On the Role of Fine-Scale Non-Stationary Magnetic Field Perturbations in FAC Systems: Swarm Satellite Observations

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Abstract

The orbital configuration of the Swarm satellites, with along-track and cross-track separations on the scales of tens of kilometers, allows for the estimation of field-aligned current (FAC) density during traversals of the auroral zones. However, such FAC estimates rely on the assumption that the magnetic field perturbations are quasi-stationary on the temporal scales of the crossings. Past work has focused on elucidating large-scale current features employing techniques such as low-pass filtering to remove any large-amplitude Alfven waves and/or azimuthally localised current filaments which might invalidate these assumptions. In the new work presented here, we present evidence that in a significant proportion of auroral zone crossings the quasi-stationarity assumption may be violated and that the scales at which is it violated are energetically significant and cannot be easily discounted as small scale filamentations. Large-amplitude non-stationarities appear to be ubiquitous in the FAC associated with the coupled magnetosphere-ionosphere system and may have the potential to account for a significant part of the total energy budget. The non-stationarities are analysed statistically with relation to season, meridian and IMF Bz to further elucidate the nature of these dynamics and the potential extend of their energetic significance.

Introduction

- Field-aligned currents (FACs, or Birkeland currents) flow between magnetosphere and mid- to high-latitude ionosphere, transfer energy and momentum between the two systems
- Iijima and Potemra (1978) study using Triad – often exhibit concentric ring structure with Region 1 (R1) closing just inside magnetopause, Region 2 (R2) closed by the partial ring current
- More irregular structures often exist during northward IMF Bz orientations
- Measured using Ampere's law with current density assumed proportional to cross-track dB/dt. Assumption is that there are no temporal variations – all ... to the current

$$j_z = \frac{1}{\mu_0}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right]$$

- Large amplitude Alfven waves can violate this assumption and interfere with current density measurements. Often addressed by low-pass filtering, implicit assumption is that Alfven waves are separate from quasi-static FACs
- This treatment will remove any fine-scale filamentary FACs – valid under the assumption that they are not energetically significant
- ESA Swarm mission launched in 2013 into LEO at 450 km (Swarm A, C) and 550 km (Swarm B). Swarm A, C cross track separation in main science phase – 1.4 degrees. Along-track separation – varies, on the order of seconds
- Carry 50 Hz fluxgate magnetometers and 16 Hz Thermal Ion Imager (TII) experiments. Measure FACs using cross-track dB/dt. Figure 1 shows orbits of time periods under study.
- Modern literature (e.g. Lühr et al., 2015) characterises small-scale FACs below scale lengths of ~150 km as Alfven waves, separate from large FACs. This consideration carries into modern FAC models (e.g., Prokhorov et al., 2014). This is energetically valid under the assumption that net energy flow for these scales is zero.
- Figure 1 shows an example of non-stationarity in the transverse magnetic field during an auroral crossing. It can be seen that even if the data is lagged by a time period corresponding to maximum correlation, the residuals are still of the order of the peak-to-peak dB/dt caused by the quasi-static FACs.
- This study statistically analyses how often the quasi-stationarity assumption is violated

