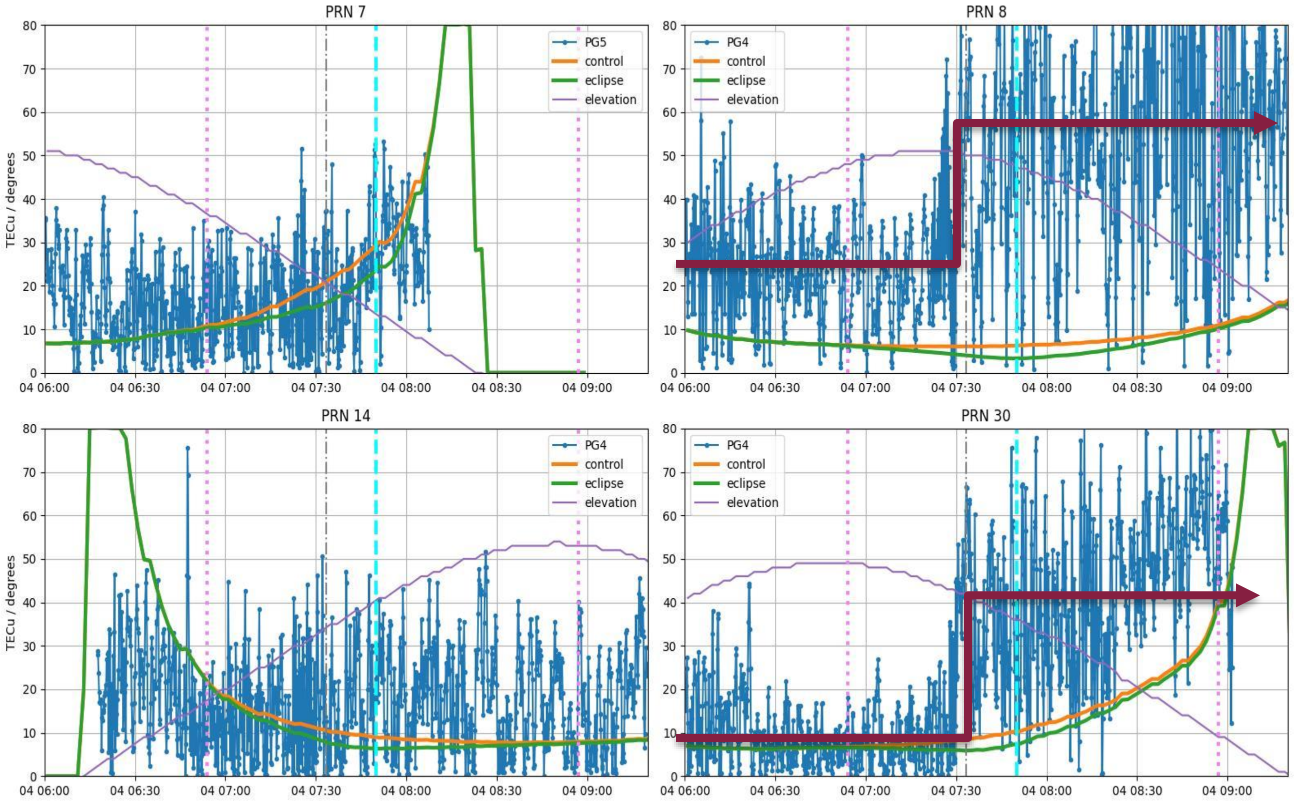

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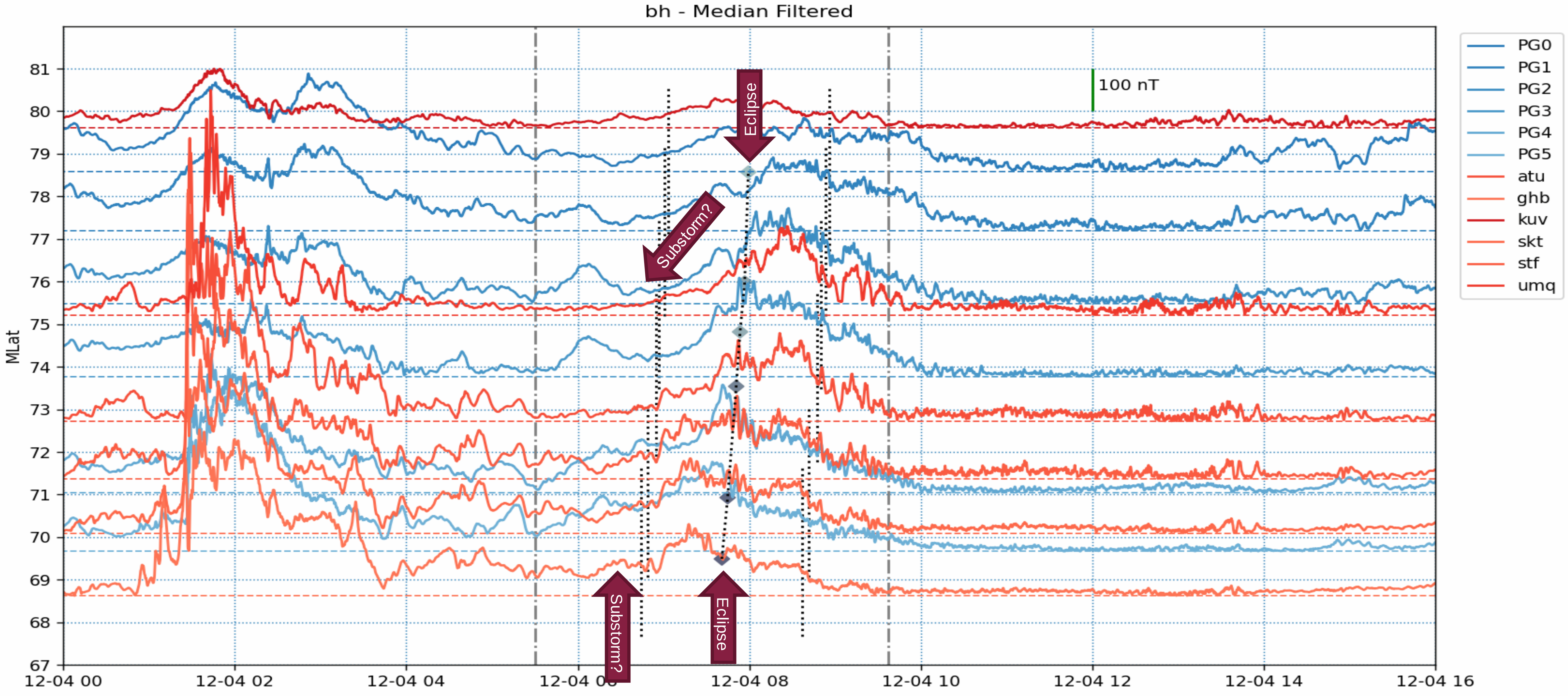
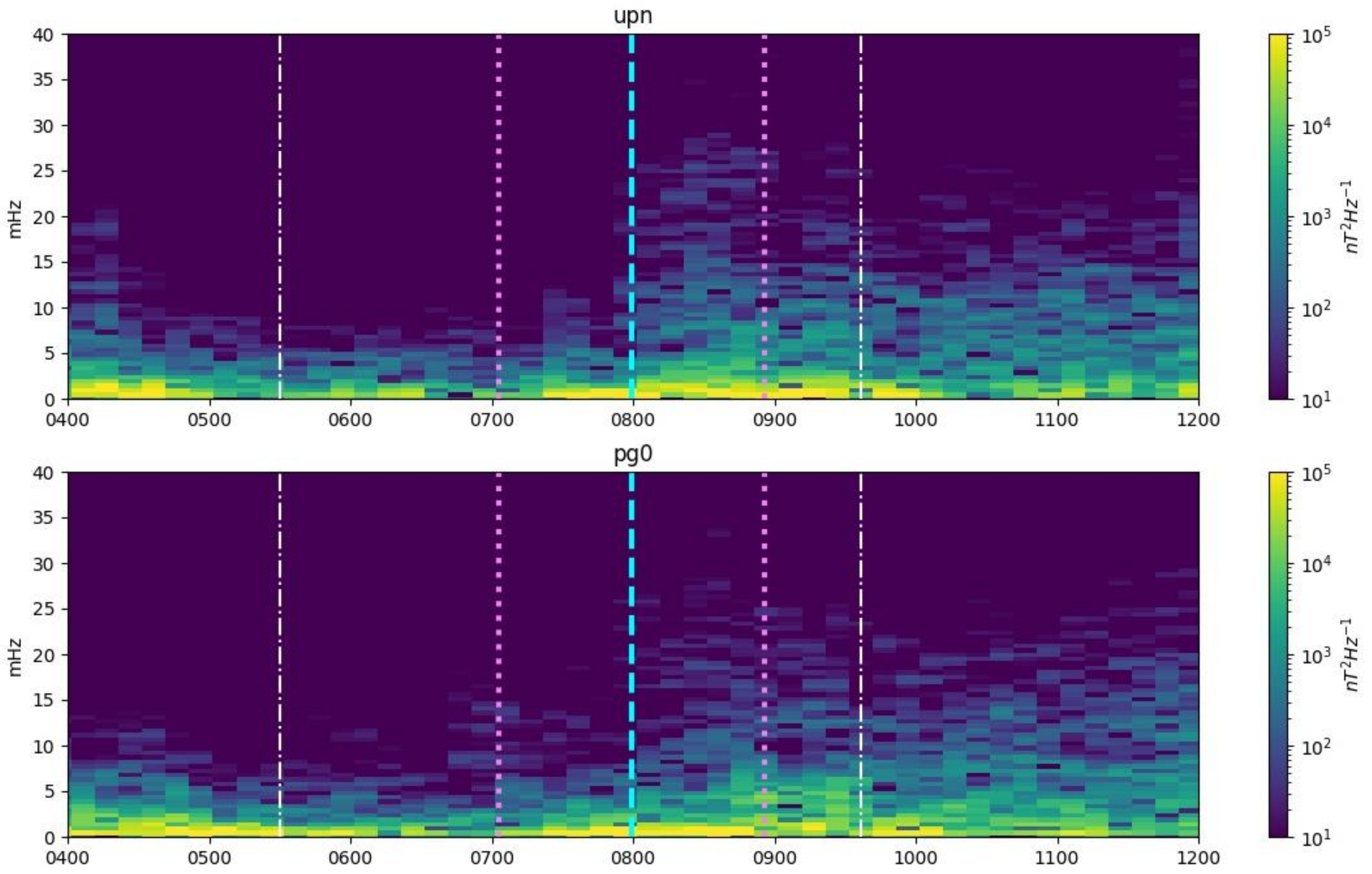


