Chapter 8
ESA Field-Aligned Currents—Methodology Inter-comparison Exercise

Lorenzo Trenchi and The FAC-MICE Team

Abstract Various ESA projects and several proposals to first Swarm DISC Call for Ideas (May 2016) suggested possible evolution for the current Swarm Level 2 FAC products, and the implementation of quality flags for the FAC products. The Field-Aligned Currents—Methodology Inter-Comparison Exercise (FAC-MICE) consisted in comparison of the various methods to determine the FAC from Swarm data, with a test dataset of 28 Swarm auroral crossings delivered to participants last June. Eight groups performed the FAC-MICE analysis. The results of this exercise, discussed in the dedicated 'Swarm Ionospheric Currents Products workshop' in ESTEC on September 2017, highlighted the strengths of the various methods/approaches. Following discussion with the participants to this workshop, we are now working to develop an open source platform for user-definable FAC calculation.

8.1 Introduction

Field-aligned currents (FACs), also called Birkeland currents, are electric currents flowing along geomagnetic field lines at high magnetic latitudes, where they couple the magnetosphere and the ionosphere.

The presence of FACs was first proposed by the Norwegian explorer Kristian Birkeland, who reported magnetic perturbations on the ground near the Artic circle associated with auroras (Birkeland 1908, 1913). The existence of FACs was then confirmed by magnetic field perturbations detected in space, when the polar orbiting satellite 1962 38C made the first observations (Zmuda et al. 1966). On a global scale, FACs are organized along a persistent pattern around both magnetic poles, first highlighted by the statistical studies based on Triad data (Iijima and Potemra 1976a, 1976b, 1978). The FAC pattern consists of two concentric rings in the auroral

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oval, with opposite polarities at dawn and dusk: the poleward ring (Region 1) connects with the magnetopause current, and the equatorward ring (Region 2) connects with the magnetospheric ring current (e.g. Cowley 2000). Both Region 1 and Region 2 currents are closed via horizontal currents (primarily Pedersen currents) within the ionosphere current layer, at altitudes between approximately 100–150 km. The Region 1–2 pattern is an almost permanent feature, while the shape, the size and the intensity of these currents are related to the amount of energy transferred from the solar wind into the magnetosphere, which in turn is determined by the orientation of the interplanetary magnetic field (IMF), and the solar wind parameters.

Swarm is a three-satellite constellation mission developed from the European Space Agency (ESA) to measure, as a primary goal, the Earth's magnetic field with unprecedented accuracy. The three identical spacecraft, launched on November 22, 2013, are flying in polar orbits: the lower pair (Swarm A and C) at 460 km altitude, while Swarm B is flying at 510 km. Each spacecraft carries two magnetometers that measure the vector magnetic field and its absolute value, an electric field instrument, an accelerometer, and the instruments to determine the attitude and the position of the spacecraft, which are the GPS receiver, the startracker and a laser retroreflector.

By using magnetic field models, it is possible to separate the various contributions of the magnetic field signals measured by Swarm, i.e. the contribution from the core, the lithosphere and the magnetosphere components. This allows to use Swarm data to study several different phenomena. One of the main objectives of Swarm regards the study of the Ionospheric currents, and in particular FACs. The 'in situ' determination of current densities in space plasmas is generally obtained from spacecraft magnetic field data using the Ampere's law, under various assumptions regarding the stationarity and the orientation of the current sheet, and the uniform spatial variation of the magnetic field. Less strict assumptions are needed when multi-spacecraft data are used. For this reason, the multipoint measurements provided by the Swarm constellation, together with the unprecedented accuracy of Swarm magnetic field measurements, represent an optimal asset for the determination of FACs. Currently, ESA provides two different estimates of FAC, based on a single or multi-spacecraft approach (Ritter et al. 2013, see also Chap. 6 of this book):

- single spacecraft FAC products, based on 1 Hz magnetic field data, which provide three individual products for each of the 3 satellites
- dual spacecraft FAC product, based on 1 Hz magnetic field data collected by the lower pair (Swarm A and Swarm C), low-pass filtered at 20 s time scale in order to meet the time stationarity assumption (Ritter et al. 2013, see Chap. 6 of this book).

Various ESA projects are developing new methods to compute FAC and the ionospheric currents with Swarm data. In particular the Swarm data quality Investigation of Field-Aligned Current products, Ionoshepere, and Thermosphere systems (SIFACIT) is developing new algorithms to estimate FAC from single, dual and three spacecraft methods, together with quality indicators about the assumptions underlying FAC estimates (http://gpsm.spacescience.ro/sifacit/, see also Chap. 4 of this book).

Swarm-SECS is instead applying a two-dimensional version of the Spherical Elementary Current Systems (SECS) method to recover the Ionospheric currents and conductivities from Swarm magnetic and electric field data (http://space.fmi.fi/MIRACLE/Swarm_SECS/, see also Chaps. 2 and 3 of this book).

Also several proposals in response to the first ESA Swarm Call for Ideas for new data products and services (May 2016, https://earth.esa.int/web/guest/news/-/article/esa-swarm-call-for-ideas-for-new-data-products-and-services) focussed on FACs, suggesting possible new approaches to estimate FAC densities and quality indicators.

In order to identify a possible evolution of the present FAC products, and/or potential new FAC products and FAC quality indicators, ESA organized a FAC Methodology Inter-comparison Exercise (FAC-MICE), which consisted in comparison of the different FAC methods, based on a test dataset of 28 Swarm auroral crossings.

8.2 The FAC-MICE Test Dataset

The events in the FAC-MICE test dataset have been selected according to the following criteria:

- events uniformly distributed in local time
- events sampled during both quiet and active geomagnetic conditions, identified according to the values of the AE index
- some of the events were sampled when the orbit of Swarm B was close enough to the one of the lower pair, to allow FAC estimates based on the data collected by all the three Swarm spacecraft
- for some of the events, also the high time resolution magnetic field data (50 Hz) were provided
- some events were selected near the geographic poles in the exclusion zone (latitude>86°), where the longitudinal separation between Swarm A and C is small, and therefore FAC estimation from the dual spacecraft method is more difficult.

According to these criteria, ESA identified the 28 events sampled by Swarm in years 2014–2015 listed in Table 8.1, which are part of the FAC-MICE test dataset.

Moreover, in order to estimate the possible influences of the choice of magnetic residuals on FAC results, as input for FAC calculation, ESA provided, for each of these events, the magnetic field residuals obtained from two different field models: the same residuals as L2 products (AUX_CORE, Lithosphere-MF7, magnetosphere-POMME-6) and also CHAOS-6 residuals (Finlay et al. 2016; see also Chap. 12 of this book).

