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- Temporal variability of field-aligned currents
- Longitudinal correlation length of field-aligned currents
- Small-scale FACs show very different characteristics than large-scale FACs

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Field-aligned currents' scale analysis performed with the Swarm constellation

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Abstract We present a statistical study of the temporal- and spatial-scale characteristics of different field-aligned current (FAC) types derived with the Swarm satellite formation. We divide FACs into two classes: small-scale, up to some 10 km, which are carried predominantly by kinetic Alfvén waves, and large-scale FACs with sizes of more than 150 km. For determining temporal variability we consider measurements at the same point, the orbital crossovers near the poles, but at different times. From correlation analysis we obtain a persistent period of small-scale FACs of order 10 s, while large-scale FACs can be regarded stationary for more than 60 s. For the first time we investigate the longitudinal scales. Large-scale FACs are different on dayside and nightside. On the nightside the longitudinal extension is on average 4 times the latitudinal width, while on the dayside, particularly in the cusp region, latitudinal and longitudinal scales are comparable.

1. Introduction

Intense electrical currents flow along the magnetic field lines between the Earth and near space. These field-aligned currents (FACs) are the dominant transport mechanism for energy and momentum and are thus of fundamental importance for our understanding of the solar wind-magnetosphere-ionosphere-thermosphere coupling. FACs are present in the auroral zones at all local time sectors and are flowing all the time although with highly variable intensity. Due to their fundamental importance, a vast amount of studies has been published since the first ground-breaking papers by *Zmuda et al.* [1966, 1967]. FACs have, however, almost solely been derived from single-satellite observations [e.g., *Iijima and Potemra*, 1976] which are subject to two crippling assumptions: the currents are static and the currents have a simple geometric configuration (e.g., infinite current sheets). Only recently it has become possible to test these assumptions and thereby gain new understanding of the system behavior (e.g., The Auroral Turbulence II sounding rocket mission, *Lynch et al.* [1999]; the Enstrophy sounding rocket mission, *Zheng et al.* [2003]; the CLUSTER II mission, *Escoubet et al.* [2001]; and ST5 mission initial results by *Slavin et al.* [2008]).

The only large statistical study to date of the spatiotemporal characteristics of FACs was published by *Gjerloev et al.* [2011]. They used the three ST5 satellites to perform a comprehensive correlation analysis and found that the characteristics of FACs depend on local time and geomagnetic activity. Due to their orbital geometry, the ST5 spacecraft were cycling the Earth in Sun-synchronous mode, causing limitations in local time coverage. Furthermore, the orbits of the three spacecraft were well lined up, providing no information on the longitudinal correlation length of FAC structures. Another multisatellite approach is the AMPERE project [*Anderson et al.*, 2000]. Average configurations of the FAC distribution are derived at short cadences of less than an hour from 66 Iridium satellites. However, the low-resolution magnetic field measurements make the AMPERE results less suitable for the topics of this study.

These open issues warrant another study on temporal-spatial FAC characteristics. A suitable data set for such investigations has been sampled by the Swarm constellation during its early mission phase when the three spacecraft were close together. Here we address the questions of FAC temporal variability depending on scale size and the FAC longitudinal correlation length.

In section 2 we describe the data used and the technique employed for evaluation; section 3 describes the spacecraft constellation; in section 4 we show our results; in section 5 we discuss the findings and draw conclusions, and finally, we summarize the results.

2. Data and Techniques

Swarm is European Space Agency's (ESA) fourth Earth Observation Opportunity Mission. The three satellites were launched together on a Russian Rockot on 22 November 2013 into a near-polar (87.5° inclination) orbit at an altitude of about 500 km. After a commissioning of the subsystems and scientific instruments the spacecraft were maneuvered into their final orbits from middle of January 2014 onward. On 15 April 2014 Swarm had achieved its final constellation. Two satellites, Swarms-A and -C, are flying side by side in a formation, separated by only 1.4° in longitude and at an altitude of about 460 km. The third spacecraft, Swarm-B, orbits the Earth at about 520 km with a somewhat higher inclination, such that the angle between the orbital planes increases by about 20° per year.

