SIEMIC

Ivan Pakhotin, University of Alberta

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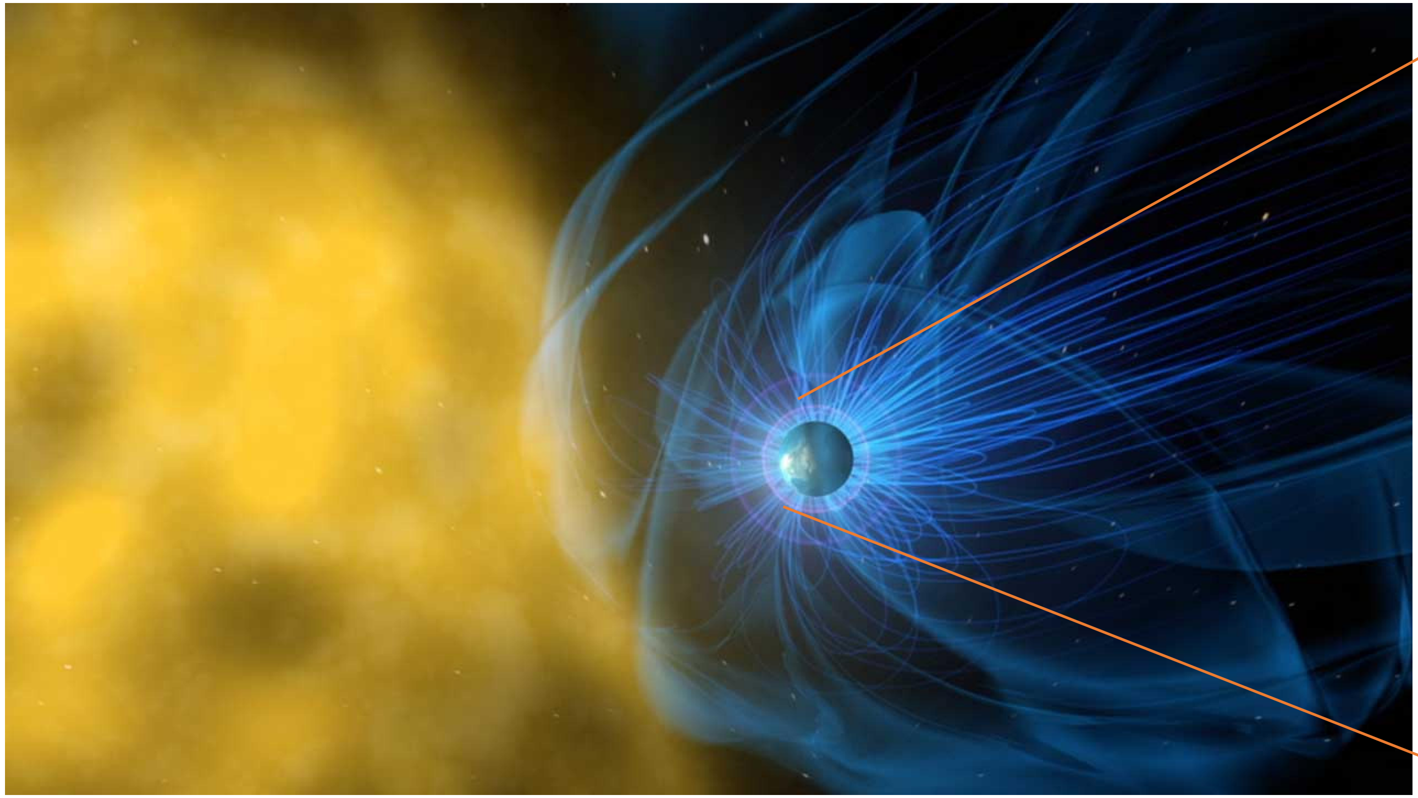
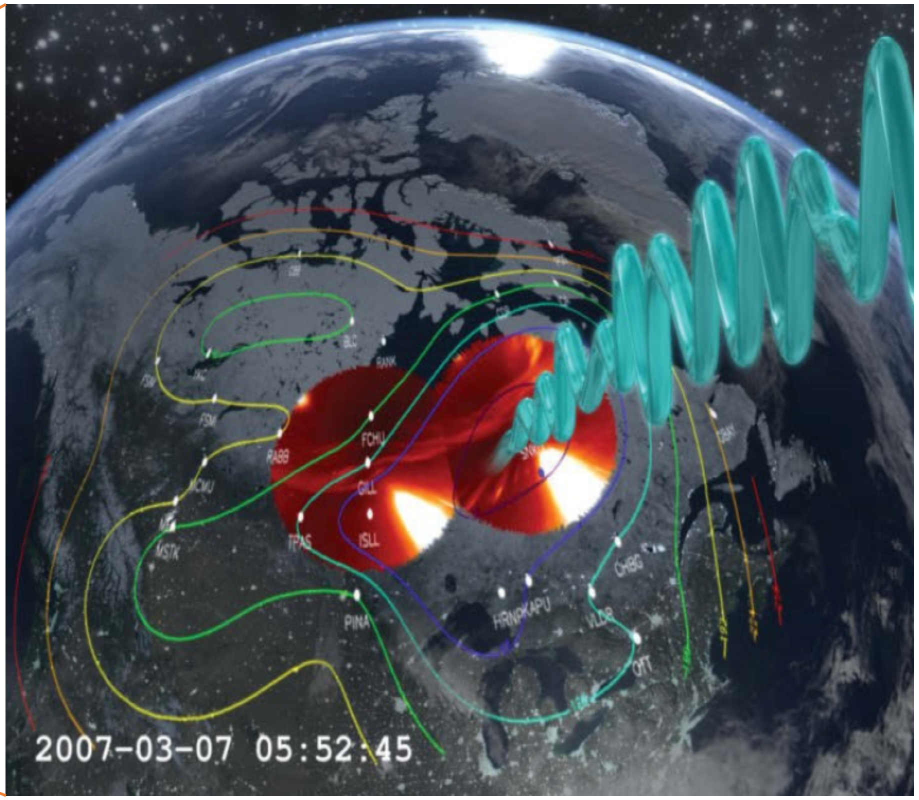
LIVING PLANET FELLOWSHIP

