Swarm Expert Support Laboratories

Swarm L2 FAC-single Product Description

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Doc. no: SW-TR-GFZ-GS-0005, Rev: 5, 2017-09-18

Contents

1 Document Change Log

Issue	Issue Date	Pages Affected	Remarks	Author
1.0	27.08.2014	All	Initial Issue	J. Park
2.0	18.02.2015	8	Table 2: text for digits 5 and 7 are switched	G. Kervalishvili
3.0	24.03.2016	5	Text in Scope is updated starting from "In the following ..."	G. Kervalishvili
		5	Eq. (1): $\frac{1}{\mu_0}$ was missing	
		5	where j is current density ... $\rightarrow$ where j is current density, μ_0 is magnetic permeability ...	
4.0	21.03.2017	4	AD1 is added	G. Kervalishvili
		5	FAC-single and -dual product document links are added	
		7-8	Section 6: text is updated	
		8	Table 2 is updated	
5.0	18.09.2017	5-6	Eq. (2) with its description is updated	G. Kervalishvili

2 Applicable Documents

AD1 SW-TR-GFZ-GS-008, Swarm L2 FAC-dual Product Description.

3 Reference Documents

RD1 Ritter, P., H. Lühr, and J. Rauberg (2013), Determining field-aligned currents with the Swarm constellation mission, Earth Planets Space, 65(11), 1285-1294.

RD2 He, M., J. Vogt, H. Lühr, E. Sorbalo, A. Blagau, G. Le, and G. Lu (2012), A high-resolution model of field-aligned currents through empirical orthogonal functions analysis (MFACE), Geophys. Res. Lett., 39, L18105, doi:10.1029/2012GL053168.

RD3 Wang, H., D.-D. Mao, S.-Y. Ma, and H. Lühr (2010), Substorm Time Ionospheric Field-Aligned Currents as Observed by CHAMP. Chinese Journal of Geophysics, 53: 339-346. doi: 10.1002/cjg2.1502.

RD4 Gjerloev, J. W., S. Ohtani, T. Iijima, B. Anderson, J. Slavin, and G. Le (2011), Characteristics of the terrestrial field-aligned current system, Ann. Geophys., 29, 1713-1729, doi:10.5194/angeo-29-1713-2011.

RD5 Kervalishvili, G. N. and H. Lühr (2013), The relationship of thermospheric density anomaly with electron temperature, small-scale FAC, and ion up-flow in the cusp region, as observed by CHAMP and DMSP satellites, Ann. Geophys., 31, 541-554, doi:10.5194/angeo-31-541-2013.

RD6 Maus, S. and P. Weidelt, Separating the magnetospheric disturbance magnetic field into external and transient internal contributions using a 1D conductivity model of the Earth (2004), Geophys. Res. Lett., 31(12), L12614, doi:10.1029/2004GL020232.

RD7 Kan, J. R. and L. C. Lee, Energy coupling function and solar wind-magnetosphere dynamo (1979), Geophys. Res. Lett., 6, 577.

RD8 Prokhorov, B. E., M. Förster, M. He, A. A. Namgaladze, and M. Holschneider (2014), Using MFACE as input in the UAM to specify the MIT dynamics, J. Geophys. Res. Space Physics, 119, doi:10.1002/2014JA019981.

RD9 Swarm Level 2 Processing Facility Product specification for L2 Products and Auxiliary Products (SW-DS-DTU-GS-0001).

4 Scope

This document reports the results obtained from scientific quality validation of the Swarm Level-2 Field-Aligned Current (L2-FAC) data: FACATMS_2F, FACBTMS_2F and FACCTMS_2F. In the following, "single FAC" and "single radial current" refer to FAC and radial current that are defined for a single satellite A, B, or C. Currents defined for the satellite pair A and C are called dual FAC and dual radial current, and are not subject to this report. The Swarm L2 FAC-dual Product Description document AD1 is available on the EO web page: https://earth.esa.int/web/guest/document-library/browse-document-library/-/article/swarm-level-2-fac-dual-product-description.

Current or updated version of the FAC-single product description document is available on the EO web page: https://earth.esa.int/web/guest/document-library/browse-document-library/-/article/swarm-level-2-fac-single-product-description.

5 Introduction

5.1 Algorithm

As has been outlined by RD1 and RD2, we can calculate vertical current density using spatial gradient of geomagnetic field data. The basic equation is the Ampère's law:

$$j_z = \frac{1}{\mu_0}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right], \tag{1}$$

where j is current density, μ_0 is magnetic permeability, and B is magnetic field. The z-axis is pointing vertically downward, x-axis northward, and y-axis eastward.

First, model values of geomagnetic field from the Earth's core, lithosphere, and magnetosphere, which are called 'mean field' in assembly, are subtracted from the 1 Hz magnetic field readings of the Vector Field Magnetometer (VFM): MAGA_LR_1B, MAGB_LR_1B and MAGC_LR_1B. The magnetic field residuals are used to retrieve the FAC density.

The method is based on the assumption that vertical current sheets are elongated infinitely in the zonal direction: that is, the second term of the right-hand side of Eq. (1), $-\frac{\partial B_x}{\partial y}$, is negligible. Then, we can estimate vertical current density using along-track variation of magnetic field observed by one single satellite: that is, using the first term of the right-hand side of Eq. (1), $\frac{\partial B_y}{\partial x}$.