Table 8.1 The 28 events sampled by Swarm in years 2014–2015, which are part of the FAC-MICE test dataset

#	Date (YYYY-MM-DD)	Start	Stop	Swarm s/c	1 Hz data	50 Hz data	3 s/c conjunction
1	2014-04-22	04:05	04:20	A-B-C	YES	NO	YES
2	2014-04-22	04:40	05:00	A-B-C	YES	NO	YES
3	2014-04-28	09:45	10:00	A-B-C	YES	YES	YES
4	2014-04-28	10:30	10:45	A-B-C	YES	YES	YES
5	2014-05-04	15:20	15:35	A-B-C	YES	NO	YES
6	2014-05-10	21:30	21:45	A-B-C	YES	NO	YES
7	2014-05-17	03:05	03:15	A-B-C	YES	NO	YES
8	2014-05-29	13:35	13:45	A-B-C	YES	YES	YES
9	2014-06-04	18:10	18:25	A-B-C	YES	NO	YES
10	2014-06-04	18:20	18:30	A-B-C	YES	NO	YES
11	2014-06-10	23:40	23:50	A-B-C	YES	NO	YES
12	2014-06-17	03:50	04:00	A-B-C	YES	NO	YES
13	2014-07-11	19:30	19:45	A-B-C	YES	NO	YES
14	2014-07-30	06:05	06:15	A-B-C	YES	NO	YES
15	2014-08-11	10:00	10:10	A-B-C	YES	NO	YES
16	2015-03-16	22:35	23:00	A-C	YES	NO	NO
17	2015-03-17	08:50	09:15	A-C	YES	NO	NO
18	2015-03-21	08:55	09:20	A-B-C	YES	NO	NO
19	2015-08-15	04:30	04:50	A-C	YES	YES	NO
20	2015-08-15	12:20	12:45	A-C	YES	YES	NO
21	2015-09-20	02:00	02:25	A-B-C	YES	YES	NO
22	2015-09-20	11:20	11:45	A-B-C	YES	YES	NO
23	2015-10-07	02:10	02:30	A-C	YES	YES	NO
24	2015-10-08	17:10	17:35	A-B-C	YES	YES	NO
25	2014-04-22	05:40	05:55	A-C	YES	NO	NO
26	2014-05-04	19:05	19:30	A-C	YES	NO	NO
27	2014-06-29	12:25	12:45	A-B-C	YES	NO	NO
28	2014-07-11	20:20	20:40	A-B-C	YES	NO	NO

8.3 The Active Participants to FAC-MICE

The FAC-MICE test dataset has been delivered by ESA on June 2016 to a list of 38 potential participants, identified among the researchers who already have developed algorithms to compute FACs, or other researchers who have a good experience with high latitude currents. This list included also researchers who have developed new FAC algorithms, as part of ESA projects. The var-

ious FAC algorithms have been tested based on this dataset, and the first results of this exercise have been discussed in ESA—ESTEC on 07th—8th September 2017, during a dedicated meeting called Swarm Ionospheric Currents Products Workshop (https://earth.esa.int/web/guest/missions/esa-eo-missions/swarm/activities/conferences/swarm-ionospheric-currents).

Eight different groups performed the FAC-MICE analysis:

- Finnish Meteorological Institute (FMI)
- Institute of Space Science (ISS)—Jacobs University Bremen (JUB)
- Rutherford Appleton Laboratory (RAL)
- Deutsches GeoForschungsZentrum (GFZ)
- University of Alberta (UofA)
- Mullard Space Science Laboratory (UCL-MSSL)
- University of Calgary (UC)
- Johns Hopkins University (JHU)

Some of the new approaches adopted by these groups for FAC-MICE are illustrated in other Chapters of this book, while other approaches are documented by scientific papers.

FMI adopted a new two-dimensional version of the Spherical Elementary Current Systems (SECS) developed in the context of Swarm-SECS ESA project (http://space.fmi.fi/MIRACLE/Swarm_SECS/). This approach is applied to magnetic and electric field data measured by Swarm A and C, and allows the determination of the ionospheric currents, i.e. the Hall and Pedersen horizontal components and FAC, the ionospheric conductances and the plasma convection in the Ionospheric current layer. For FAC-MICE, FMI delivered three FAC density products: two single-spacecraft FAC products based on data measured by Swarm A and C, and one dual-spacecraft FAC product based on data acquired by the lower pair (Swarm A and C). The theory of SECS approach is described in Chap. 2, and the application of this method to Swarm data is described in Chap. 3.

ISS-JUB adopted the new methods to estimate FAC based on the data collected by single, dual or three Swarm spacecraft developed in the context of SIFACIT project (http://gpsm.spacescience.ro/sifacit/). For FAC-MICE, ISS-JUB delivered several different new FAC estimates and FAC quality indicators. Particularly interesting, FAC product based on the 3 spacecraft data, provided for the conjunction events, that does not require the hypothesis of time stationarity, being based on simultaneous Swarm measurements. These conjunction events occurred more frequently at the beginning of the mission, and will be again very frequent in year 2021 when the orbit of Swarm B will be coplanar with the one of the lower pair. ISS-JUB also provided a number of quality indices that can be used to verify the assumptions needed for the calculation of FAC, based on Minimum Variance Analysis (MVA, see e.g. Sonnerup and Scheible 1998) and cross-correlation analysis of time lagged magnetic field time series from Swarm A and C. They also provided the time intervals corresponding to the location of the auroral oval, selected with an automatic identification procedure based on FAC density, estimated from single spacecraft method. All the ISS-JUB approaches are described in Chap. 4 of this book.

RAL adopted the new multi-spacecraft methods based on 2, 3, 4 (or more) point measurements, partly obtained by time-shifting the positions of Swarm spacecraft. They delivered for FAC-MICE these multi-point FAC estimates, based on all the three spacecraft data during the conjunction events. The comparison among these products can be used to verify the time stationarity assumption, and validate the interpretation of the current components flowing predominantly along the field-aligned direction. These methods are illustrated in (Dunlop et al. 2015), and also in Chap. 5 of this book.

GFZ provided the single and the dual spacecraft FAC method, adopting the same algorithms illustrated by Ritter et al. (2013). Therefore, FAC products provided by GFZ are equivalent to the official ESA Level 2 single and dual spacecraft FAC products. They applied these algorithms also to 50 Hz data, not implemented in the Level 2 products, and provided also the orientation of the current sheet obtained from the relation between the two transverse magnetic components, Bx and By, in Mean-Field-Aligned (MFA) coordinates. These methods are illustrated in Chap. 6 of this book.

UofA provided estimates of dual and single spacecraft FAC density, for both Swarm A and C. The single spacecraft FAC estimates are very similar to the ESA Level 2 single-spacecraft FAC products, calculated using Ampere's law/curlometer (Lühr et al. 1996). The dual spacecraft FAC estimate is also similar to the ESA Level 2 dual-spacecraft FAC product (Ritter et al. 2013), but it is obtained without the low-pass filtering applied to the magnetic field time series. UofA also provided a quality parameter, based on cross-correlation analysis of time lagged magnetic field time series from Swarm A and C, similar to the parameter provided by ISS.

UCL-MSSL provided new quality indicators, based on cross-correlation of time lagged single spacecraft FAC estimates from Swarm A and C. Differently from the cross correlation analysis performed by ISS-JUB and UofA, UCL-MSSL performed the cross-correlation analysis separating the signals using five different band-pass filters. Under the assumption that the currents are temporally and spatially stationary, these bands correspond to the different spatial scales of FAC structure. Therefore, the indices provided by UCL-MSSL allow to assess the time stationarity assumption of FAC at different spatial scales.

UnCa provided both single and dual S/C FAC estimates, adopting the same algorithm as the Level 2 products (Ritter et al. 2013), using both the magnetic field residuals from the standard Level 2 model, but also the residuals from the CHAOS-6 model.