ATMOSPHERE

Swarm Investigation of the Energetics of Magnetosphere-Ionosphere Coupling



Courtesy of NASA



SIEMIC - Objectives

- 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

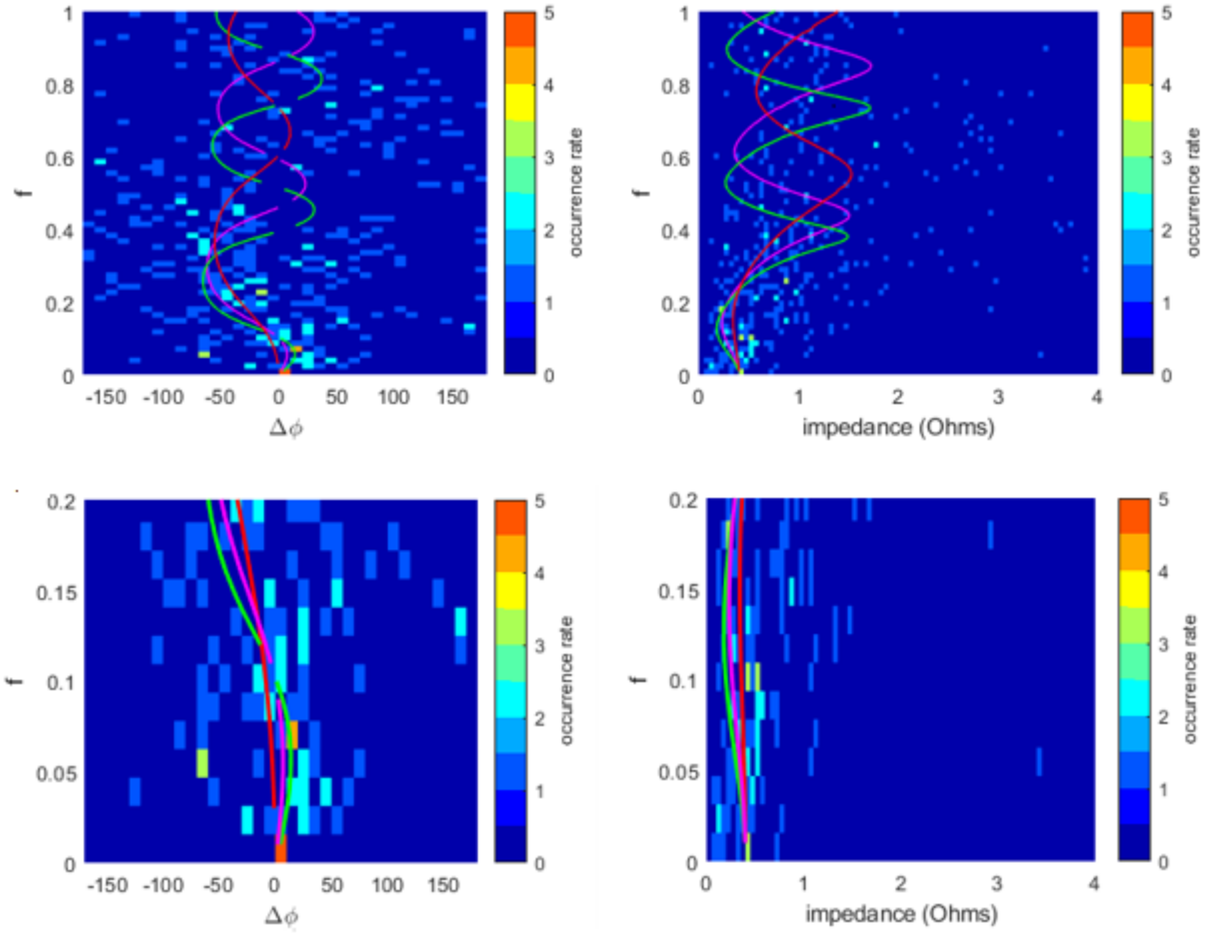
- The original proposal focused on five topics:
- Demonstrating the prevalence of **Alfvén waves during southward IMF** conditions, not just northern IMF cusp as in previously published work. ***Journal of Geophysical Research: Space Physics, minor revisions (2019)***
- Showing the **north-south Poynting flux asymmetry.** ***Presented at EGU 2018, Fall AGU 2018, DASP 2019***, *waiting on feedback from co-authors before submission*
- Analysing Poynting **flux scale dependence** at Swarm altitudes. *Will be presented at Fall AGU 2019*
- One paper to show how the histogram E/B ratio method may be used to infer **Pedersen conductance** below Swarm
- Finally 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

Alfven waves during southward IMF auroral crossings

- Alfvén waves and field-aligned currents (FACs) are both present in auroral zone (e.g. Gjerloev et al., 2011, Lühr et al., 2015)
- Small-scale perturbations tend to be seen as Alfvén waves while large-scale perturbations as FACs
- Unique ESA Swarm measurements make it possible to differentiate between waves and currents using simultaneous E and B field measurements. For FACs, E/B = 1/(µ0 * ∏p), while for free-travelling Alfvén waves E/B = V_a. For reflected and interfering Alfvén waves, E/B ratio will be frequency-dependent

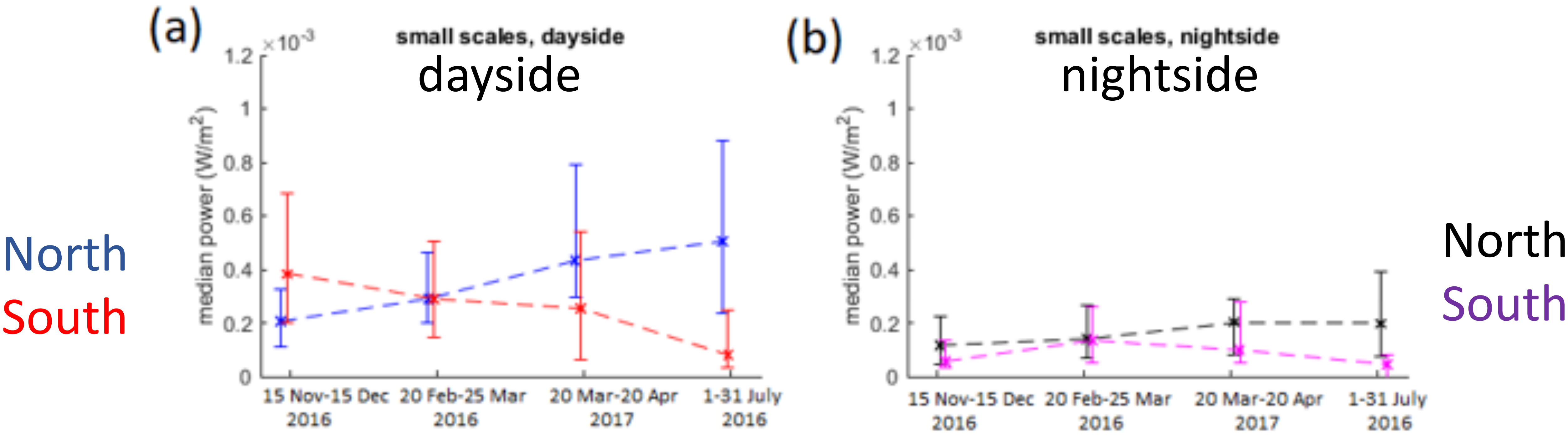
Alfvén waves during southward IMF auroral crossings

- Pakhotin et al. (2018), Miles et al. (2018) demonstrated that there is a **continuum** of energy during auroral crossings, and **no clear distinction** between Alfvén waves and quasi-static FACs. In fact, FACs may be seen as zero-frequency Alfvén waves
- Pakhotin et al. (2019; JGR, under review) show that **Alfvén waves are a fundamental part of the magnetosphere-ionosphere system for a range of geomagnetic conditions**



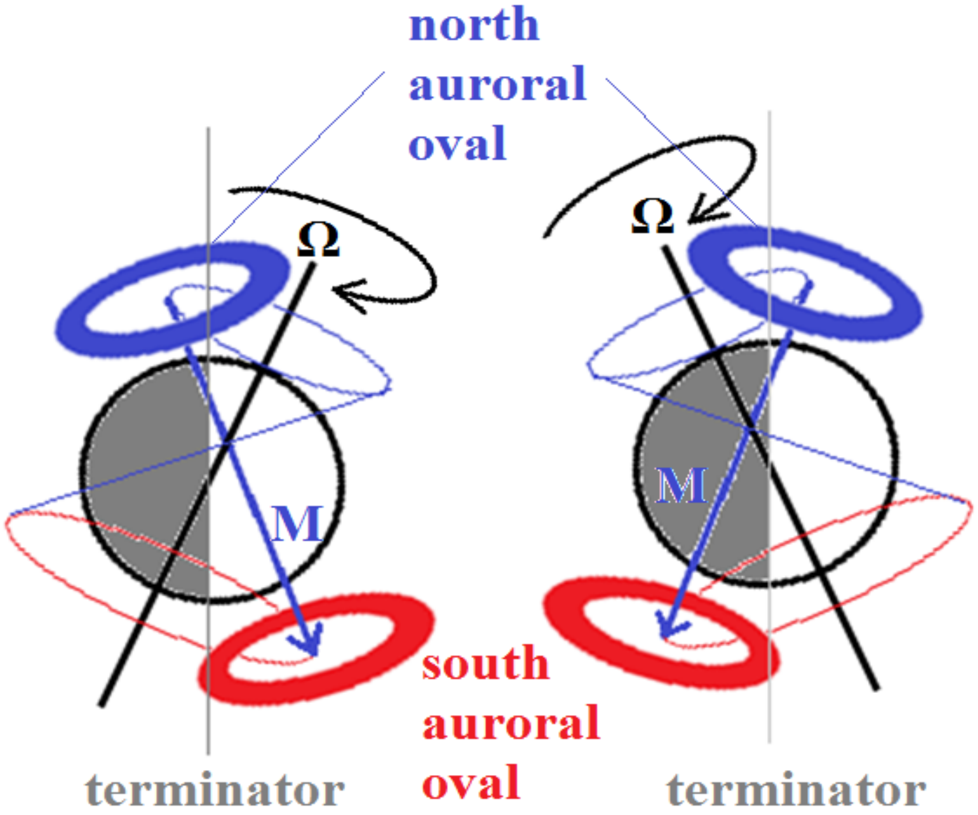
Northern Preference for Poynting Flux at Swarm

