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Key Points:
- Multispacecraft observations can test stationarity assumptions implicit in magnetic field-aligned current (FAC) estimates
- Single-spacecraft FACs estimates have correlations which depend on their spatial scale, smaller scales less correlated and more variable
- A multispacecraft technique using correlation and linear fitting can find intervals of temporal stability needed for reliable FACs

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Identifying intervals of temporally invariant field-aligned currents from Swarm: Assessing the validity of single-spacecraft methods

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Abstract Field-aligned currents (FACs) are a fundamental component of coupled solar wind-magnetosphere-ionosphere. By assuming that FACs can be approximated by stationary infinite current sheets that do not change on the spacecraft crossing time, single-spacecraft magnetic field measurements can be used to estimate the currents flowing in space. By combining data from multiple spacecraft on similar orbits, these stationarity assumptions can be tested. In this technical report, we present a new technique that combines cross correlation and linear fitting of multiple spacecraft measurements to determine the reliability of the FAC estimates. We show that this technique can identify those intervals in which the currents estimated from single-spacecraft techniques are both well correlated and have similar amplitudes, thus meeting the spatial and temporal stationarity requirements. Using data from European Space Agency's Swarm mission from 2014 to 2015, we show that larger-scale currents (>450 km) are well correlated and have a one-to-one fit up to 50% of the time, whereas small-scale (<50 km) currents show similar amplitudes only ~1% of the time despite there being a good correlation 18% of the time. It is thus imperative to examine both the correlation and amplitude of the calculated FACs in order to assess both the validity of the underlying assumptions and hence ultimately the reliability of such single-spacecraft FAC estimates.

Plain Language Summary Electric currents flowing along the Earth's magnetic field link the stream of particles coming off the Sun with the Earth's upper atmosphere and allowing the Earth to gain energy from this interaction. These currents have a multitude of widths, with the widest currents being linked to the circulation of charged particles in Earth's upper atmosphere and the narrowest being associated with bright aurora. Detecting the currents directly is very challenging; however, in principle, the currents can be measured by detecting the magnetic field associated with them using spacecraft orbiting the Earth. This type of detection requires a number of assumptions to be made in order to calculate the strengths of the currents from the measured magnetic field. Using multispacecraft observations, these assumptions can be tested. In this paper, we examine a new way of comparing the currents estimated from two coorbiting spacecraft to determine when and where our estimates of these currents is most reliable.

1. Introduction

Electric currents are ubiquitous in magnetized plasmas; currents flowing perpendicular to a background magnetic field introduce shears and separate regions of differing magnetic field connectivity or direction, whereas currents flowing along the direction of a background field can result in momentum and energy transfer between different plasma regimes. A system of field-aligned currents (FACs) in the magnetosphere was first proposed by *Birkeland*, [1908] and later confirmed by spacecraft observations of the deflection of the magnetic field above the auroral zone [*Zmuda et al.*, 1966]. These currents, on average, form a two-region current system, with Region 1 currents flowing into the polar region on the dawnside and out of the polar region on the duskside, and the adjacent Region 2 currents flowing into and out of the ionosphere in the opposite directions at lower latitudes [*Iijima and Potemra*, 1976]. The closure of these currents through the ionosphere facilitates the transfer of energy and momentum from the solar wind and magnetosphere into the ionosphere.

Ampére's Law states that the curl of the magnetic field is proportional to the sum of the electric conduction current density and the displacement current, the latter being proportional to the temporal variation of the electric field. Under typical large-scale plasma conditions in the magnetosphere, the displacement current arising from the temporal variation in the electric field can be neglected, such that the current can be calculated from the spatial gradients of the magnetic field. These spatial gradients can be obtained from the motion of a single spacecraft through the current system under the following assumptions [e.g., *Iijima and Potemra*, 1976]: the spacecraft is passing through an infinite sheet of current sheet, such that the magnetic field perturbations are confined to one direction; the variations in the current density are in one direction across the current sheet; the current sheet is stationary; and the current density profile does not change on the spacecraft crossing time. On the spacecraft crossing time, we can thus describe the current sheet as temporally invariant. For ease of calculation, the orientation of the current sheet relative to the spacecraft track also has to be assumed and is generally taken to be perpendicular to the spacecraft track and the background magnetic field, although on a case-by-case basis the orientation of individual current sheets can be calculated and accounted for [e.g., *Hoffman et al*., 1994; *Marchaudon et al*., 2006; *Forsyth et al*., 2014]. Measurements from multiple spacecraft can be combined to determine spatial gradients assuming that the magnetic field gradients between the individual spacecraft follow some predetermined form [e.g., *Dunlop et al*., 1988; *Anderson et al*., 2000; *Ritter et al*., 2013], although the relative scales of the spacecraft separation to the current systems limits the currents that can be resolved [e.g., *Runov et al*., 2005; *Forsyth et al*., 2011].