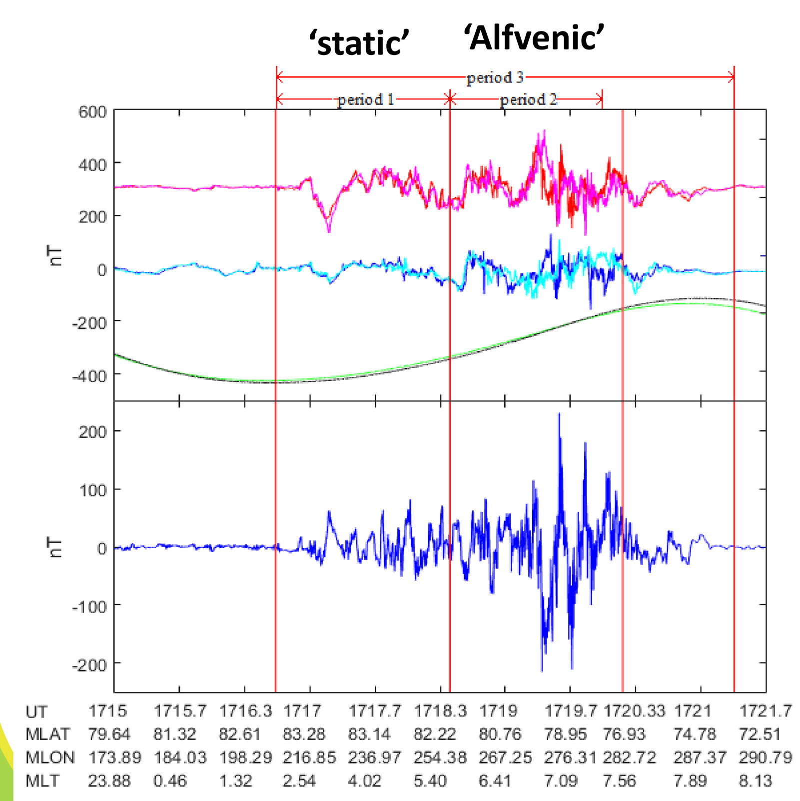

Figure 1: (top) Vector magnetic field observed Swarm A and C: MFA_1 (north-south; blue/cyan), MFA_2 (east-west; offset by +300 nT, in (red/pink) and MFA_3 (compressional; offset by -300 nT after mean removal, green/black). All components of the Swarm C lagged by 10.66 s. (bottom) Residual (red-pink on top plot). Red bars show time periods marked for E-B study.

Methodology

- Cross-track magnetic field time series on Swarm A and C used, main field removed by subtracting moving average
- Moving variance calculated on resulting time series using a sliding non-overlapping 10-second window. Periods of high variance correspond to signatures of FACs and/or Alfven waves (e.g. Rother et al., 2007). This is used to constrain the time periods under study
- Any time periods flagged this way where the range is <25 nT are discarded as too small
- Time series for the same intervals for Swarm A and C are lagged to calculate lag corresponding to maximum correlation. This lag corresponds to inter-spacecraft separation time plus any angle of attack effects
- For this time lag of maximum correlation, residual is calculated. In theory, should be zero (assuming perfect quasi-stationarity). In practice, the degree of variance and range of the residual will determine how much the quasi-stationarity assumption is violated. This will affect FAC density estimates both using single spacecraft (Lühr et al., 1996) and dual spacecraft (Ritter and Lühr, 2005, Ritter et al., 2013) methods.
- Two months are analysed (June and December 2014) using above methodology. Variances calculated on residual are scaled by the variance of constituent Swarm A time series for the same period. Ranges of residuals for the same identified FAC events, scaled by ranges of constituent Swarm A time periods, are also calculated.

Results

- Figures 2 and 3 show the variance and range of residuals normalised by the variance and range of corresponding auroral zone traversals for 2 time periods (June and December 2014). It can be seen that for 50 Hz the non-stationarities are routinely comparable to or greater than the constituent large-scale dB/dt. This is true for all IMF Bz orientations and is slightly more pronounced in local summers.

