Responses to the Reviewer #1 comments on the manuscript [angeo-2024-28]

"Small- and meso-scale field-aligned auroral current structures, their spatial and temporal characteristics deduced by Swarm constellation"

by Hermann Lühr and Yun-Liang Zhou

We are grateful to the reviewer for their thorough review of our manuscript. Their constructive comments has significantly helped us to improve the study. We have responded to all the comments and made changes wherever we regarded them as appropriate. Below, please find our point−by−point replies. For the convenience of the reviewers, we have first repeated the reviewer's comment and then give our answer in blue text.

I find that the results are largely compelling, however I have two major concerns: (1) the study uses a 60 min window to capture the variability of the magnetic field which has been pre-filtered in various pass bands from 1-3s to 39-60s - this fixed window length may introduce an inadvertent bias to the results; (2) the short-period variations that are not well correlated between the two spacecraft passes are discussed as unstable field-aligned currents, but as this is a time-varying magnetic field measurement rather than a direct measurement of the current, it is unclear that this is the only possible interpretation of these results. Given that point (1) above requires some study into the methodology, I recommend that this manuscript be considered after major revisions.

We are pleased by the generally positive rating of our study. Some of the major comments are based on an obvious misunderstanding and others are considered as justified. We are responding to all of them and suggest revisions of the manuscript in most the cases. Overall, the manuscript has been subjected to a major revision. Besides many clarifications it has become more focused on the temporal and spatial properties of the small-scale (10-50 km scale size) FAC. These have never before been studied in comparable details.

Major Comments:

1) On the methodology

As noted above, I have a concern with regards to the filtering and windowing of the data in the analysis performed. The manuscript details that various time-scales of magnetic field fluctuations are considered in order to examine different scale sizes of potential field-aligned currents (derived from the spacecraft motion in that time). However, the window used to calculate the cross-correlation between the two spacecraft and RMS values of the field remains fixed. As a result, for the smallest scales, there are between ~20 and 60 possible perturbations within the 60s window whereas for the largest scales it is 1-1.5 perturbations. If a some of the small-scale perturbations vary, then the cross-correlation will drop, whereas the whole perturbation has to vary for the largest scales. This, I feel, naturally results in fewer good correlations at the smaller scales. I suggest that the authors explore the sensitivity of their results to varying the length of the window over which they do the cross-correlation. For example, are does the success ratio for the 1-3 s scales increase for a 15 s cross-correlation window. The authors may also need to consider whether the correlation coefficient threshold needs to be increased with the smaller window size such that the P-value is consistent.

We are sorry to note that the reviewer obviously misinterpreted our approach to derive the correlation between magnetic field recordings of the Swarm A and C spacecraft. For example, it is not true that a fixed time interval (e.g. 60 s) has been used for the analysis of the various filter bands. To improve the situation, not just referring to earlier papers, we have added Table 1 at the end of Section 3 listing for the various filter bands the scale sizes, the interval lengths and step sizes.

With regards to the correlation coefficient used, I note that a correlation coefficient of 0.75 means that only 56% of the variability observed by one spacecraft is observed by the other. This feels quite low to say that the observed current systems are stable. There is also no consideration of changes of amplitudes of current that might result in relatively high cross correlations but differences in RMS values.

We agree with the reviewer that a correlation coefficient of 0.75 means that only little more than half of the signals at the two spacecraft agree with each other. However, in a statistical study like this, thresholds have to be introduced. It can be found in many studies that signals are considered as correlated, as long as their Cc is above 0.71. Following those arguments, we prefer to keep our threshold Cc > 0.75. Concerning the amplitude variations between the recordings at the two locations, we deliberately do not take them into account. It is expected that the FAC intensity varies with longitude (along the current sheet). As long as the same FAC structure is encountered by the two satellites the Swarm dual-spacecraft approach (Ritter et al., 2013) will properly report the mean FAC density that is crossing the integration area. It is a secondary objective of the study to find out, which FAC types are suitable for the dual-spacecraft approach.

(2) Discussion of results

This study examines whether or not magnetic perturbations seen by one of the Swarm spacecraft were also seen by a second spacecraft passing through at a slightly later time and at some azimuthal separation. If this is the case, then it is reasonable to assert that these perturbations arise from the quasi-stationary field-aligned current system. However, when the conditions set are not met it does not necessarily follow that it is an unstable current system. I feel it is better to described the observations as temporally or spatially varying magnetic field perturbations. Previous studies using data from Swarm and other spacecraft (e.g. the cited Ishii+ 1992 study and the Pakhotin+ 2018 doi: 10.1002/2017JA024713 study) have shown that large amplitude small-scale magnetic field perturbations may be associated with Alfven wave activity.