Using multiple spacecraft orbiting along the same, or a very similar, orbital track, it is possible to test some of the assumptions behind the single-spacecraft determination of FAC. In particular, by lagging and correlating the data from different relatively closely separated spacecraft, one can determine whether or not the variations in the magnetic field (and hence that of the inferred FAC) had the same sense in the same location and thus the currents do not move on the spacecraft crossing time [e.g., *Gjerloev et al*., 2011]. Alternatively, by cross correlating the data from multiple spacecraft, one can attempt to determine whether or not the magnetic signatures have moved in space between the two spacecraft crossing times [e.g., *Forsyth et al*., 2014; *Luhr et al*., 2015] or, if the spacecraft orbits are inclined to one another, whether the current sheets are not perpendicular to the spacecraft velocity. Such variations are important for the validity of single-spacecraft FAC estimates as we discuss further below. However, linear correlation only determines whether or not the magnetic field perturbations (and hence by inference the FACs) had the same form; it does not determine whether the trends in the data were of the same amplitude, thus simply correlating the data does not determine whether or not the FACs changed between the spacecraft crossings and thus may have changed during each crossing. Furthermore, cross correlating the data from two moving observatories cannot distinguish between wave-like variations occurring at a period close to the spacecraft separation time or the motion of a current system. Both *Gjerloev et al*. [2011] and *Luhr et al*. [2015] showed that large-scale (100 s km) FACs at Earth tend to be well correlated, suggesting that these current sheets tend to be stationary. However, understanding and attempting to account for the limitations in correlation analysis of FACs is critical at scales below a few hundred kilometers and during more dynamic times at all spatial scales.

In this technical report, we detail a new technique for analyzing some of the assumptions behind the calculation of field-aligned currents from single-spacecraft data over different spatial scales using FACs calculated from two near-co-orbiting spacecraft. This technique combines sliding correlation and linear fits to examine periods in which the FAC estimates are both similar in form and magnitude. We demonstrate the applicability of this technique using data from the European Space Agency Swarm mission.

2. Data

ESA's Swarm Mission [*Friis-Christensen et al*., 2006, 2008] is compose of three identical spacecraft designed to study the Earth's magnetic field. As of 15 April 2015, two of the spacecraft (Swarm A and Swarm C) were in circular orbits at an altitude of 465 km with their orbital planes separated by 1.4° and separated along orbit by $<$ 75 km. The third spacecraft (Swarm B) was in a circular orbit at an altitude of 530 km and at an inclination such that the angle between the Swarm B and Swarm A/C orbital planes increases by ~20° per year.

A key part of the Swarm mission is to determine the electric currents responsible for magnetosphere-ionosphere coupling. This is achieved using data from the vector field magnetometer (VFM). The VFM takes data at 50 Hz, which is then filtered to 1 Hz in the Level-1b data product. These data are processed into the Swarm Level-2 single-spacecraft FAC data product as detailed in *Ritter et al*. [2013]. In summary, the FACs are calculated by (1) removing the model "mean field" (consisting of the core, lithospheric, and magnetospheric fields) from the Level-1b magnetic field measurements; (2) in the spacecraft velocity frame, calculating the radial current as $j_z = \partial B_y / \partial \chi$, where *x* is the direction along the spacecraft track, *y* is the direction perpendicular to the spacecraft track and *z* is the radial direction; and (3) dividing the vertical current by the sine of the inclination of the magnetic field to get an estimate of the FAC. In this study, we use the Level-2 single-spacecraft FAC data products from Swarm A and Swarm C in 2014 and 2015 to test the applicability of our technique.

3. Methodology

Using data from the two near-co-orbiting Swarm spacecraft (A and C), we can examine the validity of the assumptions that the FACs are stationary and do not change between the spacecraft crossings (and by extension do not change during the individual crossings) and thus determine whether or not the calculation of FAC is valid.

Our initial data processing chain is as follows:

1. We interpolate both the Swarm A and Swarm C Level-2 FAC data onto a common, univariate time series.
2. We lag the interpolated Swarm A data by time difference corresponding to the interspacecraft separation.
3. We band-pass filter the interpolated Swarm C and lagged Swarm A FAC data using a Hanning window.