Ionospheric Electrodynamics – Antarctic Total Solar Eclipse

Fluxgate Magnetometer



- Wave activity is well correlated with local maximum obscuration
- Waves appear in both Northern and Southern hemispheres

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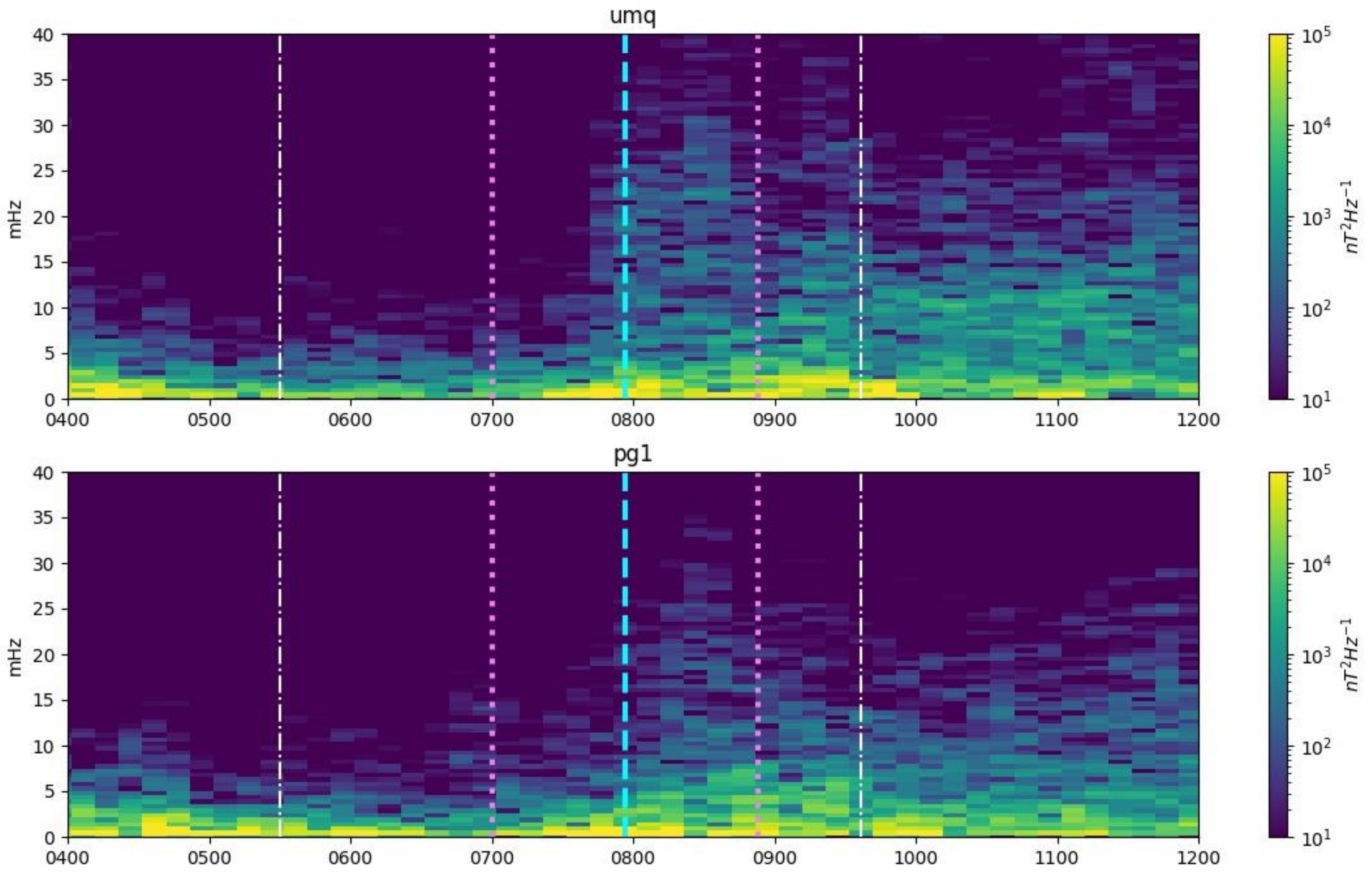

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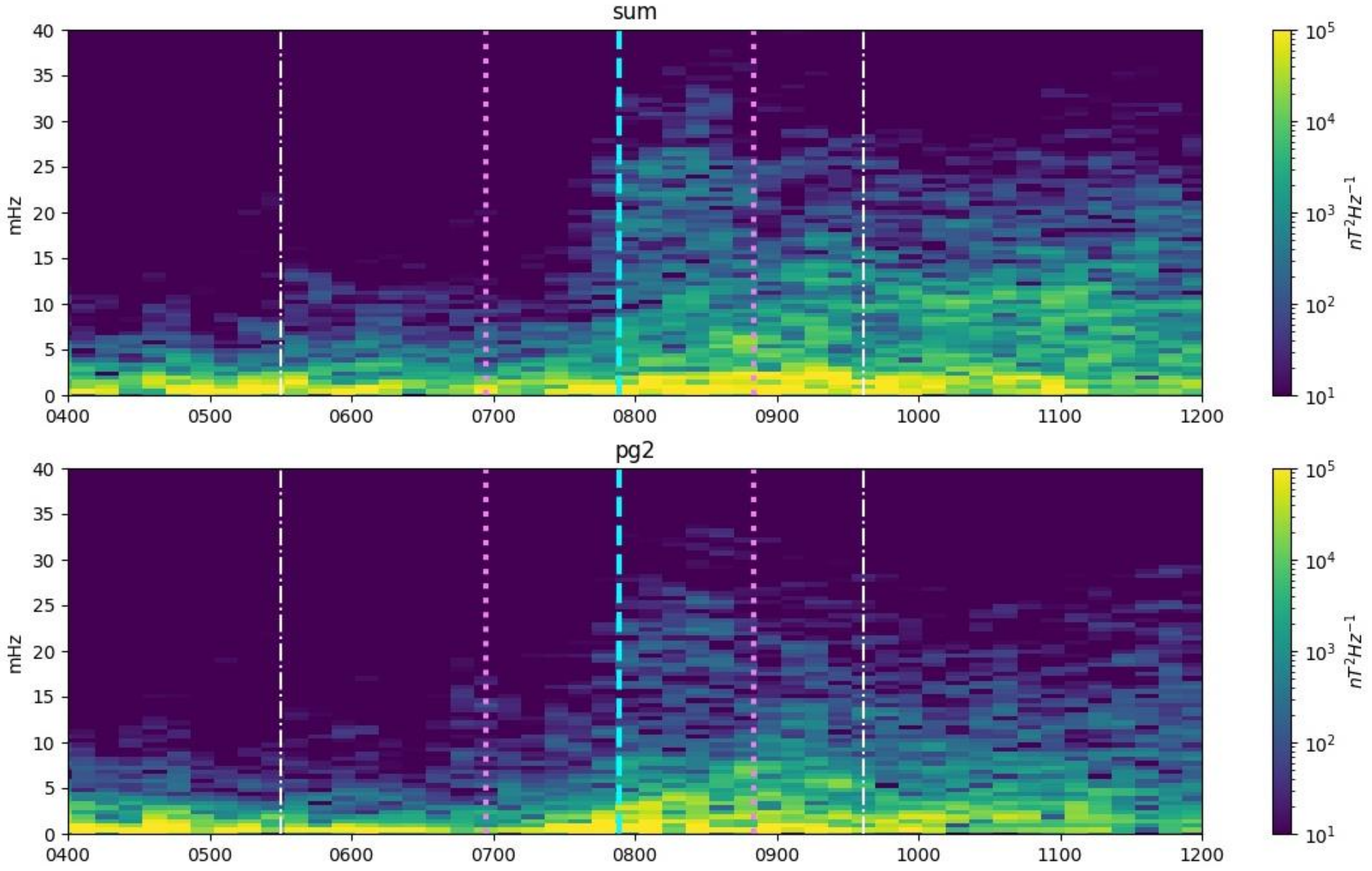