Here the reviewer brings up a valid point. The main result of this study is the temporal and spatial correlation length of FAC structure of various horizontal scales. This point has been made clearer in the beginning of the Discussion section. Overall, we have tried to avoid the term "unstable".
" The main purpose of the study is to find for FACs of small- and meso-scale sizes their azimuthal correlation length and temporal stability. Of special interest here are the properties of the small-scale FACs, which have never been investigated in comparable details, and which are known to be associated with Alfvén wave activity."

Many thanks for mentioning the study of Pakhotin et al. (2018) which had escaped our attention. It is now mentioned in the Introduction
" Similarly, Pakhotin et al. (2018) made use of Swarm satellite constellation data and investigated FAC characteristics by a comparison between electric field and magnetic field

data for one auroral region crossing. They reported for their case a change of current characteristics around a period of 5 s (~40 km wavelength) from quasi-static to dynamic, which is well in line with the results of Ishii et al. (1992)."

and more details are considered in the Discussion. But those authors cannot distinguish between temporal and spatial stability scales, thus have to rely on unproven assumptions.

"In a similar study Pakhotin et al. (2018) made use of Swarm constellation data for investigating the FAC characteristics at various spatial scales. For the one event they considered they looked at the correlation between the magnetic field recordings at Swarm A and C. For shorter FAC scales (< 40 km) they find significant differences between the readings at the two satellites (see their Fig. 2). From this single pass observation they cannot decide whether the missing correlation is caused by the difference in time between the two measurements ($\Delta t = 10.7$ s) or the longitudinal separation between the spacecraft (25-30 km). They guess that the decorrelation is caused by the time delay between observations. However, our results do not confirm their suggestion. For this class of FACs they have clearly a too large transverse separation between measurement points. Thus, the two spacecraft are sampling two different fluxtubes. The authors also made use of electric field estimates from Swarm A. By calculating the ΔB over $\mu_0 E$ ratio they obtain an estimate of the apparent Pedersen conductance. As can be deduced from their Figure 5, up to a frequency of ~0.15 Hz, constant impedance values result, for higher frequencies the impedance increases. This obtained apparent period of ~7 s, as limit for stable large-scale FACs, is well consistent with the report from Ishii et al. (1992). The shorter-scale FACs become more dynamic, thus partly driven by Alfvén waves, and some of the incoming energy is reflected."

Minor comments:

Line 44: "at the ionosphere play**s** a role"

Corrected

Line 76: please provide a reference for the Swarm L2 data product

The references to (Ritter et al, 2013; Lühr et al., 2020) have been added.

Line 77: Swarm A and C do not fly side-by-side, as is a key point of the manuscript. I believe that for the L2 product, one of the datasets is lagged so that it is treated as if they are side by side.

We are now more specific in the manuscript: "... the Swarm A and Swarm C spacecraft flying almost side-by-side with only a small along-track separation of around 7 s."

Line 86: As noted above, I was under the impression that the dual spacecraft product is a 2D curlometer, not the mean of two single spacecraft FAC estimates as implied by this line.

The reviewer is right, the dual-SC FAC estimate is derived from a kind of curlometer. We have improved the wording in the manuscript to avoid the misunderstanding.
" One of the standard Swarm Level-2 data products is the FAC density estimate (Ritter et al, 2013; Lühr et al., 2020) derived from the magnetic field measurements of the Swarm A and

Swarm C spacecraft flying almost side-by-side with only a small along-track separation of around 7 s."

Line 90: "the range dual-spacecraft FAC estimates **are valid**" ?

Corrected

Line 116: Swarm A and C are not side-by-side by are lagged by a few seconds

Thank you for the suggestion, considered.

Line 122-128: The Zhou et al figure should be referenced here. In fact, I think the Zhou et al figure (or similar) should be included in the manuscript as it is crucial to the study.

We agree and have made a reference to Fig. 1 in Zhou et al. (2024). However, we do not want to reproduce that figure here because there are already a large number of figures in this manuscript.

Line 178: " For these **example passes, we use a 60 s sliding window**...". When I first read this I was confused as I thought the whole interval shown was 60 s.

The wording has been improved. Now it is clearly stated that the 60 s are a sliding window. " For this and the example-pass in the lower frame cross-correlations have been applied to recordings of the two satellites. Here we consider a sliding window of 60 s (corresponding to a distance of 450 km) of ΔB_{trans} from Swarm A and C for deriving the peak correlation coefficients, *Cc*."

Line 238: "look at the **variable** magnetic field signal". Given that the introduction discusses the separation of waves and FACs, the current wording was confusing

Thank you for the suggestion.

Line 246-256: It would be helpful to mark some of the intervals of interest on the figure.

Labels with arrows have been added to Figs. 3, 5, 6 pointing at events mentioned in the text.

Line 287: "practically all magnetic **fluctuations above 20 s** can be..."

Thank you for the suggestion.

Line 395: give the zonal length in km as well as seconds

Corresponding scale size added.