Band-pass filtering the data enables us to examine the properties of different scale current systems [e.g., *Gjerloev et al*., 2011; *Luhr et al*., 2015]. The spacecraft are moving through the system of currents; thus, under the assumption that the currents are temporally and spatially stationary, different frequency bands or filter periods directly correspond to spatial scales. The spatial scales are calculated as the filter periods multiplied by the spacecraft velocity.

The filtered time series can either be cross correlated with fixed lags determined by the spacecraft separation [e.g., *Gjerloev et al*., 2011] or variable lags with the maximum correlation used [e.g., *Luhr et al*., 2015] to determine if the trend in the FACs are similar. However, as discussed above, cross correlation cannot distinguish between current sheet motion, inclined current sheets, or wave activity, and the absence of these is inherent in the calculation of the FAC. As such, we only examine the correlation of the data at the fixed lag determined from the spacecraft separation. However, correlation on its own does not show that the observed currents were the same on both spacecraft, and thus did not change between the spacecraft crossings. This is a key criterion for the validity of their estimation using the single-spacecraft FAC technique. Thus, in a final step, we compare the amplitudes of the observed currents:

1. We calculate the Pearson's linear correlation coefficient between the FAC estimates from Swarm A and Swarm C in a window equal to the lower period (upper frequency) of the filter and centered on each time point.
2. We calculate the gradient of the least squares linear fit between the Swarm A and Swarm C FAC estimates over the same time window as the correlation.

For ideal observations of stationary current sheet that do not vary on the timescale of the separation of Swarm A and Swarm C and which the spacecraft cross in the normal direction, the correlation coefficient and fitting gradient will be unity. In practice, this is likely never the case due to observation and calculation uncertainties. However, from the time series of the correlation and linear fit gradients, we have a measure of how similar the FAC estimates calculated from the two spacecraft are.

The above method is designed to work well for spacecraft in the same orbital plane but separated along that orbit. The orbital planes of Swarm A and Swarm C are separated by 1.4° in longitude which means that, in practice, the two spacecraft will pass through different points along any current sheets. High correlations between the spacecraft will still arise if the current sheets are east-west aligned, as required by the FAC calculation, and if the current sheets extend across the longitudinal spacecraft separation.

The separation between Swarm A and Swarm C is not constant throughout the mission but is controlled to vary between 2 and 10 s. Figure 1 shows the daily time lag between Swarm A and Swarm C calculated from the maximum of the cross correlation of the Level-2 FACs (black) and the time difference between the two spacecraft crossing the equator calculated for each day in 2014 and 2015. Negative time differences indicate that Swarm A trails Swarm C. The time lag between the spacecraft crossing the equator should correspond to

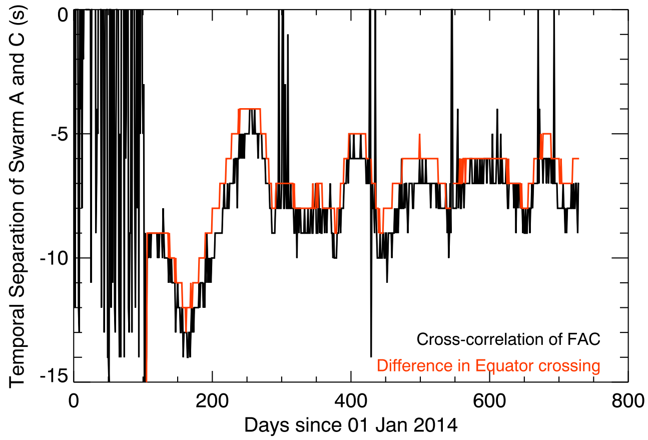

Figure 1. The variation of the daily temporal separation of Swarm A and Swarm C calculated from the Level-2 FAC and positional data at 1 s resolution. From the positional data, we determine the median time difference between equatorial crossings by each spacecraft each day (red). We also calculate the time lag that gives the maximum linear cross-correlation coefficient from the unlagged Swarm A and Swarm C Level-2 FAC for each day (black). Negative time differences indicate that Swarm A trails Swarm C.

the time lag necessary to get the maximum cross correlation between the FACs; however, Figure 1 shows that the time lag determined from the FAC data is generally 1 s less than the lag from the times of crossing the equator, although the lag from the FAC data is variable and may not be well defined on a given day. As such, in step 2 of our processing chain, we use the lag determined from the equatorial crossings minus 1 s.

