Scale Dependence of the Field-Aligned Current and Relationship to Joule Heating: Tentative Analysis Framework

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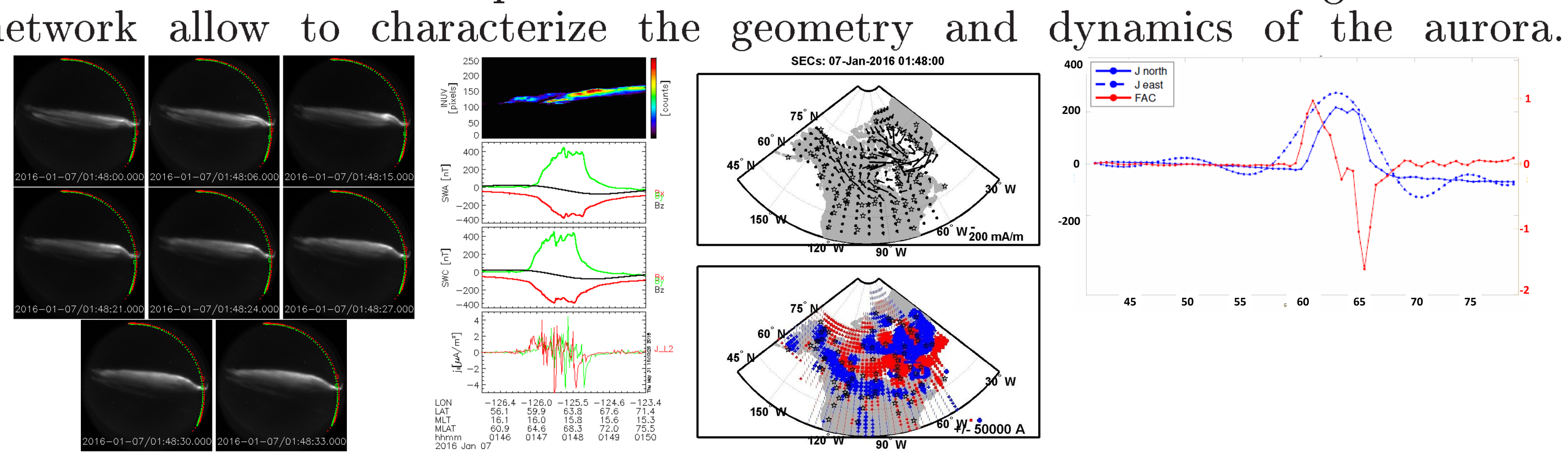
Abstract

The auroral current circuit, coupling the ionosphere and magnetosphere, is maintained by a dynamic and multiscale interaction in which both the magnetospheric and ionospheric ends provide input and receive feedback from each other in a self-consistent way. The energy input from the magnetosphere is transported by precipitating particles and Poynting flux, which is partially converted to ionospheric Joule heating and partially reflected. One of the main agents which intermediates the transfer of energy and momentum in the circuit is the field-aligned current (FAC), which couples to the curl-fee component of the ionospheric current, typically associated with Pedersen current, while the divergence-free component is in general associated with Hall current. However, these associations are not one to one and the actual Pedersen and Hall contributions to the curl-free and divergence-free ionospheric currents can vary, in particular during disturbed times. By exploring the multiscale structure of the field-aligned and Pedersen currents, one can check both the actual FAC closure and the efficiency of the related Joule heating (generated only by Pedersen current), depending on scale. In this study, we aim to develop an investigation framework, based on the application of the multiscale FAC analyzer [*Bunescu et al. 2015*] to a test-bed data set observed by Swarm.

