SIEMIC
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LIVING PLANET FELLOWSHIP
ATMOSPHERE

Swarm Investigation of the Energetics of Magnetosphere-Ionosphere Coupling

- Determine the relative contribution of various scales to total magnetosphere-ionosphere energy transfer budget for different seasons and orbital configurations, particularly focused on Alfvén wave enegy contribution

- Determine the degree of inter-hemispheric asymmetry in Poynting flux energy transfer, if any, for different seasons and orbital configurations

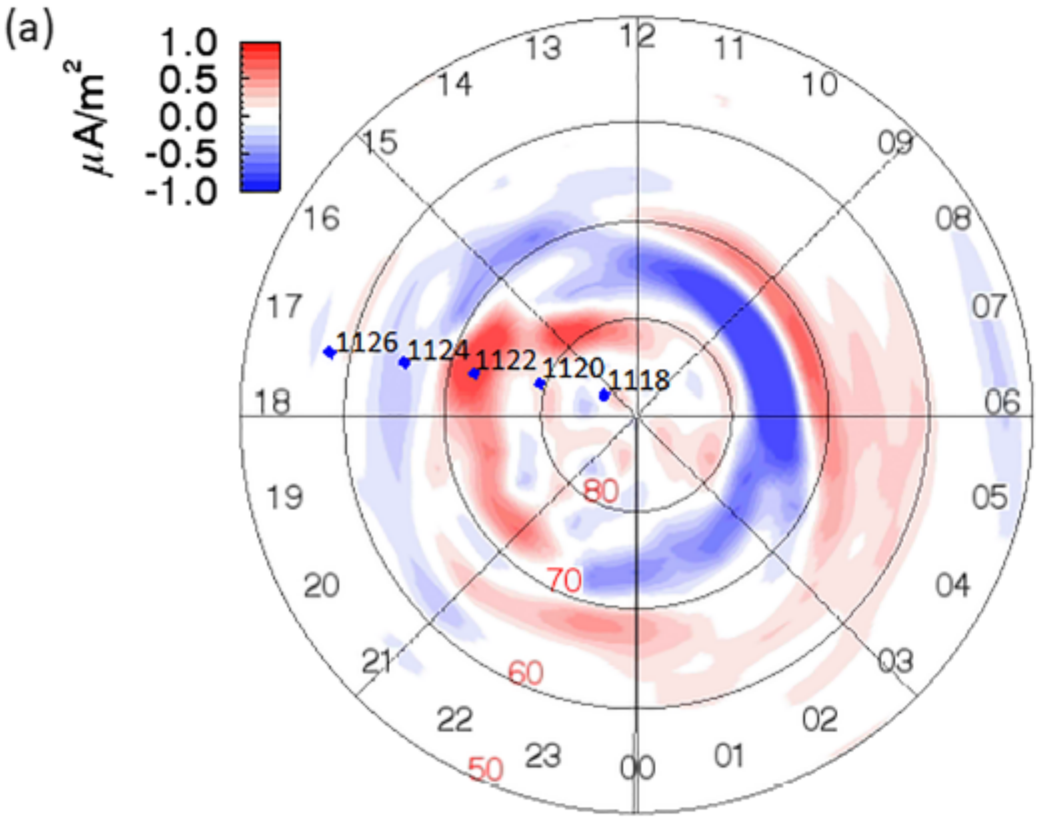
- Calculate total numbers representing Poynting flux energy flow observed by Swarm at mid- and high-latitudes using statistical simultaneousy electric and magnetic field observations

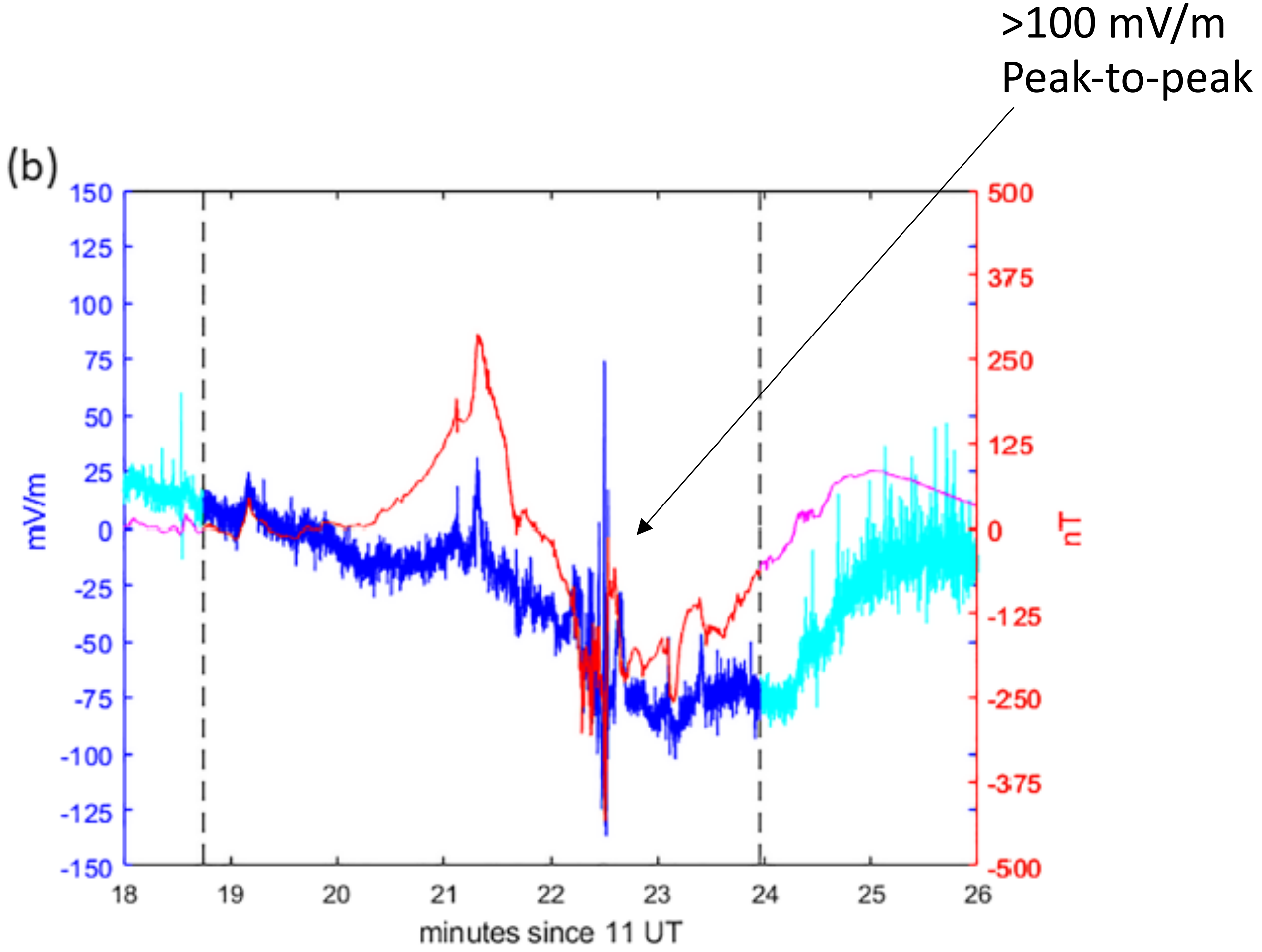
Project Overview -Aims

The original proposal focused on five topics; a sixth topic was added later:

- Demonstrating the prevalence of **Alfvén waves during southward IMF** conditions. ***Journal of Geophysical Research: Space Physics, accepted (2020). doi.org/10.1029/2019JA027277***
- Showing the **north-south Poynting flux asymmetry. *Nature Communications, accepted (2020). doi/10.1002/essoar.10502993.1***
- Analysing Poynting **flux scale dependence** at Swarm altitudes. *Presented at Fall AGU 2019*
- Paper showing Swarm observations of **Alfvén -compressional mode coupling** of Pc1 waves, in particular demonstrating how the Swarm A/C pair may be used to triangulate the energy source ***(with co-authors, to be submitted to GRL Special Issue)***
- One paper to show how the histogram E/B ratio method may be used to infer **Pedersen conductance** below Swarm *(to be submitted to GRL Special Issue)*
- *Extra topic: **Swarm as a radiation belt/EMIC monitor** – presented at Swarm 9 DQW in Prague (2019)*

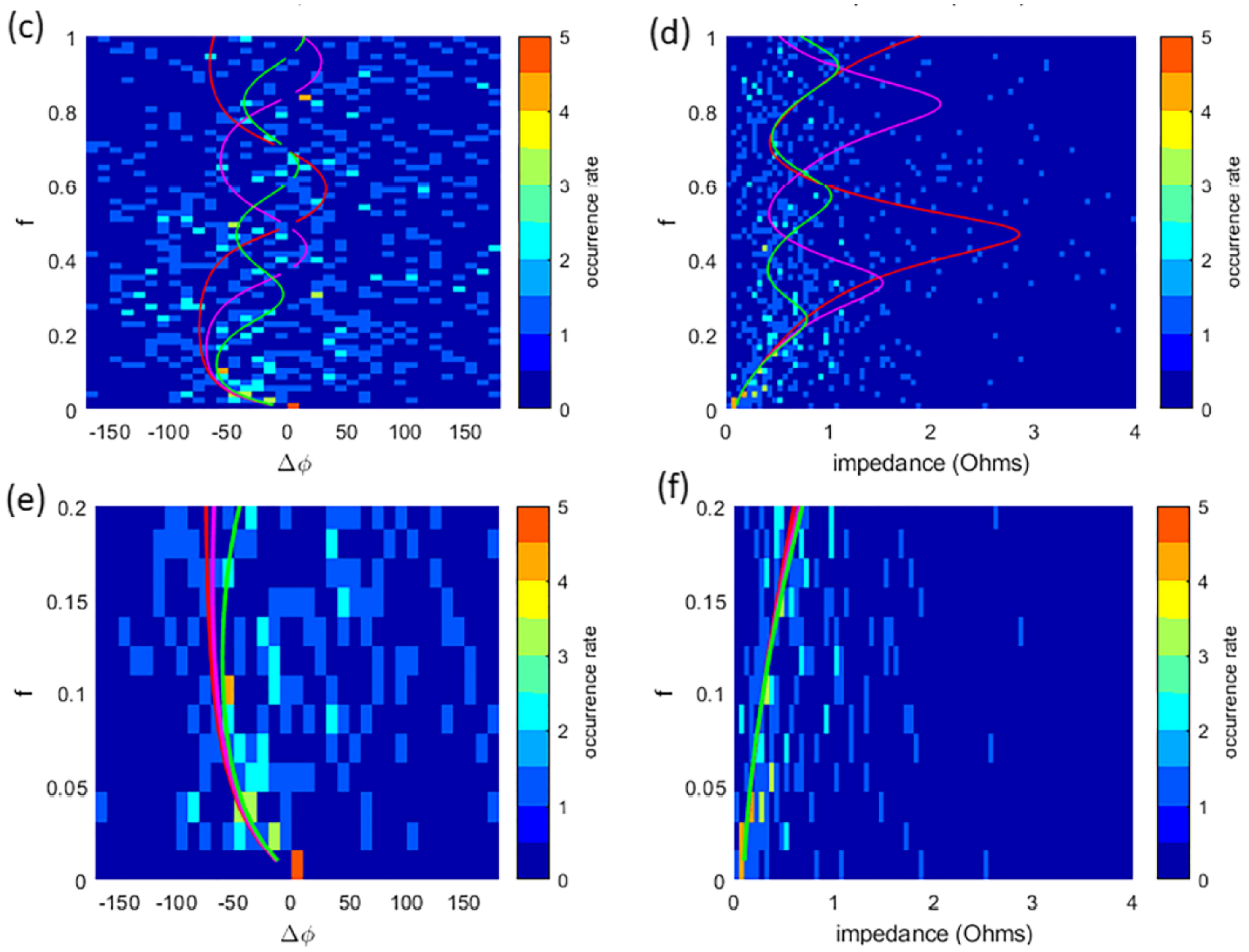
Alfven waves within field-aligned currents





Reproduced from Pakhotin et al. (2020a)

Alfven waves within field-aligned currents



The E/B ratio may be used to differentiate Alfven waves from FACs

For a FAC, the E/B ratio should be a frequency-independent value mapping to Pedersen conductance; E-B phase should be zero

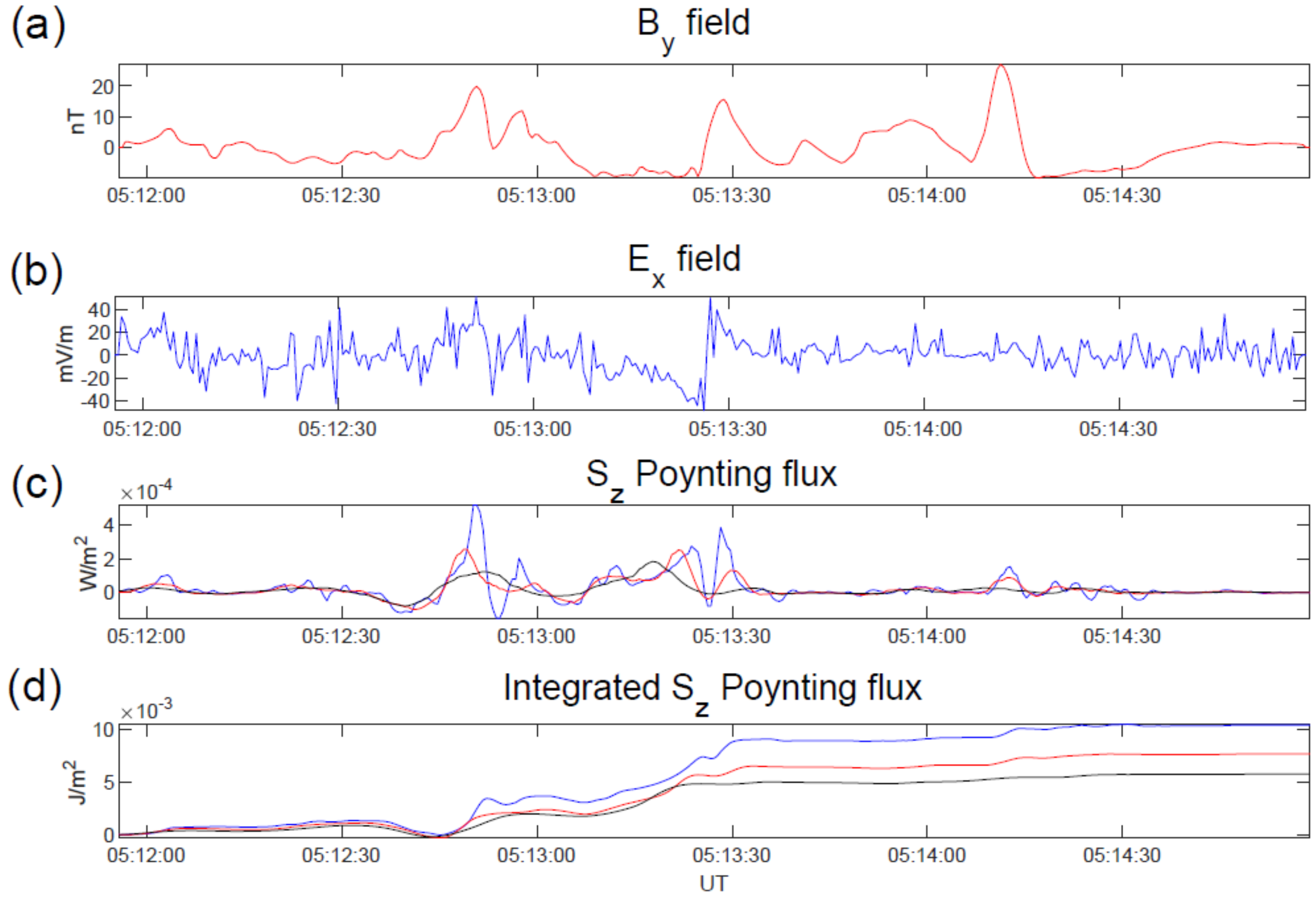
For free-travelling Alfven wave, it should be a frequency-independent value mapping to Alfven speed; E-B phase should be zero