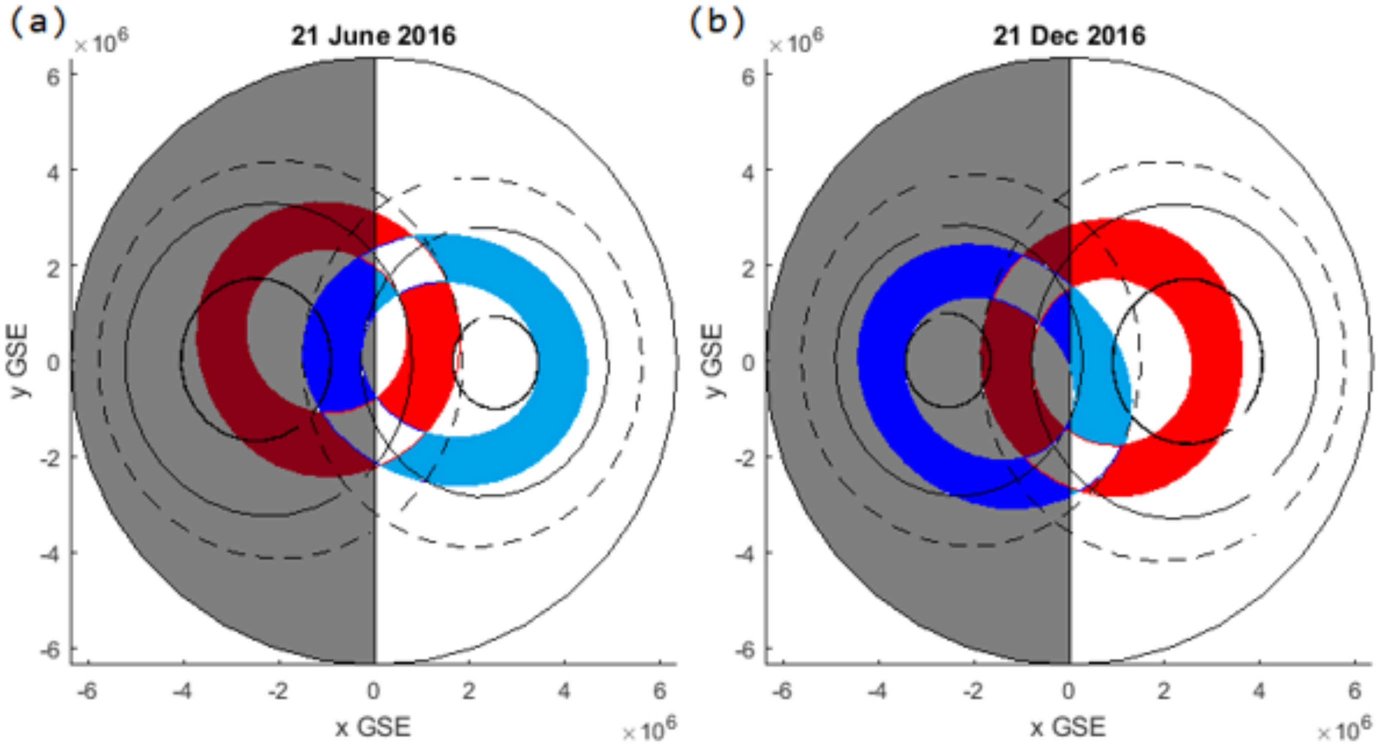
- There appears to be a statistical asymmetry such that, if averaged over seasons, **Swarm will see more Poynting flux in the northern hemisphere than in the south**
- This is **consistent across all scales**, and is even **more pronounced on**



North Preference for Poynting Flux at Swarm

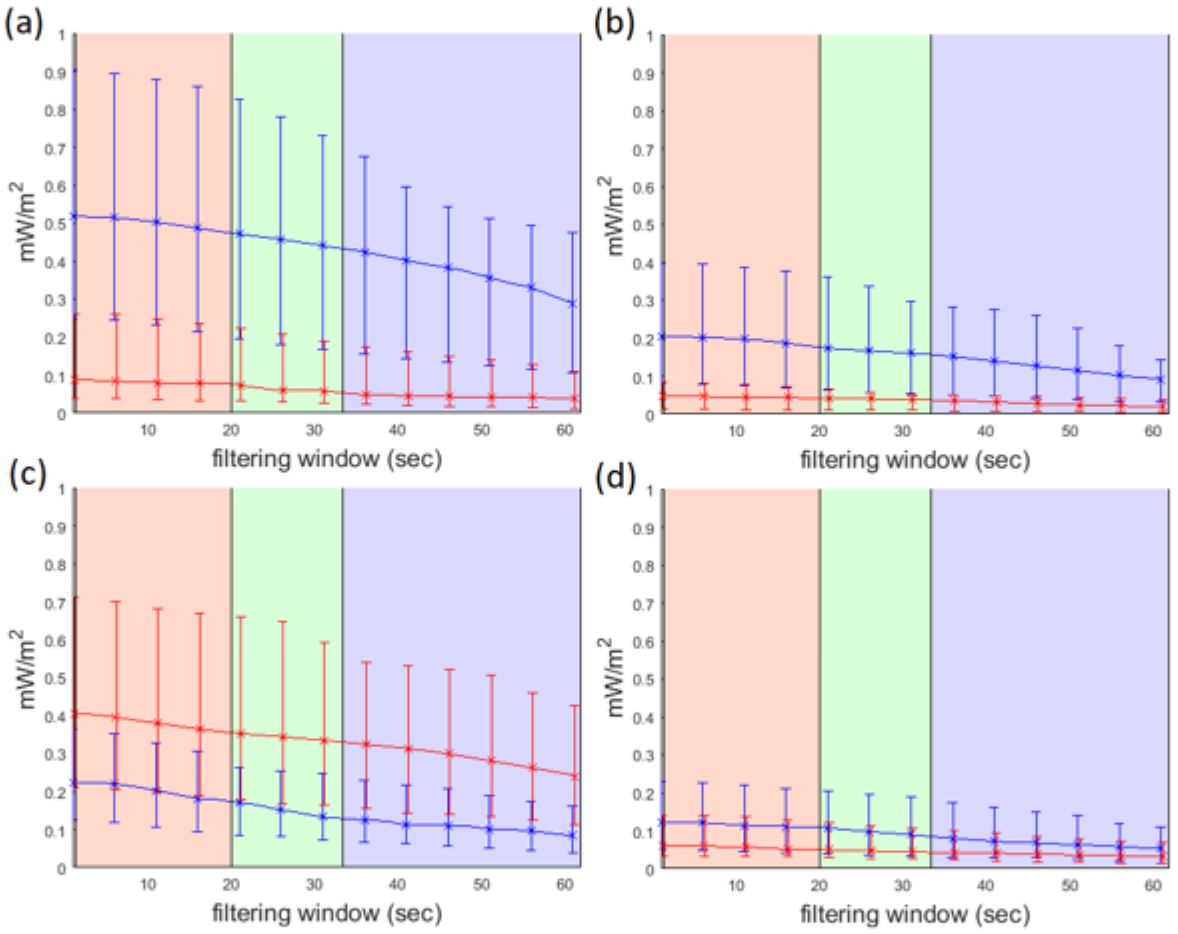
- We advance a paradigm where the northwards offset of the centre of the Earth's dipole results in a greater separation between the Earth's rotation axis and the dipole axis in the south than in the north





Scale Dependence

- Bandpass filtering allows to observe the energy fraction of Poynting flux at various scale sizes
- The patterns appear to be roughly self-similar for both local summer and winter, for both dayside and nightside
- Evidence that energy (Poynting flux) content **tapers off around 1-2 sec** (i.e. 0.5-1 Hz in the frame of Swarm)



Scale Dependence

- Using the 16 Hz E-field data from the TII instrument, it is possible to resolve the energy content down to discrete arc scales. Individual event studies suggest a Poynting flux **plateau**, where no more energy exists above ~ 1 Hz.
- This contrasts with Chaston et al. (2008) results from FAST (higher altitude) which show roughly a power law. **This may imply that the auroral acceleration region preferentially absorbs energy at discete arc scales**
- Running statistical analysis on this high-resolution dataset will allow to confirm or deny whether this plateau exists statistically