JHU provided a number of different FAC products, based on multi-point measurements obtained from two or three Swarm S/C. They used only high resolution magnetic field data (50 Hz), and were able to recover FAC at various spatial scales.

8.4 FAC-MICE Comparison Results

In order to compare the various FAC products provided by FAC-MICE participants, we decided to start from the events characterized by higher values of the quality parameters based on correlation analysis of magnetic field time series measured by Swarm A and C, provided by ISS-JUB and UofA. In theory, higher correlations are expected when the two assumptions needed for FAC calculation, i.e. time stationarity of the current sheet and linear variation of the magnetic signatures measured by the two spacecraft (i.e. constant gradient), are satisfied. This latter condition implies that when the correlation coefficients are very high, localized FAC structures, detected by one spacecraft but not the other, are absent. In this case, the various FAC estimates based on different Swarm spacecraft should agree well with each other.

The correlation analyses performed by ISS-JUB and UofA are similar: ISS-JUB performed the correlation analysis on the magnetic perturbations along the direction of maximum magnetic field variance, obtained from MVA, in the auroral time intervals obtained from their automatic identification procedure, using both filtered (with the low-pass filter) and unfiltered magnetic field time series. The correlation analysis is computed as a function of the time lag between Swarm A and C field data, the optimal correlation is selected, and the time lag corresponding to optimal correlation is also provided. Therefore, ISS-JUB provided the average value of the correlation coefficients, for each FAC-MICE event.

On the contrary, UofA computed the correlation of 2nd NEC magnetic field component (East-West component) of the magnetic residuals obtained by removing the provided core, external and lithospheric fields from the CHAOS model. They performed the analysis in a 4 min sliding window. The maximum correlation is achieved by first calculating the along-track latitude difference between Swarm A and C, and then fine-tuning this time lag corresponding to optimal correlation. Therefore, UofA provided a time series of the correlation coefficient for each of the events. In order to obtain an average correlation coefficient also for the analysis from UofA, we averaged the correlation time series provided by UofA in the auroral time intervals provided by ISS.

The values of the correlation parameters provided by ISS-JUB, based on filtered and unfiltered data, and the values of the averaged correlation parameter from UofA, for all the events of FAC-MICE are shown in Fig. 8.1. In this graph, we also reported the average values of the AE index, downloaded from NASA cdaweb (https://cdaweb.sci.gsfc.nasa.gov/index.html/). Along the X axis is reported the number of the event, as listed in Table 8.2, identified through the auroral automatic identification procedure from ISS-JUB. The number of events is now 36, because some of the intervals in the FAC-MICE list (Table 8.1) contained two auroral crossings, corresponding to the ascending and descending branches of the orbit. In Fig. 8.1, we can note that the values of the three correlation coefficients for each event are quite similar to each other, and no relation with the geomagnetic activity is observed.

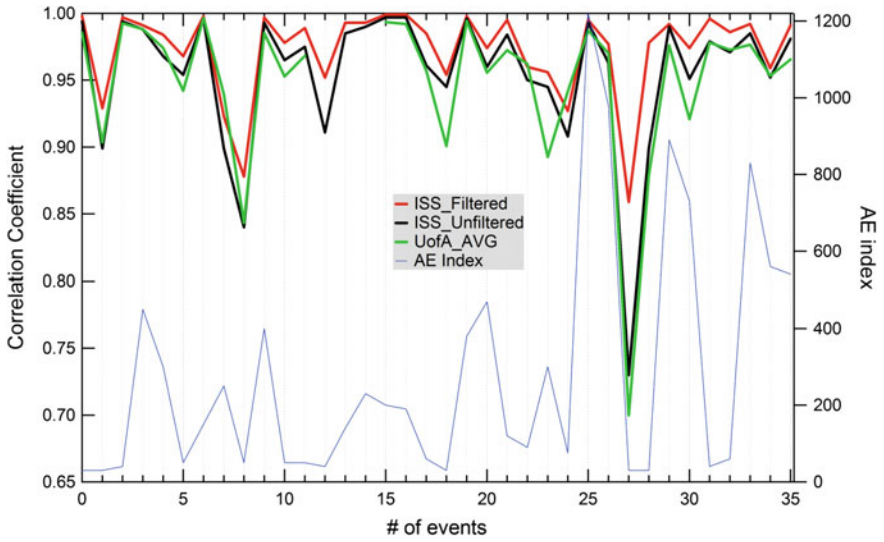

Fig. 8.1 FAC quality parameters based on cross-correlation analysis of magnetic field data measured by Swarm A and C, for the 36 events of the FAC-MICE dataset listed in Table 8.2. In this figure, also reported, is the average value of the AE index for each of the events

8.4.1 Comparison for the 'High Correlation' Events

As a first event for the comparison of various FAC estimates, let's consider the event # 15, observed on 2014-07-11 in the interval 19:30–19:45 UT, characterized by very high correlation coefficients and low AE index. This is a conjunction event, when all the three Swarm spacecraft are close together during the auroral crossing, and it was observed in the northern hemisphere at 18 MLT.

The magnetic field residuals from the standard magnetic field models (AUX_CORE, Lithosphere-MF7, magnetosphere-POMME-6) detected by the three Swarm spacecraft are illustrated in Fig. 8.2, in NEC reference frame. We can see that the magnetic signatures observed by the three spacecraft appear very similar, and are nearly simultaneous, apart for the time delay among Swarm A and C, which is approximately 8 s for this event.

Figure 8.3 shows the comparison among some of the FAC products delivered to ESA for FAC-MICE, for the event # 15. In panel (a) are displayed the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. The filtered single S/C products, the three S/C products and the unfiltered dual S/C products provided by ISS-JUB are displayed in panels (b), (c), (d) respectively. In panel (e) the products from FMI based on SECS method, in panel (f) the multi-point estimates from RAL, and in panel (g) the single S/C products from UnCA. In all these panels, the dual S/C product from GFZ is also shown for comparison.

The single and dual FAC estimates provided by GFZ, which are equivalent to ESA Level 2 FAC products, are displayed in panel a. The single spacecraft FAC product

Table 8.2 The FAC-MICE auroral events, as identified through the auroral automatic identification procedure from ISS-JUB. The number of events is now 36, because some of the intervals in the FAC-MICE list (Table 8.1) contain two auroral crossings, corresponding to the ascending and descending branches of the orbit

