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

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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 #3

Comment 3.1 - The first paragraph is written in a bit loose way, e.g. Are FACs flowing only from boundary layers? Why FAC system is evolved only by dayside (not nightside) reconnection? FAC may exceed its nominal level – what is meant by nominal level?

Reply to Comment 3.1 The first para of Introduction has been rewritten in order to address the issues pointed out by Referee. The revised version reads as follows. “Field-aligned currents (FACs) provide electrodynamic coupling of the solar wind-magnetosphere-ionosphere system. FACs flow along the high-conducting geomagnetic field lines between different magnetospheric domains and the high latitude ionosphere. This current system is driven by the internal magnetospheric circulation of plasma and magnetic field within the global reconnection cycle (Dangey, 1961) and by additional viscous-like interaction at the flanks of magnetosphere (Axford, 1964). Configuration of FACs is primarily controlled by the interplanetary magnetic field (IMF) orientation. Other parameters of the solar wind (velocity, density, IMF strength) and the ionospheric conductivity also play a role (e.g. Christiansen et al., 2002; Ridley 2007; Korth et al., 2002).

Schematic distribution of large-scale FACs has been established by Iijima and Potemra (1976) based on the Triad satellite data. Subsequent space missions allowed constructing comprehensive empirical models of FAC parameterized by the IMF direction and strength, by season, and by hemisphere (Weimer, 2001; Papitashvili et al., 2002; Green at al., 2009). The ionospheric projection of the 3D FAC system consists of a pair of sheets elongated along the auroral oval, namely, Region 1 (R1) and Region 2 (R2), with opposite current flow directions in the morning and evening local time sectors and additional current sheets (R0) located on the dayside poleward of R1/R2. R1 is downward (flows into the ionosphere) and upward (flow from the ionosphere) on the dawn and dusk side, respectively. R1 currents, if reside on closed field lines of the Earth’s magnetic field, are believed to originate in either the boundary layer or in the plasma sheet (Ganushkina et al., 2015). R2 FAC is a diversion of the partial ring current to the ionosphere driven by pressure gradients in the inner magnetosphere (Cowley, 2000). R0 current is connected to the dayside magnetopause and its polarity strongly depends on the IMF By component. On the Northern Hemisphere, the R0 current flows predominantly out of the ionosphere for positive IMF By and into the ionosphere for negative IMF By (Iijima et al., 1978; Papitashvili et al., 2002). Additional (NBZ) current associated with the sunward ionospheric flow may appear inside the polar cap, if IMF Bz is northward (Iijima et al., 1984)."

Comment 3.2 In the second paragraph it is said that Wang et al. (2006) and Anderson and Korth (2008) have studied storms, but no results are given

Reply to Comment 3.2 A brief description of the results obtained by the authors cited has been added to the forth para (former 2nd) as follows. "Utilizing the magnetic field measurements by CHAMP satellite Wang et al. (2006) investigated the northern and southern hemisphere dayside and nightside FAC characteristics during the extreme October and November 2003 magnetic storms. It was shown that as Dst decreases, the FAC region expand equatorward, with the shift of FACs on the dayside controlled by the southward IMF. For both case studies, on the southern (late spring) hemisphere the minimum latitude of the FACs is limited to 50° magnetic latitude (MLat) for large negative values of Bz (The minima are the same, although in October the IMF Bz drops dawn to -28 nT, while in November it reaches -50 nT.) On the northern (late autumn) hemisphere the equatorward boundaries of the FAC region are located at 55-60° MLat. Using the global maps from the Iridium constellation Anderson et al. (2005) studied the FACs intensities during severe magnetic storms which occurred during the solar cycle 23 with a particular attention to the evolution of FACs in the course of the storm of August 2000. The results revealed the dawn–dusk asymmetry of the R1/R2 current sheets, with an increase primarily found on the duskside. It was shown that under disturbed conditions the total current is not linearly related to the interplanetary electric field, with the intensity constrained to be below 20 MA (Anderson and Korth, 2007)."

Comment 3.3 Please swap Sections 2 and 3, it would be more logical

Reply to Comment 3.3 Done. Also, Section 2 Swarm satellites has been divided into two subsections: 2.1 Instrumentation (descriptions of the methods used for FAC derivation and the EFI instrument have been added). and 2.2 Orbits on 6-9 September 2017.

Comment 3.4 Section 2: - Maybe the Clilverd et al. (2008) paper should be referred to?