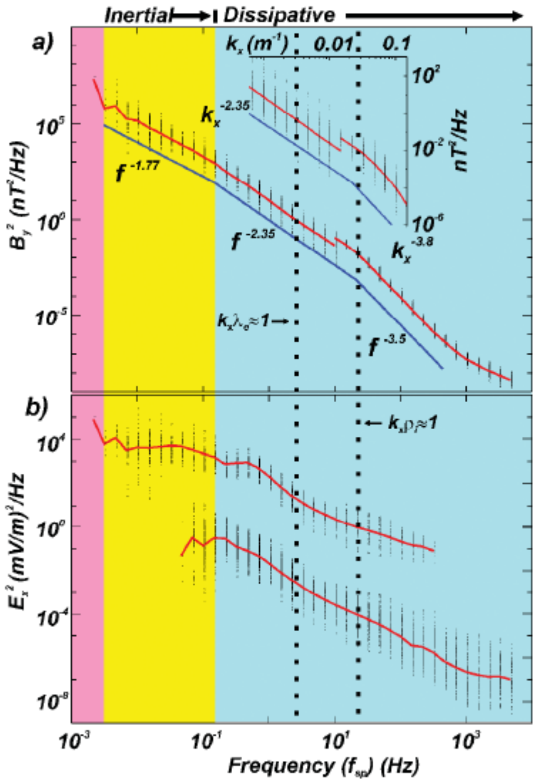
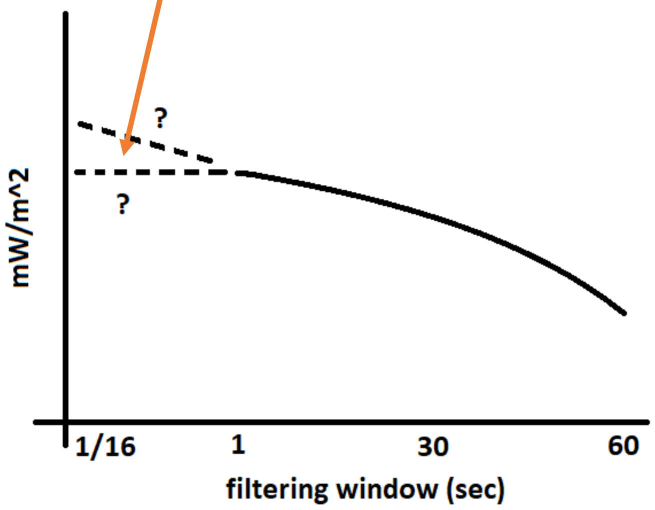


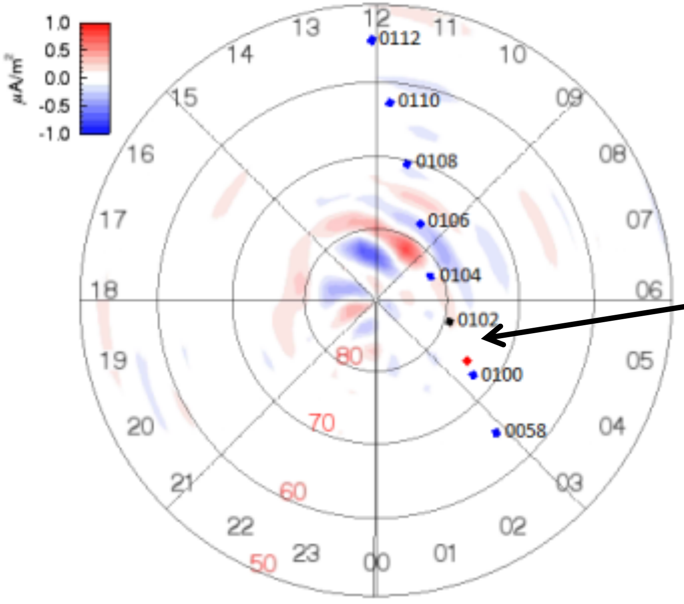
Figure 2 from Chaston et al. (2008)

Energy absorbed at discrete arc scales?