#	Year	Month	Day	Time start	Time stop
0	2014	4	22	04:05:00	04:20:00
1	2014	4	22	04:40:00	05:00:00
2	2014	4	22	05:40:00	05:55:00
3	2014	4	28	09:45:00	10:00:00
4	2014	4	28	10:30:00	10:45:00
5	2014	5	4	15:20:00	15:35:00
6	2014	5	4	19:05:00	19:21:00
7	2014	5	10	21:30:00	21:45:00
8	2014	5	17	03:05:00	03:15:00
9	2014	5	29	13:35:00	13:45:00
10	2014	6	4	18:10:00	18:22:00
11	2014	6	4	18:20:00	18:30:00
12	2014	6	10	23:40:00	23:50:00
13	2014	6	17	03:50:00	04:00:00
14	2014	6	29	12:25:00	12:40:00
15	2014	7	11	19:30:00	19:45:00
16	2014	7	11	20:27:00	20:40:00
17	2014	7	30	06:05:00	06:15:00
18	2014	8	11	10:00:00	10:10:00
19	2015	3	21	08:55:00	09:04:00
20	2015	3	21	09:04:00	09:20:00
21	2015	9	20	02:00:00	02:14:00
22	2015	9	20	02:13:00	02:25:00
23	2015	9	20	11:20:00	11:35:00
24	2015	9	20	11:35:00	11:45:00
25	2015	10	8	17:10:00	17:24:00
26	2015	10	8	17:24:00	17:35:00
27	2015	3	16	22:35:00	22:49:00
28	2015	3	16	22:48:00	23:00:00
29	2015	3	17	08:50:00	09:03:00
30	2015	3	17	09:03:00	09:15:00
31	2015	8	15	04:30:00	04:39:00
32	2015	8	15	04:39:00	04:50:00
33	2015	8	15	12:20:00	12:45:00
34	2015	10	7	02:10:00	02:18:00
35	2015	10	7	02:18:00	02:30:00

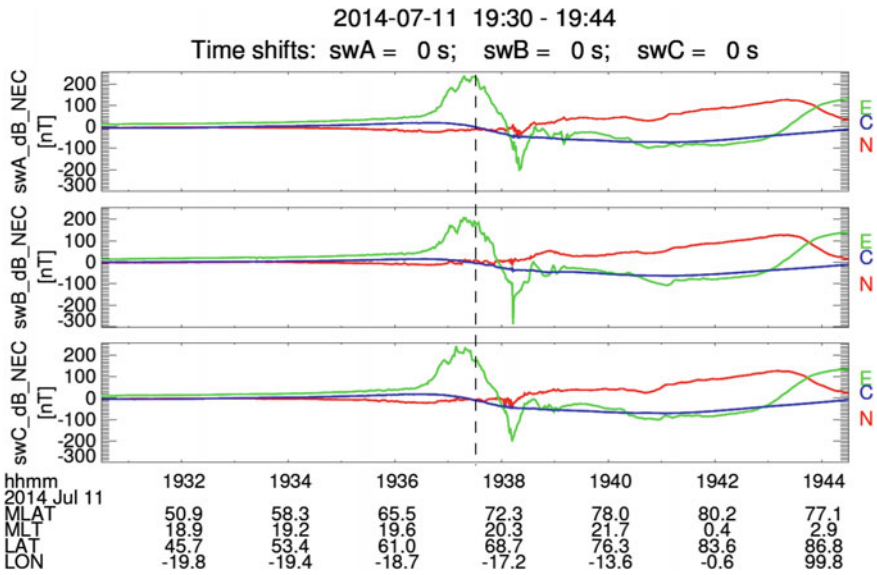

Fig. 8.2 The magnetic field residuals detected by the three Swarm spacecraft, in NEC reference frame, for the auroral event on 2014-07-11, 19:30–19:44 UT. Note that this is a conjunction event, when the three spacecraft are close together during the auroral crossing

obtained from Swarm C has been delayed by 7.9 s to take into account the spacecraft separation along the orbit.

The single spacecraft FAC products show several high frequency fluctuations, at time scales of few seconds, which sometimes are similar among the three spacecraft.

The dual spacecraft FAC product appears much smoother with respect to the single spacecraft FAC products. This difference is related to the low-pass band filter adopted for the dual spacecraft FAC product, at 20 s time scale (Ritter et al. 2013). This filter is necessary in the dual spacecraft FAC product to meet the time stationarity assumption, suppressing the FACs carried by kinetic Alfven waves and also to filter out FAC structures smaller than the separation among the 4 point measurements used for FAC calculation (quad size), which is approximately 50 km. Both these conditions are equally important.

In order to better compare the single and dual spacecraft FAC products, ISS-JUB provided filtered single spacecraft FAC products, obtained using the same the low-pass band filter adopted for the dual FAC product, which are shown in Fig. 8.3 panel (b). The agreement of the filtered single spacecraft FAC products with the GFZ dual spacecraft FAC product is now remarkable. This confirms that the current sheet is time stationary and invariant in longitude during this event since all the three spacecraft, at different times, recover the same FAC structure.

ISS-JUB also provided a FAC product based on data measured from all the three Swarm spacecraft, which can be obtained only during the conjunction events. Since this three-spacecraft ISS-JUB FAC product is based on simultaneous multipoint