Reply to Comment 3.4 What paper by Clilverd et al. (2008) does the Referee mean? In the 1st para of Section 3 Space weather conditions on 6–9 September 2017 (former Section 2) I refer to several recent papers in which the different effects of this storm were analyzed.

Comment 3.5 Section 3: - Here one should shortly explain how 1-s FAC data products are derived from the original magnetometer data

Reply to Comment 3.5 The description of FAC data products has been added to Section 2 Swarm satellites 2.1 Instrumentation (former Section 3) as follows.

"The mission has a multi-instrument payload. 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. 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 a dual-satellite and a single satellite method are considered to be in a 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 center 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 s 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 3.6 - Please explain what coordinate system for MLAT is used and how MLAT and MLT are derived

Reply to Comment 3.6 The location of the satellite is presented in an geographic coordinate system NEC (x North, y East, z Center), where the x and y components lie in the horizontal plane, pointing northward and eastward, respectively, and z points to the centre of gravity of the Earth. For the purpose of present study all projections of the passes are recalculated to the magnetic local time (MLT) and MLat domain according to coordinate definitions from Laundal and Richmond (2017). The corrected geomagnetic (CGM) coordinates with the Definite/International Geomagnetic Reference Field (DGRF/IGRF) Models is used.

Comment 3.7 - SwB is not separated by 1.5 h in LT from SwA and C, but this difference depends on time

Reply to Comment 3.7 This previous erroneous statement has been corrected. The corresponding para in Section 2.1 Instrumentation reads as follows. SwA and SwC fly in a tandem separated by 1-1.4° in longitude and the differential delay in orbit is $\sim$3 s. The orbit period is about 93 min and slightly different between SwA/SwC and the upper satellite SwB, so that their along-orbit separation in local time gradually changes. Their orbital planes also gradually drift apart and the separation angle increases by $\sim 20^\circ$ longitude per year. Slowly drifting in longitude, the orbits cover all the local time sectors over about 130 days.

Comment 3.8 - First sentence in Sect. 4.1.: give a reference

Reply to Comment 3.8 The references to (Weimer, 2001; Papitashvili et al., 2002; Green at al., 2009) have been added.

Comment 3.9 - Figure 3: Define FAC positive values (up- or downward current)

Reply to Comment 3.9 Definition has been added to the figure caption: “Downward (upward) current is positive (negative)”.

Comment 3.10 Figure 4: It would be more informative for the reader to see in the upper right corner the mean MLT value (or text “pre-noon” etc) than the track identifier. One could also add standard deviations to the mean values by error bars (and expand the horizontal width of the figure)

Reply to Comment 3.10 Figure 4 has been re-plotted. Standard deviations, the centered MLT (instead of the track identifier) and SYM-H and AL indices have been added. Shading has been eliminated to avoid a overloading of the figure. The description of the figure has been modified accordingly. The revised version reads as follows.

“To demonstrate the temporal evolution of FACs in Fig. 4 the FAC intensities for each MLT sector are presented separately for the northern (Fig. 4a, c, e, g) and southern (Fig. 4b, d, f, h) hemispheres. Red (blue) point is determined by averaging the downward (upward) FAC density from a current-free location at the lowest and highest MLat of each crossing. The upper plots (a-d) and the lower plots (e-h) show the data from day side and night side, respectively. For comparison the evolution of the FAC intensities with the storm development the SYM-H and AL indices are shown in the plots (a, b) and (e, f), respectively. Overall, FACs shown in Fig. 4 exhibit three pronounced enhancements, which are of different intensity depending on the MLT sectors. (Note, that the measured FAC densities do not exhibit any systematic changes associated with the daily variation of the orbit.) The first, smaller enhancement in the very beginning of September 7 is seen on the day side (Fig. 4a-d). This increase of FAC intensity is associated with the SW dynamic pressure front impinges the magnetosphere causing a positive excursion of SYM-H. Unlike the day side, on the nightside FACs (Fig. 4e-h) respond to the shock with a considerable delay, so that FACs are peaked at about 06 UT, 7 September. A moderate substorm occurred in the middle of September 7 also contributes to the increase in FAC intensity.