The FAC current density, j_{FAC}, is calculated by dividing the radial current, j_{IRC}, by the sine of the magnetic inclination angle:

$$j_{FAC} = -\frac{j_{IRC}}{sinI}\left[\frac{\mu A}{m^2}\right], \tag{2}$$

where I is the inclination of the magnetic field. At high latitudes, where magnetic field is approximately in the vertical direction, FAC density is nearly the same as the IRC density. For more details of FAC density calculation, readers are referred to RD1.

5.2 Scientific Relevance

FACs are an essential component in the space weather. As FAC acts as connector between the magnetosphere and ionosphere at high latitudes, exact information on FACs can help to give constraints on many physical parameters related to space weather: e.g., ionospheric conductivity.

6 Descriptions of the data format

One data file of L2-FAC (FACATMS_2F, FACBTMS_2F or FACCTMS_2F) is produced per day and per Swarm satellite (Alpha, Bravo, or Charlie). A daily file is produced only when the Level 1b (L1b) 1 Hz magnetic field data (MAGA_LR_1B, MAGB_LR_1B and MAGC_LR_1B) of the corresponding satellite and date are available.

Table 1: The list of variables in the L2 FAC-single data product (FACATMS_2F, FACBTMS_2F and FACCTMS_2F).

Variable name	Description	Unit
Timestamp	Time stamps in Universal Time	cdf epoch
Latitude	Geographic latitude of the Swarm satellite	degree
Longitude	Geographic longitude of the Swarm satellite	degree
Radius	Distance of the Swarm satellite from the Earth's center	m
IRC	Ionospheric radial current (vertically upward)	$\mu A/m^2$
IRC-Error	Error in ionospheric radial current	$\mu A/m^2$
FAC	Ionospheric field-aligned current	$\mu A/m^2$
FAC-Error	Error in ionospheric field-aligned current	$\mu A/m^2$
Flags	Flags characterizing the L2 FAC-single product quality	no unit
Flags F	Flags about the magnetic field intensity measurement (zero is nominal), passed through from the L1b data	no unit
Flags B	Flags about the magnetic field vector measurement (zero is nominal), passed through from the L1b data	no unit
Flags q	Flags about the attitude information (zero is nominal), passed through from the L1b data	no unit

The cadence of the L2-FAC data (FACATMS_2F, FACBTMS_2F and FACCTMS_2F) is 1 Hz. One FAC data point is obtained by differencing two adjacent data points of L1b 1 Hz magnetic field data (MAGA_LR_1B, MAGB_LR_1B and MAGC_LR_1B). Hence, the time stamps of L2-FAC data (FACATMS_2F, FACBTMS_2F and FACCTMS_2F) are halfway between the time stamps of the L1b 1 Hz magnetic field data (MAGA_LR_1B, MAGB_LR_1B and MAGC_LR_1B). The Table 1 presents the list of variables in the L2-FAC data product (FACATMS_2F, FACBTMS_2F, and FACCTMS_2F). The variable, 'IRC' (ionospheric radial current) is calculated by Eq. (1) irrespective of latitudes, while the variable, 'FAC' is calculated by Eq. (2) only at low latitudes, where inclination angles are larger than 30° ($|I| > 30°$). The variable 'FAC' is not calculated at low latitudes because the field-aligned direction is nearly perpendicular to the radial direction: conversion from IRC into FAC by Eq. (2) is not justified. For more complete description on the algorithm and data content, readers are referred to RD1 and RD9.

The Table 2 presents the list of 10 individual and independent digits, characterizing the L2 FAC-single product quality. Digits from 1 to 8 report issues that may have been occurred at one or more of the measurement points used for the computation of a current density value. Digits 9 and 10 report whether the NaN values for the current density were used or not. Values N>0 mark the number of points that were affected and value 0 marks not affected ones. For the single FAC processing N can equal to 1 or 2, because 2 measurement points are involved.

Table 2: Flags characterizing the L2 FAC-single product (FACATMS_2F, FACBTMS_2F and FACCTMS_2F) quality.

Digit-Number	**Value**	**Meaning of each digit**
1	0/N	A short (< 5 seconds) data gap occurred, which was interpolated linearly.
2	0	For single FAC, this digit is always zero because no filtering is done.
3	0/N	No EST (external part of DST [RD6]) data were available, and a default value was used for the magnetospheric field model.
4	0/N	No IST (internal part of DST [RD6]) data were available, and a default value was used for the magnetospheric field model.
5	0/N	No solar radio flux ($F10.7$) data were available, and a default value was used for the magnetospheric field model.
6	0/N	No interplanetary magnetic field (IMF) data were available, and a default value was used for the magnetospheric field model.
7	0/N	No Em (merging electric field [RD7]) data were available, and a default value was used for the magnetospheric field model.
8	0/N	No magnetospheric field coefficients were available, and magnetospheric field is set to 0.
9	0	For single FAC, this digit is always equal to 0.
10	0/1	This digit is equal to 1 if inclination $\|I\| < 30°$ (FAC $= NaN$).

7 Selected Examples

Here we present three examples of L2-FAC data (FACATMS_2F and FACCTMS_2F). Figure 1 shows a typical example of Swarm L2-FAC data. The corresponding magnetic local time (MLT) is near midnight. The top panel presents FAC density calculated from magnetic field observations by Swarm-Alpha (red) and Swarm-Charlie (blue). The bottom panel shows electron density measured by the Langmuir Probe (LP) onboard Swarm. Please note that absolute values of the electron density data are not yet fully calibrated when this document is being written. Nevertheless relative variation of the electron density is expected to be reasonable. Swarm-Alpha and Swarm-Charlie were in a formation flight (at the same altitude with longitudinal/latitudinal separation of approximately 1°) on that day (20-April-2014). In the top panel the agreement between two FAC density curves are quite good: even tiny details match each other around 80° in geographic latitude (GLAT). In the bottom panel electron density fluctuation is strong in regions with high FAC density.