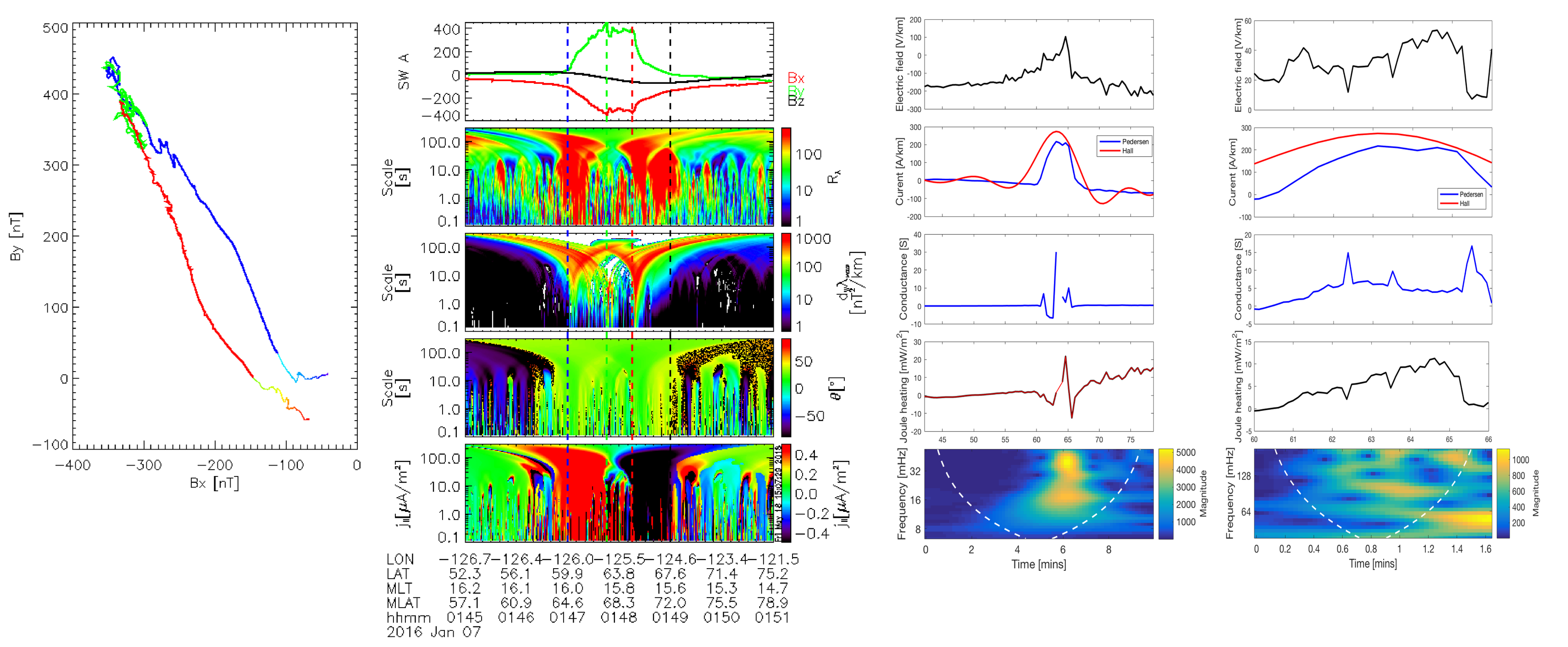
Observation of stable aurora

The multiscale analysis of both FAC and Joule heating is performed on the measurements taken by the Swarm spacecraft flying on polar orbits at 460 km altitude. Optical observations from the THEMIS ground ASI network allow to characterize the geometry and dynamics of the aurora.



Left: Optical observations from Inuvik (INUV) station and spacecraft footprints of SwA (green) and SwC (red) over east-west aligned aurora. *Center left:* Keogram from INUV indicates stability of the arcs over Swarm crossing. $\Delta\mathbf{B}$ from SwA and SwC together with the single-spacecraft FAC density from SwA (green)/SwC (red). Similar $\Delta\mathbf{B}$ signatures at large scale and variation at small scales. *Center right:* Ionospheric current (top) and FAC (bottom) maps derived from THEMIS ground network [3]. *Right:* Ionospheric currents and FAC inferred from Swarm.

Multiscale analysis of FAC and wavelet analysis of Joule heating



Left: Hodogram representation of $\mathbf{B}_\perp$ shows the large scale downward (blue) and upward (red) FACs. The region between these FACs shows small scale FAC signatures consistent with FAC estimates. *Center left:* MSMVA analysis for the linear scale sampling scheme. a) Magnetic field perturbation; b) Planarity R_λ; c) FAC location and characteristic scale $\partial_w\lambda_\eta$; d) Orientation; e) Multiscale FAC density. *Center right:* a) Optimized electric field; b) Pedersen and Hall currents; c) Pedersen conductance; d) Joule heating, W; e) Wavelet power spectra of W. *Right:* Zoom into the center right panels.

Conclusions and Prospects

- MSMVA analysis provides quantitative estimates of the local characteristics of FACs (location, scale, and current density).
- The multiscale FAC density separates well the FACs present at various scales.
- Multiscale scale structure of the Joule heating is explored by wavelet analysis, however at a coarser spatial resolution.
- A detailed comparison between the multiscale structure of FAC and Joule heating is still to be done.
- This comparison is expected to provide insight also on the FAC ionospheric closure.
- In order to extend the analysis to small scales, we plan to use also FAST data.
- In order to make full use of Swarm multi-spacecraft data, we plan to investigate as well the longitudinal variation of the FAC closure and Joule heating.

