

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 #2

General comments In general, the paper presents a case study, interesting new observations, however, in some cases it is not clear whether the presented observation and result is new or just confirmation of previous findings. This should be clarified and

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emphasized in the discussion section.

The study of the dawn-dusk asymmetry comparing the dusk-side and dawn-side portions of the same orbit (practically in 1D), especially at small scales, is questionable since this approach ignores the 3D distribution of the current system.

Based on the presented figures and tables the calculation of the MLT is very suspicious (see below in the specific comments). Since the MLT information is essential for the whole analysis that may fundamentally affect all the results and conclusions, the paper cannot be accepted before this serious issue is fixed. There are a series of other smaller issues (listed below) that have to be considered before a possible acceptance.

Reply General comments

All sections have been considerably modified in order to better structuring and emphasis of the new findings.

Yes, the dawn-dusk asymmetry can not be resolved in 1D distribution. This issue was also mentioned in the Referee #1 comments. AMPERE product is more relevant to this kind of analysis (The appropriate references for the previous AMPERE results are included). However, it does not exclude a possibility to reveal signatures of such asymmetry even in the Swarm measurements during a severe magnetic storm. 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, some signatures of 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.

Concerning the MLT problem please see Reply to Comment 2.5

Comment 2.1 p 3 l 1-10 The description of the storm evolution needs some correction and complementation. Give the time of the shock arrival on 6 Sep. The trigger of the first substorm is first identified as the southward turning Bz at 18:30 on 7 Sep, then a few lines later, as the second shock arriving at 22:00. In contrast with your description,

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SYM-H was not recovered on 8 Sep.

Reply to Comment 2.1 Corrected. The description of the storm evolution has been modified as follows. "The arrival of the first shock late on 6 September (23:50 UT) results in a sudden increase in all parameters except the AL index. Since IMF Bz turns northward, this initial disturbance is only weakly geoeffective as a result. At 20:40 UT on 7 September, IMF Bz turns southward that triggers a substorm growth phase and a ring current build up. The second shock arrived at ~23:40 UT on 7 September, with the SW speed up to 800 km/s and strongly negative Bz and By. This shock causes an abrupt drop of SYM-H down to -150 nT and a spike-like decrease of AL down to -2200 nT. After 03:00, 8 September the IMF Bz becomes positive, AL gradually approaches to zero and SYM-H starts to recover until the next southward turn of Bz. At ~06 UT on 8 September another strongly negative Bz period is seen, and the SW speed remains high (>700 km/s). This causes the second substorm (AL is -2000 nT) and ring current intensification (SYM-H is -100 nT). A steady recovery occurs in the AL index throughout 9 September, while the SYM-H gradually increases from -75 to -35 nT. The SW parameters are not available for this day."

Comment 2.2 p 4 l 4 and 6 Description of the Swarm constellation has to be revised. The orbit inclination for SwB is different from that of the other two. As a consequence, the separation between B and (A and C) is increasing. In Sep 2017 it was already close to 6 h (and not 1.5 h) as you can easily check on your Fig. 2. p 4 l 6 The slow drift is in MLT not in longitude. p4 l 7 Since any orbit consists of two parts separated in local time by 12 h, you only need around 4 and a half (and not 7-10) month of data to cover all local times.

Reply to Comment 2.2 Corrected. The description of the orbits has been modified as follows. "SwA and SwC fly in a tandem separated by 1-1.4° in longitude and the maximal differential delay in orbit is ~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

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the separation angle increases by ~20° longitude per year. Slowly drifting in longitude, the orbits cover all the local time sectors over about 130 days."

Comment 2.3 p 4 l 8 The description of the derivation of the FAC product is very inaccurate ("from the measured magnetic field variations, which results from FACs, the current densities are computed: : :"). You may just describe the Swarm single-satellite FAC product mentioning its limitations.