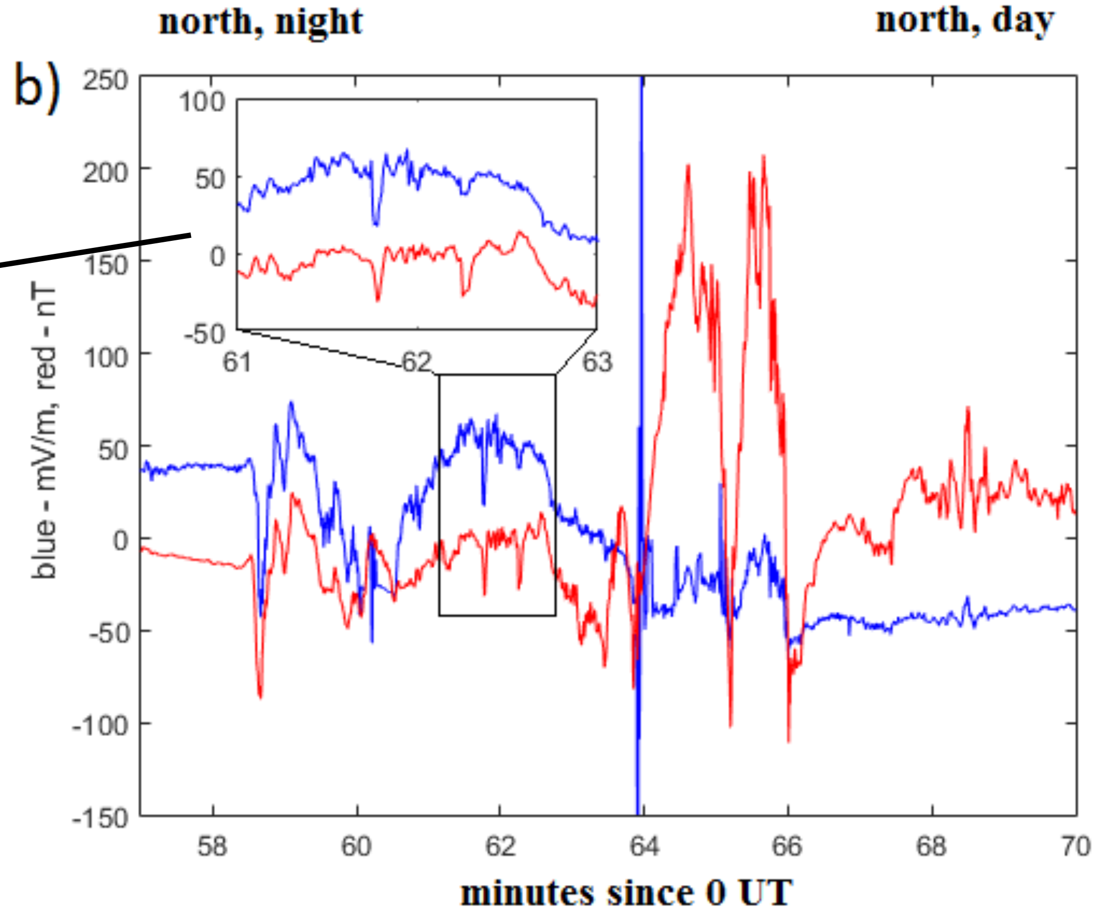
Pedersen Conductance

$E / B = 1/\mu_0 \Sigma_P$



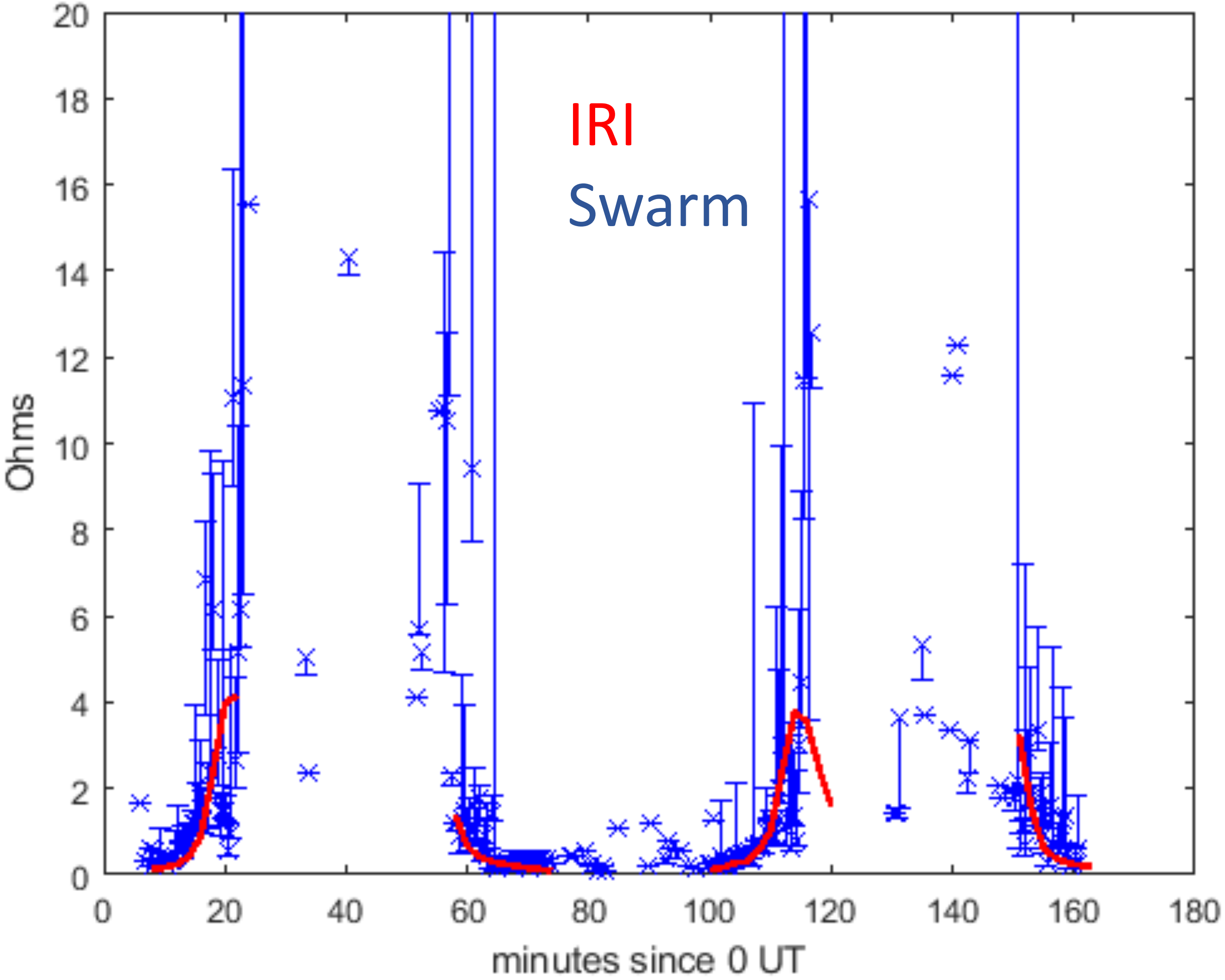
- Σ_P determination from E and B on Swarm

- time series data shows good correspondence and clear-cut changes in E/B ratio across the terminator

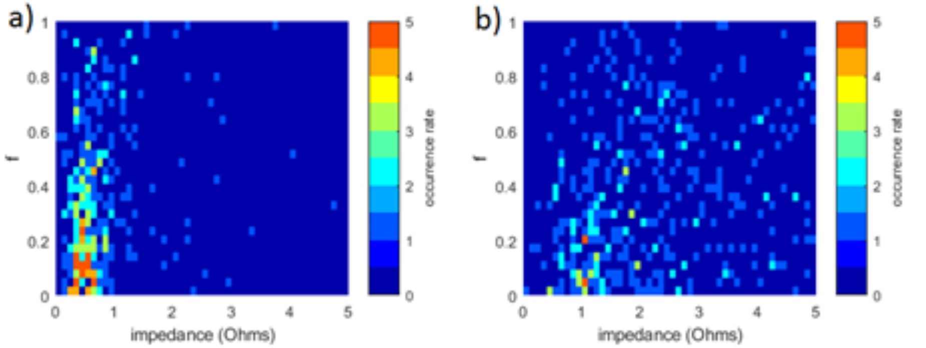


(This slide was presented at 2017 post-AGU THEMIS workshop in New Orleans, LA, USA)

Pedersen Conductance – quiet conditions

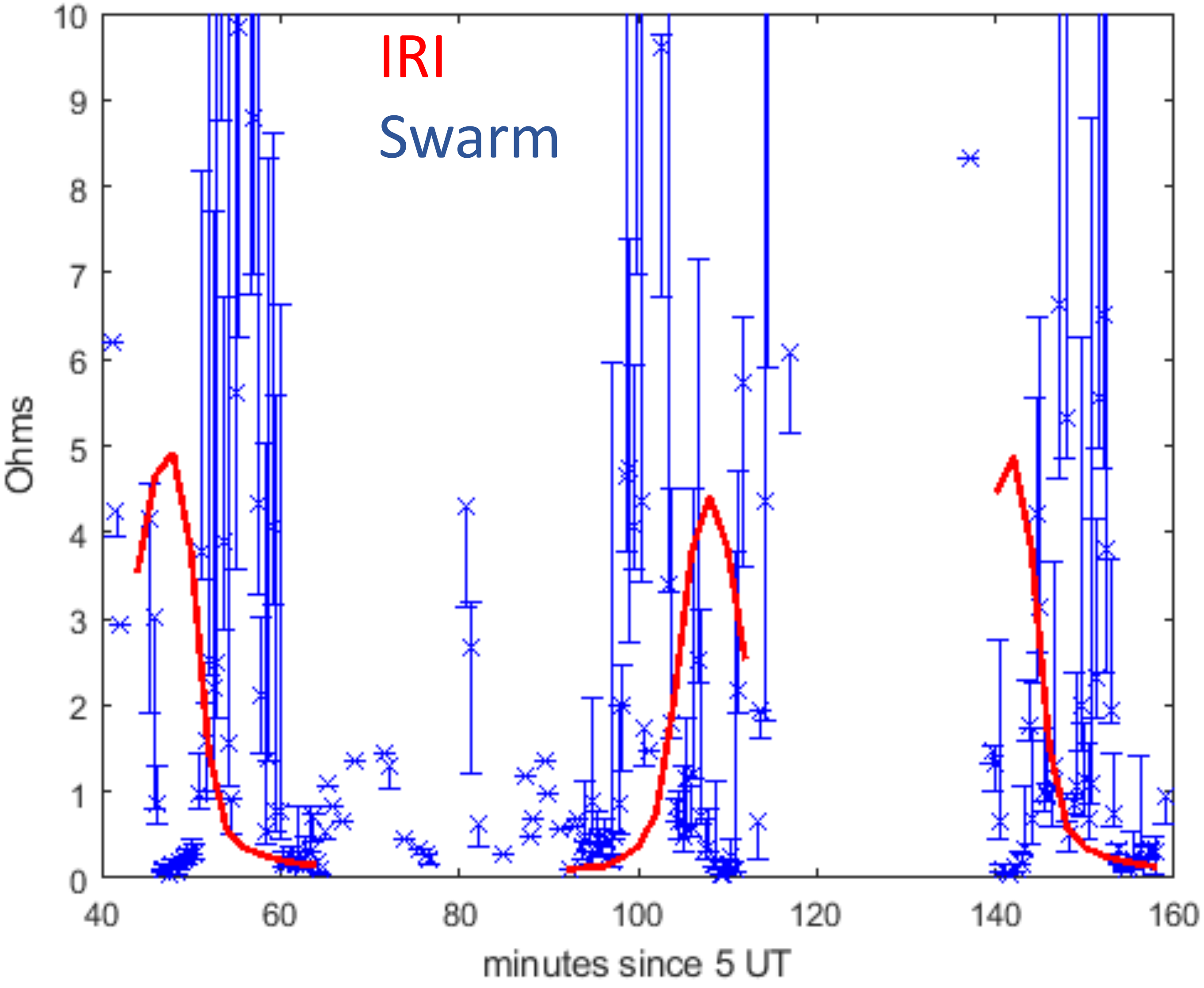


- Histogram analysis as seen in previous slides may be used to get E/B ratio at low frequencies (where it is expected to correspond to 1/(μ0 * Πn)