We are utilizing the Vector Field Magnetometer (VFM) observations. Measurements from this fluxgate magnetometer are routinely calibrated against the readings of the Absolute Scalar Magnetometer (ASM). For our analysis we consider primarily data from the early mission period, beginning of December 2013 to middle of January 2014, when all three spacecraft were fairly close together. For the investigation of longitudinal correlation some data are taken into account from the early time of constellation flight, after middle of April 2014.

The quantity of interest is the field-aligned current (FAC) density estimate at all three satellites. Basic relation for that is Ampère's law. When solving for the vertical current component j_z, we can write

$$j_z = \frac{1}{\mu_0}\left(\frac{\mathrm{d}B_y}{\mathrm{d}x} - \frac{\mathrm{d}B_x}{dy}\right) \tag{1}$$

where B_y and B_x are the magnetic fields caused by the currents; x and y are coordinates in northward and eastward direction, respectively, μ_0 is the permeability of free space. Since the magnetometers measure the complete geomagnetic field, we use models to subtract the main and crustal field (e.g., CHAOS-4+, [*Olsen et al.*, 2014]) and the large-scale magnetospheric field (e.g., POMME-6, [*Maus et al.*, 2010; *Lühr and Maus*, 2010]). The B field residuals are routinely processed by ESA to estimate FACs for each Swarm satellite and provide the results as level 2 data products to the community. We use for this study the same processing approach as that implemented by ESA for the level 2 processing.

When considering single-satellite measurements, commonly spatial field gradients are derived from field changes between successive readings. Since only along-track gradients can be determined it also assumes that cross-track gradients are insignificant. For the actual FAC estimates we use a formulation that had earlier been developed by *Lühr et al.* [1996]. The equation for deriving vertical current density reads

$$j_z = \frac{1}{2\mu_0 \mathrm{d}t}\left(\frac{\mathrm{d}B_y^{\mathrm{VSC}}}{V_x^{\mathrm{VSC}}} - \frac{\mathrm{d}B_x^{\mathrm{VSC}}}{V_y^{\mathrm{VSC}}}\right) \tag{2}$$

where B_x^{VSC} lies in the horizontal plane and is rotated by 45° to the west from the flight direction, B_y^{VSC} is rotated by 45° to the east. V_x^{VSC} and V_y^{VSC} are the spacecraft velocity components in the same coordinate frame; dt is the time difference between successive measurements, here 1 s. More details on equation (2) can be found in *Ritter et al.* [2013]. This equation assumes, as usual, FAC current sheets are perpendicular to the flight direction. From a statistical survey we deduce that 90% of the northern hemisphere passes make an angle with the auroral oval of larger than 45°. In the southern hemisphere the situation is less favorable for single-satellite solution with only 64% of the passes are larger than 45°.

3. Constellation

An important condition for the scale analysis of FAC structures is the close spatial formation of the three Swarm satellites. Figure 1 gives an overview of the evolution in space and time of spacecraft separation. The time considered is the commissioning phase before injection into the final orbits. Here Swarm-A is used