For incident and reflecting Alfven waves, it should be a frequency-dependent function; E-B phase can vary within typically +-90

This third case is typically observed in Swarm auroral zone crossings

Left: reproduced from Pakhotin et al. (2020a)

North/South Asymmetry - algorithm

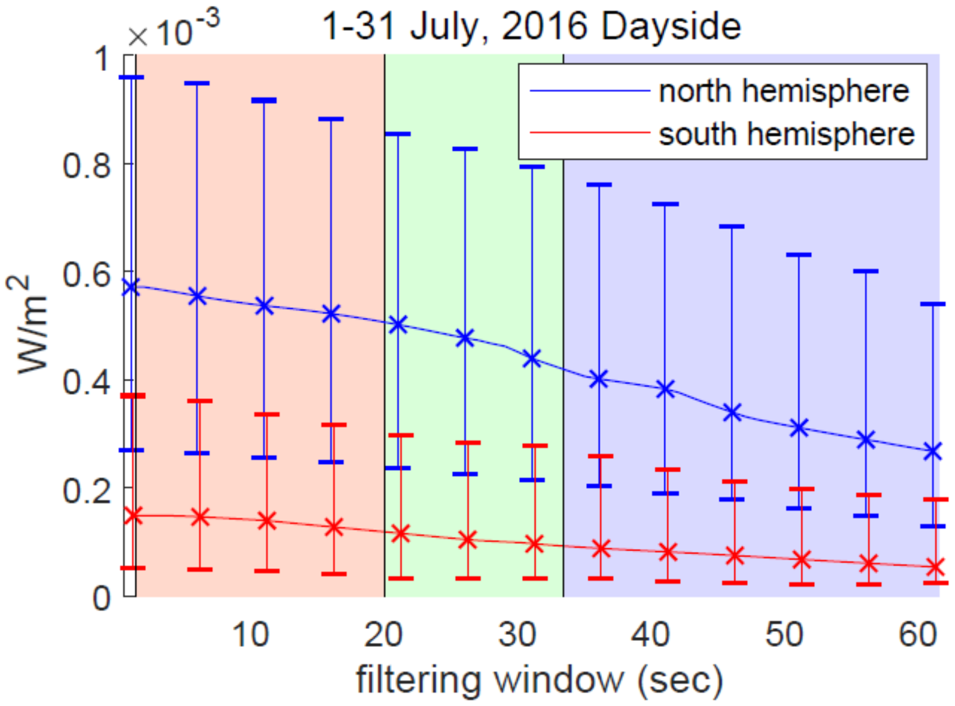


Reproduced from Pakhotin et al. (2020b)

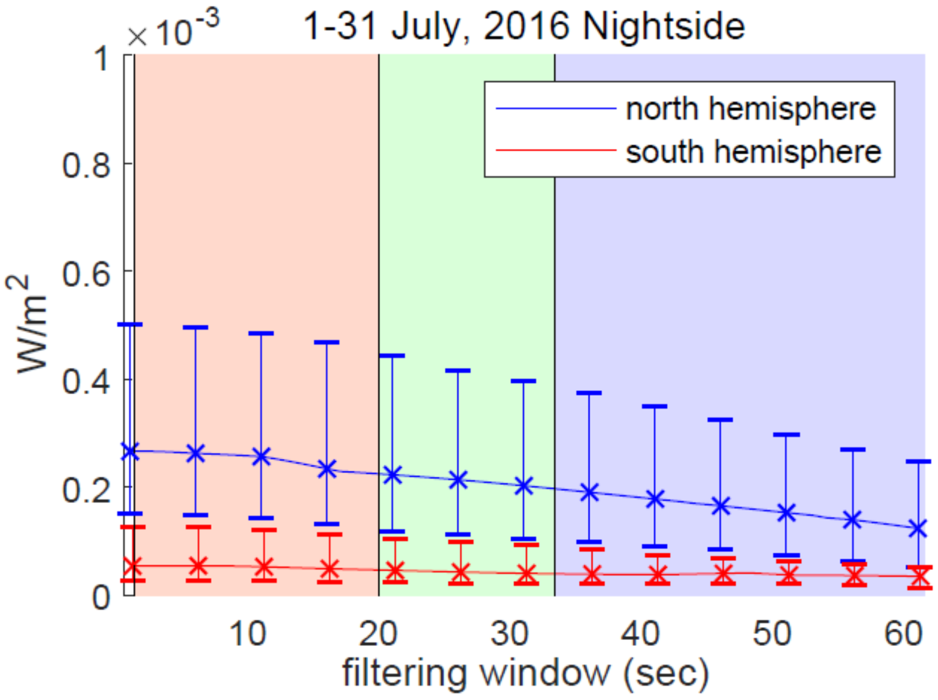
Reprocessed with TII v0301 dataset

North/South Asymmetry – northern summer

summer dayside



summer nightside

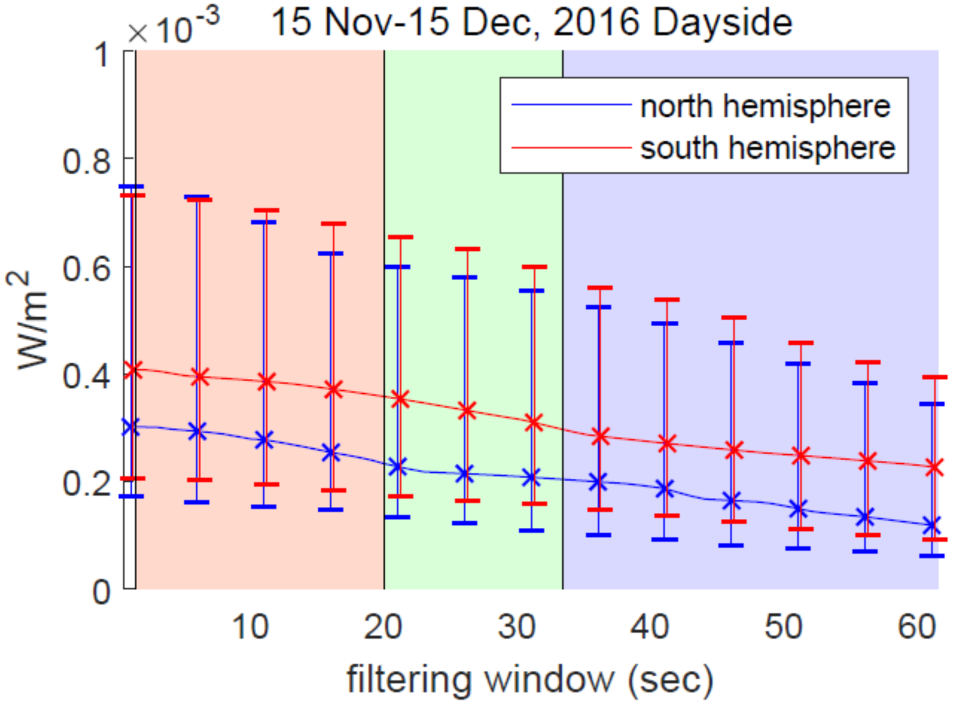


Reproduced from Pakhotin et al. (2020b)