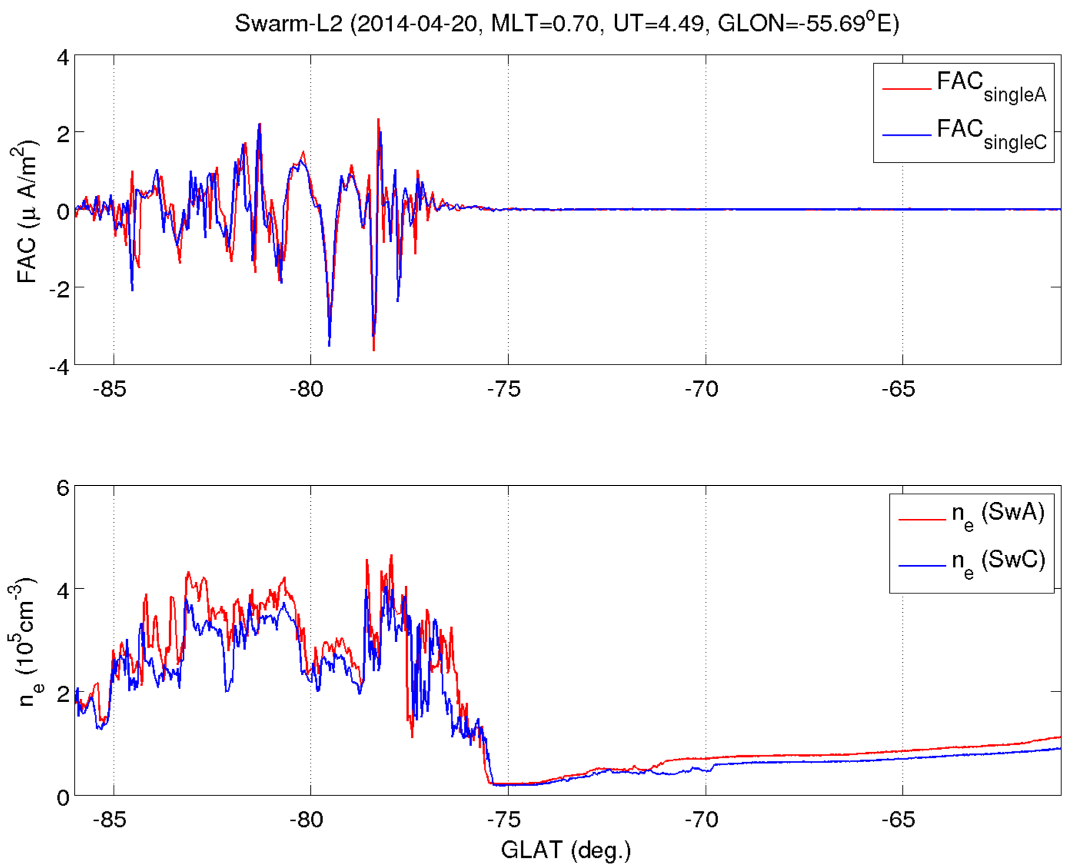

Figure 1: Example of Swarm L2-FAC data (FACATMS_2F and FACCTMS_2F).

Figure 2 shows another example of L2-FAC and LP data, and the figure format is the same as that of Figure 1. The corresponding MLT is near dawn. In the top panel two FAC curves exhibit similar profiles. In the bottom panel enhanced electron density fluctuations accompany high-amplitude FAC regions in the top panel.