4. Example Results: Case Study From 31 May 2014

To demonstrate the results of our technique, we examine an auroral zone crossing between 17:10 and 17:25 on 31 May 2014 by Swarm A and Swarm C. The crossing took place during an extended interval of slow, dense solar wind and strongly northward interplanetary magnetic field. Swarm A and Swarm C were moving toward the dayside at ~08 magnetic local time.

Figure 2 shows the Swarm A and Swarm C FAC estimates, correlation, and linear fit gradients. Figure 2 (top row) shows the FAC density filtered using different band-pass filters. For this example, we show data filtered from 3–7 s, 27–60 s, and a low pass filter of 60 s. These correspond to spatial scales of 22.5–52.5 km, 202.5–450 km, and >450 km, respectively. Data in the 52.5–202.5 km band showed similar results to the 22.5–52.5 km band and are not shown in this figure for clarity. Data from Swarm A (black) have been lagged by 10 s to bring it into alignment with the data from Swarm C (red). Figure 2 (middle row) shows the running Pearson's correlation coefficient as described above, and Figure 2 (bottom row) shows the running gradient from the linear fit. Times whereby the correlation coefficient is greater than 0.9 and the linear fit gradient is between 0.9 and 1.1 are highlighted in grey.

This event shows that the highest amplitude calculated FACs is in the high-frequency (3–7 s period) band. However, while many of these FACs shown have a correlation coefficient greater than 0.9, the linear fit gradients are predominantly less than 1. This indicates that the FAC estimates derived using data from each of the two Swarm A and Swarm C spacecraft are varying between the two spacecraft crossings (10 s apart). This variability may arise from temporal variations in components of the magnetic field arising from, for example, wave activity, current sheets with variations away from the east-west direction, or current sheets with small-scale or filamentary structures that do not extend uniformly across the spacecraft longitudinal separation. Note that at auroral latitudes, the spacecraft cross-track separation is approximately 60 km, and as such is greater than the 22.5–52.5 km scale size observed by the 3–7 s filter.

The currents in the longer period bands (larger spatial scales) show intervals in which the correlation coefficient is greater than 0.9 and the linear fit gradient is between 0.9 and 1.1. One of these intervals (17:15–17:18:30 UT) is common to both frequency bands, suggesting structuring of the currents across a range of scales. However, also of interest is the interval between 17:17:30 UT and 17:20:00 UT in the 27–60 s period filter band. During this time, although the currents look very similar by eye, our analysis