Pedersen Conductance - Active Conditions

- **During active conditions, IRI seems to under-estimate the Pedersen conductance** on the nightside as it has no means of recognising **precipitation** caused by small-scale processes (e.g. discrete arcs) which would locally increase the conducance
- In these situations, **Swarm may provide superior estimates for this important ionospheric parameter**



Bonus: Swarm as a radiation belt/EMIC monitor

- EMIC waves are Pc-1 Alfven waves (0.2-10 hz) in the inner magnetosphere
- They are believed to be responsible for **rapid scattering of ultra-relativistic (1-2 MeV) electrons in the radiation belts**. Traditionally detected on near-equatorial satellites like Van Allen Probes; Swarm's orbit would provide more coverage… If they can be distinguished from FACs

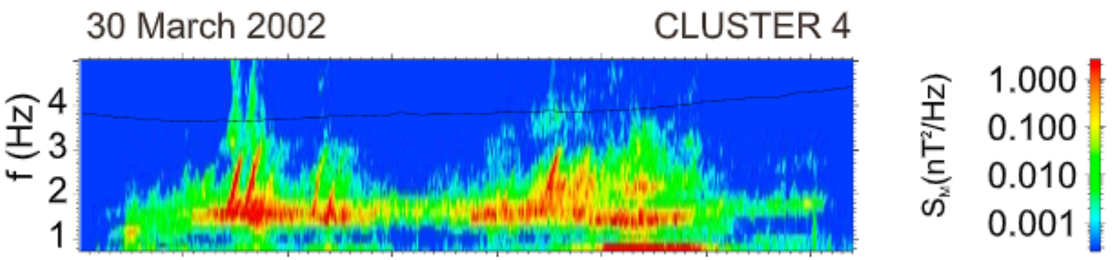


Figure 2 from Pickett et al. (2010)

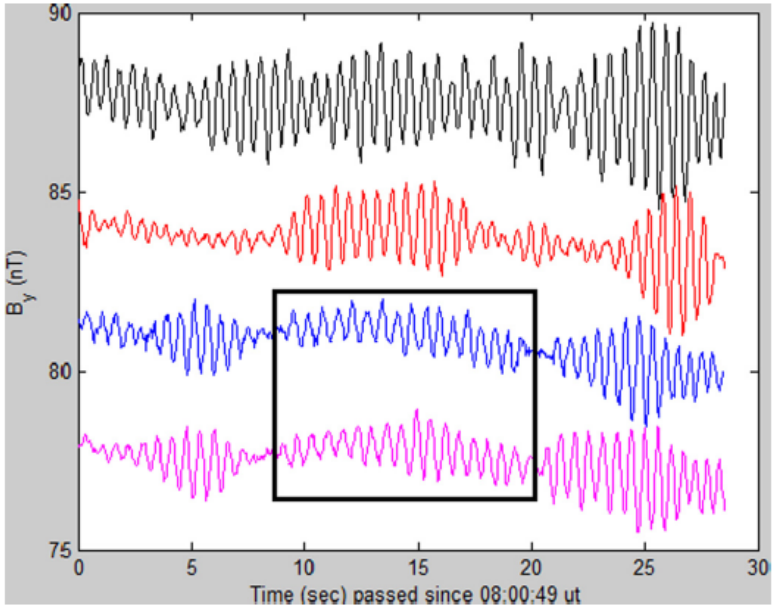
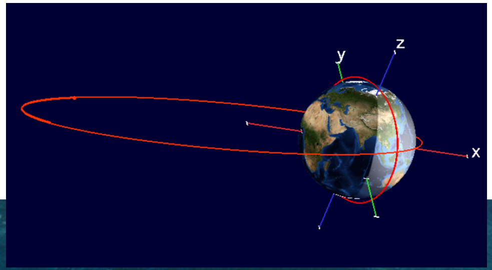
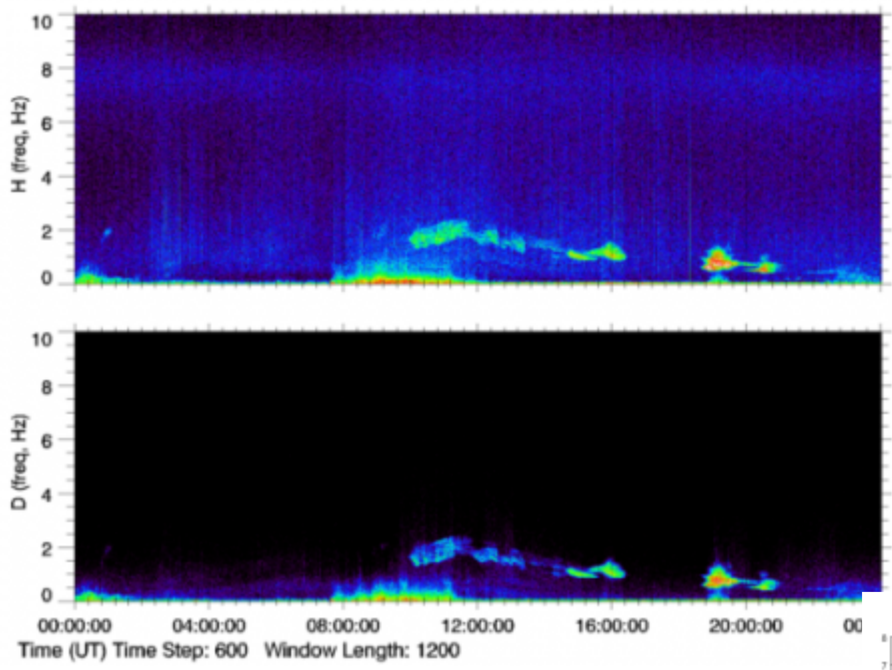
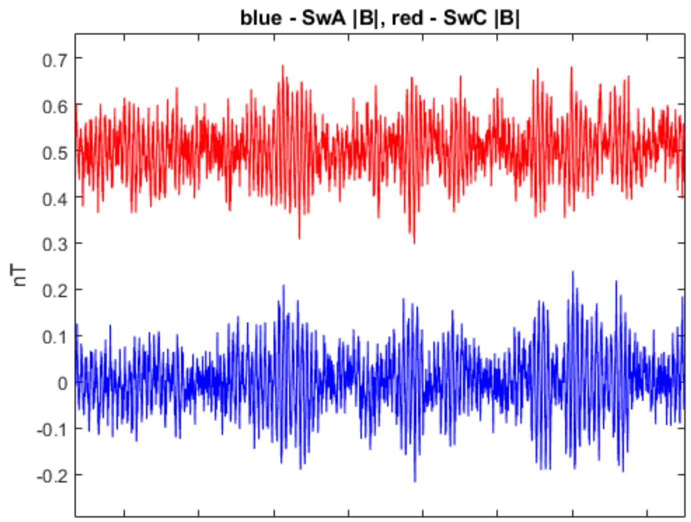


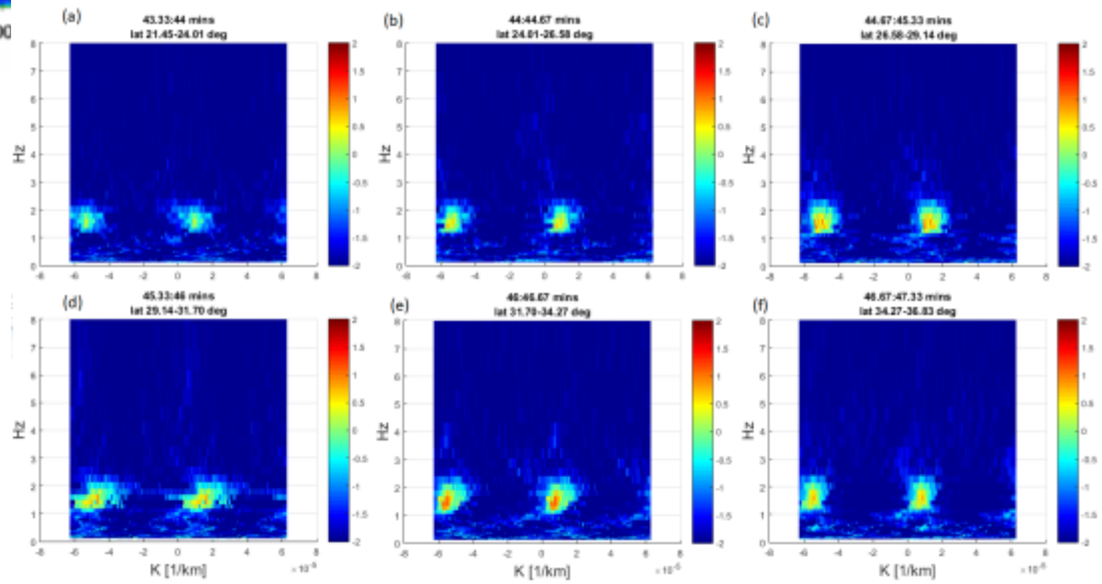
Figure 3 from Pakhotin et al. (2013)