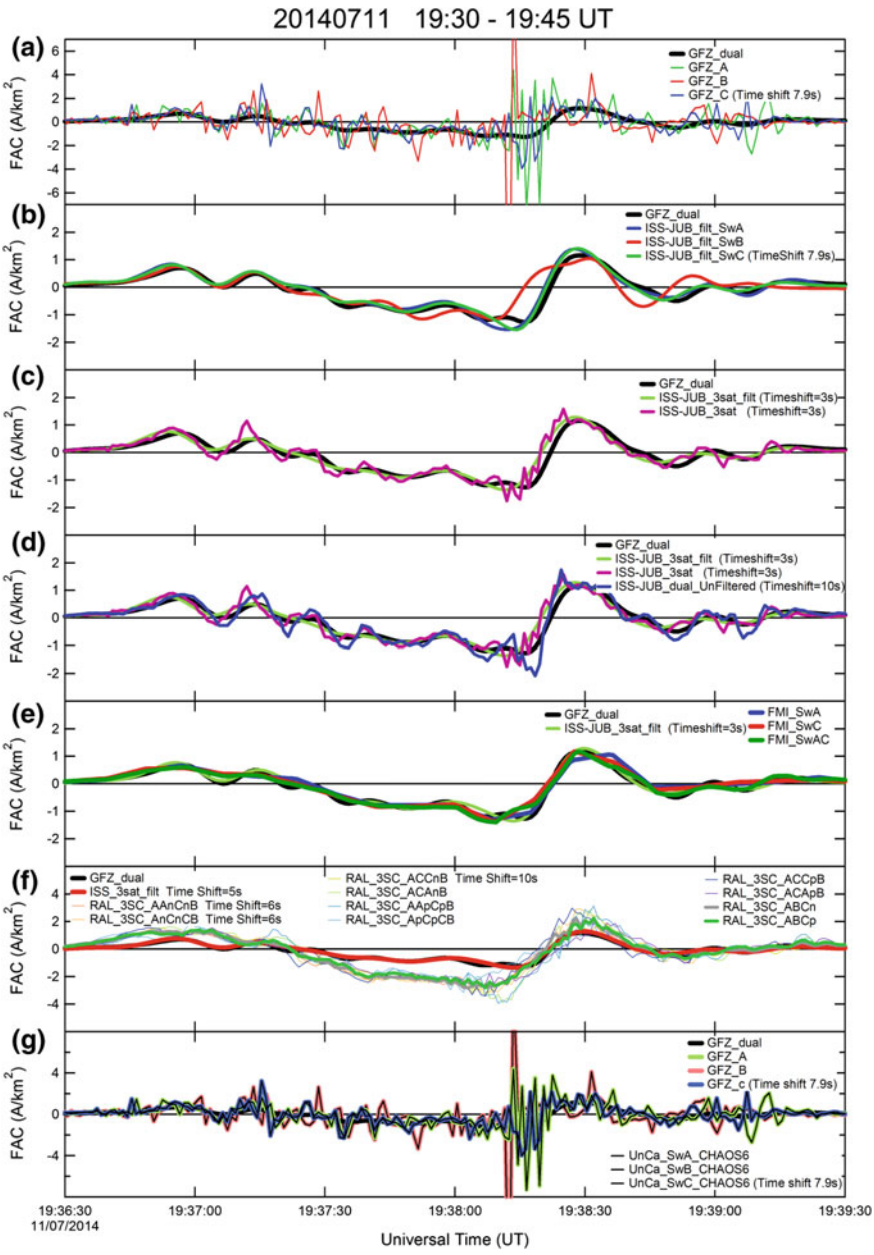

Fig. 8.3 Some of FAC products delivered to ESA for FAC-MICE, for the auroral event observed on 2014-07-11, 19:30–19:44 UT. Panel **a** shows the single and dual s/c products provided by GFZ, which are equivalent to ESA Level 2 FAC products. The filtered single S/C products, the three S/C products and the unfiltered dual S/C products provided by ISS-JUB are displayed in panels **b**, **c**, **d** respectively. In panel **e** the products from FMI based on SECS method, in panel **f** the multi-point estimates from RAL, and in panel **g** the single S/C products from UnCA. In all these panels, the dual S/C product from GFZ is shown for comparison

measurements, it does not require the filtering in order to satisfy the time-stationarity assumption. However, as for the dual spacecraft Level 2 FAC product, also in this case only current structures with dimensions larger than the separation among the three spacecraft can be recovered, otherwise spatial aliasing can occur. This three-spacecraft ISS-JUB FAC product is computed both from the unfiltered 1 Hz data, and from the filtered magnetic field data, using the same low-pass filter as the dual S/C Level 2 product.

Figure 8.3 panel (c) shows the comparison of dual GFZ FAC with the three ISS-JUB FAC products. This comparison can be considered as a sort of validation for the dual S/C product, given that the three spacecraft product is based on simultaneous measurements, not requiring the stationarity assumption. The general trend of these FAC products agree quite well and the unfiltered ISS-JUB three s/c product provide more details about small scales currents features.

For the events characterized by very high correlation coefficients between the unfiltered magnetic field series (higher than 0.99, like this event), ISS-JUB delivered also a dual S/C FAC product obtained from 1 Hz unfiltered magnetic field data. The justification for this product relies on the fact that, when the correlation coefficient is very high, local FAC structures with dimension smaller than separation between Swarm A and C, should be absent.

The comparison of this ISS-JUB dual S/C unfiltered, with the GFZ dual S/C, and ISS-JUB three S/C FAC product is illustrated in Fig. 8.3, panel (d). We can note that this ISS-JUB unfiltered dual S/C product agree well with the ISS-JUB unfiltered three S/C product, and provide more details about the small scale structure of FAC with respect to the GFZ dual S/C product. This suggests that, at least for the 'stationary events' characterized by very high correlation coefficient, it is possible to remove the low-pass filter in the dual S/C product, obtaining more information about the small scale structures with respect to the Level 2 dual S/C product.

In Fig. 8.3 panel (e) are displayed the FAC products obtained with SECS by FMI, using Swarm A and Swarm C alone, or the lower pair combined. These SECS FAC products recover only the large scale features, but agree remarkably well with the dual S/C FAC product from GFZ and also with the three S/C FAC product from ISS-JUB, also displayed in Panel (e) for comparison. This agreement is particularly important, since the FAC estimates from FMI are based on the expansion in Spherical Elementary Current System (SECS, see Chaps. 2 and 3 of this book), which differ substantially with respect to the methods based on the Ampere's law, used for all the other FAC products.

In Fig. 8.3 panel (f) are shown the various RAL FAC estimates based on 4 non-planar points using the full curlometer technique (Dunlop et al. 1988, 2002). These 4-point measurements are obtained from 3 S/C data by time-shifting the data from one S/C. The various FAC products displayed in panel (f) differ each other according to which S/C is time-shifted to obtain the fourth point measurement, and the names in the caption adopt the same convention of Dunlop et al. (2015), where p refers to positive time-shift and n to negative time-shift. The various FAC products provided by RAL show a similar behaviour, with a similar trend also with respect to the Level 2 dual S/C product. The time-shift among the various RAL products is related to

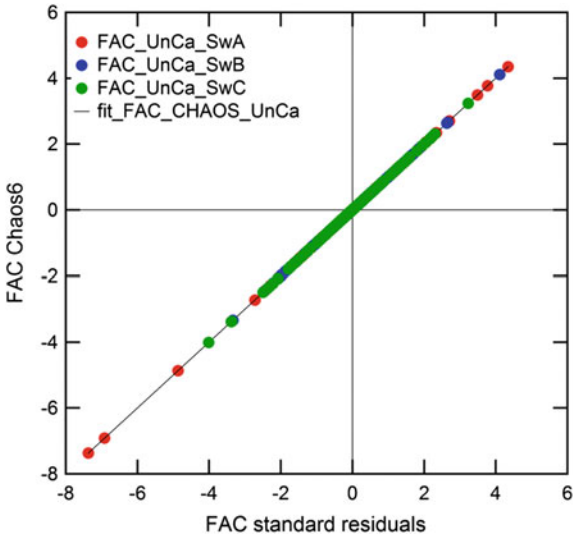

Fig. 8.4 A comparison among the single S/C FAC products from UnCA based on residuals obtained from CHAOS-6 model, with the single S/C Level 2 FAC product, for the auroral event displayed in Fig. 8.3

the change in effective barycentre and different tetrahedral shapes formed by each configuration. All the RAL products recover a significantly larger current density than the standard Level 2 dual S/C product, also larger with respect to the other FAC products from ISS. This can be due to the fact that RAL estimated FAC from the three components of the current density vector, while the other FAC products used the radial component only, which can omit some of the actual FAC. Dunlop et al. (2015) suggested that the degree of stationarity of the current sheet can be obtained from the variance over all different FAC estimates.

The single s/c products obtained from UnCa, based on magnetic residuals from CHAOS-6 model are compared to single s/c Level 2 products provided by GFZ in Fig. 8.3, panel (g). These FAC products from UnCa are perfectly coincident with the Level 2 products, which are instead obtained from the residuals from different magnetic field models (AUX_CORE, Lithosphere-MF7, magnetosphere-POMME-6, see Chap. 6 of this book). This perfect agreement is also confirmed in the scatter plot in Fig. 8.4, where the single s/c FAC products obtained from UnCa using the CHAOS-6 models are displayed as a function of the Level 2 single s/c FAC products. This agreement demonstrates that the choice of the model used to compute the residuals does not affect FAC calculation.

Other examples of events characterized by high correlation coefficients are the events numbered 25 and 26 in Table 8.2, observed on 20151008 in the intervals 17:10–17:24 UT and 17:24–17:35 UT.