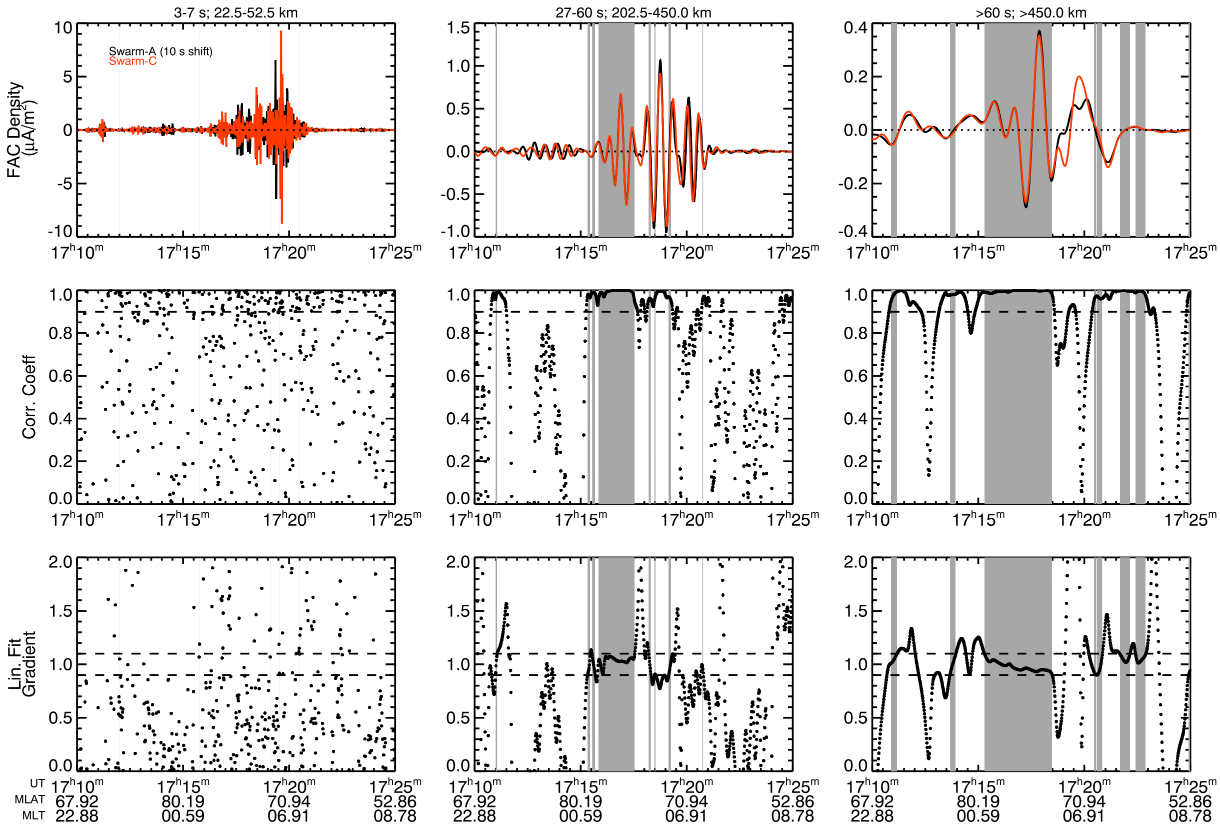

Figure 2. An example of the results of our data processing technique on the Level-2 Swarm single spacecraft FAC. (top row) The FACs calculated from Swarm A (black) and Swarm C (red) and filtered in the (left) 3–7 s, (middle) 27–60 s, and (right) >60 s bands. (middle row) The running Pearson's correlation coefficient calculated over a window of length equal to the smallest period in the filter. (bottom row) The running least squares fit gradient between the FAC from Swarm A and Swarm C over the same window. The dashed lines Figure 2 (middle row) show a correlation coefficient of 0.9. The dashed lines in Figure 2 (bottom row) show fitted gradients of 0.9 and 1.1. The grey bands show intervals in which the correlation coefficient is greater than 0.9, and the fitted gradients are between 0.9 and 1.1.

technique is able to determine a variation between them. On the timescale shown, it is unclear whether this variation is due to a slight movement of the currents, such that the spatial stationarity is violated, or a temporal change in the magnetic fields. More in-depth analysis of the original magnetic field data may enable the FACs to be recovered, but this is beyond the scope of this technique and hence this technical report.

This example demonstrates the applicability and benefit of our technique. In particular, it shows that well-correlated FAC estimates from two spacecraft crossings even when only separated by 10 s along track do not necessarily have a near one-to-one relation. Instead, there is some temporal or spatial variation in magnetic field data between the two crossings which reduces the validity of interpreting the magnetic field variations as FACs. However, this example also demonstrates that there are some (albeit in this example rather limited) intervals in which the underlying assumptions of temporal and spatial stationarity appear to be met across different scale sizes.

5. Impact on Exploitation of Swarm FAC Data

5.1. Correlation and Fit Occurrences

Figure 2 shows that only a small proportion of the Level-2 FACs from Swarm A and Swarm C are well correlated and show a linear fit gradient close to unity, at least during that specific auroral zone pass. In order to examine this further, we have processed the Level-2 FAC data from 2014 and 2015 as outlined in the Methodology. Due to the changes in the orbits of Swarm A and Swarm C in the early part of 2014, we consider data from 1 May 2014 onward. At magnetic latitudes greater than 60 or less than −60, this gives >17 million data points at 1 Hz sampling.

