**Responses to the Reviewer #2 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.

General comments:

The manuscript presents a study of small- and meso-scale field-aligned current (FAC) structures using Swarm satellites. The study presents interesting statistical properties of these currents obtained from the close and unique positions of the Swarm constellations. The study finds that merging electric field can affect FAC structures and densities. The statistical properties reported in the manuscript may be useful for researchers of FACs. However, there are serious concerns, which shall be divided into two parts: (a) presentation and (b) technical.

Thank you for the generally positive rating of the study. We have tried our best to improve the manuscript, following the suggestions of the reviewer.

Presentation: The labels on all the figures are difficult to read because they are too small. Please increase the label font sizes on all figures. The manuscript contains many typographical errors, some of them are pointed out below, but the authors should go through the manuscript carefully to check the English grammar and errors. Finally, the organization can be improved. Section 5 (discussion) does not read like a discussion, but rather a continuation of the Section 4 (results/analysis). The discussion section usually provides context, interpretation, physical insights gained from the results (see below).

We have enlarged the labelling of the figures wherever regarded necessary. Limitations on the sizes are imposed by the available space.

We tried our best to remove the errors in English. Many thanks for spotting some of the typos.

Following your suggestion, we added now in the Discussion some paragraphs about magnetospheric processes that are know to generate small-scale FAC at auroral latitudes.

Generally, the study is now more focused on the small-scale FAC structures (10-50 km scale sizes), which have never before been investigated in comparable detail. Please see also our Responses to Reviewer #1.

Technical: The manuscript does not provide much physical interpretation of the results, which usually goes into the discussion. What causes the small- and meso-scale FAC structures? How does merging electric affect the FAC structures on the dayside and more curiously on the nightside? What is the mechanism? What causes the local time variations? It would be nice if the manuscript can discuss some these questions. Perhaps, the following example may help.

In the Discussion we have added an additional subsection on *Possible drivers for the small-scale FACs*

" We may ask, which magnetospheric processes are responsible such filamentary FAC structures. In the literature several suggestions can be found. We may start with the noon time, where the small-scale FACs appear particularly frequent. In this local time sector flux transfer events are believed to be the main source of transient and filamentary FAC structures. They manifest themselves optically as poleward moving auroral forms (e.g., Lookwood et al., 1990; Omidi and Sibeck, 2007). The related field-aligned currents are expected to spatial scales down below 100 km, thus fitting into the 3-13 s period range. On the duskside a viable generation process for transient filamentary FACs is the formation of Kelvin-Helmholtz plasma vortices. They are a result of strong plasma flow sheer in the range of the LLBL. According to Johnson et al. (2021) filamentary FACs in the scale 50-100 km in the ionosphere are expected to connect to the vortex centers at the LLBL. For the example they presented they find a scale of about 70 km. Also this fits into the range of our class of small FACs. A transient phenomenon on the morning side are the travelling convection vortices (TCV) (e.g. Fries-Christensen et al., 1988; Lühr et al., 1998). They are caused by local pressure pulses in the solar wind causing undulations of the magnetosphere that move with the solar wind from the day to the nightside. Related ionospheric effects propagate from the prenoon sector to the morning side. The magnetopause undulations are coupled by a pair of oppositely directed FACs to the ionosphere. Unfortunately, there exist so far no reports of FAC observations by satellite that could be related directly to TCV observation. Even though, filamentary FACs structures with scales of less than 100 km in the ionosphere are also expected from this phenomenon. The dynamic nature of all the mentioned processes infers that they are influenced by kinetic Alfvén waves."

FACs of different spatial scales at different MLTs may be caused by different processes. Generally, large scale FAC structures such as R1 and R2 (Iijima and Potemra, 1976) are fairly stable, but superimposed on these large FAC structures are small and meso scale FAC structures that may be transient in nature. For example, in the afternoon near the open-closed boundary, large scale upward FAC with spatial scale hundreds of km (but can be as small as several tens of km or as large as 1000 km in some cases depending on the solar wind condition) can be attributed to the velocity shear between the solar wind and magnetospheric plasma at the magnetopause boundary layer (Lyons, 1980, Siscoe, 1991, Echim et al., 2008, Johnson and Wing, 2015; Wing and Johnson, 2015). This large scale upward FAC structure is nearly always present because the velocity shear at the magnetopause boundary is always present (but the FAC thickness and strength may vary depending on the solar wind condition). Superimposed on this large scale FAC are small/meso scale FAC structures of tens of km (~50-70 km) in the afternoon sector can be linked to the KH vortices at the magnetopause boundary layer at dusk flank (Petrinec et al., 2022; Johnson et al. 2021). These KH vortices are not static but rather they move anti-sunward with the solar wind and hence the small and meso scale FAC structures associated with these vortices are not static either. Perhaps, a discussion along this line in the introduction and/or discussion section may help the readers appreciate how the statistical results presented in the manuscript may help improve the physical understanding of the magnetosphere and ionosphere and help provide context.

Thank you for the advises. They have been very helpful and guided us to improve our Discussion.

Specific comments:

1. Line 45. “dominate” should be “dominant”
   Done

2. lines 70-71, the sentence is a bit awkward. Would the following capture the meaning better?
   The sentence has been revised (line 88-89)
   "Larger-scale FACs (>150 km) can be regarded as quasi-stationary, being stable over more than 60 s. The longitudinal extent of the small FAC sheets was reported to be about 4 times large on the nightside than their latitudinal scale, but on the dayside both scales were found to be of comparable size. In spite of these valuable results, the Lühr et al. (2015) study had a number of limitations."