In Fig. 8.5, the magnetic field residuals are reported, in NEC reference frame measured by the three Swarm spacecraft, with the same format as Fig. 8.2. Note that

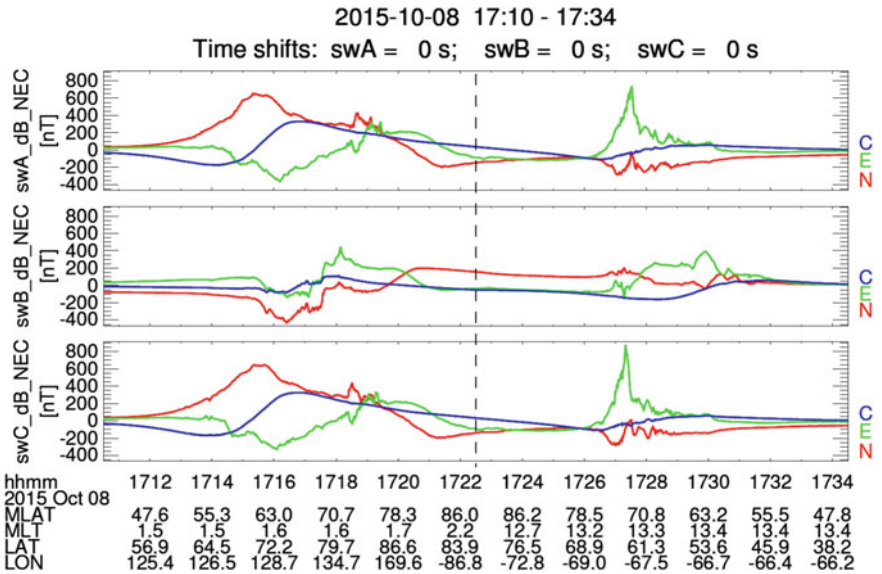

Fig. 8.5 The magnetic field residuals detected by the three Swarm spacecraft, in NEC reference frame, for the auroral event on 2015-10-08, 17:10–17:34 UT. Note that this is not a conjunction event among the three Swarm spacecraft. Indeed, Swarm A and C were in the northern hemisphere, and the magnetic signatures detected around 17:16 and 17:28 UT correspond to the entry and exit from the polar cap. Swarm B instead was flying in the southern hemisphere

this is not a conjunction event among the three Swarm spacecraft. Indeed, Swarm A and C were in the northern hemisphere, and the magnetic signatures detected around 17:16 and 17:28 UT correspond to the entry and exit from the polar cap. Swarm B instead, even if it detected similar magnetic signatures approximately at the same times as Swarm A and C, was flying in the southern hemisphere.

In Fig. 8.6 are reported some of the FAC estimates provided for FAC-MICE: In panel (a) are displayed the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. In panel (b) the filtered single S/C products provided by ISS-JUB and in panel (c) the products from FMI based on SECS method, together with the dual S/C product from GFZ for comparison.

With respect to the previous event (20140711), this event is characterized by higher geomagnetic activity, with AE $\approx$ 1000, and FACs are more intense. The comparison illustrated in Fig. 8.6 confirms the features highlighted in the previous event: in panel (a) the single and dual S/C products provided by GFZ, which are equivalent to the ESA Level 2 FAC products, show large discrepancies related to the high frequency fluctuations characterizing the single S/C FAC products. This discrepancy is related to the low-pass filters used for the dual S/C FAC product. Indeed, the comparison in panel (b) the dual S/C products from GFZ show a reasonably good agreement with the filtered single S/C FAC products delivered by ISS, obtained using the same low-pass filter.

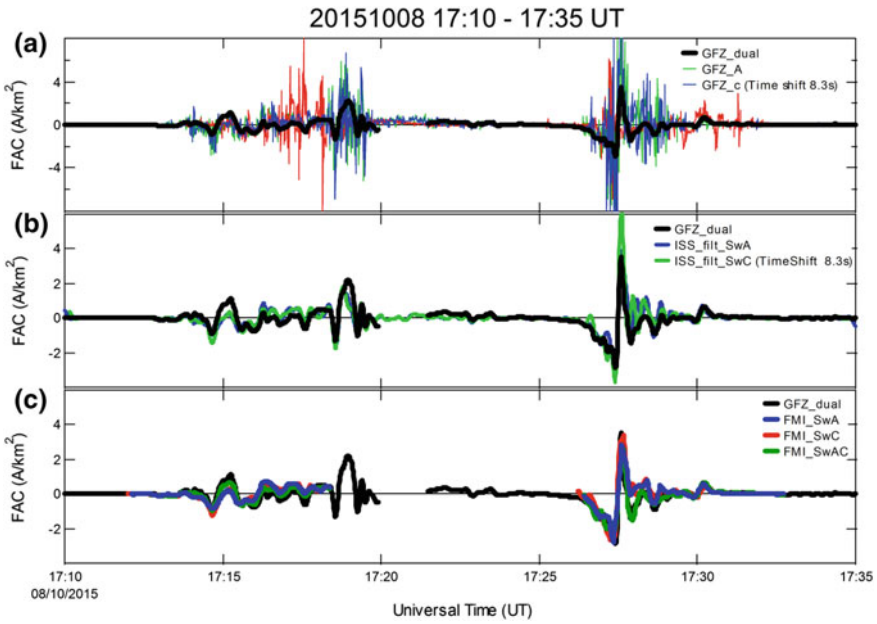

Fig. 8.6 Some of the FAC products delivered to ESA for FAC-MICE, for the auroral event observed on 2015-10-08, 17:10–17:34 UT. In panel **a** the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. In panel **b** the filtered single S/C products provided by ISS-JUB and in panel **c** the products from FMI based on SECS method, together with the dual S/C product from GFZ for comparison

Also in this event, the FAC products obtained from SECS method agree reasonably well with the dual S/C product from GFZ (see panel c).

8.4.2 Comparison for the 'Low Correlation' Events

The comparison among the various FAC products delivered for FAC-MICE has been performed also for a number of events characterized by lower values of the correlation parameters (Fig. 8.1), to see how the various FAC estimates compare with each other during these 'low-correlation' events.

As an example, we considered the event observed on 2014-05-17 in the interval 03:05–03:15 UT in the southern hemisphere. This is a conjunction event, during which the three Swarm spacecraft were close together, and the magnetic field residuals measured by the three spacecraft are shown in Fig. 8.7, in the NEC reference frame, with the same format as Fig. 8.2. The current sheet is observed approximately at the same time by the three spacecraft, but the differences among the magnetic signatures measured by the three spacecraft are now noticeable.