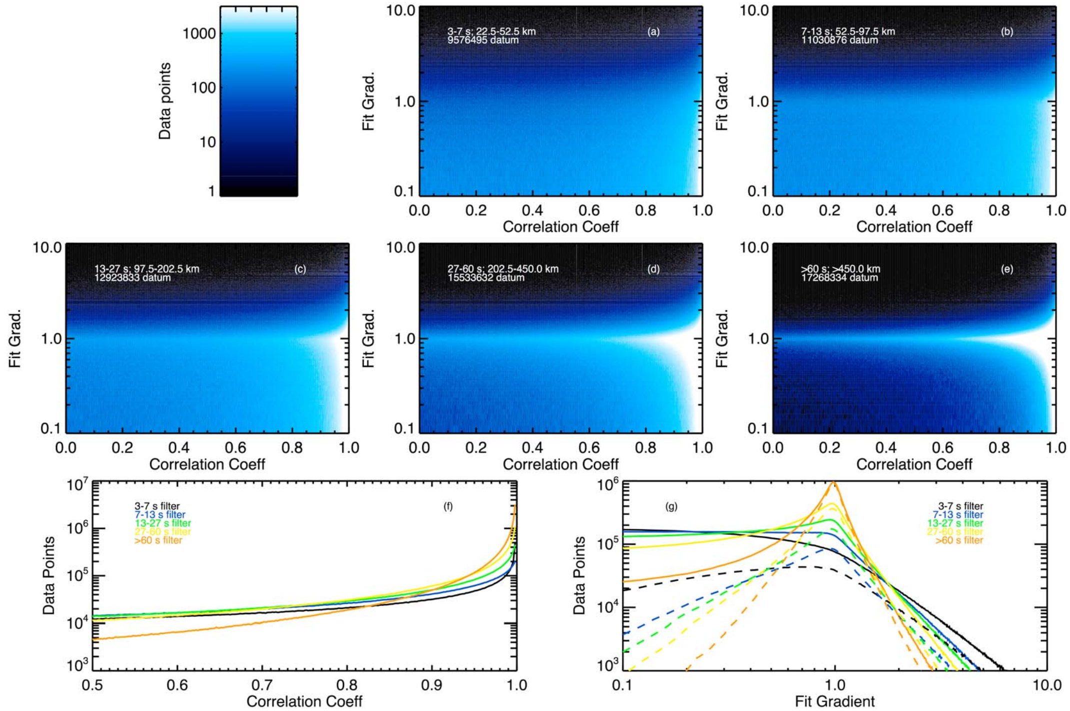

Figure 3. Two-dimensional histograms of the correlation coefficients and linear fit gradients between the Swarm A and Swarm C FAC data from 1 May 2014 to 31 December 2015 in period bands (a) 3–7 s, (b) 7–13 s, (c) 13–27 s, (d) 27–60 s, and (e) >60 s. Histograms of the (f) correlation coefficients and (g) linear fit gradients, with the period bands shown in black (3–7 s), blue (7–13 s), green (13–27 s), yellow (27–60 s), and orange (>60 s). The dashed lines show the distribution of gradients for which $r > 0.9$. The bin sizes are 0.002 for the correlation coefficients and 0.02 for the linear fit gradients.

Figures 3a–3e show 2-D histograms of the linear correlation coefficient and least squares fit gradient occurrence for five different filter period ranges (3–7 s, 7–13 s, 13–27 s, 27–60 s, and 60 s low pass). The bin sizes are 0.002 for the correlation coefficients and 0.02 for the linear fit gradients. The plot labels show the number of data points with a correlation coefficient greater than 0. Figures 3f and 3g show histograms of the linear correlation coefficient and least squares fit gradient occurrence, respectively.

The 2-D histograms in Figure 3 show that the distributions of fit gradients are similar in each correlation coefficient bin. As such, high correlation does not necessarily translate into the same amplitude FACs being observed by both spacecraft. In the five filter bands examined, between 16% (3–7 s filter) and 66% (>60 s filter) of the data had correlation coefficients greater than 0.9, but only between 1.9% (3–7 s filter) and 34% (>60 s filter) were well correlated and had fit gradients between 0.9 and 1.1. These data thus emphasize that correlating the data is insufficient to identify those intervals in which the assumptions required for calculating a reliable single-spacecraft FAC are met, and that a measure of the relative amplitudes of the calculated FACs is needed.

Figure 3 also shows that the correlation of larger-scale currents tends to be higher (Figure 3f), and these are more likely to have a fit gradient close to 1 (Figure 3g). The results of the correlation analysis are qualitatively consistent with the earlier results of *Gjerloev et al.* [2011] and *Luhr et al.* [2015], in that larger-scale currents tended to be well correlated and be well correlated over a larger range of spacecraft separations. However, our results show that these currents not only tend to have the same form but also show a greater tendency to have the same amplitude, such that the assumptions in calculating the FAC are met. In contrast, magnetic estimates of the small-scale (<50 km) FACs are generally not well correlated nor have similar amplitudes. This indicates that assumptions inherent in the single-spacecraft FAC technique may not be valid at these scales. Temporal variations in the magnetic field will arise from significant ultralow frequency (ULF) wave activity. We note that our four band-pass filters are close to the Pc 1–3 bands and Pi 1 band [*Jacobs et al.*, 1964]. Given that Pc 1 waves occurrence peaks close to 60° magnetic latitude [*Park et al.*, 2013] and Pi 1 waves are closely linked with auroral activity (see review by *Rae and Watt* [2016]), it is perhaps