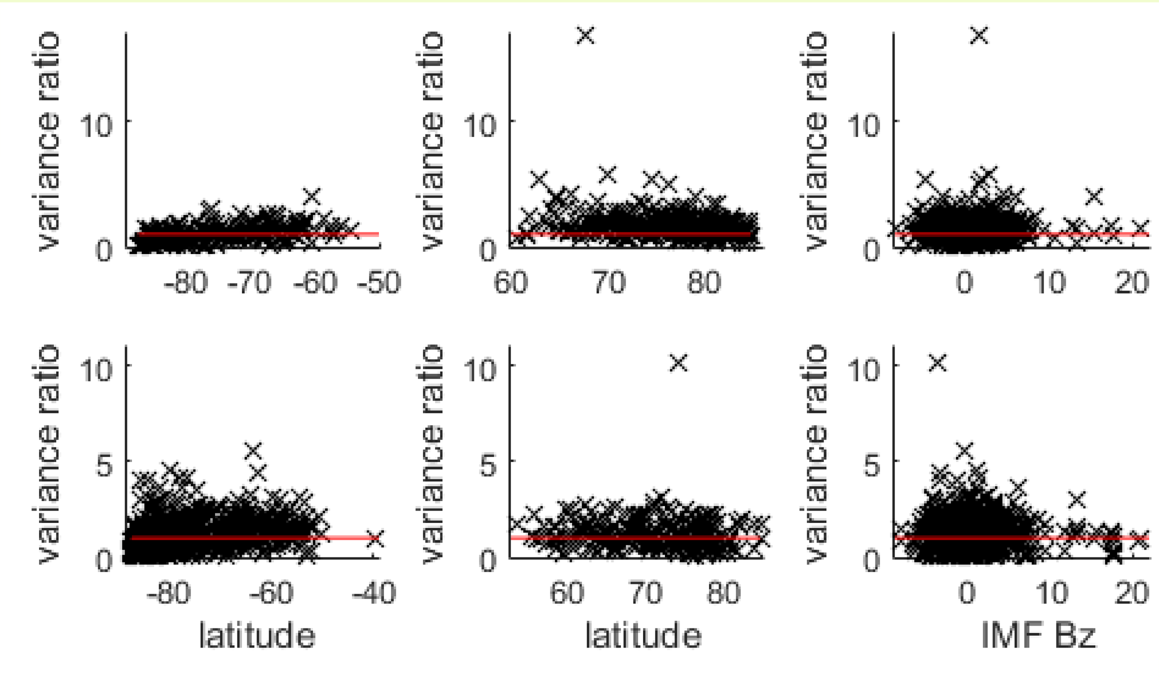

Figure 2: normalised variances. June 2014 median variance ration: 1.57 for positive latitudes, 0.86 for negative latitudes. December 2014 gave 1.05 for positive latitudes vs. 1.13 for negative latitudes

