Responses to the comments of Reviewer #2 on: "Properties of large-amplitude kilometer-scale field-aligned currents at auroral latitudes, as derived from Swarm satellites," by Zhou and Lühr

We are very thankful to the anonymous reviewer for his/her generally positive rating of the manuscript. Furthermore, we find the constructive comments and suggestions very helpful for improving the quality of the manuscript and to make it clearer for the readers. We considered all the comments and made changes in the manuscript where we regarded them as appropriate.

Below, we have repeated the comments and added our responses in blue text. In the revised manuscript the main changes are marked by bold text.

This paper presents observations of field-aligned currents from the Swarm satellite magnetometers. It is well-written and provides very important new results regarding field-aligned currents in the high latitude ionosphere. The use of dual satellites enables new insights regarding the nature of FAC of different scale sizes. There is no question that this work should be published. Provided below are minor comments requesting clarifications and some suggestions to the figures to improve the impact of some of the main points.

Comments

1. Large spikes in the FAC data

The paper refers to large current spikes (see line 418 and abstract, for example). Presumably, these are the peaks shown in the enlarged time series plots in Figure 2. The authors should comment if these peaks are well resolved with the 50 s/sec data or would higher sampling reveal even sharper spikes?

In preparation for the CHAMP mission we have made use of Freja magnetic field recordings to determine a suitable sample rate. Freja had a burst mode of 128 Hz. From that dataset it could be shown that for more than 90% of the narrow features in FAC bursts true amplitudes can be derived with 50 Hz sampling. Based on that assessment the CHAMP and Swarm magnetic field sample rates had been chosen. This explanation is now given in lines 71ff.

Remark: It appears likely that such spikes might be associated with narrow electron beams. Alternatively, they might exhibit steepening of Alfven waves, as reported and modeled by Seyler et al. [1995] in the Freja magnetometer data.

We prefer to keep our interpretation of turbulent down-scale cascading to finest structures, which is supported by the roll-off of the magnetic field power spectral density that fits well over a large frequency range the Kolmogorow index of -5/3, see the new Figure 10.

2. Spectrum of FAC and magnetic field variations

The spectrum of the km-scale magnetic field FAC variations is extremely important, particularly because there are not that many examples from other high latitude satellites with 50 s/sec sampling of the magnetometer. (Maybe reference Freja data?).

A few comments: It is well known that a power spectrum of a time series of "spikey" fields appears as a broad spectrum. The authors are asked to comment on whether the spectrum shown at the bottom of Figure 9 might obscure the higher frequencies associated with the spikes in the time series data.

As outlined above, we are confident that the spectrum presented in Figure 9 reflects well the typical frequency content of bursty km-scale FACs, and the roll-off starting at 8 Hz is not caused by band limitation of the magnetometer.

Is the spectrum shown in Figure 9 from Swarm A or C or any average from both satellites? The authors may wish to consider presenting the spectrum in nT for comparison with other measurements or at least comment on how the FAC spectrum represents that of the magnetometer components. It is suggested that a vertical dashed line be placed on the spectrum at 0.2 Hz to immediately inform the reader that there is an instrumental cutoff.

Yes, the shown spectra in Figure 9 for ΔB_{trans} and ΔB_{along} are averages from Swarm A and C results for enhancing the significance. This is stated in line 442. As expected, the spectra from the two satellites are very similar, thus a merging makes sense. We follow your suggestion and added a vertical line in Figure 9 at the cutoff frequency of the high-pass filter.

Along these lines, a spectrum of the unfiltered data would be very powerful. Since the paper includes longer-scale FAC, the authors are encouraged to consider including a spectrum that includes the longer scales (i.e., without the filtering.)

In response to this comment, we added a new Figure 10 that shows the magnetic field Power Spectral Density (PSD) of the event presented in the top panel of Figure 9. In this case no frequency limitation by filtering has been applied. Just the finite duration of the burst in the recordings causes a decrease in amplitude for apparent periods longer than 100 s. Overall, the magnetic signal exhibits a spectral decay which is close to the Kolmogorow Index of -5/3, which is added for reference as dashed blue line. This agreement supports our interpretation that the intense narrow FAC structures are a result of turbulent Alfvén wave interaction. The steeper falloff at the high-frequency end indicates progressive dissipation.

3. Scale length instead of wavelength

The paper discusses FACs organized by distance covered along the satellite path. Therefore, it is suggested to use the term “scale length” and not wavelength when referring to the different scales. See use of wavelength in the abstract, for example. Wavelength, in general, refers to a well-defined wave with a k-vector, etc.

In the initial manuscript we tried already to avoid the term "wavelength". Following the convention in geodesy, we rather use "scale size" or "scale length" for half the wavelength, as described in line 204. Here recorded temporal variations are interpreted as spatial structures. As part of the evaluation, we have divided the signal into several period bands. Periods are in a first place related to wavelengths. Therefore, we think, this term cannot be totally avoided. In the revised manuscript we tried to replace "wavelength" wherever possible, e.g. in the Abstract and Conclusions.