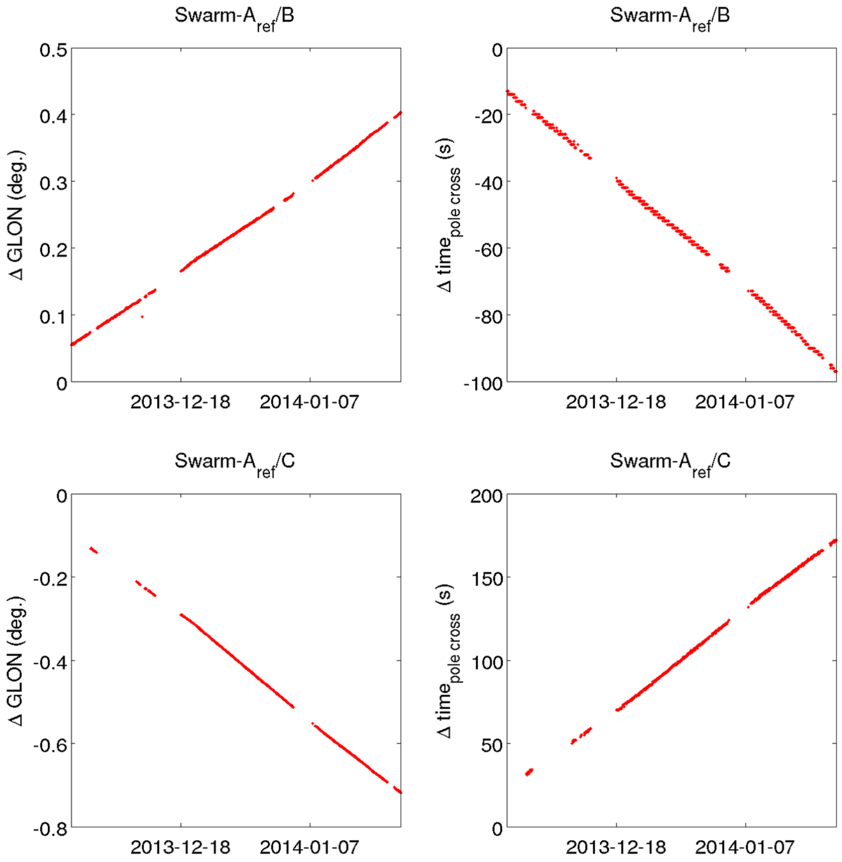

Figure 1. Evolution of Swarm satellite separation during the commissioning phase. Time differences are with respect to the polar crossover points.

as reference since it flew in the middle. As can be seen, Swarm-A/B are closer together starting at 0.05° in longitude and 10 s time difference at the polar crossover. For the couple Swarm-A/C we find about twice the values. Over time the separation increases to 0.7° in longitude and 170 s. Negative longitude (GLON) means that a satellite passes the equator to the west of Swarm-A, and negative time means that it passes the pole earlier than Swarm-A. In addition, we considered some data from the final constellation. There the pair Swarm-A/C is constantly separated by 1.4° in longitude and shifted by about 7 s in time. The longitudinal separation of the higher-satellite Swarm-B is constantly increasing at a rate of about 1° in longitude per 18 days. From the data available we can study separations up to 10° in longitude. It takes 5–6 days for the lower Swarm-A/C couple to overtake Swarm-B in orbit.

4. Results

In this section we test the two assumptions mentioned in the section 1: (1) recorded magnetic variations are due to static currents and (2) currents can be assumed to be infinite current sheets. First, we looked into the scale size dependence of the FAC temporal variability. For that we considered occasions when the two spacecraft sampled the magnetic field at the same location but at different times. In case of Swarm these are the orbital crossover points near the poles. Since we are mainly interested in the FAC characteristics at auroral latitudes, we had to limit the study to the Southern Hemisphere where the South Pole overlaps with the auroral region at magnetic latitudes around −75°. One example of such a measurement is shown in Figure 2. Figure 2 (top) presents the original data at 1 Hz resolution; the panels below reflect filtered time series at different cut-off periods. The untreated data show rather strong FACs reaching current densities beyond 10 μA/m^2. The scale size of these structures is about 10 km (filter window periods have to be multiplied by the spacecraft velocity of 7.5 km), and we find significant changes in amplitude over the 16 s that separates the two satellites. Even though we compare measurements at the same location there is an