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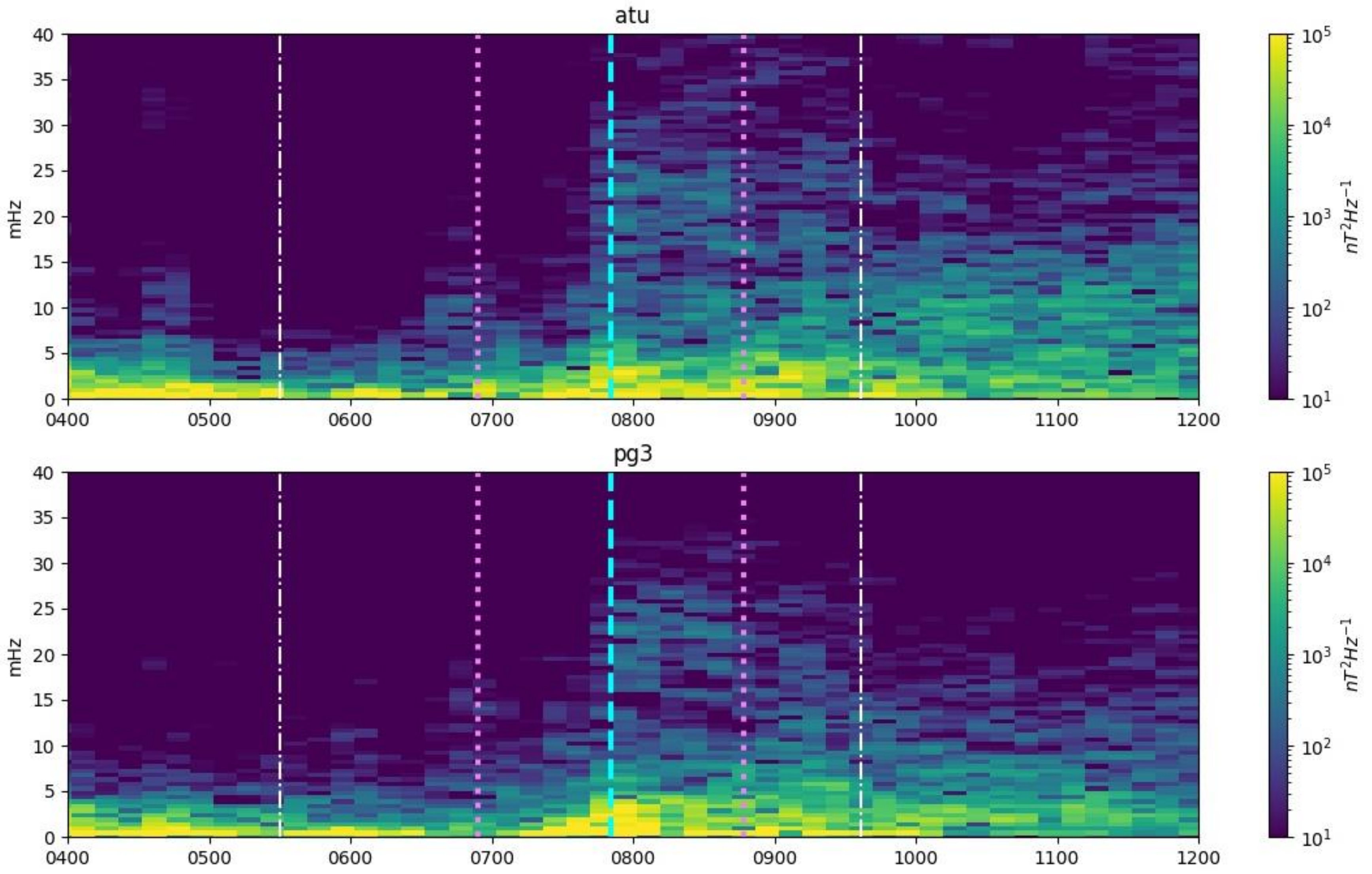

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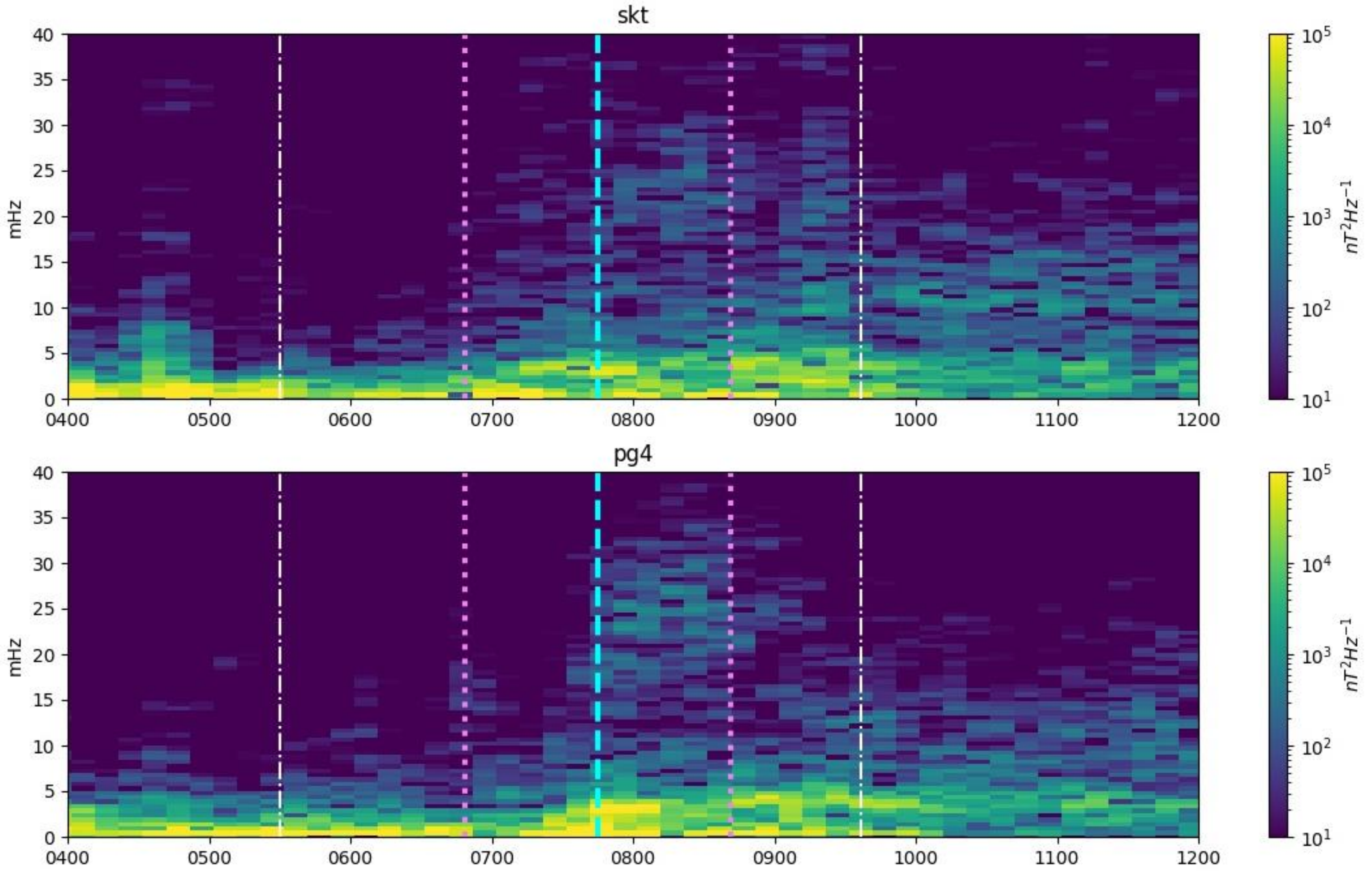

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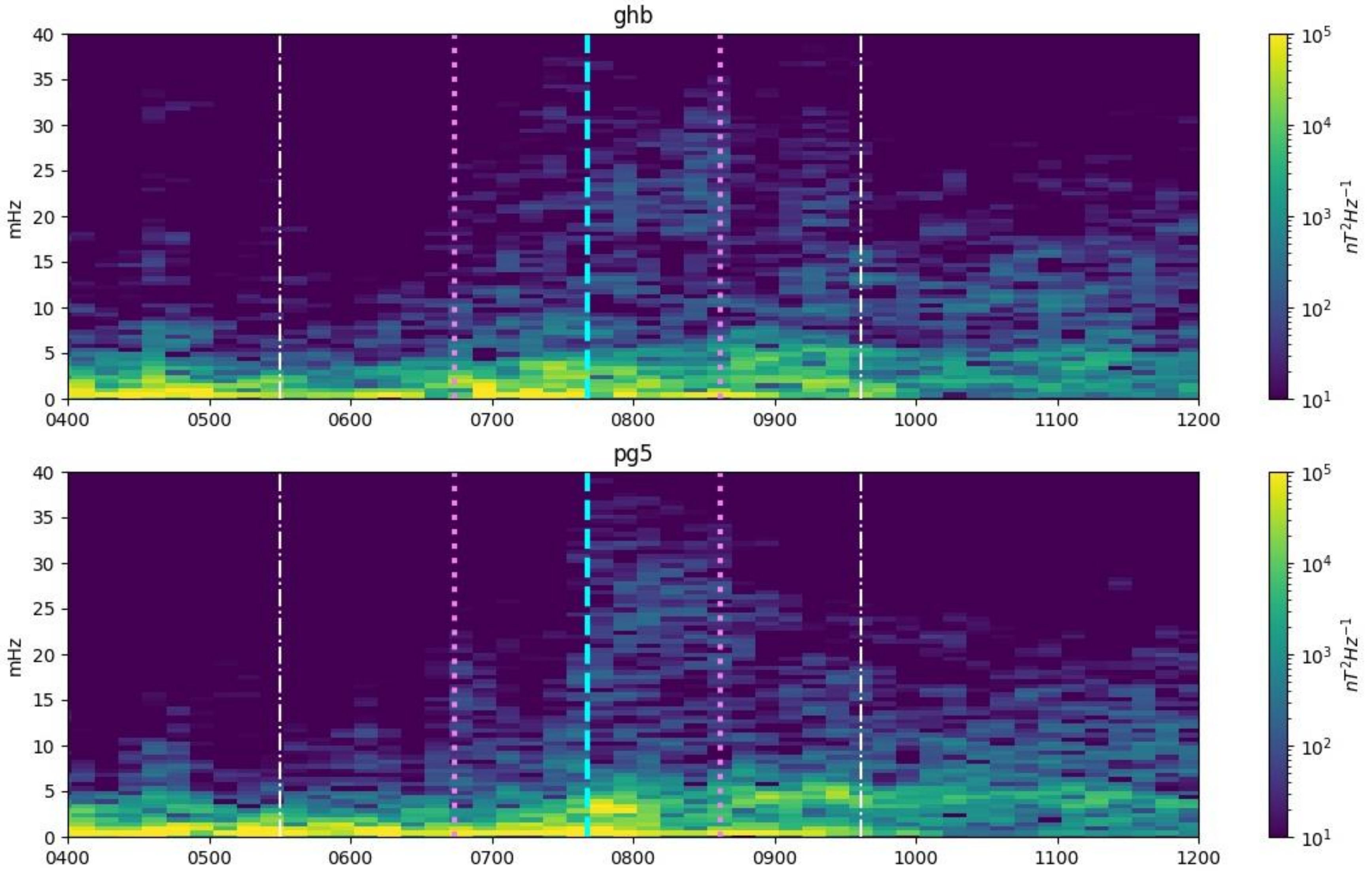