Method

I. Multiscale analysis of FAC

- Multiscale FAC analysis (MSMVA) is based on 2D Minimum Variance Analysis (MVA) performed on $\mathbf{B}_\perp$ in the magnetic field aligned (MFA) frame.
- MSMVA performs MVA on sliding windows of different widths (scales) that vary linearly within $[w_{\min}, w_{\max}]$ range
- Eigenvalues ($\lambda_{\max}$, $\lambda_{\min}$), eigenvalues ratio, $R_\lambda = \lambda_{\max}/\lambda_{\min}$, and the orientation, $\theta \equiv \sphericalangle(\mathbf{e}_{\min}, \mathbf{x}_{\mathrm{MFA}})$ depend on time and scale.
- FAC thickness and location by $\partial_w \lambda_{\max}$ *[Bunescu et al., 2015]*
- Multiscale FAC density by computing in the FAC at each scale.

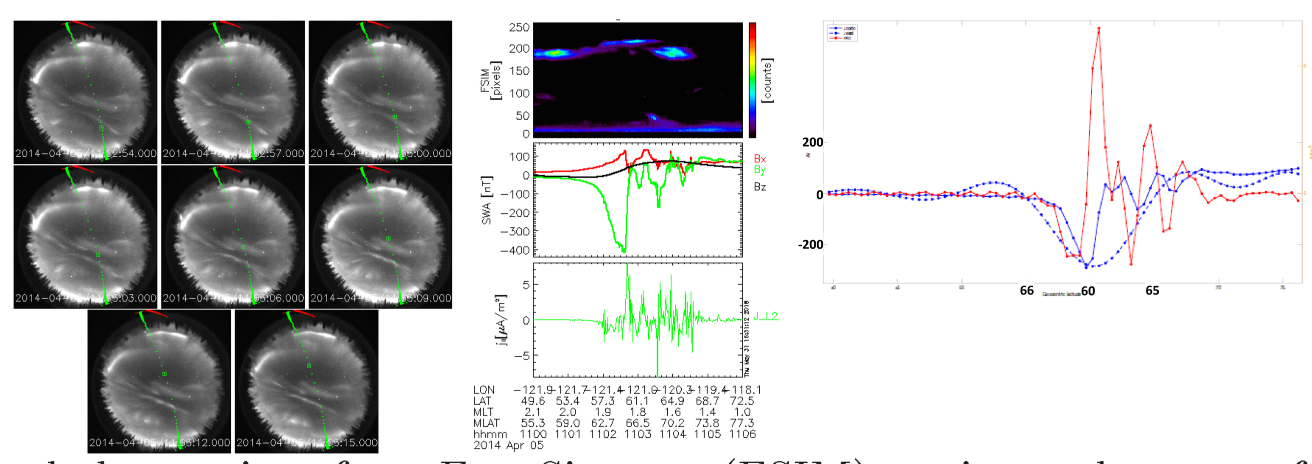
II. Ionospheric currents and optimization of the electric field measurements.

- Spherical elementary current system (SECS) technique [*Amm, 1997*] is used to derive the the ionospheric equivalent currents, the divergence free (Hall) and the curl-free (Pedersen) components.
- Current continuity equation $j_\parallel = \nabla \cdot \mathbf{J}$ with $\mathbf{J}_\perp = \Sigma_P \mathbf{E}'_\perp + \Sigma_H \mathbf{e}_B \times \mathbf{E}'_\perp$ is used together with SECS to derive the 2D quantities like Σ_P, Σ_H, $\mathbf{J}_{\mathrm{eq}}$, $\mathbf{J}$,$\mathbf{J}_\parallel$ using $\Delta\mathbf{B}$ and electric field measurements.
- Based on *Robinson et al., 1987* equations: $\Sigma^e_H/\Sigma^e_P = 0.45\overline{E}^{0.85}$ and $\Sigma_P = 40\overline{E}^{1.5}\sqrt{j_\parallel}/\left[\sqrt{e}(16+\overline{E}^2)\right]$ we can derive and independent estimate of Σ_P for the upward current regions.
- A linear least squares approach that minimize the merit function $F = \sum_{upward}\left(\Sigma^{SECS}_P - \Sigma^{ROB}_P\right)^2$ allow the determination of an optimized electric field.