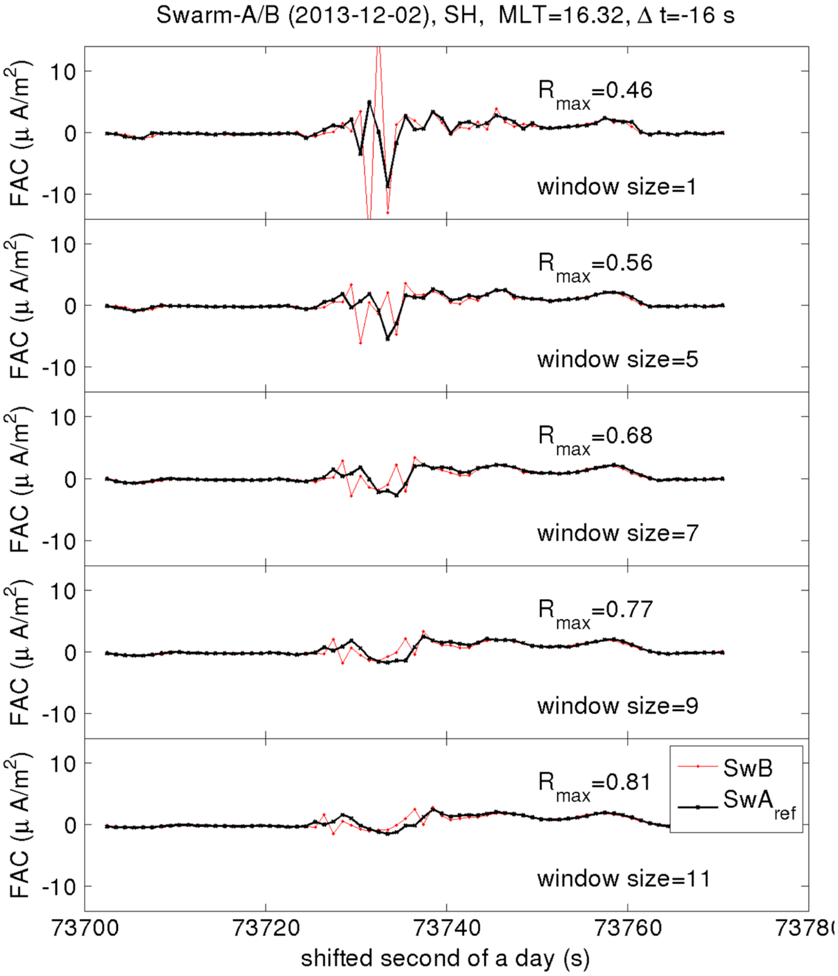

Figure 2. Example of temporal FAC variation for different scale sizes. The various panels show FAC variations filtered at different cutoff periods (window size in seconds). The time difference between the two recordings amounts to 16 s.

obvious time shift between the FAC features. At Swam-B they appear earlier by 1–2 s. This difference reflects a motion of the current features in satellite flight direction at a speed of about 0.5 km/s.

In order to get a more quantitative picture of the temporal variability we performed correlation analyses of the original and filtered FAC density time series. Because of the rather common shift between the two time series, we applied cross correlations over the displayed time interval of 60 s (less than 4° in magnetic latitude) and report the maximum correlation coefficient ($R_{\max}$). Figure 3 shows the distribution of $R_{\max}$ as a function of the two independent parameters: (1) delta-time, and (2) scale size. We show the distributions for the dayside and nightside separately. The vertical column at about 10 km in Figure 3 represents correlation results from unfiltered time series. All the other values are from filtered data with latitudinal scales as listed in the abscissae. The unfiltered recordings show poor correlation at almost all time differences. These data are dominated by FAC structures with horizontal scale length of order 10 km. Only at time differences up to 10 s, we find significant correlations. The correlation improves gradually as the filter removes the smaller-scale features. On the dayside this relation appears quite clearly. FAC structures of 150 km size exhibit significant temporal correlation up to 80 s. On the nightside we obtain similar results. Here again, the FAC densities sampled at 1 Hz (unfiltered) reveal significant correlation only up to 10 s time differences. Also, the distribution of correlation coefficients of filtered data is similar to that of the dayside. The picture on the nightside is not so clear although similar numbers of samples are used on dayside and nightside (about 4500 on dayside versus 4600 on nightside).

Now we will test the infinite current sheet assumption or determine the longitudinal correlation length of FAC structures. Longitudinal separations are deduced from the satellite position data. All passes through