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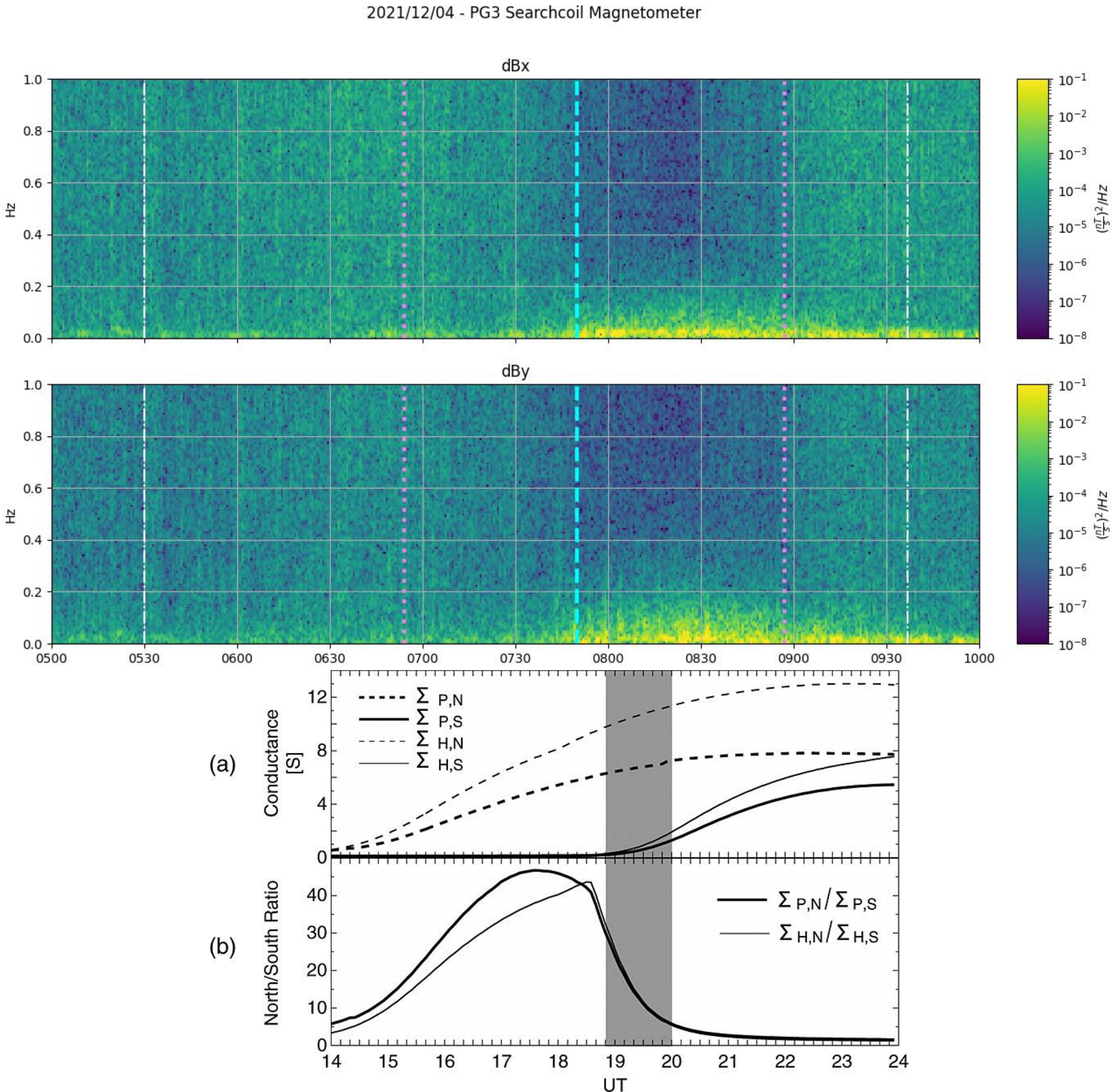
Ionospheric Electrodynamics – Antarctic Total Solar Eclipse

Searchcoil Magnetometer

- High frequency (>200 mHz) damping after local peak
  - Similar to prior observations
    Kim and Chang, 2018
- Simultaneous increase in activity at lower frequencies in GMAG and TEC
- Similar observations at dawn terminator ("sunrise effect")
  Obana et al., 2015



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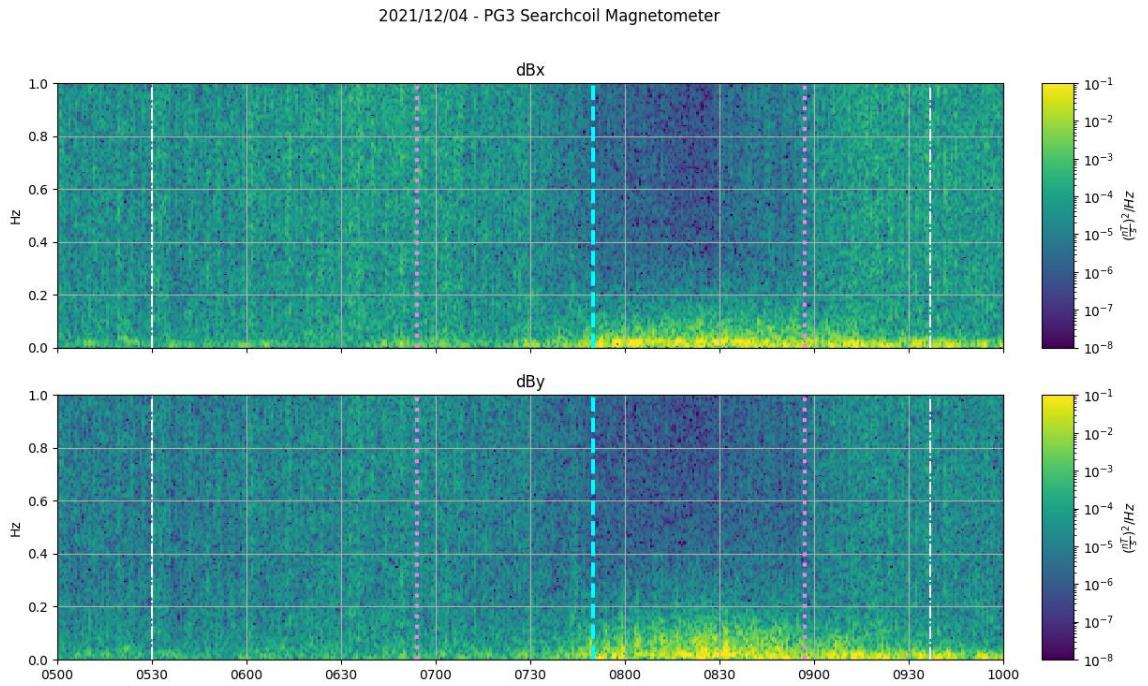
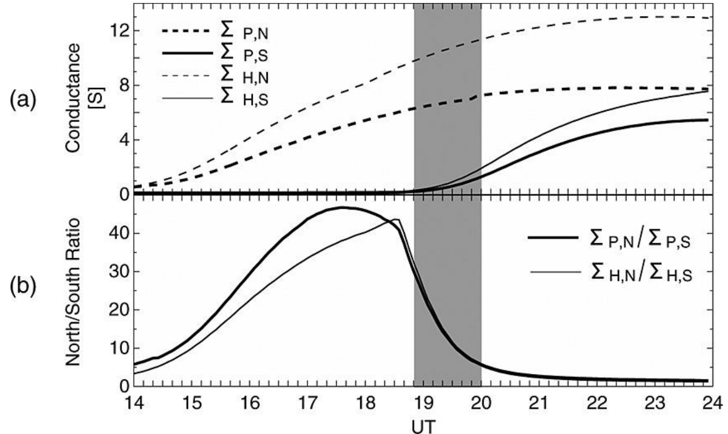