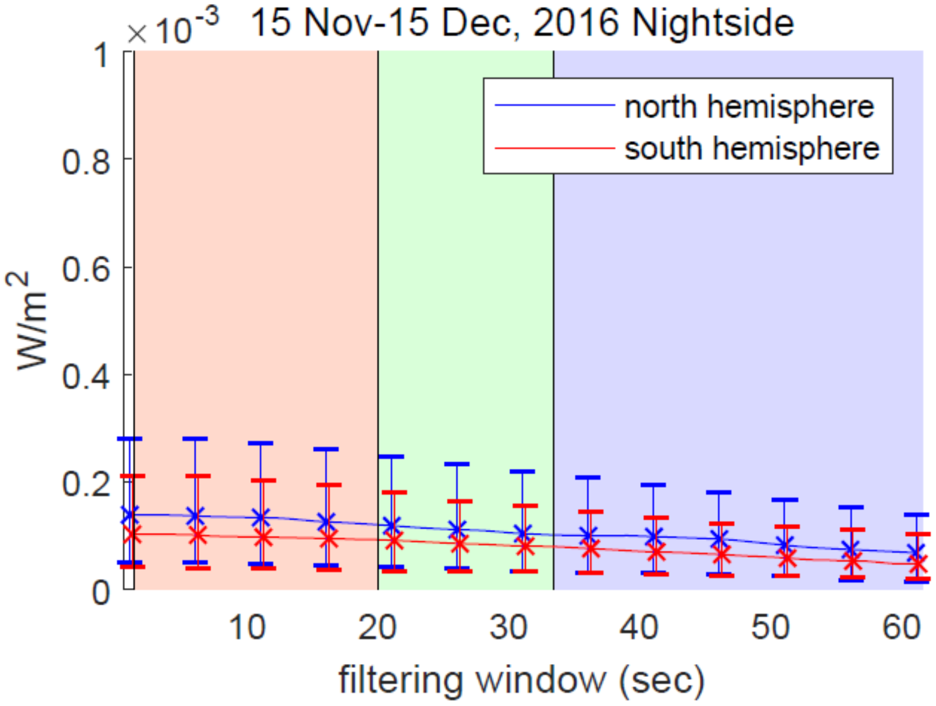
North/South Asymmetry – northern winter

Reproduced from Pakhotin et al. (2020b)

winter dayside

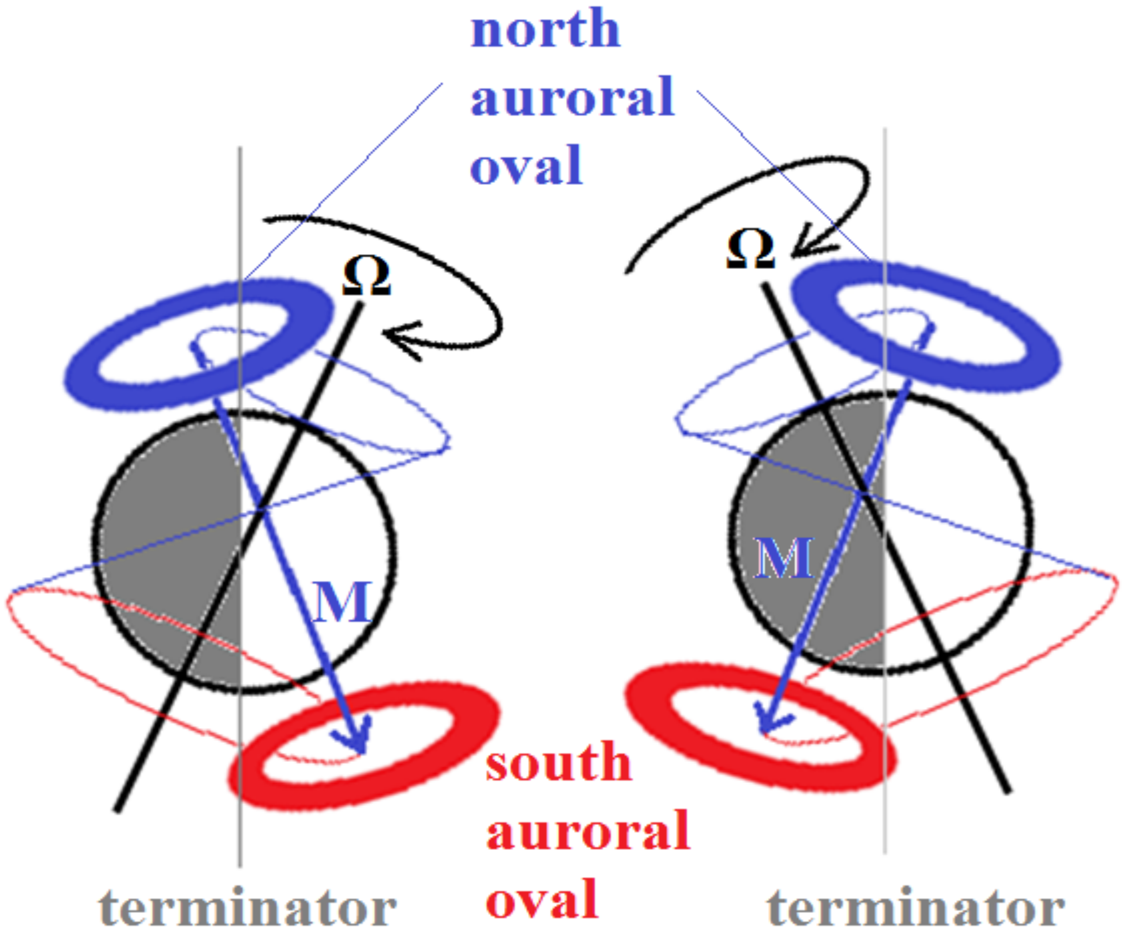


winter nightside



Seasonally averaged energy input <u>not</u> symmetric!

