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Interactive comment on "*Swarm* field-aligned currents during a severe magnetic storm of September 2017" *by* Renata Lukianova

Renata Lukianova

renata@aari.nw.ru

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I thank the reviewers for valuable comments and constructive critique. All comments were carefully considered and addressed. Answers to all the questions are presented below. Corresponding changes have been made in the revised manuscript.

The comments and answers are numbered according to the Referee number and the order of comments. The changes in the revised manuscript are indicated in red.

Referee #1

Comment 1.1 The introduction consists of two very general paragraphs, and does not contain any clear motivation for the study. It is claimed that it is "of interest to analyze [storm FACs'] unique characteristics", but it is not explained why.

Reply to Comment 1.1 The introduction has been extended and the motivation for the study has been formulated as follows.

"It is the purpose of this paper to characterize the magnitude of the large- and smaller scale FACs as well as their reaction to the magnetic storm development. The Swarm observations are used in order to identify various characteristics of the storm-time FACs for the event of 6–9 September 2017, which was one of the two most severe magnetic storms of the recent solar cycle 24 (the previous event was the St-Patrick storm on 17 March 2015). The September 2017 event is of particular interest because it was a two-step storm during which two intense substorms occurred and the FAC system is affected by the storm-substorm interplay. In this paper we investigate the time evolution of FAC intensities, the displacement of FAC equatorward boundaries and the extreme small/medium-scale (∼7.5 km width) currents."

Comment 1.2 The main dataset is the 1 second FAC estimates from Swarm. The assumptions involved in deriving this should be clearly described. There are several alternative techniques which could be mentioned, especially techniques that utilize the Swarm A-C conjunction. How does the results depend on the choice of technique?

Reply to Comment 1.2 The Swarm data base contains FACs computed using as the single–satellite as the dual-satellite approaches. In the present study the single-satellite FACs are used because this technique is identical for all three satellites. Since FACs from A, B and C satellites are used, we need the similar method of derivation for all of them. If the dual-satellite method is applied, the resulted FACs are seem to be slightly weaker, than those obtained by the single-satellite method. The following additions explaining the single–satellite as the dual-satellite approaches have been included to section 2.1 Instrumentation.

"FACs can be detected by their magnetic perturbations in the orthogonal plane which are obtained after subtracting the Earth's main magnetic field model from the total measured values. From single spacecraft the FAC density can be estimated based on one magnetic component with a techniques invoking Ampere's law under assumptions about the infinite current sheet geometry and the orthogonal crossing of the current sheet. This method was used for the previous one-satellite missions, such as Magsat and Ørsted (Christiansen et al., 2002). It is also applied to each Swarm satellite separately. The dual-satellite estimation method calculates current density from curl(B) measured simultaneously at 4 locations was adapted for SwA and SwC data, where measurements separated along-track will be used to create a 'tetrahedron' (Ritter and Lühr, 2006). The curl(B) method provides more reliable current density estimates, as it does not require any assumptions on current geometry and orientation. The FAC output of both the dual-satellite method and the single-satellite method are considered to be in reasonable agreement (Ritter et al., 2013). Both algorithms are implemented in the Level-2 processor to generate the Swarm products that are produced automatically by ESA's processing centre as soon as all input data are available. The products are provided using the dual-satellite method on the lower pair of satellites SwA and SwC, and the single-satellite solution for each of the Swarm spacecraft individually. The 1-sec values of FAC densities are available via the on-line Swarm data portal (ftp://swarm-diss.eo.esa.int) as Level 2 data products (Swarm Level 2 Processing System Consortium, 2012). In the present study the single-satellite FACs are used in order to apply the similar method to SwB and SwA/SwC data."

Comment 1.3 There are no references where one can find more information about the instruments (not just the magnetometers, plasma measurements are also used in the paper without proper introduction).

Reply to Comment 1.3 More information about the magnetometers and the plasma probe along with the appropriate references has been added to section 2.1 Instrumentation. The following para describes the mission instruments and provides references.

"The ESA Swarm mission is a constellation consisting of the three identical satellites (hereafter SwA, SwB and SwC, respectively), all are at the low-altitude polar orbit (Friis-Christensen et al., 2008). .... The main module is the high-sensitivity vector (fluxgate type) and scalar magnetometers for determining the magnitude and direction of the total vector and variations of the geomagnetic field with an accuracy of more than 0.5 nT (Merayo et al., 2008). Magnetometers make it possible to carry out measurements in a wide range, including the main magnetic field and the variations of external magnetic field generated by FACs. .... Each Swarm satellite is also equipped with the Electric Field Instrument which includes the Langmuir plasma probe to provide measurements of electron density, electron temperature and spacecraft potential (Knudsen et al., 2003). These data are available at 2 Hz sampling rate as the standard product of the Swarm data base."