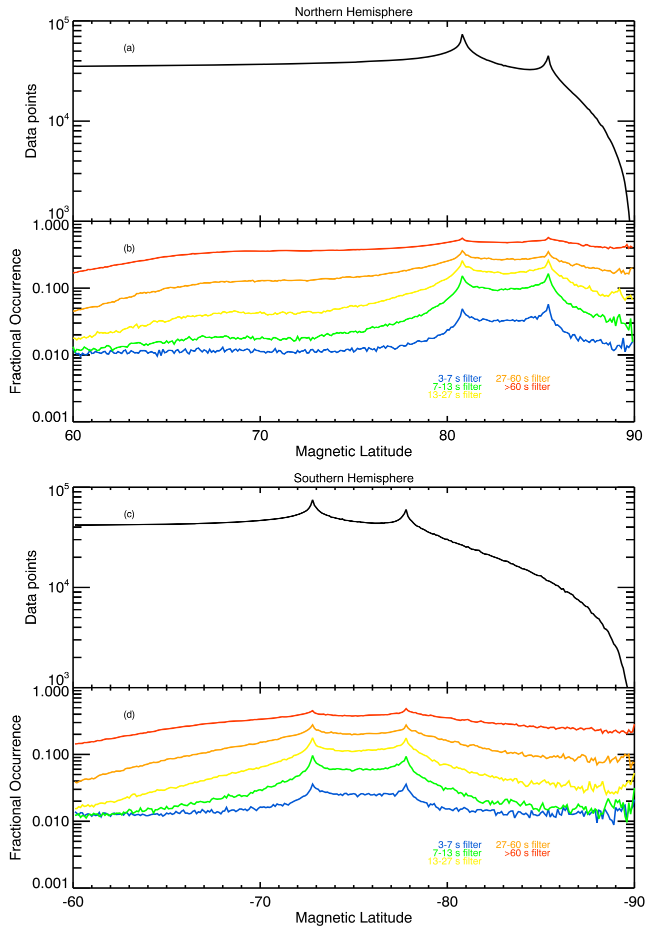

Figure 4. (a and c) Histograms of the number of FAC data points at each latitude and the (b and d) relative occurrence of well-correlated ($r > 0.9$) and similar amplitude FAC ($0.9 < m < 1.1$) estimates to the whole. Blue indicates the relative occurrence of 3–7 s filtered data; green shows 7–13 s data; yellow shows 13–27 s data; orange shows 27–60 s data; and red shows >60 s data. Figures 4a and 4b show data from the Northern Hemisphere, and Figures 4c and 4d show data from the Southern Hemisphere.

unsurprising that wave activity disrupts the calculation of FACs on these scales. However, according to *Park et al.* [2013], Pc1 waves at these altitudes should have comparatively small amplitudes. This suggests to us that the magnetic disturbances at these smaller scales might instead be related to the exchange of Alfvén waves, perhaps acting as an integral part of the magnetosphere-ionosphere coupling processes involving Birkeland currents. Alternatively, small-scale auroral structures, such as curls, folds, and spirals which have widths in the 20–50 km range [e.g., *Hallinan*, 1976], may not be east-west aligned or extend over the spacecraft cross-track separation. The data presented here indicate that in-depth studies of the Swarm data promise the potential for significant advances in studying these phenomena, which we intend to pursue in future work; however, interpreting the magnetic field perturbations as FACs at these scales must be done with caution.

Figure 3 shows that the distribution of fitted gradients is not symmetric about a gradient of 1, instead showing peaks toward 0 for the short period filters and peaks at 1 for the longer period filters. This is a direct result of the use of a least squares fitting algorithm to determine the gradient. At low correlations, this algorithm tends toward gradients of 0 due to the minimization of the residual "*y* axis" data. Since we are comparing data from two closely separated spacecraft and expect the variations in the FAC to be largely on timescales greater than the spacecraft temporal separation, when the data are highly correlated we expect the peak of the distribution of fitted gradients to tend to 1. This is as the data show in Figure 3. For the low-period filters, particularly the 3–7 s filter, there is a greater proportion of the data with low correlation coefficients (Figure 3f); thus, the distribution of gradients in Figure 3g is peaked at 0. At high correlations ($r > 0.9$, dashed lines in Figure 3g) the distribution of gradients is peaked at 1 with approximately equal numbers above and below 1. It should be noted that a nonunity gradient is not necessarily an indication of an increasing or decreasing current system, but instead that $dB/dt \neq 0$ such that the assumptions in the calculation of the FAC are not met.