EMIC Alfvén/compressional mode coupling

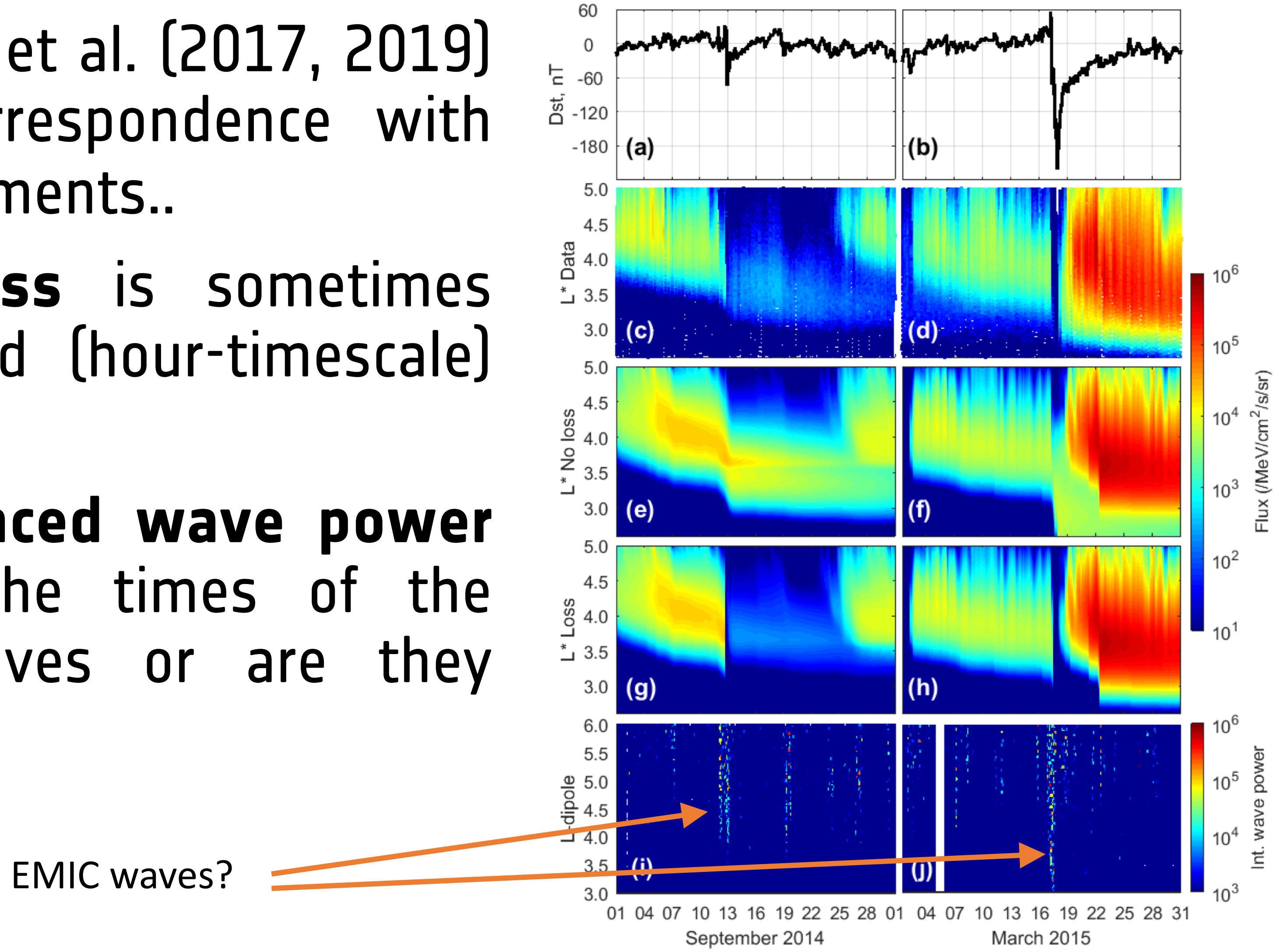




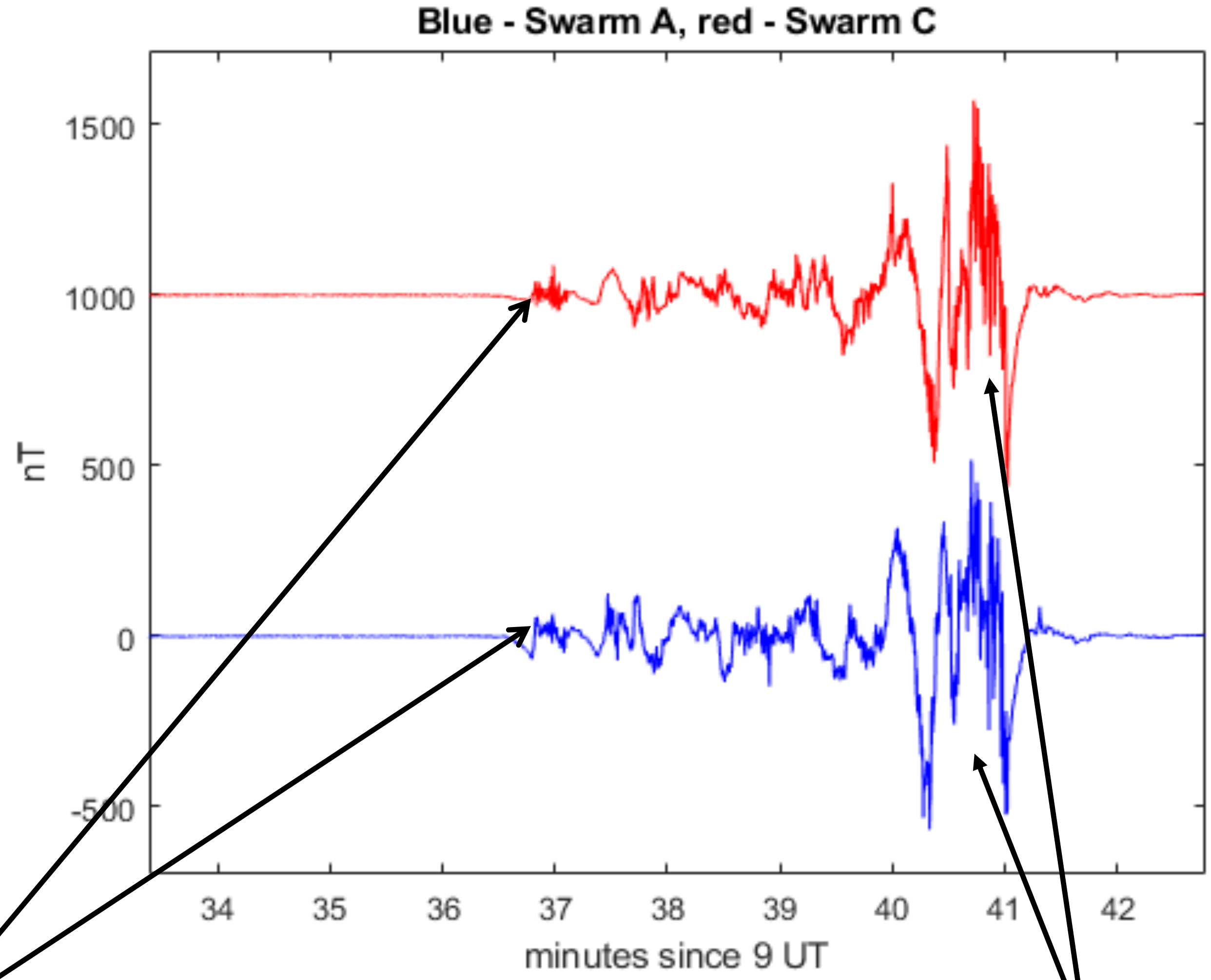


Bonus: Swarm as a radiation belt/EMIC monitor

- Modelling work by Ozeke et al. (2017, 2019) mostly shows good correspondence with Van Allen probe measurements..
- However, **additional loss** is sometimes required to explain rapid (hour-timescale) radiation belt dropouts
- **Swarm observed enhanced wave power** in the Pc1 band at the times of the dropouts. Are they waves or are they currents?..