North/South Asymmetry – offset dipole

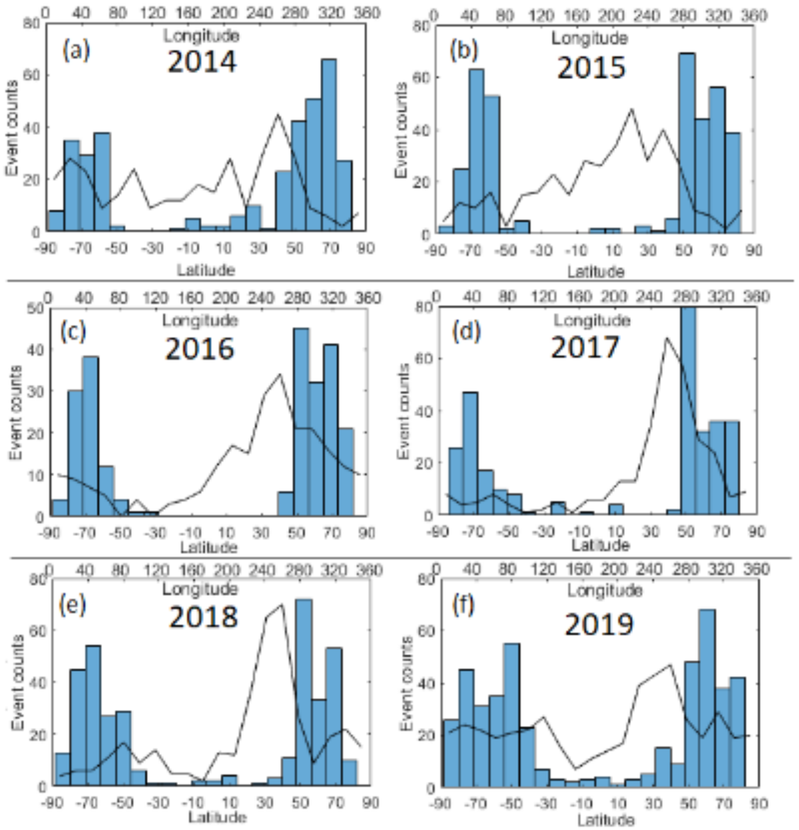


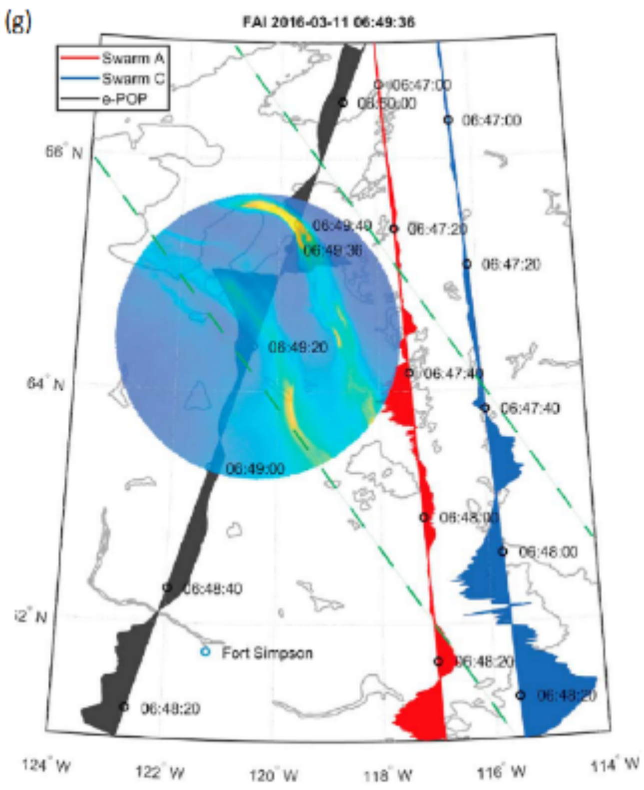
- the center of the magnetic dipole is ~ 500 km **northwards** of Earth's center

- As such, the effective surface offset of south mag pole from rotation axis is ~**8.5 deg more** than north mag pole

- the south oval extends **further** into both light and dark illumination regions

North/South Asymmetry – nightside





(Reproduced Fig. 1(a) from Miles et al. (2018))

Swarm observes **residual energy below AAR**

On nightside, small-scale discrete arcs may preferentially drain energy in south hemisphere

Maybe more/stronger auroras in south hemisphere?

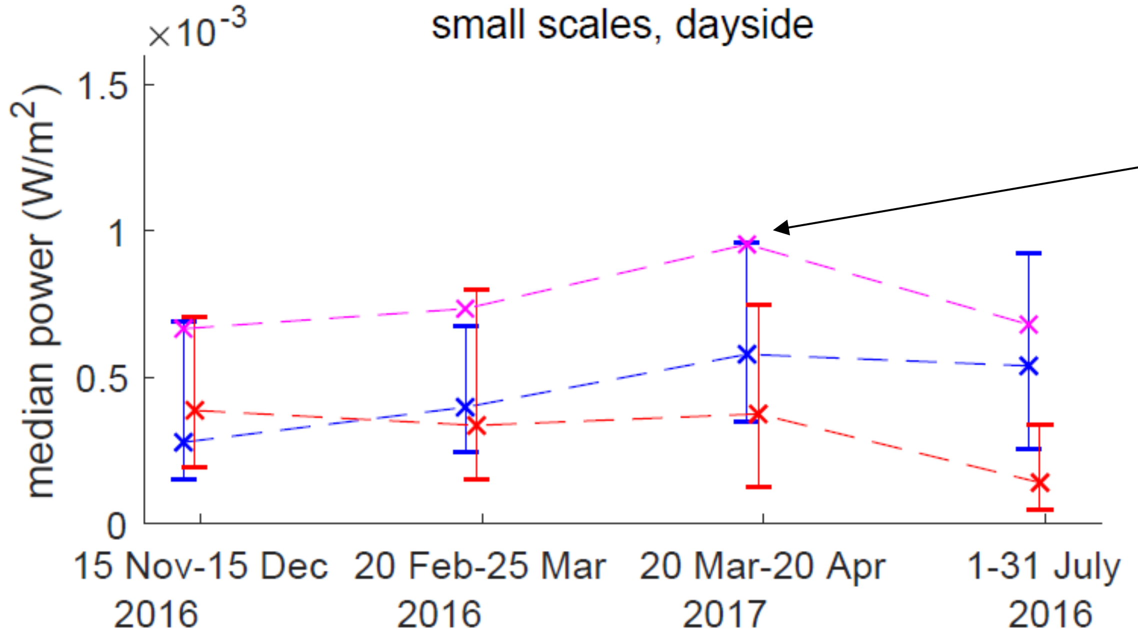
This would result in less Poynting flux left over in south hemisphere at Swarm altitudes

- **Swarm-Echo** (formerly CASSIOPE e-POP) carries the Fast Auroral Imager to observe discrete arcs. A database of events has been collected over several years

- **Multi-satellite approaches** make it possible to conduct detailed studies of discrete arc events at small scales

North/South Asymmetry – dayside

Possible redistribution of incoming energy away from one hemisphere to the other



Russell-McPherron Effect?

Blue: north hemisphere, red: south hemisphere, pink: sum total

Reflection Coefficient

- The reflection coefficient may be approximated as in e.g. Knudsen et al. (1992):

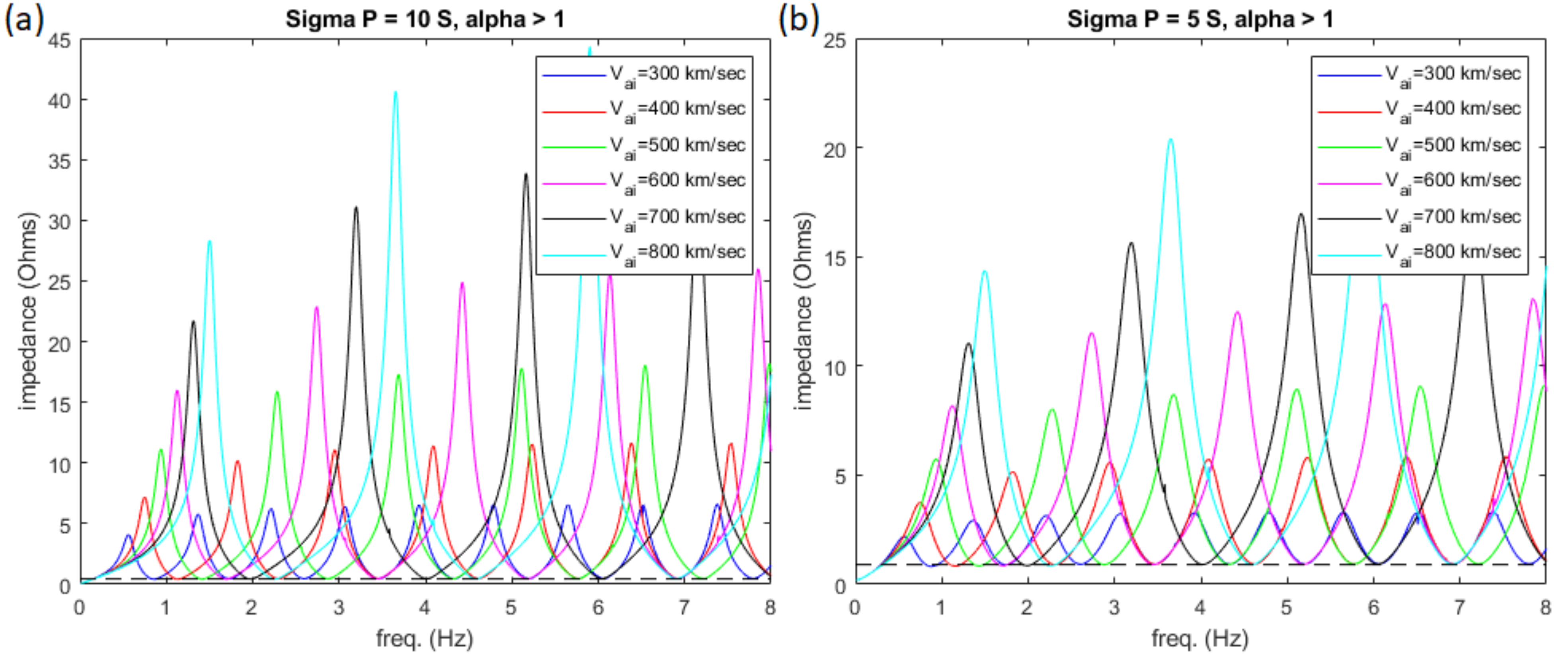
$$\Gamma = \frac{(\Sigma_P^{-1} \; - \; Z_A)}{(\Sigma_P^{-1} + \; Z_A)}$$