5.2. Spatial Biasing

The Swarm orbital configuration introduces natural, but limited, spatial biases to the data set. In particular, the near-polar orbit of the spacecraft in the geographic frame means that the spacecraft pass close to the geographic poles on every orbit but do not necessarily pass close to the magnetic poles. As such, the spatial distribution of observations in Altitude Adjusted Corrected Geomagnetic Coordinates magnetic latitude and local time shows a ring of elevated coverage at ~80 and ~ −74 magnetic latitude due to the offset of the magnetic poles. Given that our technique enables a downselection of data based on linear fit gradients and correlation coefficients, we examine whether this downselection introduces any additional spatial biases.

Figures 4a and 4c show histograms of the number of data points against magnetic latitude and Figures 4b and 4d show histograms of the fraction of data points at each latitude that have a correlation coefficient greater than 0.9 and a linear fit gradient between 0.9 and 1.1, with the results from different spatial scale bands shown in different colors. Results from the Northern Hemisphere are shown in Figures 4a and 4b, and results from the Southern Hemisphere are shown in Figures 4c and 4d.

At the smallest spatial scales, only 1–5% of the data meet our selection criteria and, as such, most of the FACs at this scale are either poorly correlated or change in amplitude (or both). At the largest scales, this increases to 10–50% of the data meeting our criteria. Figures 4b and 4d show that the occurrence peaks are also evident in the fractional occurrence. This implies that the Swarm FAC data are more likely to be correlated and have a linear fit gradient close to 1 in the vicinity of the geographic poles. This can be explained by considering that the orbital planes of Swarm A and Swarm C are offset by ~1.4 with an intercept between the orbital planes close to the geographic poles. Away from the geographic pole, the calculated FACs will not correlate if the current sheets are not perpendicular to the spacecraft track, since the two spacecraft will pass through the current sheets at slightly different latitudes. As the longitudinal separation of the spacecraft decreases toward the pole, the current sheets require a much larger inclination to the direction of motion of the spacecraft for this to be a noticeable effect. Thus, there is a slight spatial bias from our technique, which increases the likelihood of a good correlation and linear fit where the longitudinal separation of the spacecraft is small.

6. Conclusions

Previous studies [*Gjerloev et al*., 2011; *Luhr et al*., 2015] have shown that field-aligned currents estimated using a single-spacecraft technique on data from two near-co-orbiting spacecraft are not always well correlated, but that the occurrence rates of good correlation tend to increase with the scale size of the currents being considered. We have demonstrated that correlation alone is insufficient to assess whether or not the observed FACs are stationary in time and space such that the assumptions inherent in calculating FAC from single-spacecraft observations are met. Instead, the correlation must be combined with some determination of the relative amplitude of the two signals. We have demonstrated a new technique which uses linear correlation and least squares fitting to provide a quantitative assessment of both the correlation between the derived FAC estimates. The technique allows the determination of times at which the currents observed by both spacecraft are similar in both sense and amplitude, indicating that the assumptions that the currents are stationary and do not change amplitude on the spacecraft crossing time are met. Applying this technique over specified window lengths, we quantify the correlation and linear fits of the data and thus determine the validity of the estimated FAC across a range of scale sizes at each data point.

By applying this technique to the Swarm A and Swarm C spacecraft, which are in similar orbital planes, we demonstrate that only 1–5% of the observations of the smallest-scale currents (22.5–52.5 km) exhibit good correlation and linear fit gradients, whereas the 10–50% of the largest-scale currents (>450 km) exhibit good correlation. This would suggest that much of the magnetic field perturbations at small scales may contain a significant fraction of magnetic perturbations which are the result of magnetic wave activity in the vicinity of the spacecraft or current sheets inclined to the motion of the spacecraft. As a result, extreme care must be taken in interpreting the temporal variation of the magnetic field observed by a moving spacecraft as relating to the spatial structures which can be used to infer field-aligned currents. Since such assumptions are used to produce the Swarm Level-2 single-spacecraft FAC data product [*Ritter et al*., 2013], care should be taken when using or interpreting this data product as well.

Acknowledgments
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