The longitudinal extension of the small FAC sheets on the dayside was found to be comparable to the latitudinal width, but 4 times larger than the latitudinal width on the nightside.

1. line 91, “erose” should be “arose”.
   Done
2. lines 134-136, What are the assumptions here? Would this technique only work at high latitude, e.g., in the auroral oval? If so, please state.

   It is now mentioned that the limitation to the two horizontal components is justified at auroral latitudes since the magnetic field lines are almost vertical to the Earth surface.
3. lines 147-148, do the authors mean FAC intensity (unit = A/m) or density (unit = A/m^2)? FAC density is usually obtained by dividing FAC intensity by the width of the FAC (see for example, Ohtani et al., JGR, 2005).

   Thank you for the advice. We use now consistently FAC density.
4. line 184, should FAC density be closer to 15 microA/m^2 (100/7.5) rather than 10 microA/m^2?

   No, we think our conversion from $\Delta B$ to FAC density is more correct. According to Eq. (2), $\Delta B$ has to be divided by $\mu_0$ and the satellite velocity.
5. line 240, “base” should be “basis”
   Done

6. Figures 3-5 (and other figures), rather than displaying the six period ranges in sec, would it be more useful and practical to display them in spatial scale, i.e., km? Most readers would care more about the spatial scale of FAC structures rather than delta t.

   We mention now in the figures both the period band and the scale size. Furthermore, we have added now a table which summarizes all parameters used for the cross-correlation analysis.

| Period band | Scale-length | Data interval | Step size |
|---|---|---|---|
| 1 -3 s | 4-11 km | 32 s | 4 s |
| 3 - 7 s | 11-26 km | 32 s | 4 s |
| 7 - 13 s | 26-49 km | 32 s | 4 s |

| | | | |
|---|---|---|---|
| 13 - 23 s | 49-86 km | 64 s | 8 s |
| 23 - 39 s | 86-156 km | 64 s | 8 s |
| 39 - 60 s | 156-225 km | 96 s | 12 s |

7. lines 279-280, how do the authors remove the local time and seasonal effects?

   The sentence has been rephrased. It is made clearer that our approach normalizes possible dependences of the event occurrence rates on local time and seasonal or other effects.
   "When normalizing the identified stable FAC structures by the number of wavy signal events with amplitudes above the threshold (RMS > 2 nT/s), the environmental influences on the occurrence rates of such features, depending possibly on solar wind input, local time or season, are largely removed, but the effect of the Swarm constellation on positive detections prevails. Therefore, these plots are more suitable for evaluating the properties of the detected currents."

8. lines 282-283, “larger ratios of stable FACS are obtained in the afternoon sector”. Perhaps, something is missed. Where can we see this in Figure 5? Figure 5 shows that afternoon sector has lower ratios.

   We admit that our description was a little bit too short. Now the dependence of stable FAC occurrences on the local time has been outlined in more details for both hemispheres.
   " During the first half of the study period we find the blue curves in Figure 5 on higher levels than the red in the northern hemisphere. This means larger ratios of stable FACs are obtained in the afternoon to late evening sector, compared to the early morning to prenoon local times during summer season. Conversely, when looking at the southern hemisphere (right frame), where winter conditions prevail during the first half, the red lines tend to be higher than the blue. This means, a higher percentage of stable FACs in the morning than in the evening sector."

9. lines 310-311, would 10-20 km is more precise for “1-3 s periods “than “10 km”?

   We now clarified in Section 2 that the quoted spatial scales amount to halve of the wavelength. Wavelength includes both the pair of up and downward FACs while the scale refers to only one of them.

10. lines 313-319, In Figure 5 there are local time variations as well as temporal (UT) variations. The authors would like to attribute the minimum FAC ratios to 4 Nov 2021 storm. However, the minimum is located in the afternoon sector or morning sectors. Is there an ambiguity in local time vs. UT (storm) effect?

    Thank you for pointing that out. We have now commented on the obvious differences of occurrence ratios, at least in the northern hemisphere, between afternoon and morning sectors for the very quiet and stormy days.
    " The storm-related reduction of stable FACs on 4 November is present at all wavelength but is more prominent at shorter scales. Conversely, for the very quiet days, 27-29 October 2021, a dip in ratio appears only at long periods, and, at least in the northern winter hemisphere, it is much more evident in the morning than in the evening sector."

11. line 502 and elsewhere in the manuscript, the terms “selected” and “deselected” are a bit confusing. What do the authors mean by “deselected” and “selected”. Can these terms be described more clearly?

    We have now introduced a definition for "selected" and "deselected" in Section 5.2. " In the following we use the term "selected" for those current structures in the above defined scale range that passed the stability checks and "deselected" for those not passing the checks."

12. line 538, “cause” should be “caused”
    Corrected

13. Figure 8, what causes the gap near the top right? Is it the result of the constraint on the selected periods? Please explain.

    The blank areas at the top and on the left side are caused by constrains of the satellite constellations. The 2-s along-track separation occurred only during the two weeks close to coplanarity. Similarly, during the period of increased along-track separation (up to 41 s) happened at a time when the longitudinal separation did not exceed 12 km. These constellation constrains are now mentioned in the context of Figure 8.

14. Section 6. The manuscript provides many statistical results, which, at times, are hard to keep track. It would be nice if the authors can provide a table, which can summarize the various properties of the FAC structures.

    Rather than adding a table, we prefer to list the major results verbally in the Conclusions, Section 6.