4. Cross correlations in Figure 10 are somewhat obscure

Figure 10 also shows cross-correlations and the caption says the format is the same as Figure 1. However, in Figure 10, it is not clear if the cross correlations are between SWARM A and C or between the shorter and longer period waveforms which are shown in the upper panels. This should be clarified.

Thank you for the advice. We have modified Figure 1 according to your Suggestion #2. In order to provide the reader already upfront with the central topic of this study we have added results from the longest-period field variations. In different colors we show the contrasting behaviors of the broad-band signal and the longer-period (2.5-5 s) variations. With this modification the main messages provided by the former Figure 10 are now presented already here. As a consequence, we drop the former Figure 10. The expanded description of Figure 1 can be found in the manuscript in lines 143ff.

5. Use of the term "small scale" is somewhat counter-intuitive when compared to the term "km-scale," since small scale is really larger than km-scale, at least in this paper

A main thrust of this paper is to compare two groups of FACs: those with km-scales and those with 10's of km scales. The authors have chosen to call the longer scale FACs "small scale". This is extremely confusing, as this group of data refers to FACs that are longer scale than the km-scale FACs, even though they are referred to as short scale. Suggestion: Why not refer to the two groups as either: "10's km scale and km scale FACs" or "medium scale and small scale FACs" in which the shorter, km scale FACs are designated as "small scale".

The entire paper would then be easier to read, from the title and abstract through to the summary and conclusions. In the summary, line 526, might then read, "For medium scale FACs (5-20 km) whereas line 532 would remain as is, "The km-scale FACs (0.5-5 km size)…". The title refers simply to "km-scale FACs" and this would then be appropriate as is. Sentences such as line 519 that refer to the "smallest scale" FACs which are confusing, at least to this reviewer, could be left as is.

This may appear as a very minor point, but the authors are urged to reconsider their nomenclature.

We appreciate very much the arguments of the Reviewer. However, this is not the first paper on narrow FAC structures. Most studies have made use of magnetic field data with 1 Hz sample rate, e.g., Ishii et al. (1992) or Pakhotin et al. (2018). They have coined the term small-scale FACs for structures down to 5 km, the smallest derivable from those samples. Conversely, Neubert and Christiansen (2003); Rother et al. (2007) tried to find the smallest scales where the FACs reach their amplitude maximum. They first introduced the term "kilometer-scale FACs. Here we wanted to be consistent with those earlier studies and therefore prefer to keep chose terms for the different scale sizes. In the Introduction we have added some text for justifying the used terms, see lines 58ff

6. Typo

Line 61: suggest remove the comma before "these narrow FACs" and perhaps put: "…large amplitudes that these narrow FACs…"

This sentence has been modified.

Suggestions

1. Time series showing combined medium scale and short scale data

This paper underscores that there are two populations of FACs characterized by different scales whose appearances in the data are highly related to each other. The paper would be well served if there was a simple time series example showing the juxtaposition of the superimposed scales. Here it would be important to not filter the data. In other words, perhaps show 30 seconds or so of data that will clearly show the large-scale variations upon which are superimposed the km-scale variations? Maybe before Figure 1? Since the km-scale variations have the larger amplitude, this would be very powerful. Maybe leave in nT instead of nT/s so the waveform can be readily compared with other high latitude magnetometer data from other satellites?

The kind of plot you are asking for is presented in Figure 6a. The readings of Swarm A and C track each other almost perfectly during times without km-scale activity, e.g. 23:09:00 to 23:09:40 UT. Conversely, during times with km-scale FACs, e.g. 23:09:48 to 23:10:00 UT the signals at Swarm A and C differ significantly, this is true also at longer periods. The example plot confirms well our statistical results. In lines 481ff we draw the attention of the reader to the obvious features in this figure.

A possible relation between our small-scale FACs and the large-scale FAC environment will be the topic of a follow-up study.

2. Cross correlation curves on Figure 1

This suggestion follows the suggestion above.

The "overview" examples in Figure 1 are very powerful. However, these are just for the km scale data. Although the figure is somewhat busy with two examples, including a panel (for each example) of the longer scale length data would be highly desirable, particularly as Figure 1 introduces the reader to what the paper is all about. (Perhaps have a Figure 1a and 1b on separate pages?)

As described above, Figure 1 has been updated according to your suggestions. We agree that this improves the readability of the paper.

Since the cross correlations of km-scale variations show low correlations in the regions of km scale FACs, the reader does not immediately grasp that the longer scales have high correlations. Although this will become apparent later in the text, given the fact that this is such a unique data set with two SWARM satellites, it is suggested to have two cross correlation line plots (in different colors?) in which the 10-40 km FACs are included. It seems that this is a golden opportunity to show the different cross correlations in a pair of line plots in this introductory figure that clearly shows off the beauty of having two SWARM satellite.

Thank you for these praising words.