Reply to Comment 2.3 The description of the derivation of the FAC product has been modified and extended in order to describe the dual- and single-satellite approach. In the revised version the following additional comments have been included to section 2.1 Instrumentation.

"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

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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-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 2.4 p4 Description of the plasma product is missing.

Reply to Comment 2.4 Added as follows: "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 2.5 Figure 2 a) From the polar plot presenting the orbits in the MLT-mlat system, it is suspicious that your MLT calculation is not correct. 2 h change in MLT within a few days is not realistic. Figure 2 b) I cannot make sense of this figure: daily variation of MLT as a function of MLT. On the x-axis, MLT runs from 0-24. And it is not a straight line! Your MLT calculation has to be revisited and clearly described in the paper. Table 1 The same MLT issue.

Reply to Comment 2.5 Figure 1a is seemed to be correct. (Note that in the revised version Figure 1a is Figure 2a because Section "Swarm satellites" and Section "Space weather conditions on 6–9 September 2017" was swapped as recommended by Referee #3.) The polar plots of the orbits do not imply a systematic drift in MLT as large as 2 hr within a few days. While the daily total data coverage is expanded in MLT, it is centered in certain MLT hour (sf, e.g., Cherniak and Zakharenkova Earth, Planets and

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Space (2016) 68:136, DOI 10.1186/s40623-016-0506-1).

Figure 1b (former Figure 2b) was erroneous: it contained the erroneous x-axis title. The correct x-axis title is UT.

Projections of the passes are recalculated to the MLT and MLat domain according to coordinate definitions by Laundal and Richmond (2017) as $MLT = UT + (\varphi + \Phi_N)/15$, where φ is the magnetic longitude, Φ_N is the geographic longitude of the North Centered Dipole pole and UT is the universal time specified in hours..

Comment 2.6 Section 4.1 FAC densities You may want to rename this section in relation to the title of Section 4.4 'Small-scale FACs'.

Reply to Comment 2.6 Section 4.1 can be renamed, however I'd prefer to keep the present title because it is more general and actually both the small (1 Hz) and large (averaged) currents are considered.

Comment 2.7 Figure 3 b) and p 6 I 12-13 What I see is R1 upward and R2 downward.

Reply to Comment 2.7 The description of Fig. 3 has been made more precise. "The 1-s values are presented in Fig. 3a, while Fig.3b depicts the 21-point smoothed curve from which it can be seen that the satellite approaching the pole from the dusk observes first the downward (positive) R2 and then the upward (negative) R1 current. In the near-pole region (above approximately 72° MLat) FACs are almost absent. Then the satellite move equatorward in the early morning local times."

Comment 2.8 p 7 I 5-6 This wording ('determined by averaging the positive (negative) FAC densities from a current free location at the lowest and highest MLat of each crossing') is confusing, rephrase. What is the advantage of using the average densities instead of the 'total' (integrated?) densities? As you mention, the two correlates. Does it mean that the variation of the range of FAC latitudes is not significant?

Reply to Comment 2.8 First, the sentence about correlation has been eliminated because it is not confirmed by presentation. The advantage of using the average densi-

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ties instead of the 'total' (summed) densities is related mainly to the different length of the satellite track located within the FAC region.

Comment 2.9 p 7 | 9 precession?

Reply to Comment 2.9 Replaced by "daily variation"

Comment 2.10 p 9 | 7 'The largest FACs are observed' > 'The corresponding/associated FACs are the largest: : .' (after all the shocks and substorms already mentioned the reader is getting lost)

Reply to Comment 2.10 Rephrased to avoid duplicated wording

Comment 2.11 p 9 | 15 'there is no' > 'we could not find any'

Reply to Comment 2.11 Corrected

Comment 2.12 p 10 | 10 The definition of the EqB is not clear: "at least eight values before and after the central point do not exceed 0.1 uA/m^2 " Do you mean the smoothed values? Before and after? Central point of what? Estimate the scale of the considered FACs.