III. Multiscale analysis of the Joule heating

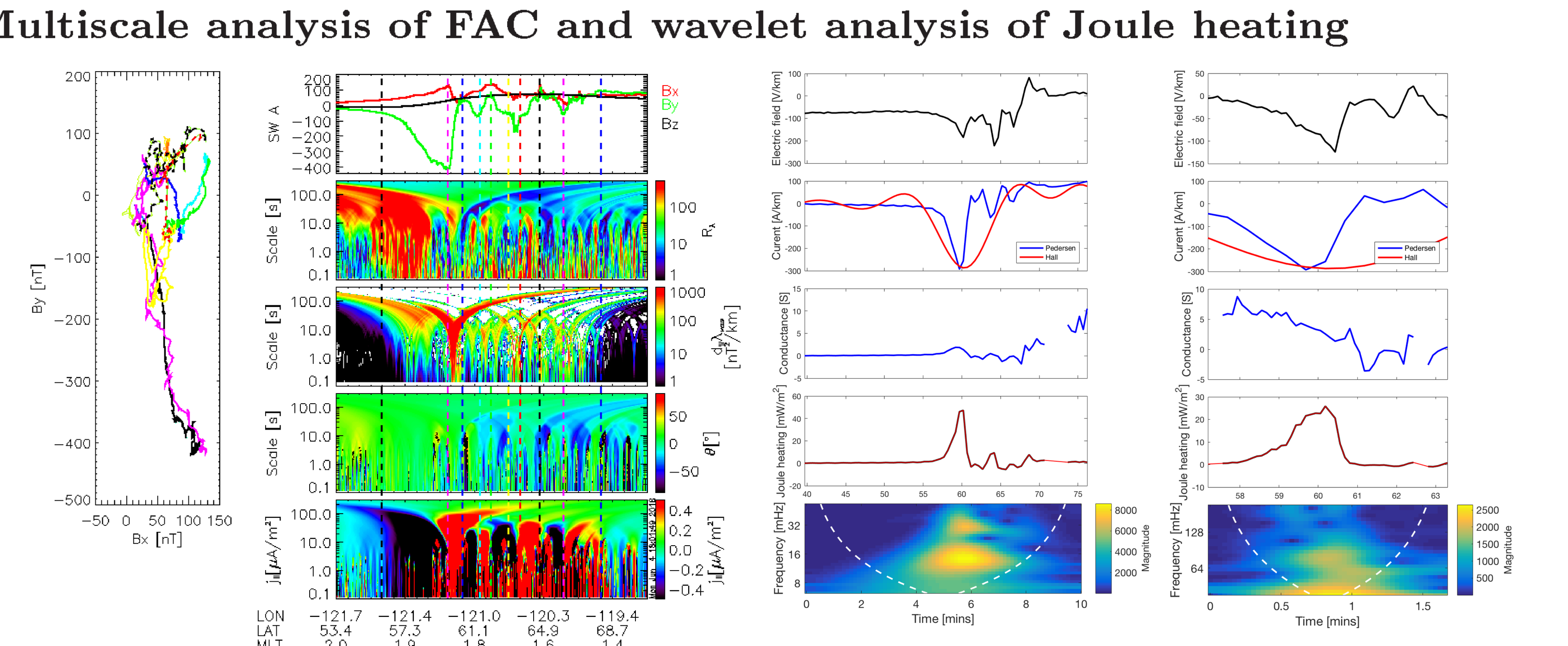
- We estimate the Joule heating by $W = \Sigma_P E^2$.
- We check qualitatively the consistency of the observations with the known theoretical studies/characteristics.
- Preliminary Wavelet analysis applied to W to show features.
- Future work aims to extend the MSMVA analysis to Joule heating.

Observation of dynamic aurora



Left: Optical observations from Fort Simpson (FSIM) station and spacecraft footprints of SwA (green) and SwC (red) over dynamic aurora. *Center:* Keogram from FSIM indicates variation of the intensity of optical emissions at the center of the ASI FoV. $\Delta\mathbf{B}$ from SwA together with the single-spacecraft FAC density from SwA. *Right:* Ionospheric currents and FAC inferred from Swarm.

Multiscale analysis of FAC and wavelet analysis of Joule heating



Left: Hodogram representation of the $\mathbf{B}_\perp$ shows a highly structured signature, dominated by mesoscale and small-scale FAC structure. MSMVA analysis is used to characterize these FACs. *Center left:* MSMVA analysis for the linear scale sampling scheme. a) Magnetic field perturbation; b) Planarity R_λ; c) FAC location and characteristic scale $\partial_w\lambda_\eta$; d) Orientation; e) Multiscale FAC density. *Center right:* a) Optimized electric field; b) Pedersen and Hall currents; c) Pedersen conductance; d) Joule heating, W; e) Wavelet power spectra of W. *Right:* Zoom into the center right panels.

References

[1] Bunescu, C., O. Marghitu, D. Constantinescu, Y. Narita, J. Vogt, and A. Blăgău (2015), *Multiscale field-aligned current analyzer*, J. Geophys. Res., 120, doi:10.1002/2015JA021670.

[2] J. Wu, D. Knudsen, M. Gillies, E. Donovan, J. Burchill, *Swarm Observation of Field-Aligned Currents in Multiple Arc Systems*, CEDAR Poster 2017.

[3] J. Weygand, Equivalent Ionospheric Currents over North America and Greenland (www.igpp.ucla.edu/jweygand/htmls/EICS NA Greenland.html)