- i.e. The mismatch between Pedersen impedance and Alfven impedance
- If the Alfven impedance (μ0 * Va) is matched to height-integrated Pedersen impedance, no reflection takes place (Poynting flux goes straight down)
- In practice, there is always some mismatch; the greater the mismatch the greater the amount of reflection
- Pedersen conductance is affected by EUV insolation and discrete arc precipitation; these effects are not hemispherically symmetric

Reflection Coefficient and Alfven waves

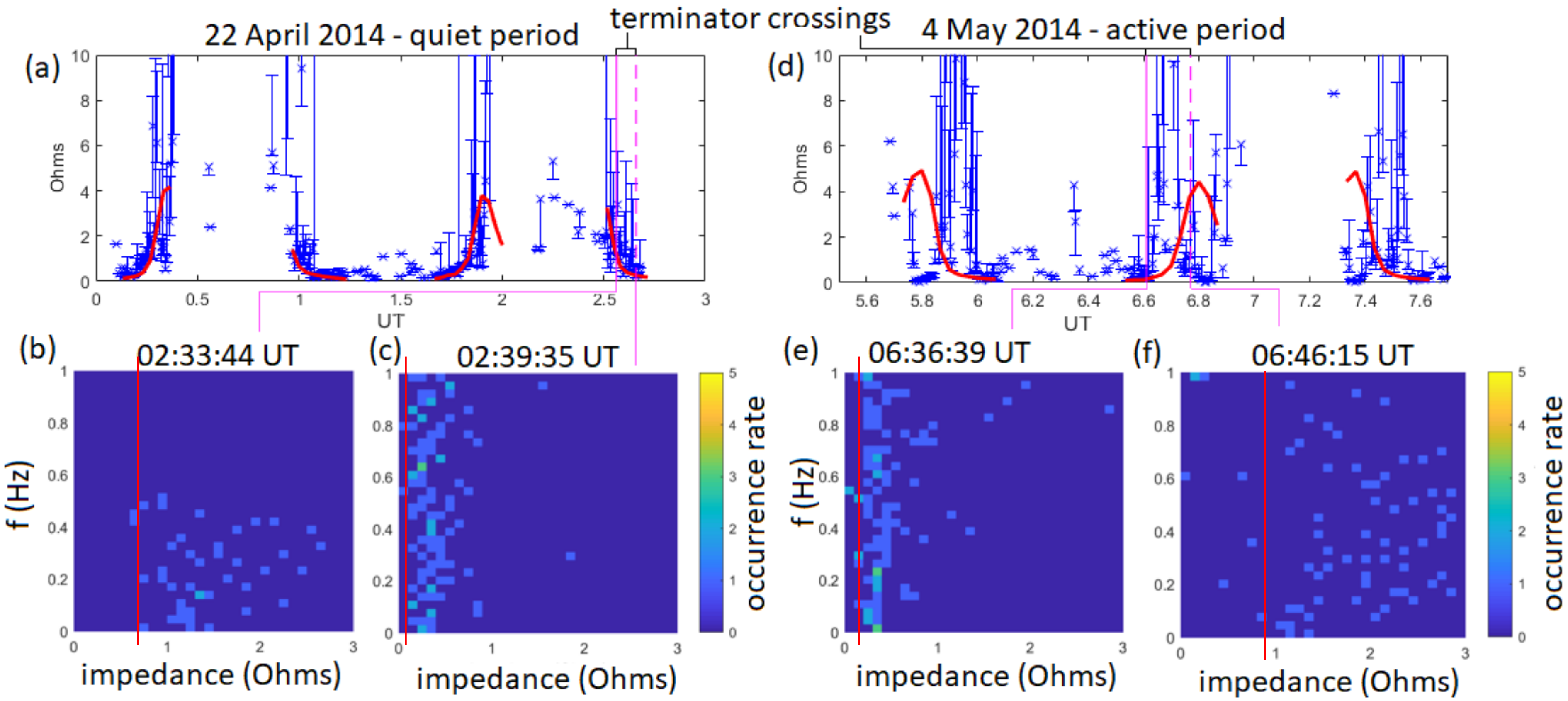
- Calculating Alfven impedance requires knowledge of ionospheric Alfven speed (function of mass density)
- Proposed Daedalus mission (Sarris et al., 2020) will greatly improve our understanding of E-layer chemistry
- Meanwhile Pedersen conductance is hard to measure at small scales
- E/B ratio scatter plot will not yield Pedersen conductance at small scales in the presence of Alfven waves… and those are ubiquitous (e.g. Pakhotin et al., 2020a)
- Here we propose the use of histogram method to estimate Pedersen conductance when Alfven waves are present in the system

Lysak (1991) wave reflection simulations



- Assuming the Alfven impedance is generally greater than Pedersen impedance (e.g. Wu et al., 2020)…
- …and assuming that scale height does not change…
- …a range of Alfven speeds still yields a stable lower limit at f > 1 Hz, which may be mapped to Pedersen impedance

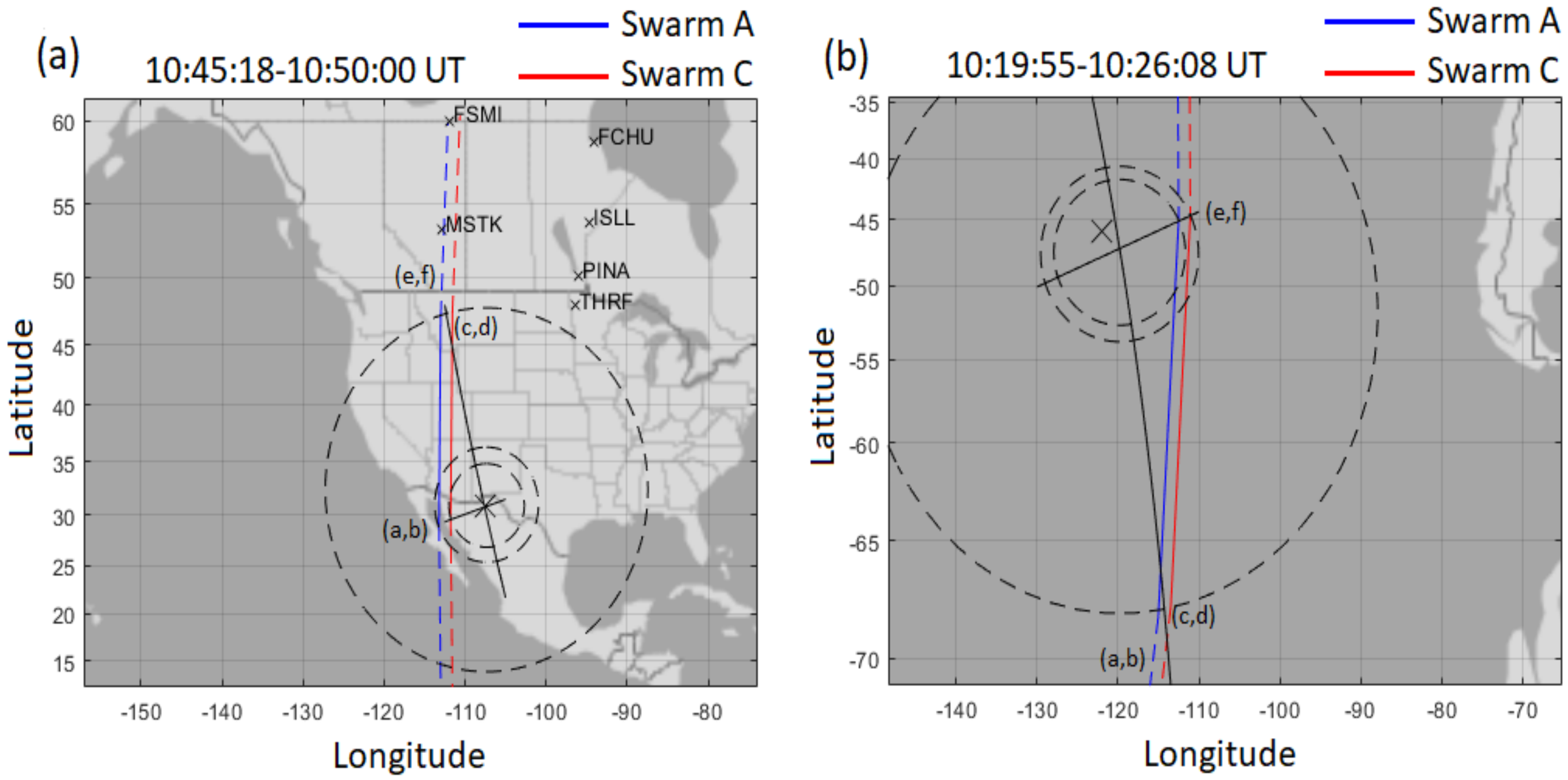
Pedersen Impedance during Terminator Crossings