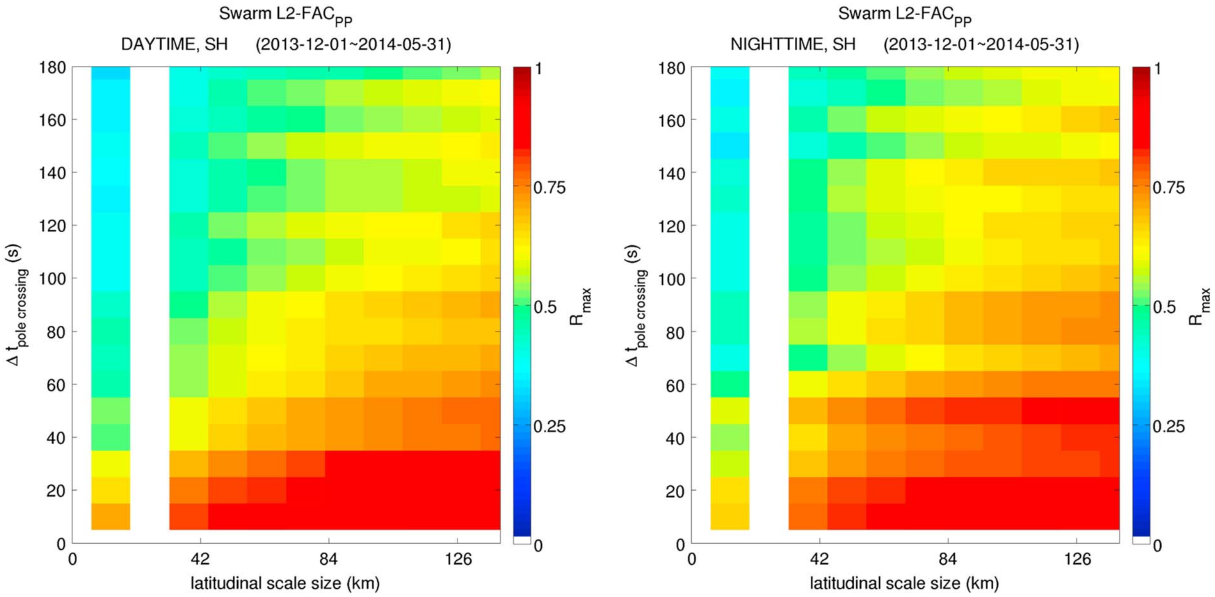

Figure 3. Temporal persistence of FAC features of different latitudinal scale sizes. Correlations with R_{max} <0.7 are considered insignificant. (left) Dayside and (right) nightside.

the auroral oval over the range 60° to 80° magnetic latitude are taken into account. As for the above analysis we use cross correlation to account for along-track propagation or tilt of the FAC structures. In this way we remove the effect of a time shift between the measurements made by two satellites at the same magnetic latitude.

During the early mission phase the longitudinal separation was small, up to 1° in longitude. At final constellation Swarm-A and -C are always close together; thus, the majority of the obtained results comes from comparison between Swarm-A and -B (and Swarm-C and -B), which is slowly increasing up to 10° in longitude. Spacecraft B has a somewhat different orbital period; therefore, only data can be used when it is closely spaced with the pair. We limit the comparisons to times when the passages of auroral latitudes differ between the three spacecraft by less than 60 s, which is consistent with the average stability of large-scale