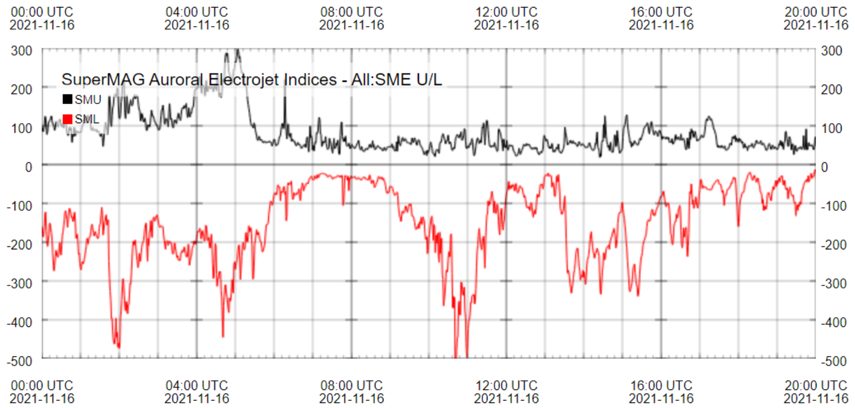
Summary

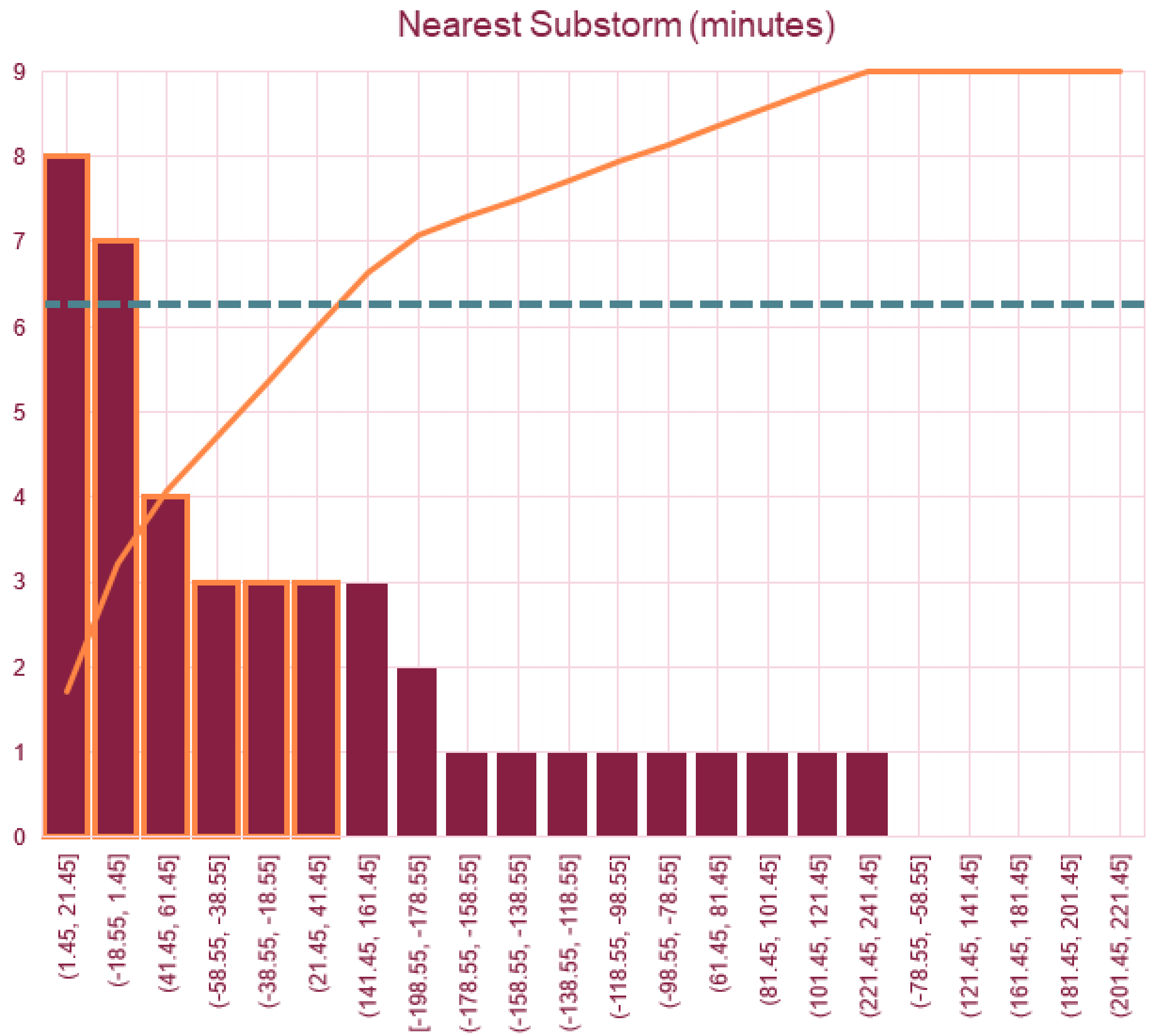
- Magnetometer/GNSS observations of ionospheric waves occur tightly coupled with site-dependent peak solar obscuration
- Waves are observed in both hemispheres, thus communicated through the magnetosphere
- TIE-GCM results support hypothesis that conductivity difference is likely contributor to waves
- This activity appears to be the result of the eclipse, not the coincident substorm

Solar Eclipses and Geomagnetic Substorms

Substorm Distributions Relative to Eclipses

- Of the past 46 eclipses, 43 show some identifyable signature in SuperMAG Electrojet Index
- ~70% have a published substorm occurring within +/- 1 hr of peak totality
    - Automated substorm detection is not perfect





Solar Eclipses and Geomagnetic Substorms

PMI Analysis Results

- In any given 2H window, there is nearly a 40% chance of a substorm having occurred
  - **Increases to 67%** in windows centered around eclipse peaks
- Substorms are **MORE LIKELY** to occur in the same window as eclipses
  - PMI is positive for eclipse/substorm combo
  - PMI is negative for eclipses without substorms
- Window size has slight impact on PMI magnitude
  - Variance of ~15% between 2-6 hours

- X: Substorms, Y: Eclipses
- From 2001-2021
  Using a 2-hour rolling window:
  - $p(x_1) \cong 0.3954$
  - $p(y_1) \cong 0.4998\text{E}^{-3}$
  - $npmi(x_0; y_0) \cong 150.875\text{E}^{-6}$
  - $npmi(x_1; y_0) \cong -125.154\text{E}^{-6}$
  - $\boldsymbol{npmi(x_1; y_1) \cong 0.0251 > 0}$
  - $\boldsymbol{npmi(x_0; y_1) \cong -0.0203 < 0}$
  - $\boldsymbol{I(X; Y) = 12.4785\text{E}^{-6}}$

Solar Eclipses and Geomagnetic Substorms

Summary

1. Is it really random chance that both eclipses would have a co-occurrent substorm? **More likely than random chance**
2. What is the likelihood of substorm occurrence during eclipses in general? **Nearly 70%**
3. Can eclipses provide a seasonally agnostic view of the role of ionospheric conductivity in MI coupling? **Yes!**

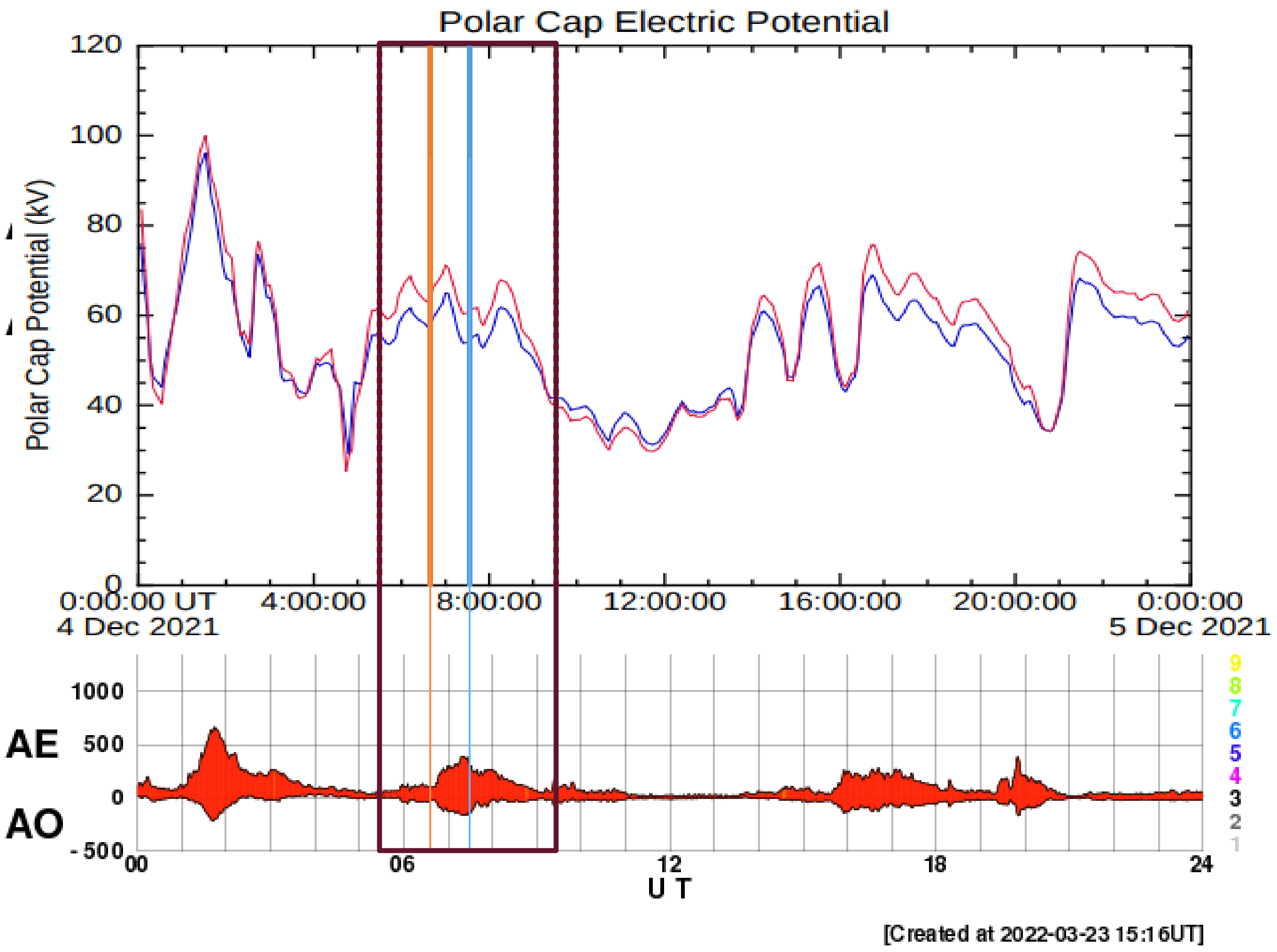
VIRGINIA TECH

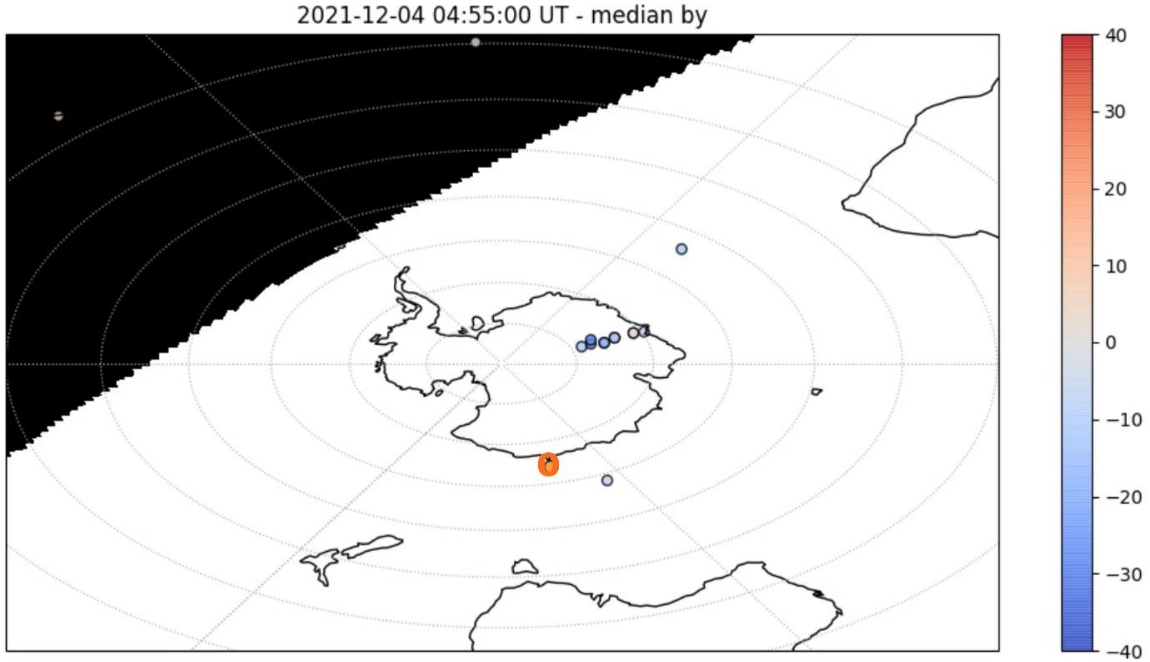
- Substorm and eclipses co-occurrence more likely than random chance
  - Substorm occurrence likelihood increases by 30% during eclipses
- It is rare that an eclipse occurs without a substorm
- A physical linkage between eclipses and substorms remains unresolved
  - Conductivity likely plays a role
  - Magnetospheric fast-mode waves?
  - Ionospheric convection/outflow?
- More observations and modeling efforts are needed to “close the loop