Reply to Comment 2.12 To determine the EqB the original 1 Hz data are used. In the sliding window the "central" point moves along the track with 1-s sampling. At each step 10 FACs values preceded and followed the central point are considered. From them at least 8 should be <0.1 . If the criterion is fulfilled, the most poleward point without FAC is selected as EqB.

Comment 2.13 p 10 | 19 "considerable" > "moderate" p 11 | 8 "is seen only : : : : unaffected" > "is the largest : : : : less affected"

Reply to Comment 2.13 Corrected

Comment 2.14 Figure 5 MLT values given in the figure caption and in the legend are different

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Reply to Comment 2.14 Corrected

Comment 2.15 p 12 | 6 "resolved spatial scale" > "spatial resolution" p 13 | 5 and 7 Reference to Fig 7a and 7b are exchanged

Reply to Comment 2.15 Corrected

Comment 2.16 p 14 | 10 FFT?? Isn't it just a boxcar smoothing?

Reply to Comment 2.16 The integrated (build-in) FFT procedure is used. Removed from the text to avoid the ambiguousness.

Comment 2.17 p 14 | 17 20000-40000 cm^{-3} seems a bit low for topside Ne, please confirm

Reply to Comment 2.17 These values are what is available via the Swarm data portal

Comment 2.18 p 14 | 19 Note, that as far as I know, the Swarm Te values are still uncalibrated. If still so, please make a note.

Reply to Comment 2.18 The data were downloaded from the Swarm data portal. There is no clear indication that they are still uncalibrated. Even if so, it is hardly affect the relatively small-scale perturbations.

Comment 2.19 p 15 | 13 " : : : : a decrease in Ne (which is usually much less pronounced than a decrease : : : : ?" p 15 | 14 "are created" > "may be created" p 17 | 24 "is associated" > "is likely associated"

Reply to Comment 2.19 Corrected

Comment 2.20 p 18 | 5 "It confirms the fact" If it is a fact, why does it need confirmation? Your statement that large-scale FACs are composed of more intense small-scale FACs is not supported by your analysis. You also mention that others found that small-scale FACs are mostly associated with Alfvén-waves.

Reply to Comment 2.20 These sentences have been rephrased as follows: "This implies

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that a substantial fraction of R1/R2 currents is composed of many small-scale FACs.

Comment 2.21 p 18 l 15 The scale length range in the brackets is for small-scales?. What scale was taken as a large scale? The given density value (0.5) is for large scale? Please clarify.

Reply to Comment 2.21

In the cited paper the large scale implies >250 km length and the density value (0.5) is for the small scale. Corrected.

Comment 2.22 p 19 l 3 Is your definition of EqB of large-scale FACs is comparable to that of the cited paper?

Reply to Comment 2.22

Wang et al. (2006) defined the latitudinal positions of peak current density but not the most equatorward boundary of the FAC region, thus the actual FAC region may expand to lower latitudes (below the reported 52-56° MLat. A note has been made.

Other comments and Technical corrections p 19 l 15 Image > IMAGE (the name is an acronym) p 19 l 22 equatorial > equatorward p 20 l 9 'indication' this asymmetry is well-known, you may say, your observation is in accordance with this. p 6 l 11 Aan > An p 7 l 4 is > are p 9 l 5 and 7 (also elsewhere) 'in the northern hemisphere', 'in the night side', 'in the day side' > 'on the night side', 'on the dayside', 'on the northern hemisphere' p 9 l 13 'coherence' > 'correlation' p 14 l 7 (and elsewhere) 1-sec FAC > 1 s FAC or 1 Hz FAC p 14 l 21 0.4 and 2% > 0.4% and 2%

Reply Corrected

Please also note the supplement to this comment:

<https://www.ann-geophys-discuss.net/angeo-2019-40/angeo-2019-40-AC2-supplement.pdf>

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Interactive comment on Ann. Geophys. Discuss., <https://doi.org/10.5194/angeo-2019-40>, 2019.