Line 397: I don't understand what is meant by "the time between samples is more decisive for the occurrence ratio"

The sentence has been improved.
"The azimuthal correlation length of the meso-scale FACs (23-60 s or 86 - 225 km scale size) is obviously larger than the experienced satellite cross-track separations (0 - 20 km)."

Line 414: My reading of the figure is that d_cross < 3 km is where the ratio exceeds 50%. Please confirm

We agree that there appears a valley in occurrence ratio at d_cross ~ 3 km for the 3-7 s period band. This slight dip below 50% is partly caused by the smoothing function. The proper and steep decline of ratio is observed beyond d_cross > 6 km. For these reasons we prefer to keep the 6 km 50% boundary.

Line 426-437: Consider also the Pakhotin et al (2018) study that examined Alfven waves using Swarm

Thank you for this advice. The study by Pakhotin et al. (2018) contains a lot of interesting features of our small-scale FACs. By comparing E- and B-field variations they could show the role of Alfvén waves for these narrow FAC structures. Their findings nicely complement our results derived for this class of FACs. They are included now in the Discussion section, see responses to Major Item 2).

Line 444: At line 415, delta-t was noted as 16 s, not 18 s. Please confirm and be consistent

Thank you for spotting that. 16 s was a typo which is now corrected.

Line 476: specify the size range where it says "in this size"

Considered

Line 536: how were the quiet days selected for the calculation of the mean merging field and what is the value of this mean?

This part of the Discussion has been greatly revised and the former Figure 10 is no longer included. We have discovered a different source for the deselection of the small-scale FACs, namely the contamination by spectral noise from the very intense kilometer-scale FACs. This modification further enhances the focus on the small-scale FACs.

Line 540-542: Are these results from another paper? The results shown do not show large amplitude FAC structures are prone to instability nor the the FAC current density largely depends on driving.

The Discussion Section 5.2 has largely been rewritten. Our arguments for the deselection of small-scale FACs during times of enhanced solar wind input has changed. We realized that there is a class of even smaller, so-called kilometer-scale FACs which can attain very large amplitudes (see Neubert and Christiansen (2003); Rother et al. (2007)). Although our present dataset is not well suited to cover those km-FACs, our shortest period band (1-3 s) provides a glimpse of the activity in that range. We thus investigated the amplitude ratio $RMS_{1\text{-}3s}/RMS_{3\text{-}7s}$ separately for the selected and deselected events within the $d_{cross} < 6$ km and $\Delta t < 18$ s range. The resulting distributions of ratios from these event types show two clearly separated functions. From fitted Gauss curves (see below, the new Fig. 10) we obtain for the stable events a mean ratio of 0.65 ±0.22 and for the deselected a somewhat broader distribution with a ratio of 0.93 ±0.28.

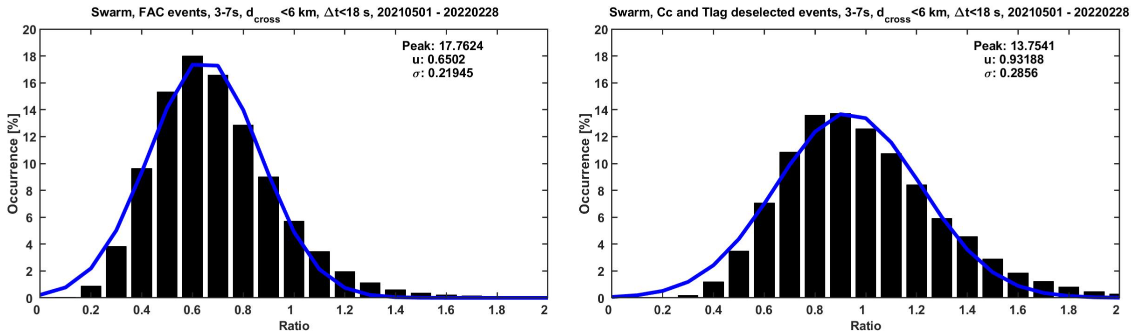

Figure . Distribution of the amplitude ratio $RMS_{1\text{-}3s}$ /$RMS_{3\text{-}7s}$ separately for the selected (left) and deselected (right) events in the d_{cross} < 6 km and Δt < 18 s range. The fitted Gauss curves reveal two clearly separated functions. For the stable events a mean ratio of 0.65 ±0.22 is obtained and for the deselected a broader distribution with a peak at 0.93 ±0.28.

The resulting distributions are in favor of our suggestion that large km-scale FACs can compromise the correlation of the 3-7 s period signals at the two spacecraft. As mentioned by Rother et al. (2007), the intense km-scale FACs tend to come as solitary current spikes (e.g. see Fig. 7, lower frame), thus causing almost a white signal spectrum. The spectral leakage from these spikes will markedly contribute to the 3-7 s period signal, and due to the short life-time of the spikes (order of 1 s) in totally different ways at the two Swarm satellites. It is thus no surprise that the peak cross-correlation coefficient of the 3-7 s signal is reduced when the km-scale FAC amplitudes are large.