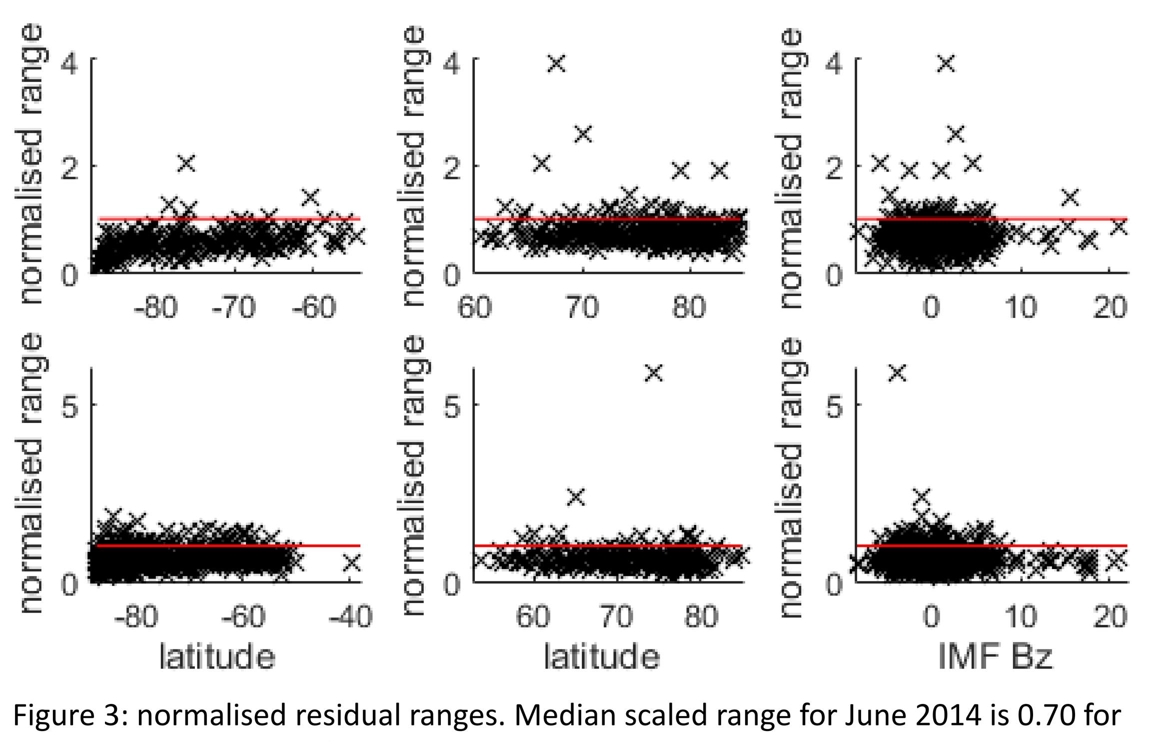

Figure 3: normalised residual ranges. Median scaled range for June 2014 is 0.70 for positive latitudes, 0.54 for negative latitudes. In December 2014, situation is reversed: 0.60 vs. 0.62.

Energy Considerations

- Modern literature (e.g. Lühr et al., 2015) characterises small-scale FACs below scale lengths of ~150 km as Alfven waves, separate from large-scale FACs. Modern FAC models (e.g., Prokhorov et al., 2014) neglect these small-scale features. This is energetically valid under the assumption that net energy flow for these scales is zero.
- However, as shown on Figures 4 and 5 as representative examples, the Poynting flux as determined from synchronous E- and B-field measurements on Swarm shows significant energetics at these scales. Thus while the low-pass filtering (<150 km scale lengths) may capture the large-scale topology of the global FAC distribution, the energetics associated with these current systems will likely be significantly underestimated.

Alfven waves?

- The frequency dependent E/B ratio and their relative phase can be used to diagnose the presence of Alfven wave interactions, including the effects of ionospheric reflection, absorption and wave interference.
- There is evidence of Alfven waves both for the quasi-stationary Period 1 (Figure 4 a, b, c) and non-stationary Period 2 (Figure 4 d, e, f) and across all frequencies. In fact, the same histogram topology, consistent with that of reflecting Alfven waves, persists across the entire crossing (Figure 4 g, h, i) and as low as 0.05 Hz (Figure 4 g, h, i).