Questions

Coincident Substorm

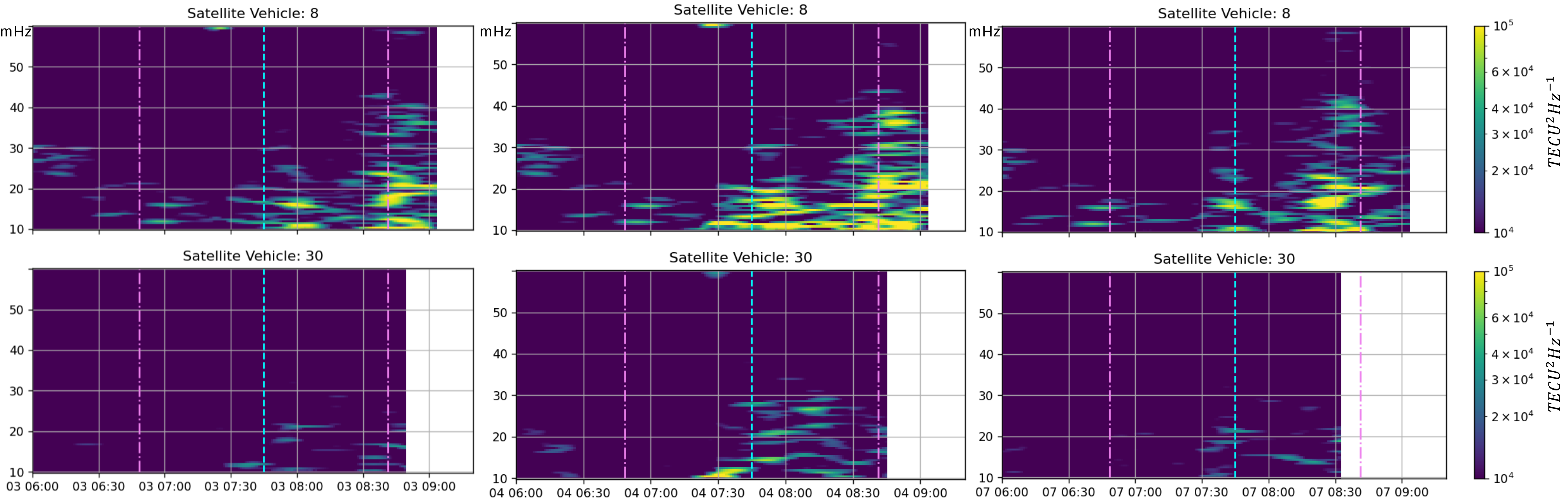
- Eclipse onset: 0530UT
- Eclipse peak: 0733UT
- Substorm onset: 0640UT
- Substorm peak: 0720UT
- Substorm $|\Delta B|$: ~300nT (~450kA)





GPS TEC

- TEC comparison across several days shows distinct increase on day of eclipse



Dec 3

Dec 4

Dec 7

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The Coincident Substorm: A Pesky Detail

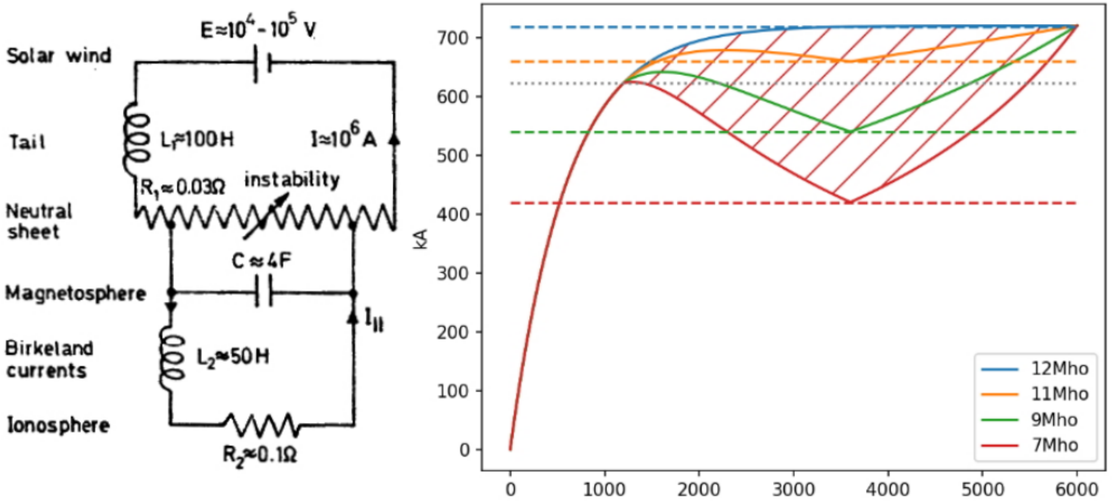

Figure 7. Circuit schematic of the SWMI system as in Boström (1974). During an eclipse, the ionospheric load changes rapidly and acts more like a variable resistance. An example current profile of the series LR circuit representing magnetosphere-ionosphere currents is given for $V_{PC} = 60kV$ (from Weimer), $L_{FAC} = 50H$ and $R_{iono} = 12^{-1}\Omega$. The resistance value is varied linearly from $12^{-1}\Omega$ to $7^{-1}\Omega$ for a time to simulate an eclipse. The area between the curves represents a difference in energy dissipation through the ionosphere because of the reduced conductivity.

- Increased resistance, decreased current - Ohms Law
- Integration of deviated energy for eclipse on order of $2 \cdot 10^{14} J$
- Similar to requisite tail destabilization energy

A Review of Studies of Geomagnetic Storms and Auroral/Magnetospheric Substorms Based on the Electric Current Approach

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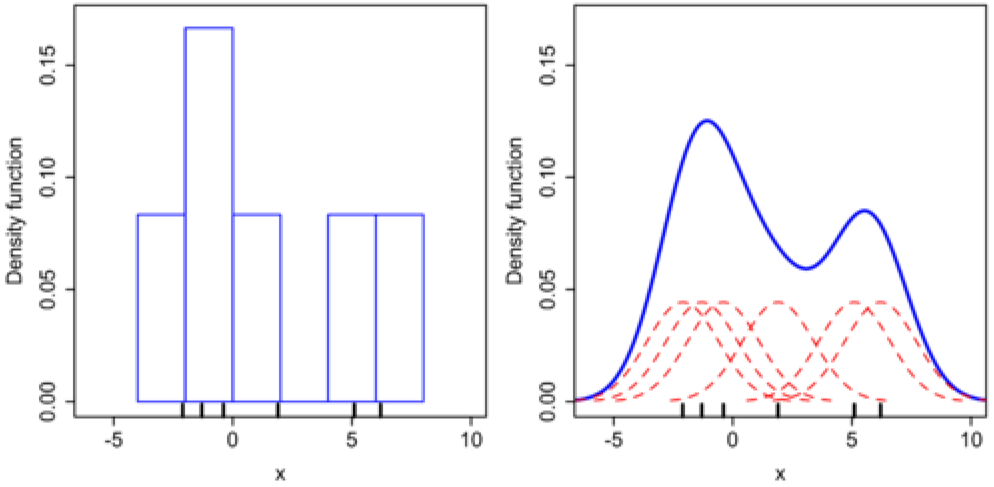
International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, United States