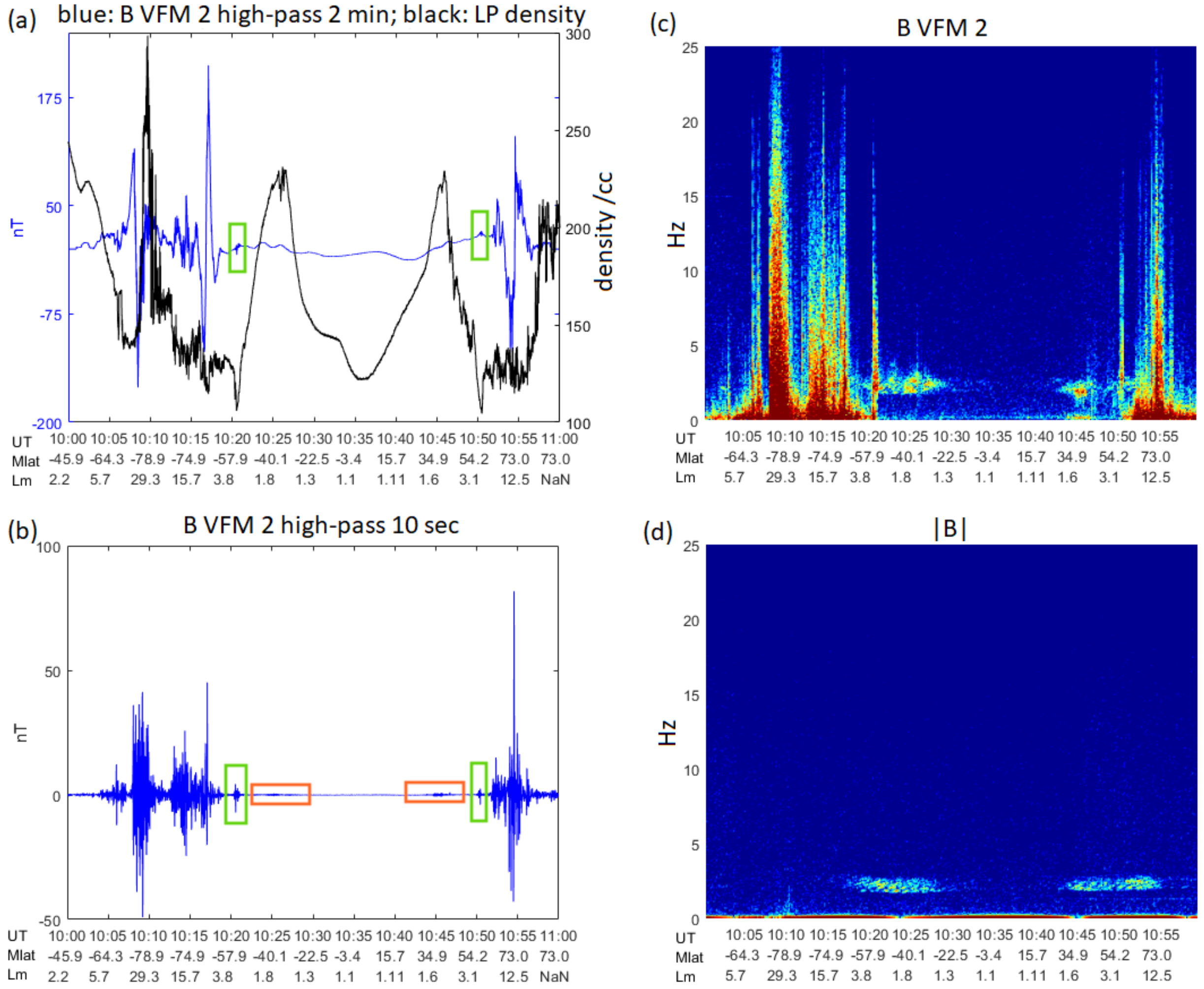
Small-Scale Pedersen Impedance Estimations