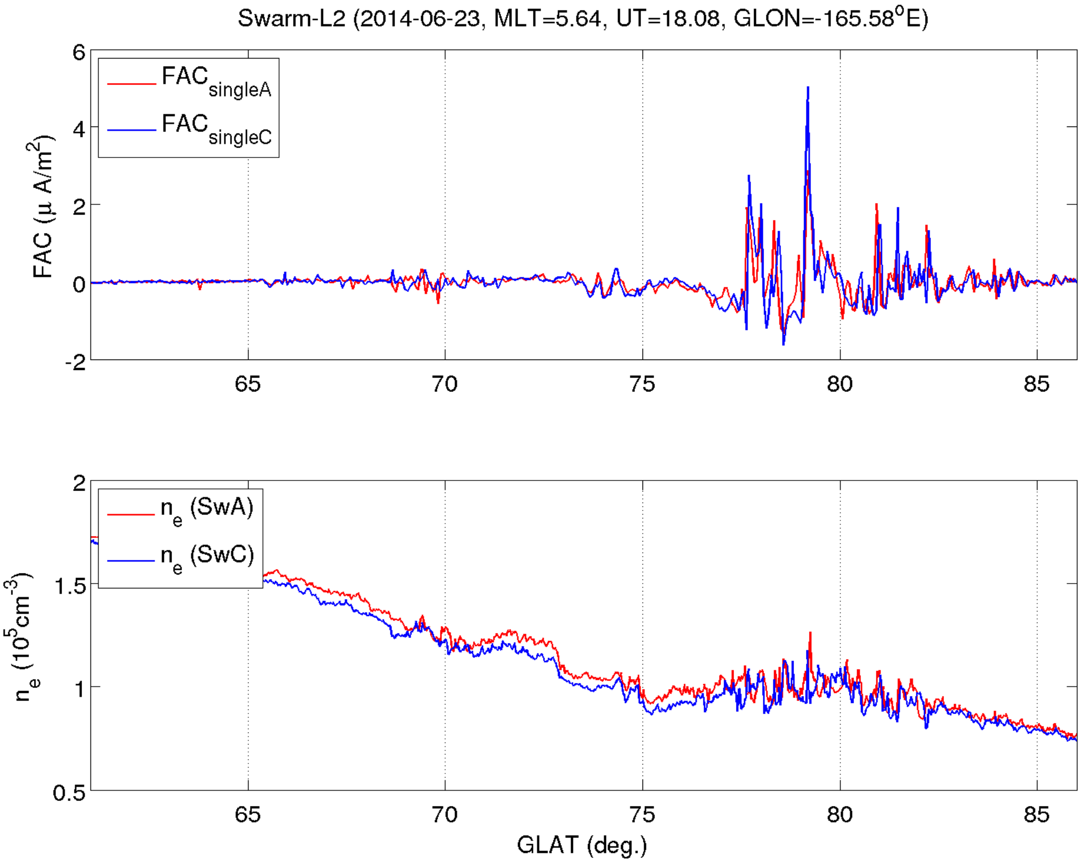

Figure 2: Another example of Swarm L2-FAC data (FACATMS_2F and FACCTMS_2F).

Figure 3 shows another example of L2-FAC and LP data, and the figure format is the same as that of Figure 1. The corresponding MLT is near dusk. In the top panel two FAC curves exhibit similar profiles. FAC fluctuation is higher in $> 67°$ GLAT than in $< 67°$ GLAT. In the bottom panel electron density fluctuation level is also higher in $> 67°$ GLAT than in $< 67°$ GLAT.

Figure 4 shows amplitude of FAC as a function of magnetic latitude (MLAT). Data from all three Swarm satellites during a short period from 2014-04-17 to 2014-04-23 are used for the figure. In Figure 4 we can see the following two points:

1. maximum FAC amplitude is around 1 (μA/m^2).
2. FACs between $65° - 80°$MLAT are generally stronger than that at lower and higher latitudes.

These two points are in good agreement with the results of RD2 and RD3.

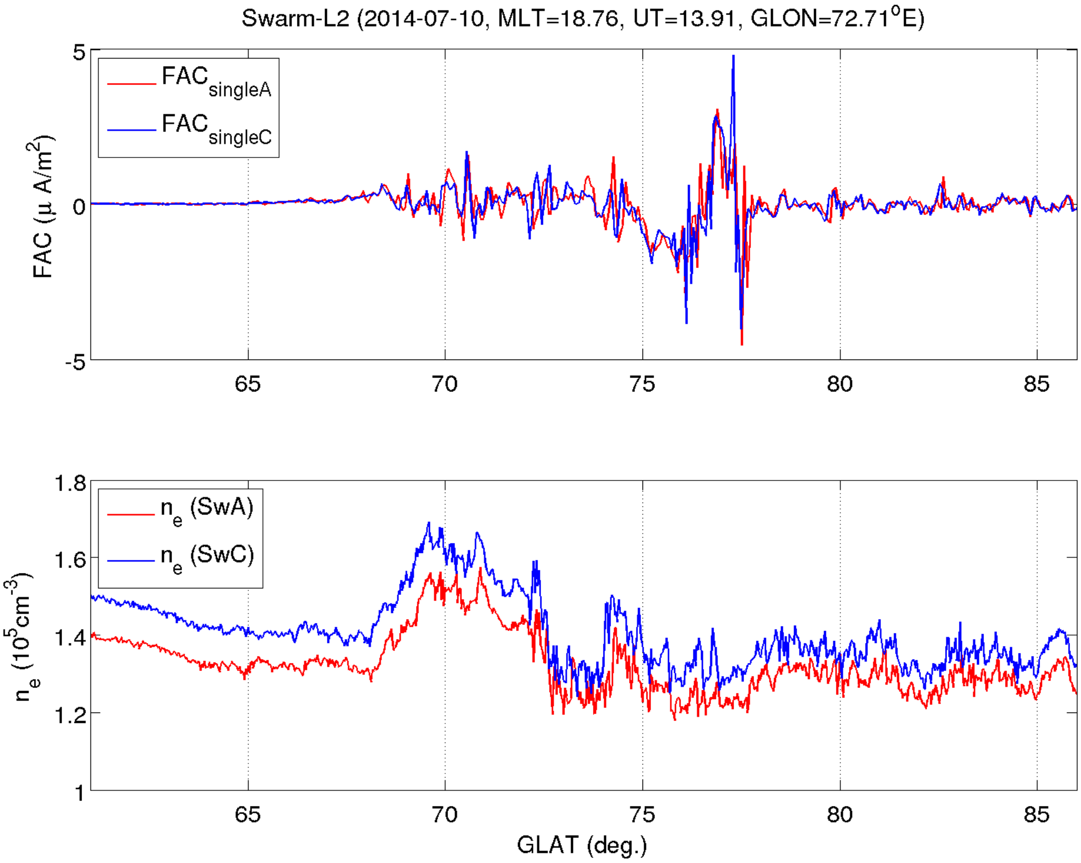

Figure 3: Another example of Swarm L2-FAC data (FACATMS_2F and FACCTMS_2F).