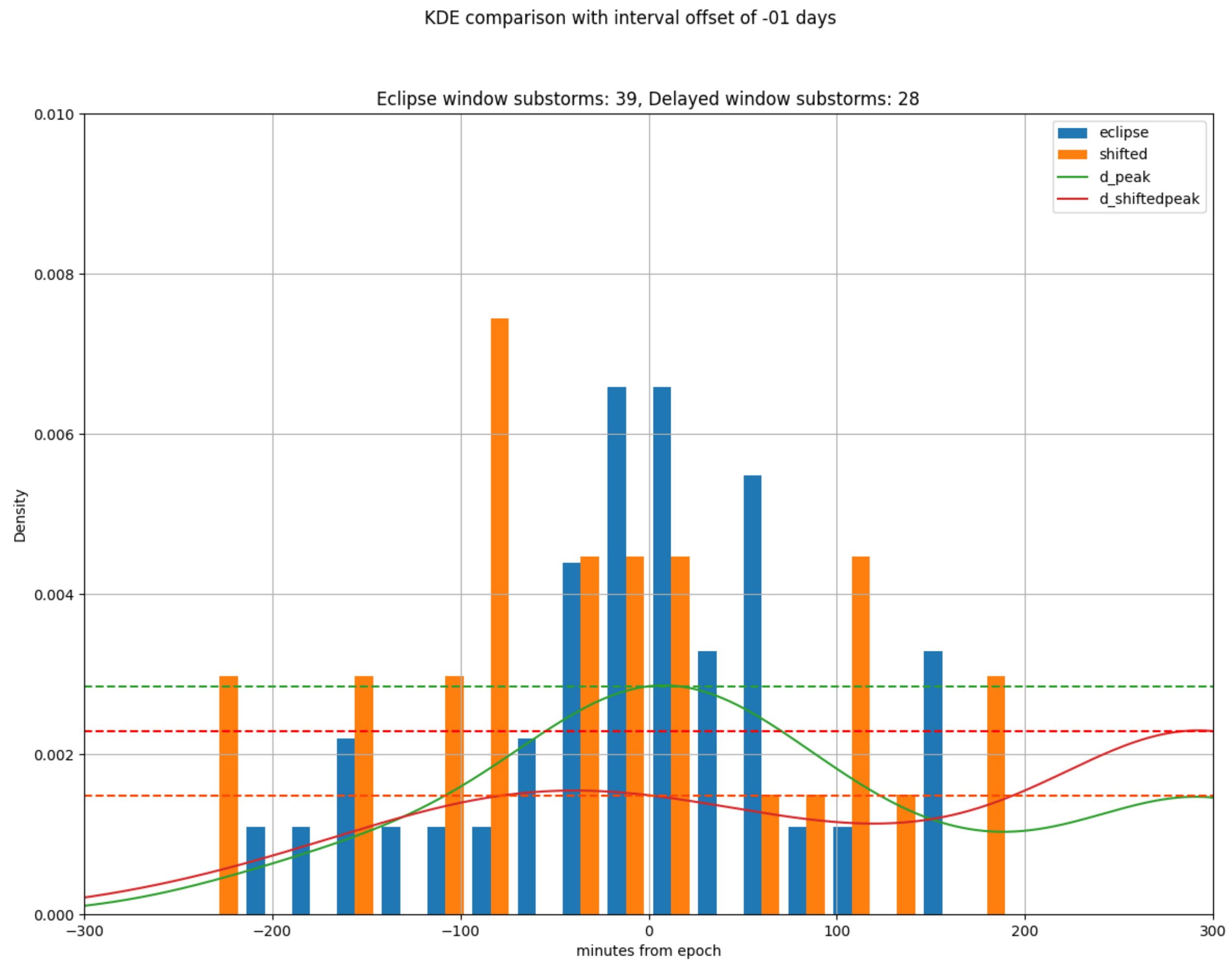
Gaussian Kernel Density Estimation

- Estimate of the PDF of a random variable
- Relies on finite sampling, a basis kernel, and a smoothing parameter
- $\widehat{f_h}(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i)$
- In essence:
  - Take histogram $(x_1, x_2, \dots, x_n)$
  - Apply weighted Gaussian (K_h) to each sample
  - Sum and Normalize $\left(\frac{1}{n}\sum_{i=1}^{n}\right)$

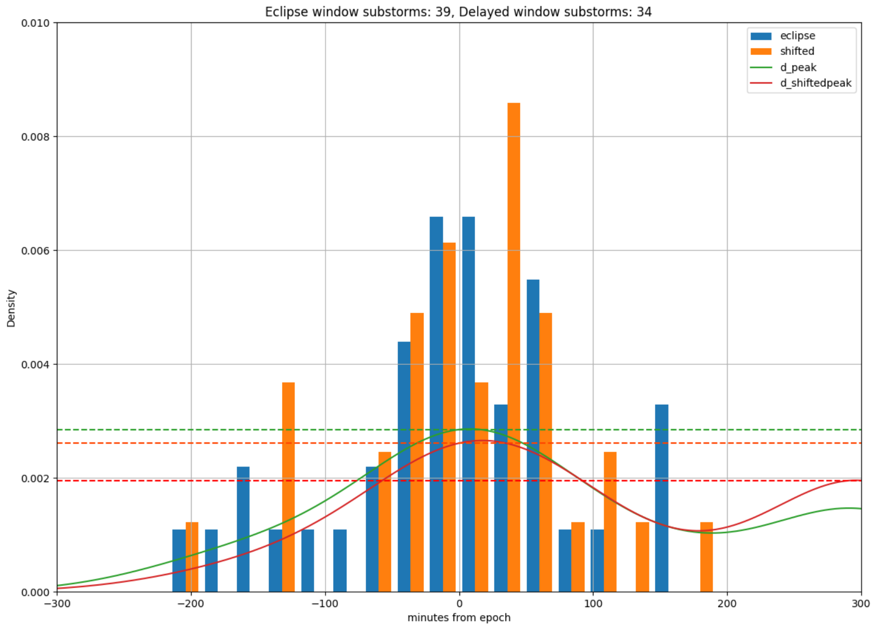


- Result is typically bimodal distribution
  - Distribution centered at eclipse peak
  - Distribution centered at value outside window representing null result

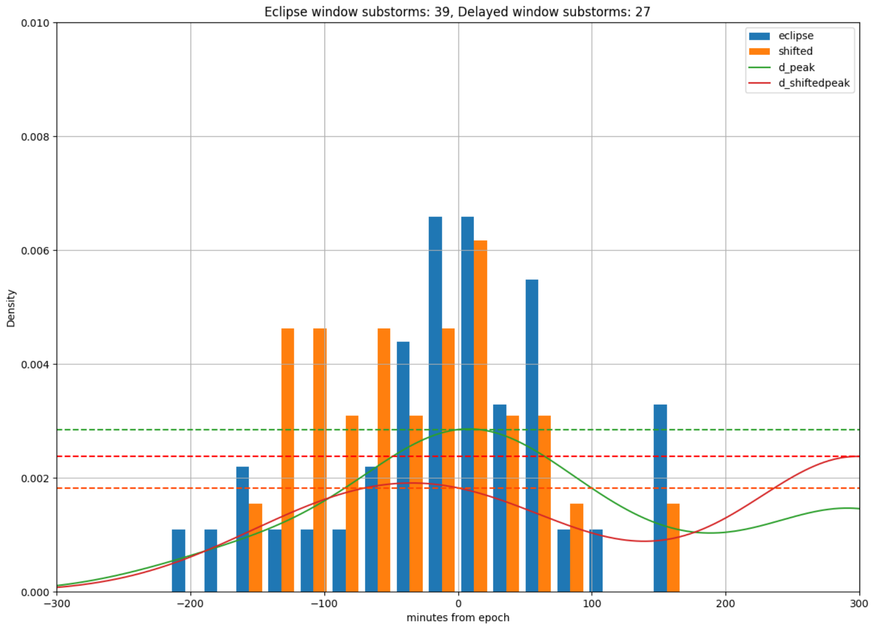
- Compare distributions between eclipse windows and offset
  - This isolates eclipse influence from random sample periods
- Eclipse windows are more closely distributed around epoch center
- Offset windows fail to capture as many substorms as eclipse window
- Multiple offsets have been applied:
  - +/- [0-7, 27, 180, 365] days

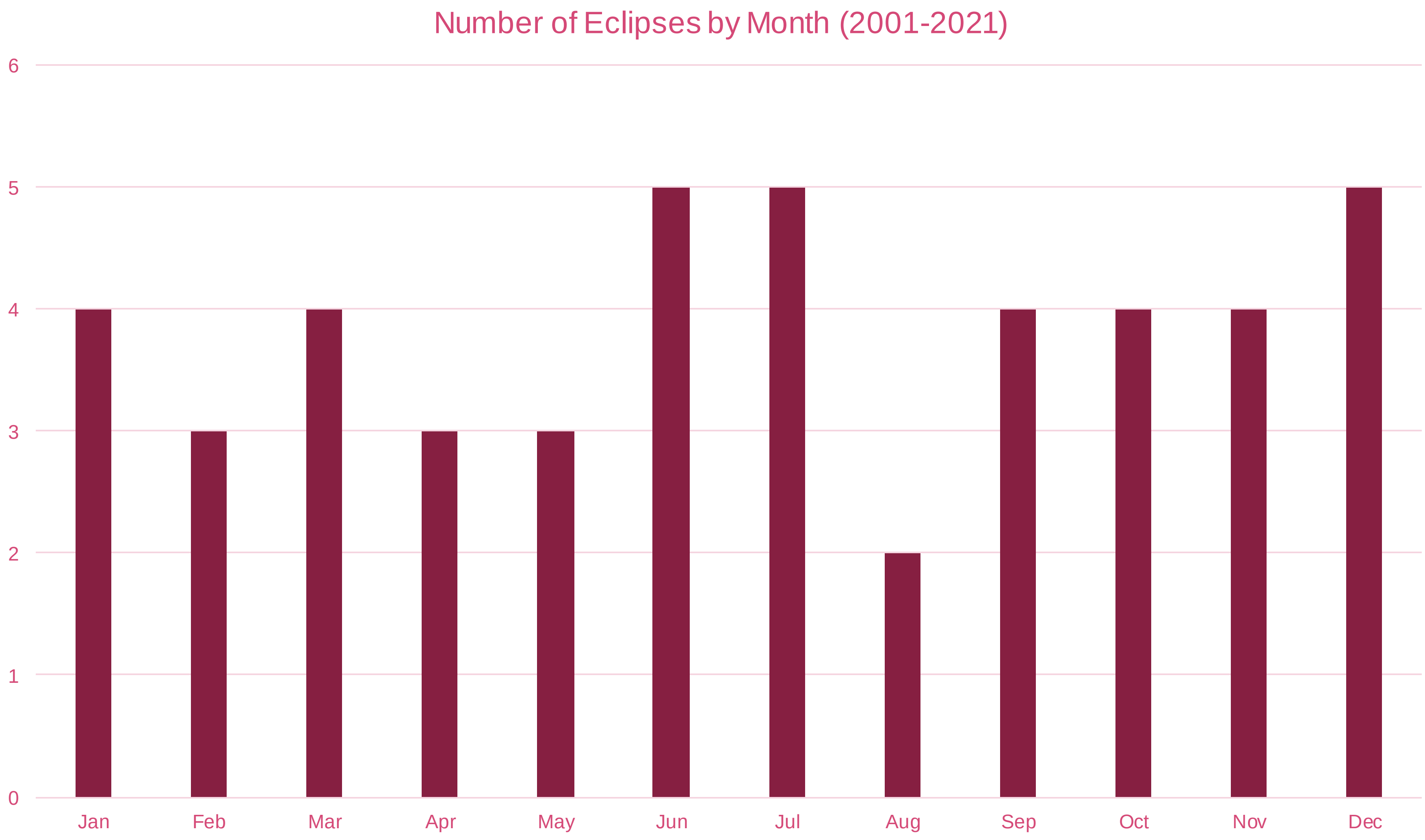


KDE comparison with interval offset of -02 days



KDE comparison with interval offset of 360 days




Number of Eclipses by Month (2001-2021)
6
5
4
3
2
1
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