Comment 1.4 It is claimed in the abstract and in the conclusions that R1/R2 currents are composed of small-scale currents. This is never really shown in the data. How do you know that R1/R2 is not a large-scale current system with small-scale currents superimposed?

Reply to Comment 1.4 Figure 3 shows that the R1/R2 are composed of small-scale currents. This figure depicts the original 1-s FACs (small scale) measured along the track, from which large scale currents are revealed after a smoothing procedure.

Comment 1.5 The word saturation is used to describe the lower limit of the equatorward boundary. It is never explained what is meant. Reference is made to Xiong et al.'s definition, but the data is never presented in such a way that we can compare with how they define it.

Reply to Comment 1.5 This word has been eliminated from the abstract and conclusion. As for the reference to Wang et al. (2006), these authors used the definition "saturation" likely in the sense that the limits of the equatorward boundary were observed not lower than at 50° MLat.

Comment 1.6 In figures 4, 5, and 6, reference is made to external parameters which are shown with rather coarse resolution in Figure 1. It is very difficult to follow the description when one has to go back and forth between the figures to check. It would help to plot SYM-h together with the panels in 4, 5, 6, and also mark the time of substorm onset.

Reply to Comment 1.6 SYM-H and AL plots have been added to Fig. 4. SYM-H plots and substorm onset time have been added to Fig. 5. Substorm onset time has been marked on Fig. 6.

Comment 1.7 The time of substorm onset is never mentioned in the paper I believe, and this is quite crucial. For example, it is stated that the FACs propagate equatorward during substorms, but you would expect something different: An expansion during the growth phase, and then a contraction. The way that the figures are presented, it is very difficult to see if this is the case.

Reply to Comment 1.7 Now the time of the two storm-time substorm onsets are indicated in Figs 4-6. As far as an expansion during the growth phase, and then a contraction is concerned, the effect is not seen in this case. It is likely because we deal with the equatorward but not the poleward boundary. It is rather the poleward boundary of FACs that is closely related to the polar cap (open-close) boundary. The poleward boundary is expected to react to the substorm development. But in the parameter presented here, indeed, it is difficult to reveal the effect of expansion/contraction. The following comment has been added to Section 4 Dynamics of the equatorward boundary.

“From Fig. 5 one can see that during the pre-storm time FACs are observed mainly poleward of 60° MLat in both hemispheres. Upon arrival of the SW shock at the very end of September 7, EqB is shifted equatorward, then tends to recover, and then drops again following the second intensification of the storm. At the very beginning of 8 September EqB is found at its lowest position of 50° MLat. The EqB drops abruptly and simultaneously with the peak of the first storm-time substorm and with the lowest drop of SYM-H down to -150 nT. The second substorm reaches its peak slightly before the second minimum of SYM-H (at 12:50 and 13:55, respectively). During the second activation of the storm the EqB is shifted again as low as 50° MLat (although SYM-H is only -100 nT). As seen from Fig. 5, the evolution of EqB tends to follow the gradual change of SYM-H rather than an abrupt drop of AL related to the substorm onset (see also Fig. 2). Unlike the current density, which exhibits sharp spike-like increases, temporal variations of EqB are relatively smooth. Note that almost no notable difference in evolution in the day- and nightside EqBs is observed during the main and recovery phases. An equatorward expansion of the FAC region during the substorm growth phase, and then a contraction are not resolved."

Comment 1.8 I think the description of dawn/dusk asymmetries is an example of not choosing the right tool for the job. If you want to investigate global dawn/dusk asymmetries, why not use AMPERE, which provides global FAC maps, instead of Swarm which only gives in-situ measurements?

Reply to Comment 1.8 Yes, AMPERE provides global FAC maps which are suitable to study the asymmetry. However, the AMPERE products are not considered here because the present paper concentrates the Swarm data and intends to reveal the storm-time effects solely in these in-situ measurements. Although the picture is not global, the expected asymmetry can be seen. Joint analysis of the AMPERE and Swarm data in order to reveal an asymmetry may be a subject of future work. The appropriate references for the previous AMPERE results are included.

Comment 1.9 In two cases (l. 25, p. 18 and l. 25 p. 19) reference is made to analyses that are not shown. If it is not shown, it should not be included unless it is completely trivial and easy to check for the reader, which does not seem to be the case here.

Reply to Comment 1.9 Following to this comment, in both cases the para referred to the preliminary, not shown analysis has been eliminated.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-40/angeo-2019-40-AC1-supplement.pdf

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