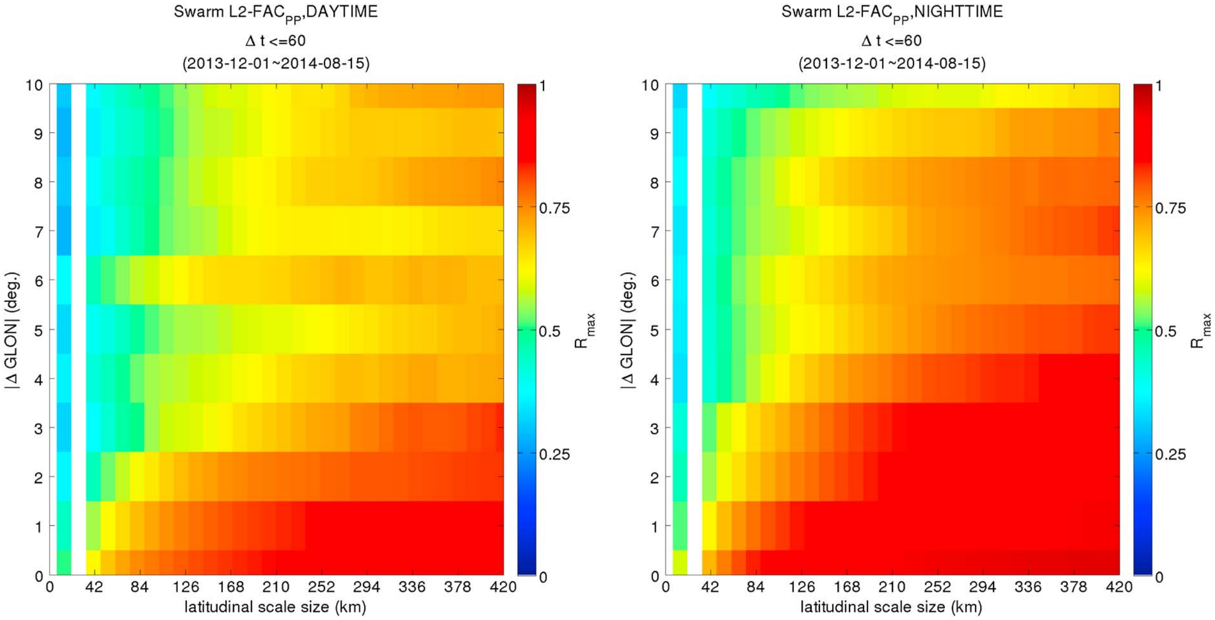

Figure 4. Analysis of FAC longitudinal correlation length. The same format as Figure 3.

FAC (see above). Such close approaches happen every 5–6 days and last for one orbit, limiting the number of suitable auroral oval crossings to less than 20 per longitude range for separations larger than 2° in longitude.

Figure 4 shows the distribution of the correlation coefficient in delta-longitude versus along-track scale size (approximately latitudinal-scale size). A clearer picture is obtained from the nightside (Figure 4, right). The leftmost column reflects again the 1 Hz sampled FAC readings. Here we find no appreciable correlation because of the temporal variation of small-scale FAC features. For FACs with latitudinal scales of 75 km (10 s filter) and larger the correlation is significant up to longitudinal separations of 3.5°. The correlation gradually decreases for larger longitudinal separations. At a spacing of 9° in longitude only very large-scale FACs (latitudinal scales of >250 km) show good correlation. Note that the scatter can be attributed to delta-longitude bins with few samples.

The correlation analysis from the dayside (Figure 4, left) shows much more scatter. For separations up to 2.5° in longitude we find good correlation for large-scale FACs with latitudinal scales larger than 150 km. At larger longitudinal separations between the spacecraft no significant correlation is found for any latitudinal-scale size. Obviously, FAC structures on the dayside are much smaller than on the nightside, hence also the correlation length is quite limited. For the daytime sector small sample numbers are obtained in the delta-latitude bins 5° and 8°, 9°. Due to the overall low correlation, this does not change the picture.

5. Discussion and Conclusions

In this study we determined the temporal and spatial characteristic of field-aligned currents in the auroral regions. During the early mission phase the Swarm constellation provides a powerful tool for such an investigation.

It is known that small-scale FAC structures are commonly associated with kinetic Alfvén waves [see *Stasiewicz et al.*, 2000]. Therefore, the current strength exhibits a significant temporal variation. From a single satellite it is not possible to distinguish between temporal and spatial variations. We thus compared observations at the same position but at two different times. Our results clearly confirm the temporal variation of small-scale FACs (up to some 10 km). In particular on the dayside a clear picture emerges. Significant correlations are only observed for the unfiltered data (Figure 3, left) at time differences up to 10 s. This is consistent with the observations of *Ishii et al.* [1992] showing that a cutoff exists for kinetic Alfvén waves at periods between 4 and 10 s depending on ionospheric conductivity.

For longer period filters the correlation gradually increases. We attribute that to the increasing role of the large-scale FACs in the correlation. From the time series in Figure 2 it becomes clear that already at 9 s cut-off small-scale FACs are significantly damped and the large-scale structures start to dominate the correlation. Vice versa we can conclude that large-scale FACs are stable for more that 60 s. *Gjerloev et al.* [2011] performed a large statistical study of the FAC scale size variability using the three pearls-on-a-string ST5 satellites. Our findings are in remarkable qualitative agreement with their conclusions despite using a different technique, different data set and different conditions. They found somewhat lower correlations but this is likely due to several differences: (1) They used spin period averaged data and the noise in our measurements is far less; (2) They correlated the time series directly and ignored along-track motion of the FAC's for determining the dB/dt, while we use cross correlation; (3) ST5 was in a Sun-synchronous dawn-dusk orbit, 105.6° inclination, 300 by 4500 km orbit with a period of 136 min, sampling the dayside sector in the Northern Hemisphere and the nightside in the southern; and (4) Differences in geomagnetic conditions between 2006 and 2014. The remarkable qualitative agreement, however, supports the surprising conclusion that the magnetosphere utilizes repeatable solutions (FAC characteristics) to transport energy and momentum to the ionosphere. A bit surprising, we find that the scale size-dependent variability on the dayside is comparable to the nightside. This is in apparent contrast to the Gjerloev et al. results. On the dayside the FACs are directly driven by solar wind-magnetosphere interactions while on the nightside the plasma sheet plays a key role.