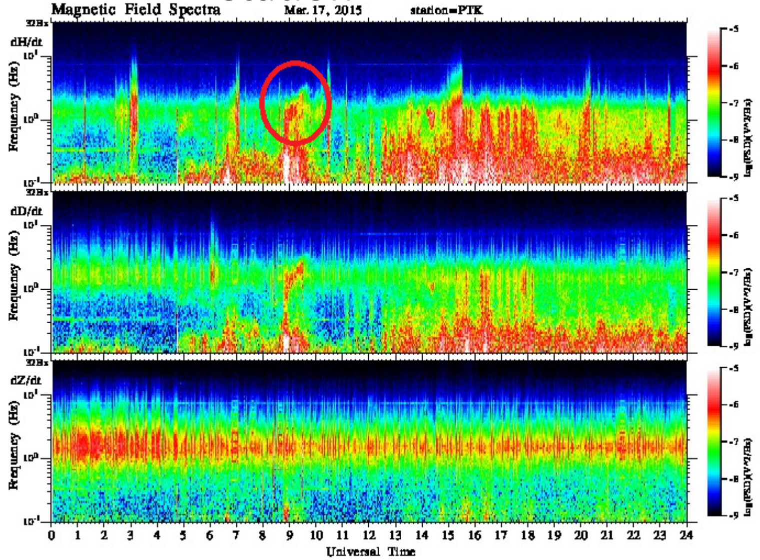
Bonus: Swarm as a radiation belt/EMIC monitor

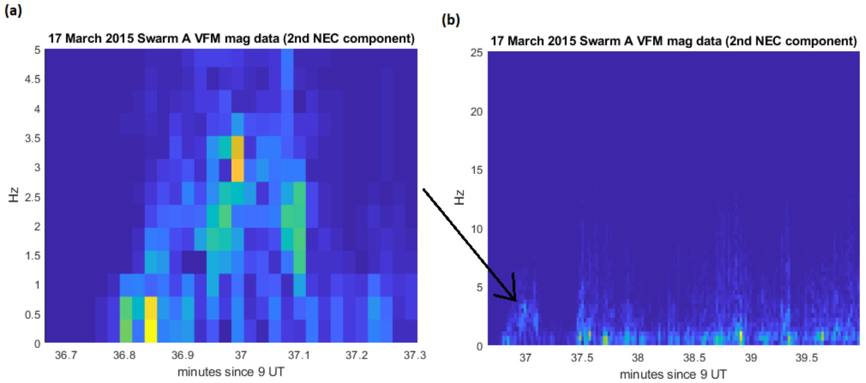


Waves!

Field-aligned currents

Paratunka (PTK) ground station





Swarm VFM

Next Steps

- Submit paper on the north/south Poynting flux asymmetry
- Get feedback on the preliminary results of the Poynting flux scale dependence from AGU 2019. In particular use the high-resolution 16 Hz E-field dataset to confirm or deny whether there is very little energy at Swarm amplitudes at ~ 1 Hz. Target publication in Physical Review Letters
- Get the remaining publicatons into submission-ready formats:
  - Pedersen conductance paper
  - EMIC/compressional mode coupling and location
  - Swarm diagnosis of radiation belt loss

Conclusions

- **Alfvén waves are a key part of the magnetosphere-ionosphere coupled system** and exist on a continuum with field-aligned currents for a range of geomagnetic conditions.
- Attempts to eliminate Alfvén waves from analysis will lead directly to systematic under-estimation of the energetics involved in magnetosphere-ionosphere coupling (MIC)
- Poynting flux energy input into the ionosphere at Swarm heights is not symmetric, with a persistent northern preference. **This suggests a key role for local ionospheric processes in MIC**
- The theory of Alfvén wave analysis based on the e.g. Knudsen et al. (1991), Lysak et al. (1991) paradigms appears to be robust enough to be used to make operational Pedersen conductance estimates with Swarm data
- Small-scale coupling between Alfvén and compressional modes may be observed by Swarm; the multi-spacecraft nature of the mission allows triangulation of the energy source
- Swarm may be used for radiation belt studies; inner magnetosphere EMIC waves may be able to be successfully differentiated from FACs using a variety of

References

- Chaston, C. C., C. Salem, J. W. Bonnell, C. W. Carlson, R. E. Ergun, R. J.Strangeway, and J. P. McFadden (2008a), The turbulent Alfvénic aurora,Phys. Rev. Lett.,100, 175003, doi:10.1103/PhysRevLett.100.175003.
- Gjerloev, J. W., Ohtani, S., Iijima, T., Anderson, B., Slavin, J., & Le, G. (2011). Characteristics of the terrestrial field-aligned current system. Annales Geophysicae, 29, 1713–1729. https://doi.org/10.5194/angeo-29-1713-2011
- Knudsen, D. J., Kelley, M. C., & Vickrey, J. F. (1992). Alfvén waves in the auroral ionosphere: A numerical model compared with measurements. Journal of Geophysical Research, 97, 77–90. https://doi.org/10.1029/91JA02300
- Lühr, H., Park, J., Gjerloev, J. W., Rauberg, J., Michaelis, I., Merayo, J. M. G., & Brauer, P. (2015). Field-aligned currents' scale analysis performed with the Swarm constellation. Geophysical Research Letters, 42, 1–8. https://doi.org/10.1002/2014GL062453
- Lysak, R. L. (1991). Feedback instability of the ionospheric resonant cavity. Journal of Geophysical Research, 96, 1553–1568. https://doi.org/10.1029/90JA02154
- Miles, D. M., Mann, I. R., Pakhotin, I. P., Burchill, J. K., Howarth, A. D., Knudsen, D. J., … Yau, A. W. (2018). Alfvénic dynamics and fine structuring of discrete auroral arcs: Swarm and e-POP observations. Geophysical Research Letters, 45. https://doi.org/10.1002/
- Ozeke, L. G., Mann, I. R., Murphy, K. R., Sibeck, D. G., and Baker, D. N. (2017), Ultra-relativistic radiation belt extinction and ULF wave radial diffusion: Modeling the September 2014 extended dropout event, Geophys. Res. Lett., 44, 2624– 2633, doi:10.1002/2017GL072811
- Ozeke, L. G., Mann, I. R., Claudepierre, S. G., Henderson, M., Morley, S. K., Murphy, K. R., et al. (2019). The March 2015 superstorm revisited: Phase space density profiles and fast ULF wave diffusive transport. Journal of Geophysical Research: Space Physics, 124, 1143– 1156. https://doi.org/10.1029/2018JA026326
- Pakhotin, I. P., Walker, S. N., Shprits, Y. Y., & Balikhin, M. A. (2013). Dispersion relation of electromagnetic ion cyclotron waves using Cluster observations. Annales Geophysicae, 31(8), 1437–1446. https://doi.org/10.5194/angeo-31-1437-2013
- Pakhotin, I. P., Mann, I. R., Lysak, R. L., Knudsen, D. J., Gjerloev, J. W., Rae, I. J.,… Balasis, G. (2018). Diagnosing the role of Alfvén waves in magnetosphereionosphere coupling: Swarm observations of large amplitude nonstationary magnetic perturbations during an interval of northward IMF. Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1002/2017JA024713
- Pickett, J. S., Grison, B., Omura, Y., Engebretson, M. J., Dandouras, I., Masson, A., Adrian, M. L., Santol`ık, O., D`ecr`eau, P. M. E., Cornilleau-Wehrlin, N., and Constantinescu, D.: Cluster observations of EMIC triggered emissions in association with Pc1 waves near Earth's plasmapause, Geophys. Res. Lett., 37, L09104, doi:10.1029/2010GL042648, 2010.