In Fig. 8.8 are reported some of the FAC estimates provided for FAC-MICE: in

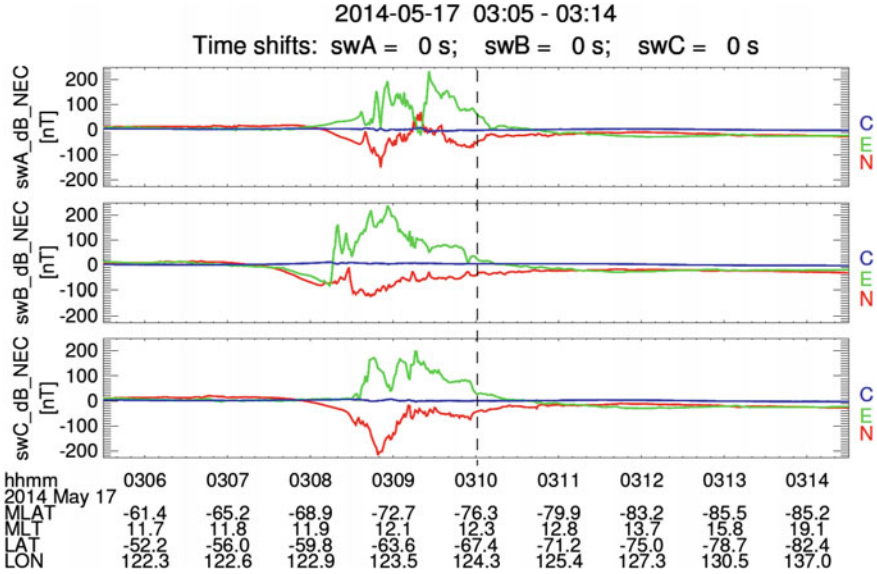

Fig. 8.7 The magnetic field residuals detected by the three Swarm spacecraft, in NEC reference frame, for the auroral event on 2014-05-17, 03:05–03:14 UT. Note that this is a conjunction event, when the three spacecraft are close together during the auroral crossing

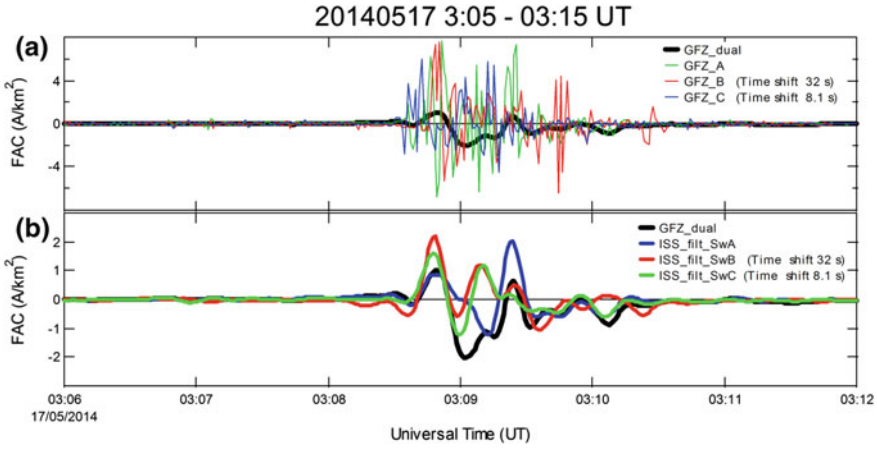

Fig. 8.8 Some of the FAC products delivered to ESA for FAC-MICE, for the auroral event observed on 2014-05-17, 03:05–03:14 UT. In panel **a** the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. In panel **b** the filtered single S/C products provided by ISS-JUB, together with the dual S/C product from GFZ for comparison

panel (a) are displayed the single and dual S/C products provided by GFZ, which are equivalent to the ESA Level 2 FAC products, and in panel (b) the filtered single S/C products provided by ISS.

Again, the single and dual S/C products provided by GFZ in panel (a) show large discrepancies, related to the high frequency fluctuations characterizing the single S/C FAC products. However, in this case, also the filtered single S/C FAC products provided by ISS-JUB differ substantially from each other, and also with respect the dual S/C L2 product. It can be noted that the larger deviation is shown by Swarm A single S/C filtered FAC product, while the filtered FAC products obtained from Swarm B and C data agree better to each other, at least until 03:09:20 UT.

This substantial difference is probably related to the presence of local FAC structures, with dimension smaller than the spacecraft separation, rather than non-stationarity of the current sheet. Indeed, only the FAC from Swarm A differ much, while FACs recovered by Swarm B and Swarm C agree quite well to each other, even if the relative time-shift between the two spacecraft is approximately 24 s. The presence of these local FAC structures affect the dual spacecraft FAC product, which is therefore not reliable for this event.

For this event, the three-S/C ISS-JUB FAC product is not available because the configuration of the Swarm constellation was too elongated. Moreover, also the FAC products based on SECS method are not available, since Swarm spacecraft were beyond 76° in magnetic latitude, the threshold beyond which the SECS analysis is not performed. Therefore, for this event, we cannot verify the large scale behaviour of the FAC structure.

As a further example of a 'low correlation' event, we considered the event observed on 2015-03-16, in the interval 22:35–23:00 UT in the northern hemisphere. This is not a conjunction event, and the magnetic field residuals measured by the lower pair are shown in Fig. 8.9, in the NEC reference frame, with the same format as Fig. 8.2.

In Fig. 8.10 are reported some of the FAC estimates provided for FAC-MICE: In panel (a) are displayed the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. In panel (b) the filtered single S/C products provided by ISS-JUB and in panel (c) the products from FMI based on SECS method, together with the dual S/C product from GFZ for comparison.

The single S/C products in panel (a) show high frequency fluctuations, while the dual S/C product is more stable. The comparison in panel (b) with the filtered single S/C products from ISS-JUB shows a better agreement in the first part of the event, while later on, i.e. after 22:43 UT, also the filtered single S/C FAC estimates differ noticeable from the dual S/C product. This can again be explained in terms of non-stationarity of the current sheet, and/or to strong longitudinal gradients. The signatures in the dual S/C product around 22:45, at ≈80°MLAT, could instead be due to high latitude filamentary FAC, which cannot be detected by single S/C methods because these currents are not planar, and therefore violate the orientation assumption needed for the single S/C FAC calculation (Lühr et al. 2016).

The FAC products based on SECS illustrated in panel (c) follow reasonably well the L2 FAC in the first part of the event (especially the dual spacecraft SECS). After

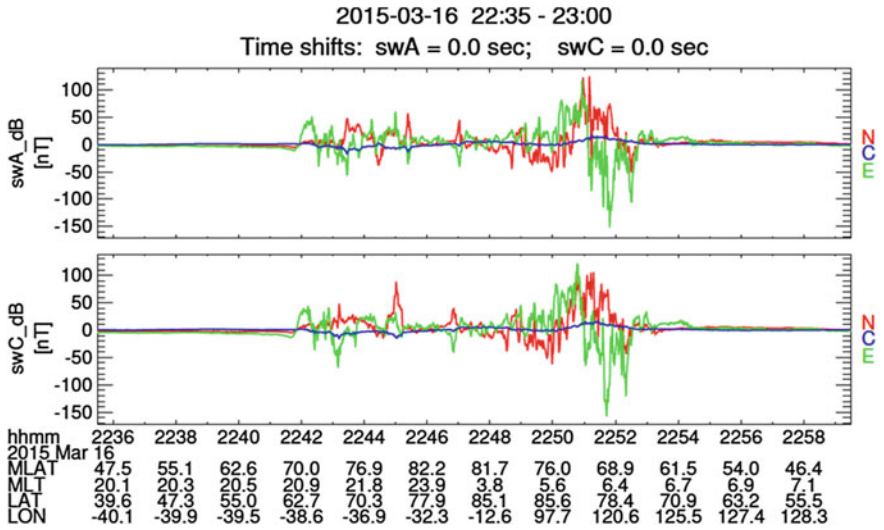

Fig. 8.9 The magnetic field residuals detected by Swarm A and C, in NEC reference frame, for the auroral event on 2015-03-16, 22:35–23:00 UT