In our analysis we have cross correlated FAC densities derived from magnetic field perturbations at auroral crossings separated in time but coincident in space. We have interpreted the results as indicative of the characteristics of the cause. However, if the measured variations from an oval crossing are due to different magnetospheric processes there is no reason to believe that these should have the same characteristics, while our analysis reflects the average behavior. For example Region 1 and Region 2 FACs are supposedly due to different causes and we mix these in our analysis. Further detailed studies are needed to clarify this point.

The missing parameter that should be investigated is the influence of current density. The results presented here are not separated by FAC amplitude. It is known that the highly variable small-scale currents have larger amplitudes [e.g., *Rother et al.*, 2007]. Likewise one may speculate that these small and rapidly changing FAC structures are more filamentary rather than sheet-like. Figures 3 and 4 show the average distribution of large and small-scale currents and are thus a result of the occurrence probability of these different FAC types.

Our second topic is the correlation length of FAC in longitude. This has never been studied from space in such detail. Here we focus on the larger-scale FACs. An immediate impression from Figure 4 is that the longitudinal correlation lengths on the nightside are much larger than on the dayside. If we assume 70° in magnetic latitude as typical for the auroral oval, 1° in longitude is equivalent to 38 km. This limits the longitudinal correlation length to about 100 km on the dayside. Here the assumption of elongated current sheets is rather questionable. This 100 km limit is likely associated with cusp currents, which then indicate that different FAC regions are caused by processes with different characteristics. We suggest that this has to be investigated further by a regional organization of the data beyond the simple dayside/nightside separation.

On the nightside larger longitudinal correlation lengths up to order 400 km are observed. The more sheet-like FAC structure in the evening and night sector has been reported earlier by several authors [e.g., *Potemra et al.*, 1987]. Here we have provided the average relation between latitudinal and longitudinal scale sizes. There seems to be a quasi-linear relation between the two; both grow at constant rates.

For large-scale FACs our findings appear to support the infinite current sheet assumption on the nightside since the longitudinal scale size typically is 4 times the latitudinal scale size. The caveats are the dayside (cusp) currents with smaller correlation length.

As mentioned, single point measurements are subject to assumptions like static FACs and infinite current sheets. To mitigate the static assumption, the observational platform should move as fast as possible but then the spatial resolution of the measurements is poor. LEO satellites move at a high speed (7–8 km/s), at the expense of spatial resolution, but are less sensitive to the variability of FACs. Figure 3 indicates that we require a velocity of at least 2.5 km/s to cross the 150 km FAC sheet within the persistent time of 60 s for ensuring that the measured perturbations can be assumed due to static FACs.

6. Summary

We presented a detailed study of the temporal and spatial scales of FAC structures derived from Swarm constellation measurements. The validity of two important assumptions is tested: The stationarity and the sheet-like geometry of FACs. We obtain significantly different results for small and large-scale currents. Small-scale FACs up to some 10 km are highly variable in amplitude. Typical persistence periods are of order 10 s or less. Their spatial structure, whether sheet-like or not, could not be tested here. For these reasons small-scale FACs, which are believed to be driven by kinetic Alfvén waves, cannot be determined reliably from single-satellite measurements.

Quite different results are obtained for large-scale (> 150 km) FACs. These can be regarded stationary up to 60 s when correcting for the propagation of the current structure. Also, their geometry is more favorable. At least on the nightside we find on average longitudinal scales about 4 times larger than the latitudinal width. This is sufficient for considering them as sheet like. Here reliable FAC estimates from single satellites can be obtained. On the dayside, especially in the cusp region, the longitudinal scales are comparable with the latitudinal width, thus causing in general an underestimation of the FAC density from single satellites.

Further detailed studies of FAC characteristics will follow as more data from the Swarm constellation become available.

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