PMI Results

- $x = PCIndex, y = substorms$
  - $p(x_1) \cong 0.2358$
  - $p(y_1) \cong 0.3954$
  - $p(x_1)p(y_1) \cong 93.2353e^{-3}$
  - $p(x_1, y_1) \cong 93.2545e^{-6}$
  - $npmi(x_0; y_0) \cong 0.1595$
  - $npmi(x_1; y_0) \cong -0.1869$
  - $npmi(x_0; y_1) \cong -0.2838$
  - $npmi(x_1; y_1) \cong 0.2109$
  - $\boldsymbol{I(X;Y) \cong 0.0605}$

- $x = B_z N\ Turn, y = eclipses$
  - $p(x_1) \cong 0.9832$
  - $p(y_1) \cong 0.4998e^{-3}$
  - $p(x_1)p(y_1) \cong 491.40336e^{-6}$
  - $p(x_1, y_1) \cong 0.4914e^{-3}$
  - $npmi(x_0; y_0) \cong -1.4947e^{-5}$
  - $\boldsymbol{npmi(x_1; y_0) \cong 0.0099}$
  - $\boldsymbol{npmi(x_0; y_1) \cong 5.9847e^{-5}}$
  - $\boldsymbol{npmi(x_1; y_1) \cong -274.1473e^{-3}}$
  - $\boldsymbol{I(X;Y) \cong 88.4764e^{-9}}$

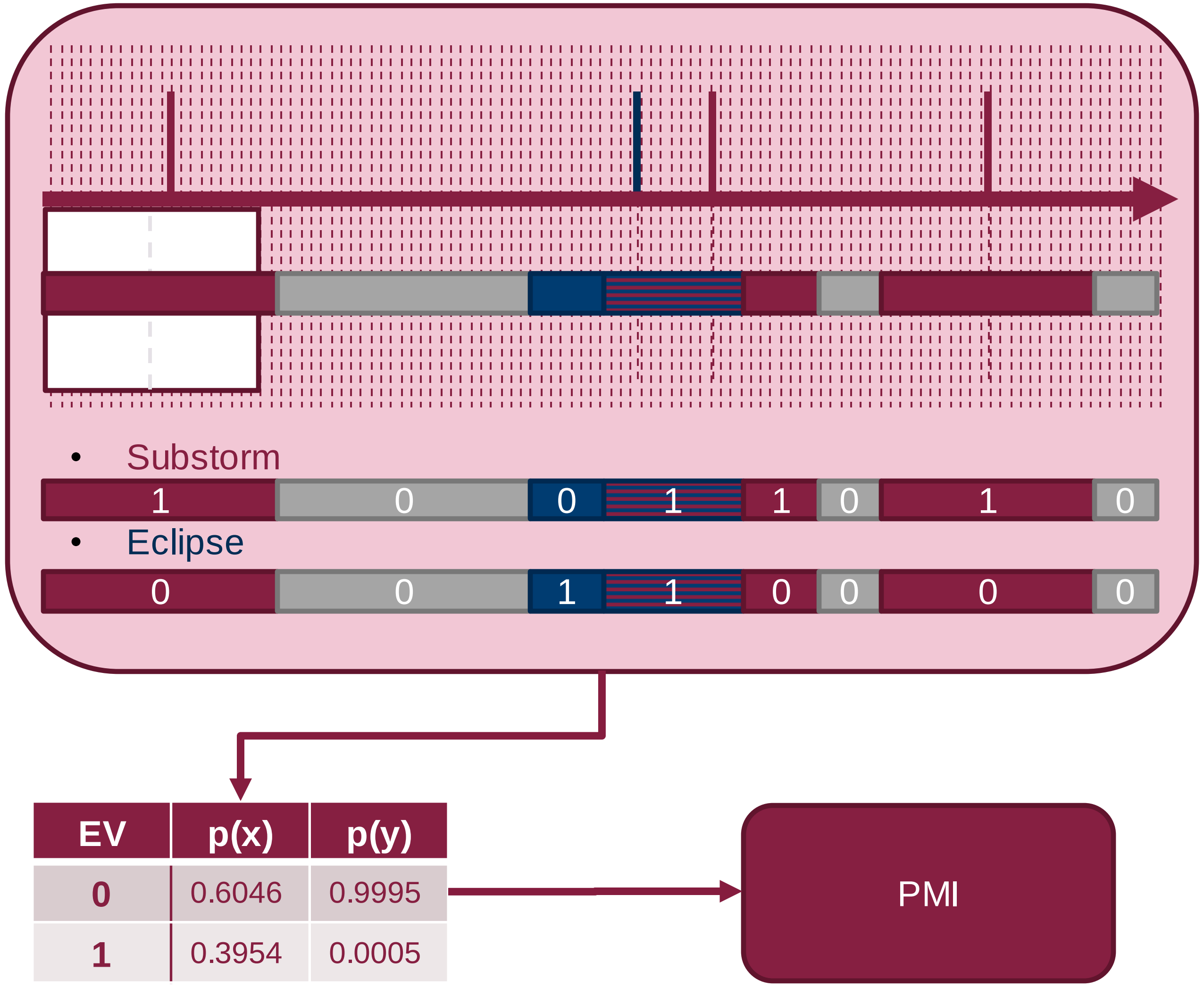
CPMI Results

- Determine sensitivity to other variables:
  - $p(z)$ = times when PC index > 5.5
- Again, information gained is small relative to original score
  - $\frac{-731.7228e^{-9}}{13.2102e^{-6}} \cong 5.5\%$
- Trend remains the same:
  - More likely than random chance that substorms and eclipses will co-occur
  - Less likely than random chance that eclipses occur without a substorm within the same 2H window.

- $p(x_1) \cong 0.3954$
- $p(y_1) \cong 0.4998e^{-3}$
- $p(z_1) \cong 0.0310$
- $p(x_0, y_0, z_0) \cong 0.5950$
- $p(x_1, y_1, z_1) \cong 12.1324e^{-6}$
- $pmi(x_0, y_0, z_1) \cong 332.3225e^{-6}$
- $pmi(x_1, y_0, z_1) \cong -144.5541e^{-6}$
- $pmi(x_0, y_1, z_1) \cong -0.9967$
- $pmi(x_1, y_1, z_1) \cong 0.2833$
- $\boldsymbol{npmi(x_0, y_1, z_1) \cong -0.0530 < 0}$
- $\boldsymbol{npmi(x_1, y_1, z_1) \cong 0.0173 > 0}$
- $I(X;Y|Z) \cong 13.2102e^{-6}$
- $\boldsymbol{I(X;Y) - I(X;Y|Z) \cong -731.7228e^{-9}}$

Pointwise Mutual Information

- $pmi(x; y) \equiv log \frac{p(x,y)}{p(x)p(y)}$
- Quantified discrepancy between probability of coincidence
- Joint distribution over individual distributions
- EX: probability a substorm occurs in a given window
  - $p(x) = \frac{number\ of\ windows\ with\ a\ substorm}{total\ number\ of\ windows}$
- PMI can be normalized between [-1, 1]
  - $npmi(x_1; y_1) \cong \frac{pmi(x_1;y_1)}{-\log p(x_1,y_1)}$
  - -1: never occurring together
  - 0: independent variables
  - 1: complete co-occurrence

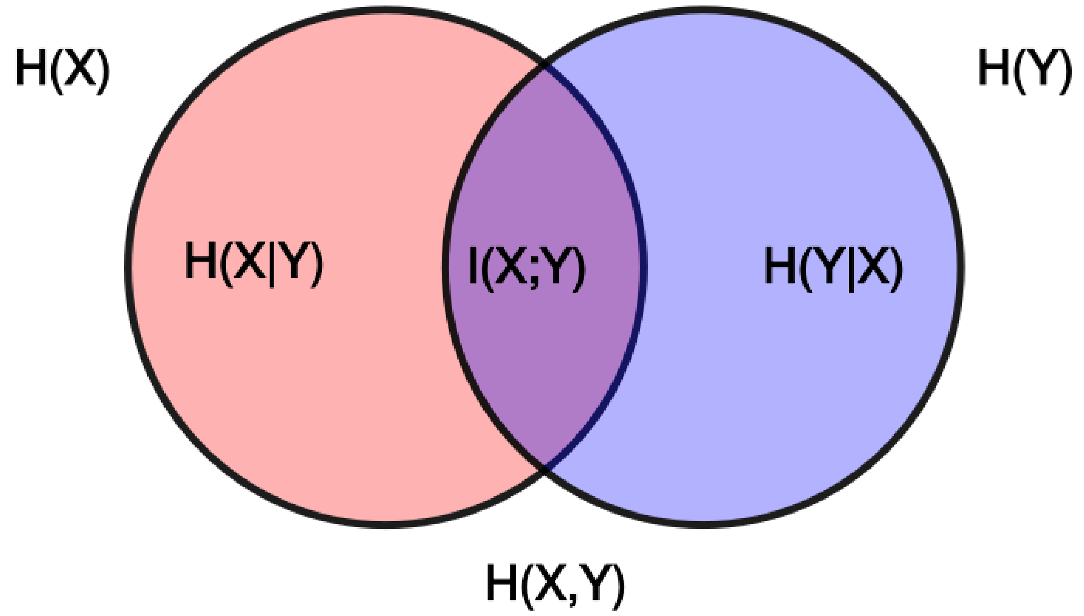


EV	p(x)	p(y)
0	0.6046	0.9995
1	0.3954	0.0005

Information Entropy

By example

- $H(X) = -\sum_{i=1}^{n} p(x_i) \log_2 p(x_i)$
- Information Entropy is the quantified uncertainty of an outcome
- For a fair coin, $H(X) = 1$
- For an unfair coin, $H(X) < 1$
- "Death and taxes have an information entropy of 0."



Mutual Information (MI)

An Example

- Think of something grey, with 4 legs
- You're likely thinking of a table, right?
  - Maybe if you're a generative AI
- More likely, you thought of an elephant
- We can condition the MI by the "has a long nose" variable
- MI is a measure of the overlapping area between variables

Mutual Information (MI)

Non-Linear Correlation

- **Correlation** typically refers to linear correlation between x, y
- **Uncorrelated** variables x, y may have identifiable dependence
  - $x^2 + y^2 = 4$
  - $y = \sin x$
- PMI quantifies regional dependence in function space
- Does not inform about type of relationship, only strength