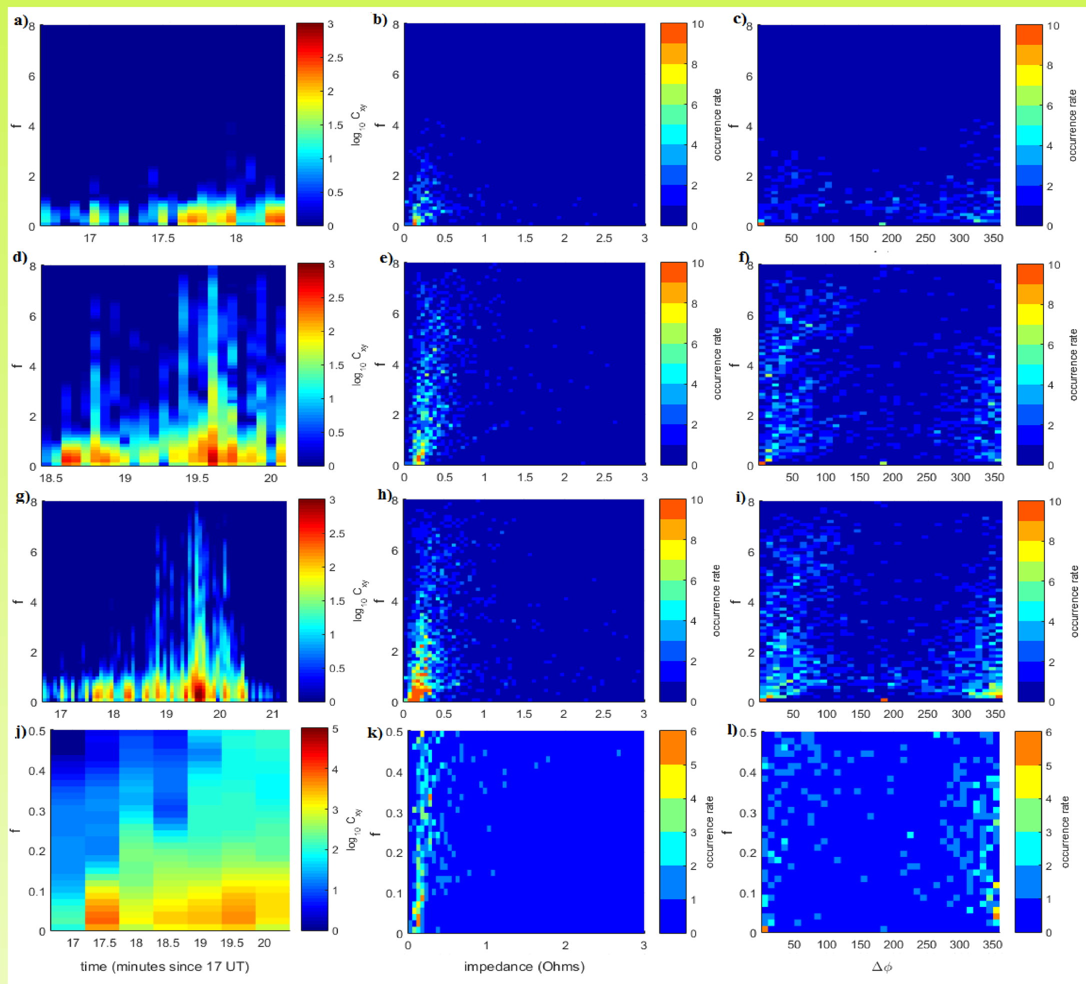

Figure 4: cross power spectral density, impedance and phase histograms for Period 1 (a,b,c) for Period 2 (d,e,f) for Period 3 (g,h,i) and for Period 3 with a larger window focusing on low frequencies (j,k,l)