In Figures 1-3 the latitudinal profiles of Swarm-Alpha FAC agree well with those of Swarm-Charlie FAC. The two satellites are in a formation flight (at the same altitude with longitudinal/latitudinal separation of approximately 1°). Note that the level of agreement between Swarm-Alpha FAC and Swarm-Charlie FAC can vary pass by pass (because of strong natural variability at small scales RD4). In this document we show selected examples of Swarm-Alpha FAC and Swarm-Charlie FAC, which support qualitative reliability of the Swarm L2-FAC products.

The FAC amplitude shown in Figure 4 is in general agreement with those in previous reports RD2 and RD3, as discussed above. Hence, Figure 4 supports that FAC density of Swarm L2-FAC product is quantitatively on the right order of magnitude.

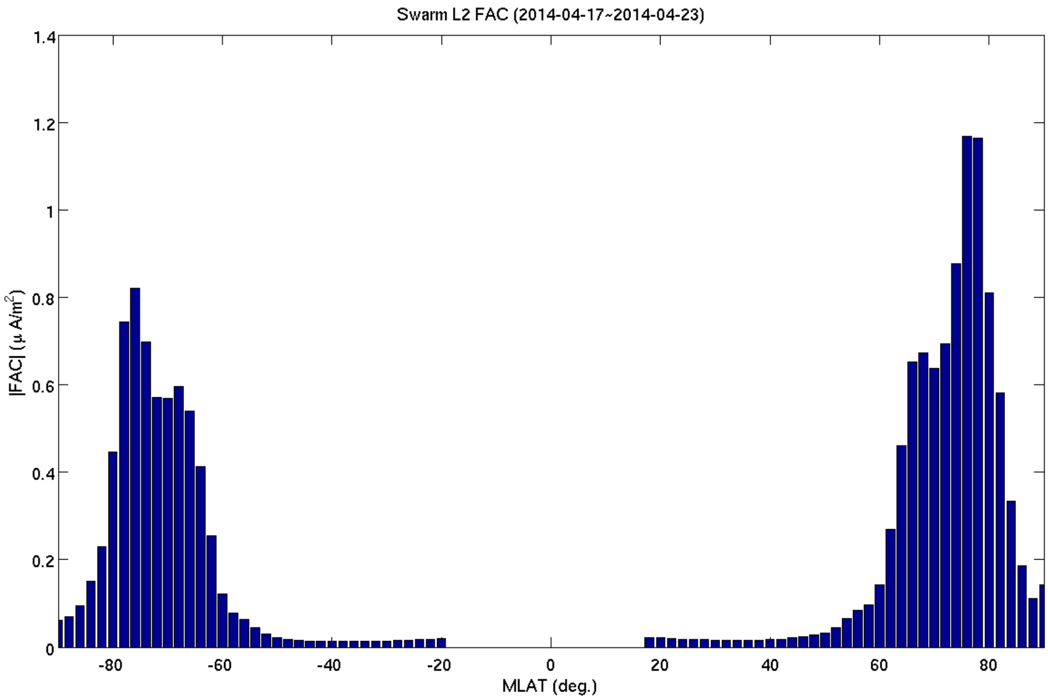

Figure 4: A short-term statistics of Swarm L2-FAC data (using the single-satellite method).

8 Spatial Distribution of single-FAC

Figure 5a presents the statistical distribution of small-scale FAC (SSFAC) amplitude, which is defined as absolute magnitude of 1 Hz FAC data, in the northern hemisphere. Each row in Figure 5a corresponds to Swarm-Alpha, -Charlie, and -Bravo, respectively. Each column corresponds to local winter, combined (spring+autumn) equinox, and local winter, respectively. In each panel the magnetic pole is at the center. Magnetic local time (MLT) increases counter-clockwise from the bottom of each plot. Note that poorly populated bins (number of data points less than 15) have been neglected when drawing the figures. The data gaps in Figure 5a are caused by the fact that Swarm data do not span a full year yet (as of October 2014). In Figure 5b SSFAC amplitudes from CHAMP data in 2005-2006 are shown for the purpose of comparison with Swarm results. In the figures it is immediately clear that:

1. SSFAC around magnetic noon is stronger than in any other MLT regions.
2. Strong SSFAC can be found at higher latitudes on the dayside than on the nightside.
3. The noontime peak SSFAC weakens from summer via equinox to winter.

In a qualitative sense, all the three Swarm satellites (Figure 5a) and CHAMP (Figure 5b) exhibit the above-mentioned common trends. Swarm results generally agree with one another in qualitative and quantitative senses. Differences in amplitude between Swarm and CHAMP results may result from different levels of solar and geomagnetic activity during the respective operation periods.

Figure 6 has the same format as Figure 5, but for the southern hemisphere. Figure 6 also shows good qualitative agreement among the FAC data from CHAMP, Swarm-Alpha, Swarm-Bravo, and Swarm-Charlie.

Figure 7 presents the statistical distribution of large-scale FAC (LSFAC) amplitude, which is defined as absolute magnitude of FAC data filtered with a $\sim$ 20-second low-pass filter, in the northern hemisphere. Figure 8 has the same format as Figure 7, but for the southern hemisphere. These figures also show qualitative agreement among the FAC data from CHAMP, Swarm-Alpha, Swarm-Bravo, and Swarm-Charlie.

In conclusion, the FAC properties shown in Figures 5-8 show that the qualitative agreement among FAC data from CHAMP, Swarm-Alpha, Swarm-Bravo, and Swarm-Charlie is reasonably good. Hence, the three Swarm products, FACATMS_2F, FACBTMS_2F and FACCTMS_2F, are recommended for scientific use.