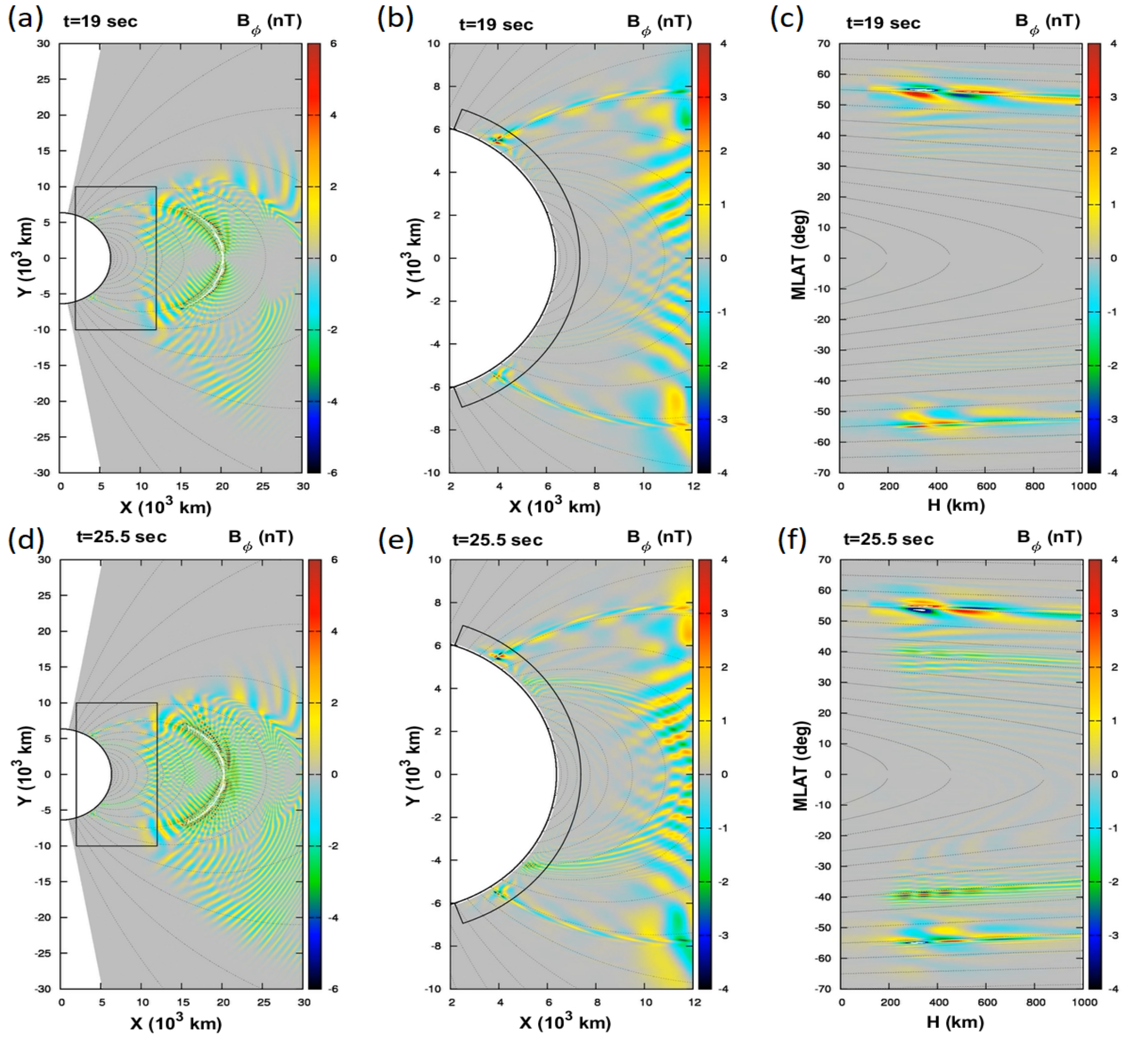
- The proposed methodology may serve to yield small-scale estimates of Pedersen impedance, making it possible to resolve feedback instability and discrete arc dynamics
- The estimated Pedersen impedance may be plugged into other equations, making it possible to derive other key ionospheric parameters
- Scale height may vary, particularly for terminator crossings… Multi-satellite approaches using Swarm A/Swarm B conjunctions (different heights) may yield both Pedersen impedance and scale height (2 equations; 2 unknowns)
- We are aiming to submit this publication to the GRL Special Issue on «Probing the Magnetosphere through Magnetoseismology and Ultra-Low-Frequency Waves» (deadline 31 Dec 2020)

Swarm A/C Fast/Shear Alfven Wave Coupling



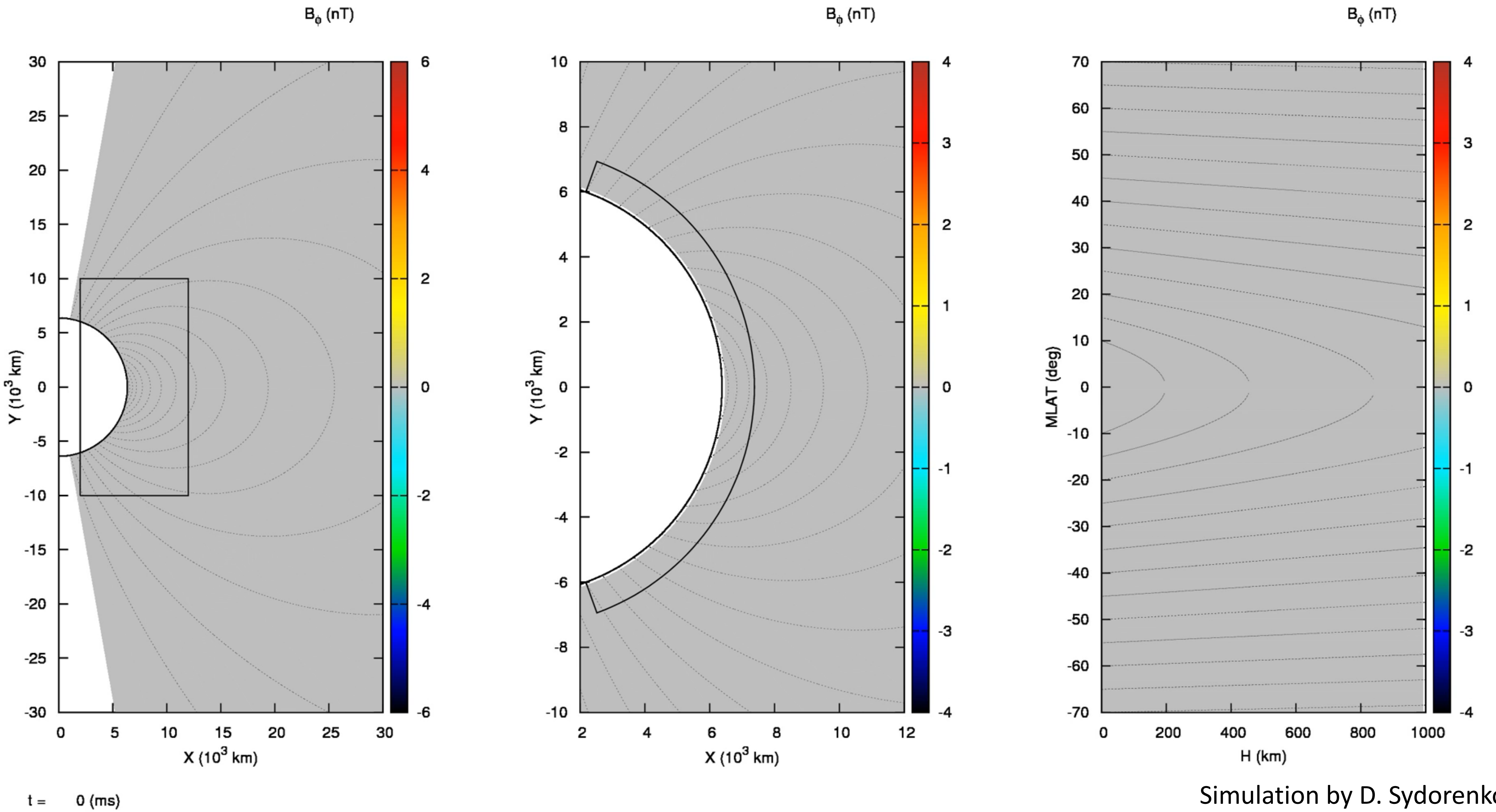
Swarm A/C Fast/Shear Alfven Wave Coupling





Above: simulation by D. Sydorenko, R. Rankin

Swarm A/C Fast/Shear Alfven Wave Coupling



Simulation by D. Sydorenko, R. Rankin

Swarm A/C Fast/Shear Alfven Wave Coupling

- Swarm A and C observe in situ conversion from shear to fast Alfven wave
- A <u>secondary peak</u> in wave power appears at lower latitudes than the main peak
- Modelling work by Robert Rankin and Dmytro Sydorenko show (1) wave power deflected equatorwards by Buschsbaum resonance, (2) waves arriving near equator, interfering with the same wave power pathway from opposite hemisphere, (3) pumping energy into field line, exciting FLR
- This complex set of behaviors is in complete agreement with Swarm observations
- Swarm may be used to validate wave propagation models under complex conditions; this may be used to infer <u>localized plasma chemistry compositions</u>

Conclusions

- The project has fulfilled its aims of resolving energy fluences as a function of scale, hemisphere, and season
- Peer-reviewed work has cemented strong evidence that small-scale Alfvenic effects are implicated in large-scale dynamics
- The developed and peer-reviewed algorithm for Poynting flux analysis makes it possible to conduct further statistics, particularly as new datasets become available
- A roadmap to further explore the discovered interhemispheric asymmetry in terms of small-scale dynamics will see Swarm constellation continue to play crucial role
- Foundations have been laid for use of Swarm for wider ionospheric analysis (e.g. small-scale Pedersen conductance; Swarm and model estimation of localised chemistry composition)
- Swarm was used to monitor localised yet intense EMIC waves which are implicated in rapid radiation belt depletion

Acknowledgements

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