The two higher peaks occur in the course of the storm main phase at the very beginning and in the middle of September 8. The intensity of a particular peak varies in different MLT sectors being more pronounced on the night side. On the day side, in the sector centered at 10 MLT (Fig. 4a, b) FACs are enhanced during the whole period of 7-8 September with only a relatively modest intensification at about 06 UT on 8 September. In the sector centered at 16 MLT (Fig. 4c, d) an abrupt increase up to 1-2 1 μA/m2 is observed at the very beginning of 8 September with association with a first deep drop of SYM-H. On the nigh side, a strong increase of FAC is also observed (Fig. 4e-h). However, the current intensities increase more gradually, although finally they reach the higher values. The nightside FACs follow the evolution of AL and start to increase as the substorm growth phase begins at $\sim$22 UT, September 7. In the sector centered at 04 MLT, northern hemisphere (Fig. 4g) a narrow peak up to 3 μA/m2 is observed in the very beginning of 8 September (for a particular crossing the average density exceeds 6 μA/m2 as seen from the standard deviation)."

Comment 3.11 Table 2 would need more explanation. Which MLATs are included in the calculation? What are the uncertainty limits behind these numbers? Has the author checked from the Southern hemisphere, which are the highest MLATs that the satellites reach and does that affect the estimates?

Reply to Comment 3.11 MLAT for 40°–90° is accounted. It is difficult to estimate the uncertainty behind the numbers presented in Table 2. The number itself has no uncertainty because this is a result of the straightforward summation. At the same time, as pointed out by the Referee, there may be a lot of indirect factors which may lead as to the under- as to the overestimation. The following additional explanation for Table 2 is suggested. “It should be noted that the numbers presented in Table 2 contain uncertainties. Although these numbers are the result of the straightforward summation, there may be indirect factors which lead as to the under- as to the overestimation. For example, the highest MLATs that the satellites reach mayt affect the estimates. However, if the under- as to the overestimation approximately compensate each other, the tendency of the prevalence of the dawn side R2 is revealed.”

Comment 3.12 - Line 29: “From the FAC values presented in columns 5 and 6 one can see that in both hemispheres the dusk side downward current is stronger than all the other currents. This predominance implies an additional amplification of the storm-time R2 FAC on the dusk side, which is related to the partial ring current.” This would need more discussion and definitely a reference.

Reply to Comment 3.12 The following addition has been made. “As pointed out by Anderson and Korth (207) this shift may result from a strong dusk side ion pressure leading to asymmetric dusk-side inflation of the magnetic field consistent with a partial, dusk side, ring current during storm main phase (Liemohn et al., 2001).”

Comment 3.13 - “pre-storm time”. It would be good to define from the beginning, what is the onset of the storm time, and maybe mark that in all the figures.

Reply to Comment 3.13 The pre-storm time is defined as the time before the SYM-H attains its stable negative values <20 nT at 22:00 on 7 September. For easier comparison of the FAC evolution with the storm phases the SYM-H is shown in Figures 4 and 5. In Figure 6 the time before the SYM-H attains its stable negative values <20 nT at 22:00 on 7 September is marked.

Comment 3.14 - l. 18 “Comparing Fig. 1 and Fig. 4 one can see that EqB more closely follows the variation of SYM-H.” I agree that since end of Sept 7, the boundaries seem to follow SYM-H, but not before that. Maybe the author could check the correlation to AE-index as well?

Reply to Comment 3.14 I do not think that the correlation between AE and EqB would help to resolve the dependence of EqB on any single parameter. For easier comparison the SYM-H index has been added to Fig. 5. More explanation on the SYM-H and EqB coherence has been added to Section 4.3 as the following.

“Even visual comparison of the SYM-H and EqB evolutions reveals a coherent behavior of these two parameters. At the same time, during a period preceding the storm main phase (before end of 7 September, when SYM-H is mainly positive) EqB is located much lower than during the end of recovery phase (after $\sim$12 UT on 9 September, when SYM-H is still negative). From Fig. 5 one can see that during the pre-storm time (before the SYM-H attains its stable negative values <-20 nT at 22:00 on 7 September) FACs are observed mainly poleward of 60° MLat on both hemispheres. Moderate equatorward shifts of EqB are associated with the modest substorms occurred before the storm main phase in the middle of 6 and 7 September. Prior the storm main phase, on both hemispheres the prenoon (04 MLT) EqB is found considerably poleward compared to the EqB location at other MLTs. The effect is well seen during the two time intervals: from $\sim$22 UT, Sept 6 till 06 UT, Sept 7 and after 12 UT, Sept 7. Both intervals are dominated by the northward IMF (sf. Fig. 2), so that a shrinking of the polar cap and a poleward shift of the auroral oval is expected. With regard to the position of FACs, the displacement of its equatorward boundary is the largest only in the pre-noon sector, while the other local times remain less affected.