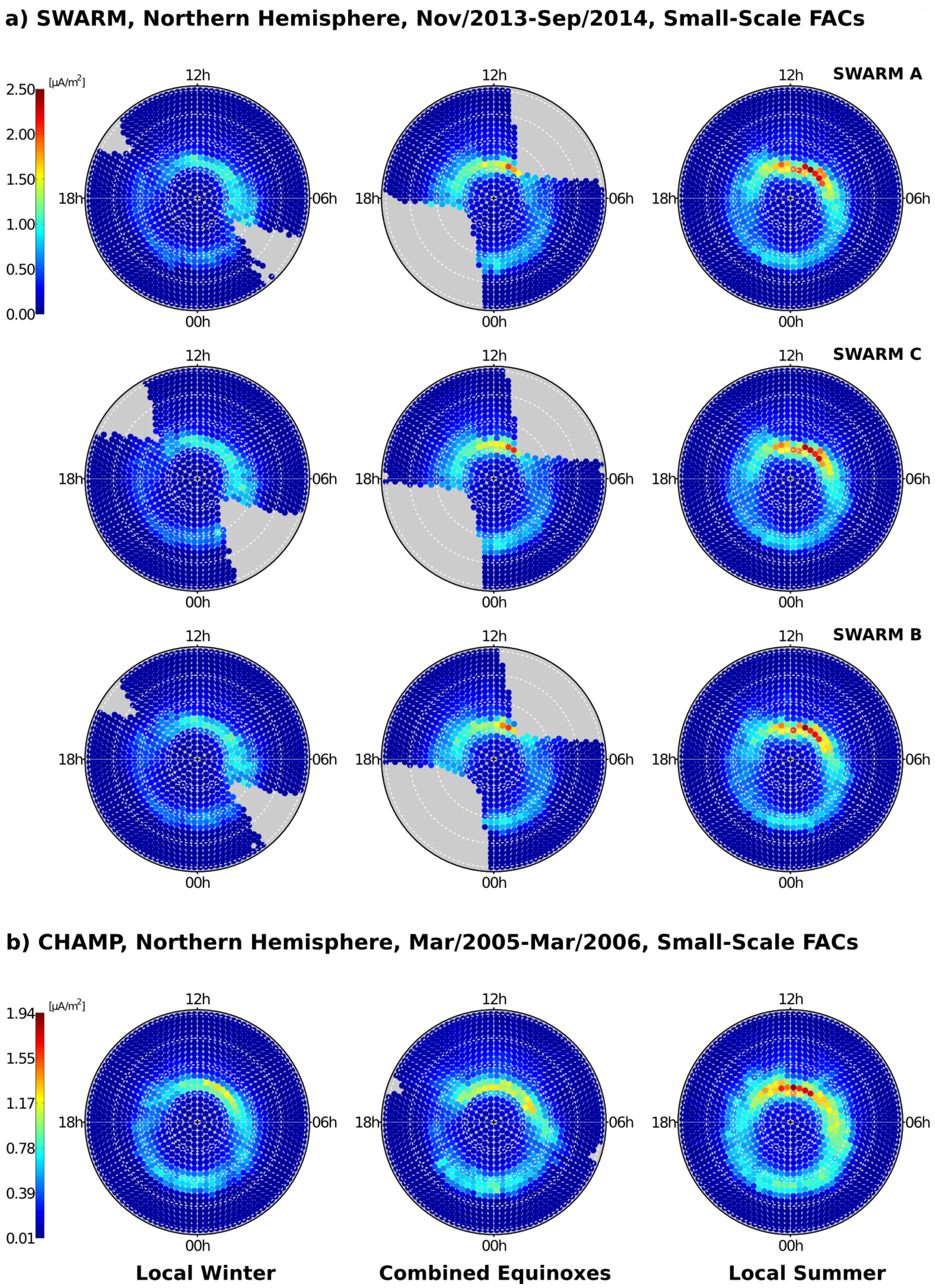

Figure 5: The bin-averaged median values of small-scale FACs for (a) Swarm satellites and (b) CHAMP in the northern hemisphere. The data are presented in the MLAT-MLT coordinate frame, where the white circles mark the MLAT at 10° spacing.