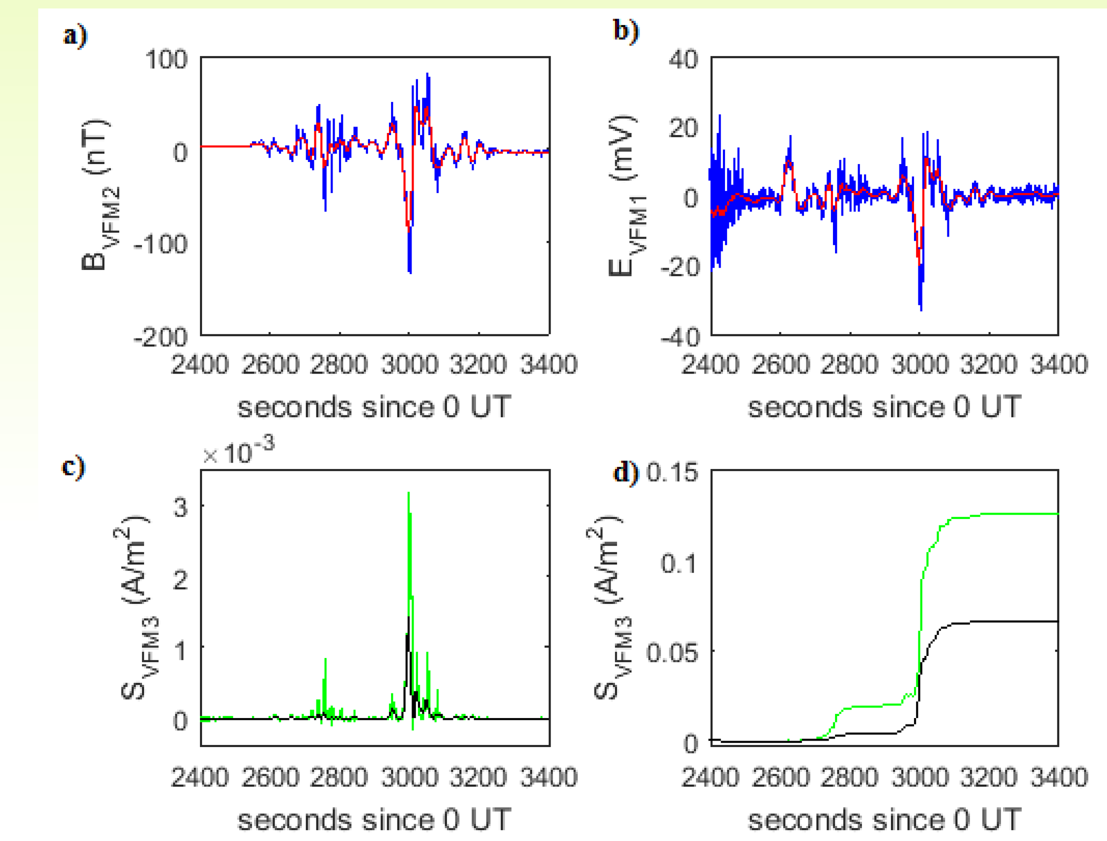

Figure 5: a) B-field at 1 Hz (blue) and after 20-sec low-pass filter (red), b) as a) but for E-field, c) as a) but for Poynting flux (green and black respectively) and d) integrated Poynting flux from c).

- Figure 5 shows that applying a 20-sec low-pass filter (150 km scale) to ostensibly remove the influence of Alfven waves leads to significant under-estimations of the Poynting flux in auroral crossings (Figure 5 c,d). In conclusion, although low-pass filtering may preserve the overall auroral topology, its energetics will be severely underestimated.

Summary

- Non-stationarities in FAC systems on scales at or above 1 Hz are **ubiquitous and energetically significant**. Large variances are **frequently** observed for various IMF conditions, latitudes and seasons, whose **peak-to-peak magnitudes are comparable** to the quasi-static FACs
- Birkeland currents appear to be **more variable on the dayside**
- Fine-scale magnetic perturbations are **coherent** between E-field and B-fields, with net **downgoing Poynting flux**. Low-pass filtering leads to a **significant under-estimation of energy in the system**

References

Iijima, T., and T. A. Potemra (1978), Large-scale characteristics of field-aligned currents associated with substorms, J. Geophys. Res., 83, 599, doi: 10.1029/JA083iA02p00599.

Lühr, H., Warnecke, J.F., Rother, M.K., 1996. An algorithm for estimating field-aligned currents from single spacecraft magnetic field measurements: a diagnostic tool applied to Freja satellite data. Geoscience and Remote Sensing, IEEE Transactions on 34, 1369–1376.

Lühr, H., J. Park, J. W. Gjerloev, J. Rauberg, I. Michaelis, J. M. G. Merayo, and P. Brauer (2015), Field-aligned currents' scale analysis performed with the Swarm constellation, Geophys. Res. Lett., 42, 1–8, doi:10.1002/2014GL062453

Prokhorov,B.E.,M.Förster,M.He,A. A. Namgaladze, and M. Holschneider(2014), Using MFACE as input in t heUAM to specify the MIT dynami cs,J. Geophys. Res. Space Physics, 119,6704–6714, doi:10.1002/2014JA019981.

Ritter, P., Lühr, H., 2006. Curl-B technique applied to Swarm constellation for determining field-aligned currents. Earth, planets and space 58, 463–476.

Ritter, P., Lühr, H., Rauberg, J., 2013. Determining field-aligned currents with the Swarm constellation mission. Earth, Planets and Space 65, 1285–1294.

M. Rother, K. Schlegel, H. Lühr. CHAMP observation of intense kilometer-scale field-aligned currents, evidence for an ionospheric Alfven resonator. Annales Geophysicae, European Geosciences Union, 2007, 25 (7), pp. 1603-1615. <hal-00318353>

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