For a closer inspection of the $RMS_{1\text{-}3s}$ /$RMS_{3\text{-}7s}$ ratio distributions we have plotted in the new Figure 11 (see below) how the ratios vary, separately for selected and deselected events, over our study time. The ratios resulting from the selected events stay on an almost straight line at constant level, as derived from the distribution curve in Figure 10, independent of season and local time. The ratio curve for deselected events is more variable but stays all the time above that of the selected. A comparison between the *Em* curve with those for the ratios shows not obvious correlation. There seems to be no direct influence of the solar wind input on the size of the ratios. In spite of that, when looking at the actual *Em* values at the times of selected or deselected events, we find on average slightly larger merging electric fields for deselected case by about 0.2 mV/m, see our old Fig. 10. All this provides further support for our suggestion of disturbing signals from the km-scale FACs. A more detailed investigation of the very small FACs is beyond the scope of this paper and will be the topic of a follow-up study.

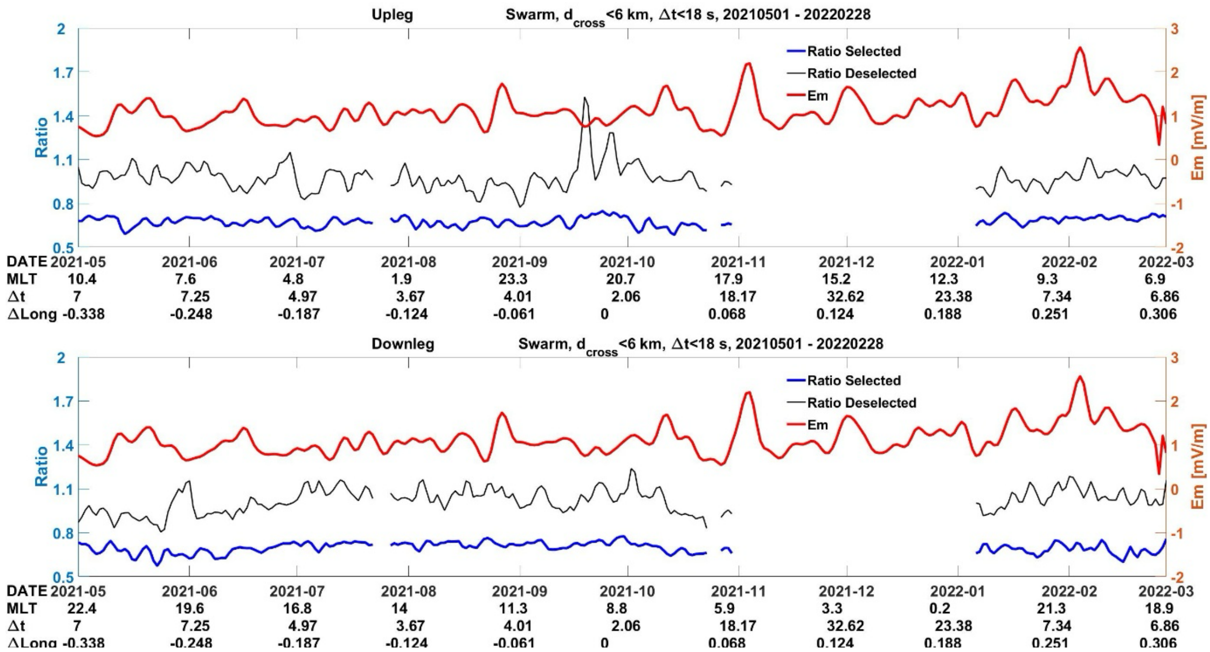

Figure. Temporal variation of the amplitude ratios, $RMS_{1\text{-}3s}$ /$RMS_{3\text{-}7s}$ over the study time. Separate curves are shown for the selected and deselected events. The upleg and downleg arcs cover different local times. For comparison, the merging electric field, Em, represents the amount of solar wind input.

Figure 10 and discussion: It would be useful to include an indication of the range of values at each epoch and whether the higher values for "deselected" events are statistically significant.

Figure 10 is no longer part of the manuscript.

Line 603 - 607: it is not evident from this study that large amplitude currents are unstable, just that large amplitude small-scale magnetic perturbations do not meet the criteria for stable FACs. They may be signatures of wave activity, something which is not examined in this manuscript.

This Conclusion Item 3 has been largely rewritten, following the new finding of spectral leakage from kilometer-scale to our small-scale FAC structures.

Line 625-627: this is speculation with no citations and no discussion in the preceding manuscript, so I suggest removing this sentence.

The sentence has been removed.