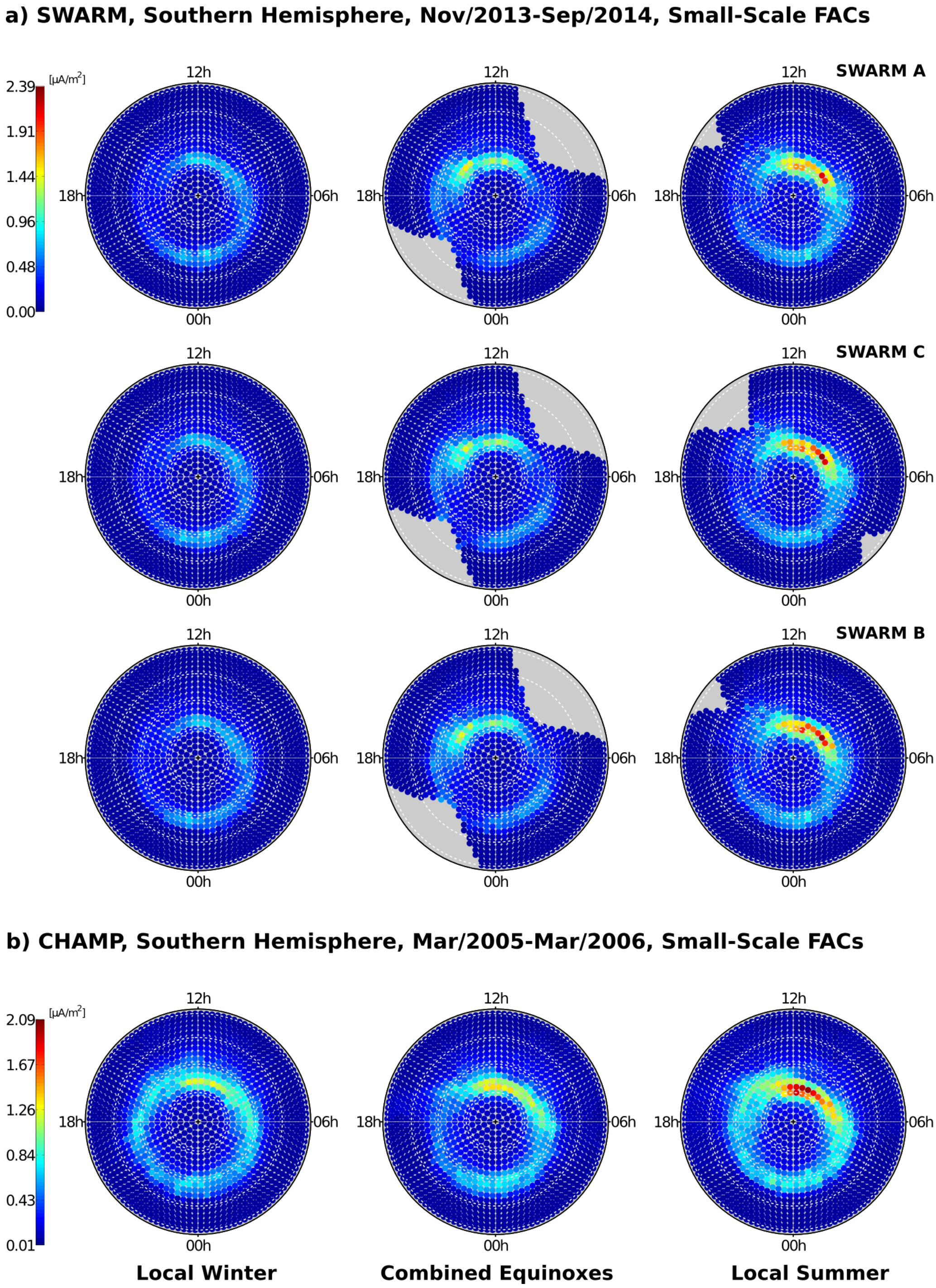

Figure 6: The same as Figure 5, but for the southern hemisphere.