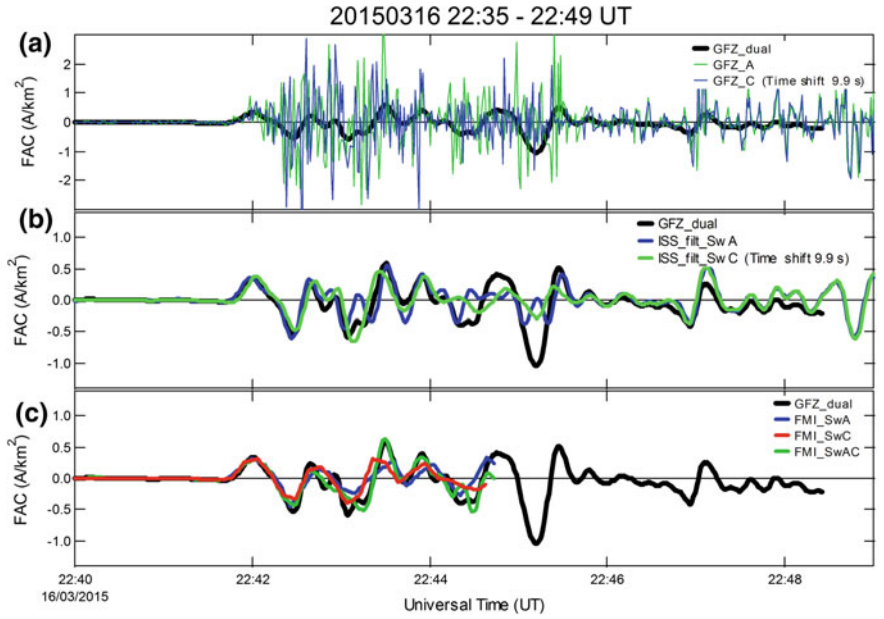

Fig. 8.10 Some of the FAC products delivered to ESA for FAC-MICE, for the auroral event observed on 2015-03-16, 22:35–23:00 UT. In panel **a** the single and dual S/C products provided by GFZ, which are equivalent to ESA Level 2 FAC products. In panel **b** the filtered single S/C products provided by ISS-JUB and in panel **c** the products from FMI based on SECS method, together with the dual S/C product from GFZ for comparison'

22:44:40 the SECS product are not available because the magnetic latitude is larger than 76°. Therefore, it's not possible to verify the signature at 22:45 UT.

8.5 FAC-MICE Comparison Summary

Three different groups participating to FAC-MICE (ISS, UofA, UCL-MSSL) provided quality parameters based on cross-correlation of lagged magnetic field time series (or FAC single spacecraft time series) measured by Swam A and C. These parameters agree well to each other for the various FAC—MICE events, and suggest the presence of two classes of events: the 'high-correlation' events characterized by the higher correlation coefficients and the 'low-correlation' events.

For the 'high-correlation' events, the various FAC estimates provided by the various groups show a reasonably good agreement. In particular, the noticeable discrepancies between the single and dual spacecraft Level 2 FAC products is highly reduced when the same low-pass filter used for dual S/C product is adopted also for the single S/C products. This suggests that the current sheet is both stationary and approximately invariant in longitude during these events. Indeed, the three spacecraft cross the current sheet at different times and in different locations, and recover approximately the same FAC structure.

Another important validation for FAC structure is given by the three spacecraft FAC products, provided for the conjunction events when Swarm B was near the lower pair (Swarm A and C), computed both from filtered and unfiltered 1 Hz data. Indeed, the three S/C products are based on simultaneous measurements from the three spacecraft, and do not rely on the stationarity assumption or orientation assumptions which are instead needed for the single or dual S/C FAC products. However, like the other FAC estimations based on multipoint measurements, these three spacecraft FAC products can recover only FAC with spatial scales larger than the spacecraft separations. During these 'high-correlation' events, also these three S/C products agree well with the other FAC estimates.

During these 'high-correlation' events, since the large scale FAC structure is reliably recovered by these filtered products, it seems possible to look at the smaller scale features of the FAC sheet, provided by various FAC estimates based on unfiltered 1 Hz magnetic field data. However, also during these 'high correlation' events, some of the high frequency fluctuations in the single S/C Level 2 FAC products differ among the various spacecraft. In particular, the differences observed between Swarm A and C, which are close together, suggesting the presence of local structures that do not satisfy the one-dimensional current sheet assumption needed for single spacecraft FAC calculation (Lühr et al. 2015).

During the low correlation events, the comparison among the various FAC products looks instead quite different: the large discrepancies among single and dual S/C FAC estimates remain, even when considering the filtered single S/C products. This suggests that the stationarity assumption is violated, and therefore FAC densities provided by the various products can be affected by non-negligible errors. Some of

the large-scale features of FAC structure given by the filtered dual S/C FAC products are confirmed by the SECS analysis also during these low-correlation events.

Other FAC estimates can be used in synergy with Swarm data to investigate the high latitude current system. For example, measurements from incoherent scatter radars can be very useful for this purpose. These radars provide various properties of the ionosphere, like electron density, ion velocity, ion and electron temperatures, ion composition, and collision frequencies, which can be used to infer the other important ionospheric parameters. However, these radars have a limited field of view, and can be used in conjunction with Swarm data only during Swarm overflights. Other methods, like AMPERE or the AMIE procedure, illustrated in Chaps. 7 and 10 of this book respectively, can provide the configuration of FACs on a global scale. Even if the resolution is not comparable with FAC obtained from Swarm, these methods can provide the global context for the more detailed Swarm measurements.

8.6 FAC-MICE Round Table Discussion and Way Forward

During the second day of the workshop in ESA-ESTEC, a Round Table discussion with all the participants debated the possible evolution of the current Level 2 FAC products, and/or potential new FAC product and FAC quality indicators.

During the discussion, it was pointed out that the various new FAC products developed for FAC-MICE could be useful to examine different features of the FAC structure:

- the small scale FAC products (single S/C, possibly also evaluated from 50 Hz mag data) correlate better with images from optical cameras and can be used to study stable arcs. Nice correspondences of the auroral structures with the single S/C level 2 FAC products have been reported in Gillies et al. (2015). The dual S/C FAC product was not used in these studies, since it is not able to recover the smaller scales structures of the arcs, which have a typical size of 10–20 km.
- the multi- S/C products (dual or three S/C) appear to be more suitable for recovering the large-scale behaviour of the FAC structure, and can be used in combination with ground based radar observation (e.g. SuperDARN Chisham et al. 2007) or incoherent scatter radar)
- a quality flag, based on cross-correlation analysis of magnetic field data measured by Swarm A and C, can give important indications about the stationarity of the FAC structure, and therefore about the reliability of the FAC products. However, it has been pointed out that a flag ‘good’ or ‘bad’ value could be dangerous, and instead a decimal value between 0 and 1, indicating the validity of stationarity assumption could be preferable.
- the inclination of the FAC sheet estimated from the MVA or from the correlation between the Bx and By components.

It has been suggested to develop a toolbox for user definable FAC calculation, where the users can choose among the various algorithms to compute FAC. The

suggested solution is to implement an open source platform, where the various codes for FAC calculation can be uploaded and shared among the users. In order to guarantee the reproducibility of the results, all the algorithms, filters and documentation used in this FAC toolbox need to be published.

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