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 at 50° MLat. The EqB drops abruptly and simultaneously with the peak of the first storm-time substorm just between 7 and 8 September 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 drops of AL related to the substorm onset (see also Fig. 2 for AL). Unlike the current density, which exhibits sharp spike-like increases, temporal variations of EqB are relatively smooth. During the late recovery phase at the second part of September 9, EqB is shifted poleward as high as 70° MLat. As far as the day-night asymmetry is concerned, almost no notable difference in evolution on the day- and nightside EqBs is observed during the main and recovery phases. An expansion of the FAC region during the substorm growth phase, and then a contraction are not resolved."

Comment 3.15 "The current intensity vary inversely with scale". Please give a reference.

Reply to Comment 3.15 The references to (Neubert and Christiansen, 2003; McGranaghan et al., 2017) have been added.

Comment 3.16 It is unclear how Figure 7 is composed. What are the horizontal and vertical axes? Is the figure even needed in this paper?

Reply to Comment 3.16 When for each crossing of the region of MLat>50° within a certain MLT sector the minimum (i.e. the peak upward current) and maximum (i.e. the peak downward current) of 1 s FACs were selected, it appears that in some cases the adjacent upward and downward currents (call them the bipolar structure) are observed, while in other cases the min/max are separated in latitude. In Fig. 7, the correlations between the MLats, at which the most intense small-scale FACs of opposite polarities are observed, are presented separately for the four MLT sectors. The x-axis (y-axis) corresponds to the MLat at which the downward (upward) 1 s FAC is observed.The x-axis (y-axis) corresponds to the MLat at which the downward (upward) 1 s FAC is observed.

Fig. 7 seems curious because it demonstrates the occurrence of the bipolar structures likely associated with the reconnection formed at the magnetopause. In this relation more explanations have been added as follows.

"In contrast to the early morning local times, in the pre-noon sector, where cusp and cleft currents are expected, the bipolar structures are quite frequent. Here, these structures may represent a signature of the cusp plasma injections which are accompanied by pairs of FACs generated due to flux transfer event (FTE) formation (Southwood, 1987) or localised reconnection at the magnetopause. Magnetic topologies associated with FTEs were previously observed by the MEO satellites (Marchaudon et al., 2004; 2006; Pu et al., 2013) but not by the LEO satellites. Neubert and Christiansen (2003) reported small-scale currents primarily found in the cusp and pre-noon region with densities 1–2 orders of magnitude larger than R1 and R2 currents. The dependence on IMF Bz and the SW turbulence was found by these authors suggesting that currents are a result of reconnection processes distributed over the dayside magnetopause and even in the tail for negative Bz. The bipolar structures were not resolved in the observations by Neubert and Christiansen (2003). The correlations presented in Fig. 7 may be interpreted in such a way that the bipolar structures dominate exactly in the region where the signatures of FTE and the multiple reconnection lines formed at the magnetopause are expected."

Comment 3.17 - In this section suddenly Te and Usc are discussed without anywhere properly explained, how it has been derived (which instrument, references etc)

Reply to Comment 3.17 A brief description of the plasma instrument has been added to Section 2.1 Instrumentation as follows. "Each Swarm satellite is also equipped with the Electric Field Instrument which includes the Langmuir probe to provide measurements of plasma parameters: 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. Combination of the vector magnetometer and the plasma analyzer makes it possible to study the plasma disturbances associated with

FACs."

Comment 3.18 - "The considerably elevated Te within the arc and just poleward of the arc is associated with a local amplification of electric field." I don't understand this sentence. To my understanding, electric field data is not used in this study. Furthermore, why Te enhancement would be associated with enhanced EF?

Reply to Comment 3.18 Yes, the electric field data is not used in this study because these data is unavailable. Thus I can only referee to previous observations, e.g. by Aikio et al. (2002). It is not necessary the Te enhancement would be associated with enhanced EF.

Comment 3.19 Reference to Wang et al. (2004) is not found from the list. maybe it should be 2006?

Reply to Comment 3.19 Wang et al. (2006) is correct.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-40/angeo-2019-40-AC3-supplement.pdf

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