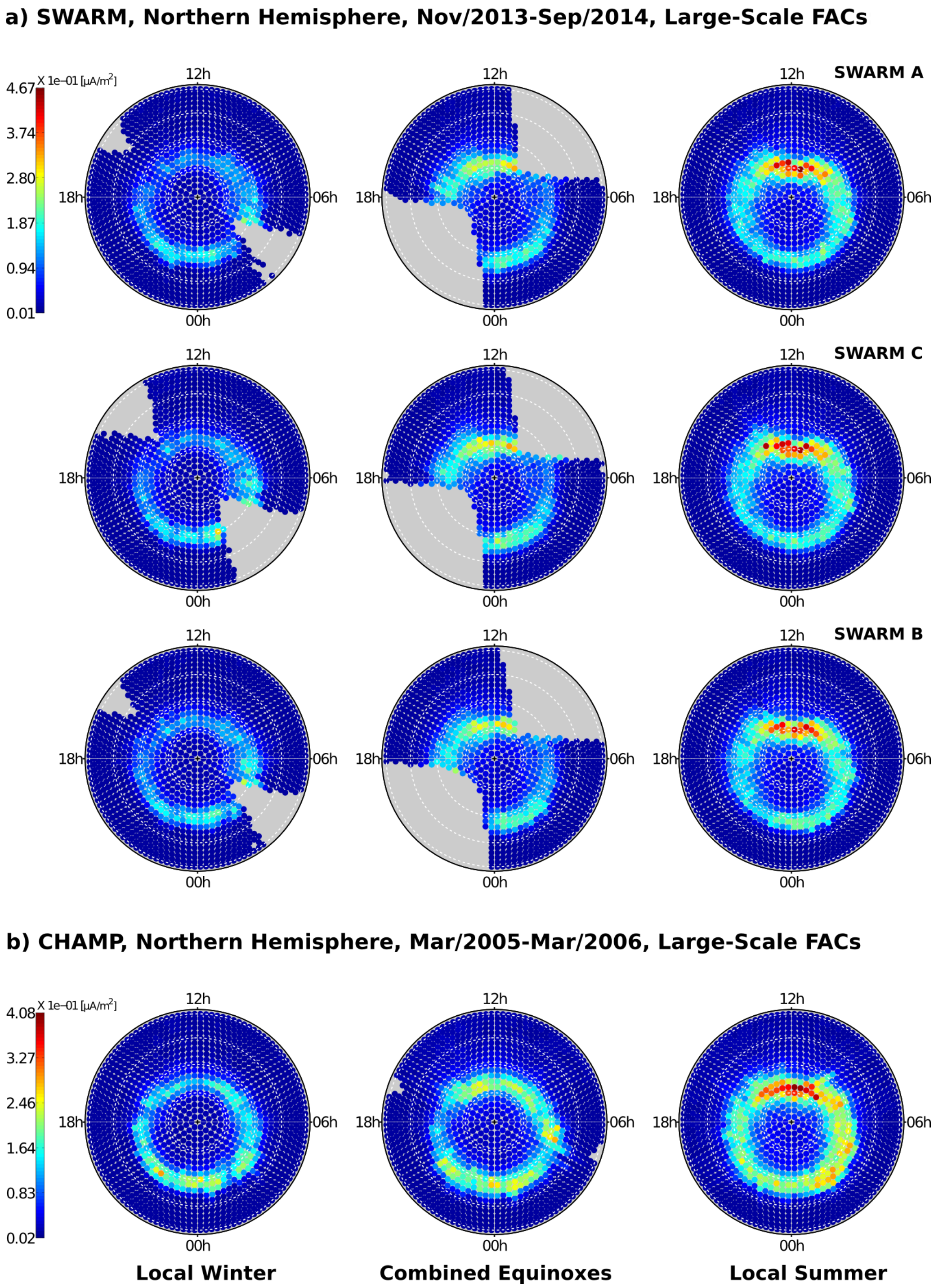

Figure 7: The bin-averaged median values of large-scale FACs for (a) Swarm satellites and (b) CHAMP in the northern hemisphere. The data are presented in the MLAT-MLT coordinate frame, where the white circles mark the MLAT at 10° spacing.

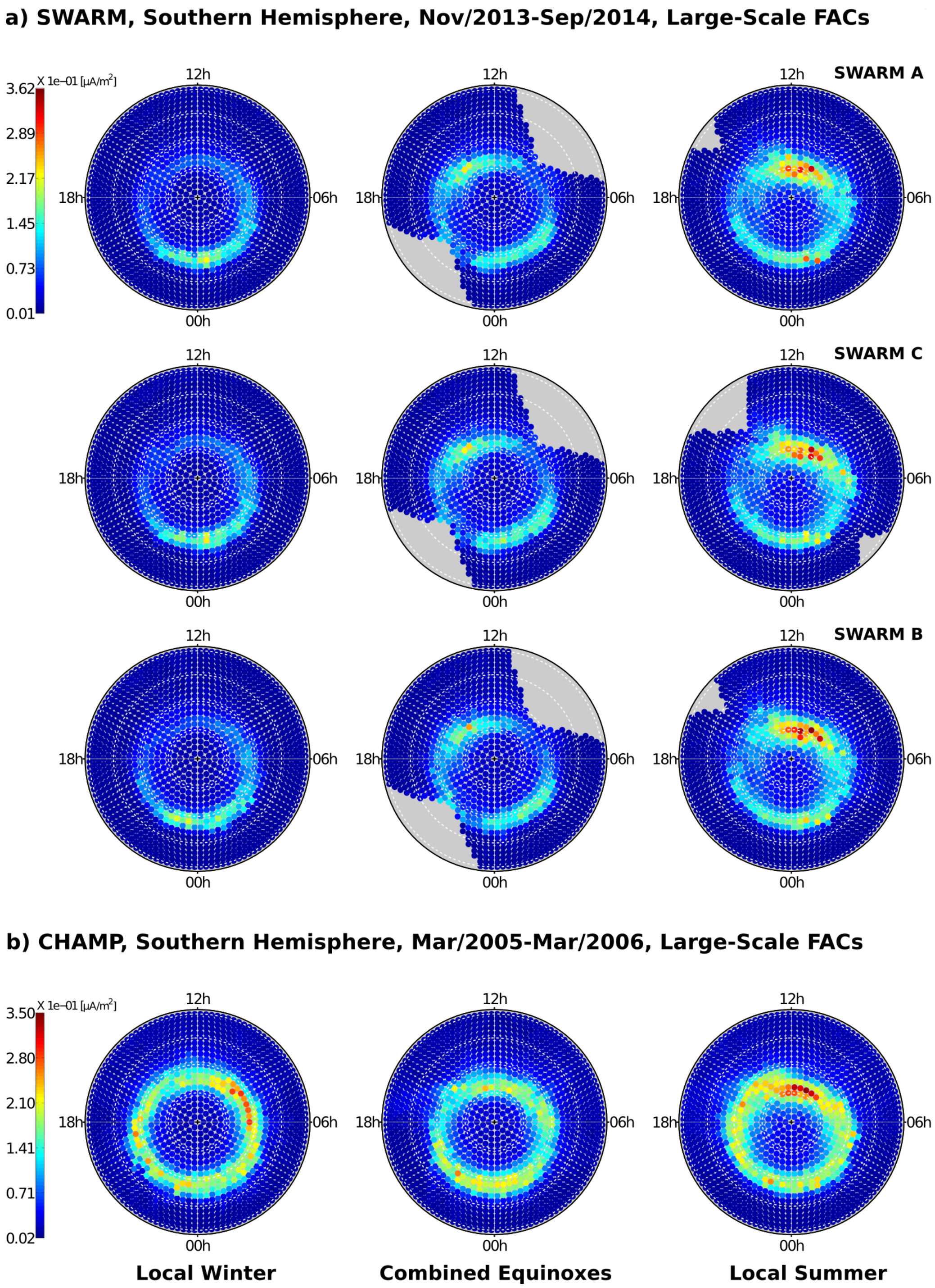

Figure 8: The same as Figure 7, but for the southern hemisphere.

9 Conclusions

The results obtained confirm the scientific validity of the L2-FAC products (FACATMS_2F, FACBTMS_2F and FACCTMS_2F).