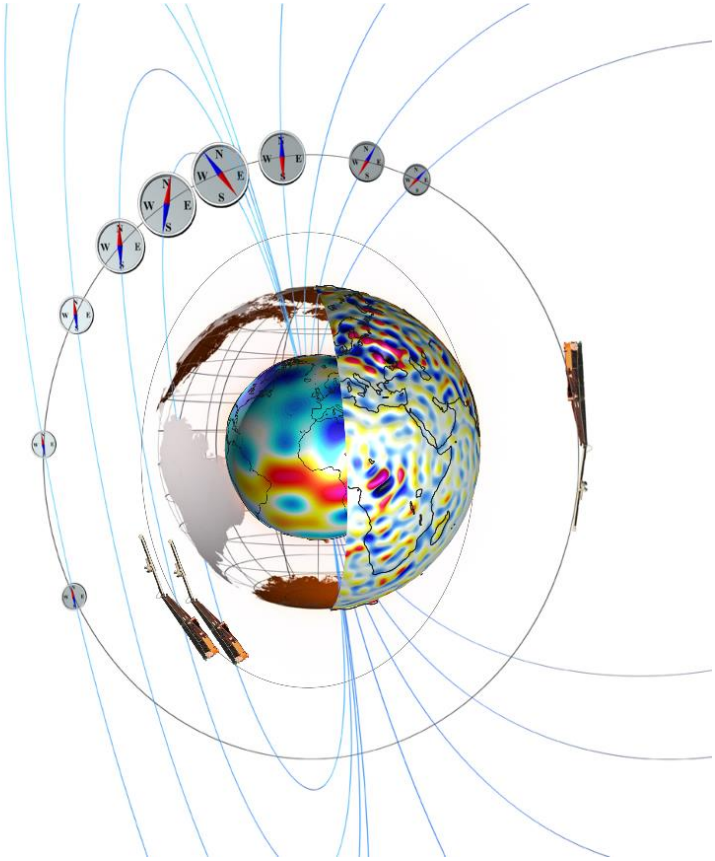
Swarm L2 FAC-dual Product Description



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1 Introduction

1.1 Scope and applicability

This document comprises the Swarm Level 2 (L2) FAC-dual Product Description document for the European Space Agency (ESA) Earth Observation (EO) Swarm Data Level 2 product FAC_TMS_2F, which includes dual Ionospheric Radial Currents (IRCs) and Field-Aligned Currents (FACs) as an output. It provides the information about product algorithm, scientific relevance, and scientific background. It also describes the approach on the scientific and quality validation. This document also includes the data format description and list of output variables.

In the following, “dual IRC” and “dual FAC” refer to IRC and FAC, respectively, which are derived from the lower satellite pair Swarm A and Swarm C. Single IRCs and FACs derived from a single-satellite Swarm A, Swarm B, or Swarm C solutions are not subject to this report. The Swarm L2 FAC-single Product Description document [AD-1] 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.

Current or updated version of the FAC-dual 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-dual-product-description.

2 Applicable and Reference Documentation

2.1 Applicable Documents

The following documents are applicable to the definitions within this document.

[AD-1] SW-TR-GFZ-GS-0005, Swarm L2 FAC-single Product Description.

[AD-2] https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/swarm

[AD-3] SW-RS-DSC-SY-0007, Swarm Level 1b Product Definition.

[AD-4] SW-PL-GFZ-GS-008, Planned Updates for Level 2 Cat-2.

2.2 Reference Documents

The following documents contain supporting and background information to be taken into account during the activities specified within this document.

[RD-1] Ritter, P., Lühr, H., and Rauberg, J. (2013): Determining field-aligned currents with the Swarm constellation mission, Earth Planets Space, 65(11), 1285-1294, doi:10.5047/eps.2013.09.006.

[RD-2] Kervalishvili, G.N., Rauberg, J., Stolle, C., and Lühr, H. (2016): Current status and new developments of the Swarm L2 Cat-2 dual and single FAC products, ESA's 6th Swarm Data Quality Workshop, September 26-29, Edinburgh, Scotland.

[RD-3] Maus, S. and Weidelt, P. (2004): Separating the magnetospheric disturbance magnetic field into external and transient internal contributions using a 1D conductivity model of the Earth, Geophys. Res. Lett., 31(12), L12614, doi:10.1029/2004GL020232.

[RD-4] Kan, J.R. and Lee, L.C. (1979): Energy coupling function and solar wind-magnetosphere dynamo, Geophys. Res. Lett., 6, 577, doi:10.1029/GL006i007p00577.

[RD-5] Kervalishvili, G. N. and Lühr, H. (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.

[RD-6] Lühr, H., Kervalishvili, G., Michaelis, I., Rauberg, J., Ritter, P., Park, J., Merayo, J.M.G., and Brauer, P. (2015): The interhemispheric and F region dynamo currents revisited with the Swarm constellation, Geophysical Research Letters, 42(9), 3069-3075, doi:10.1002/2015GL063662.

[RD-7] Lühr, H., Kervalishvili, G., Rauberg, J., and Stolle, C. (2016): Zonal currents in the F region deduced from Swarm constellation measurements, Journal of Geophysical Research: Space Physics, 121(1), 638-648. doi:10.1002/2015JA022051.

[RD-8] Lühr, H., Huang, T., Wing, S., Kervalishvili, G., Rauberg, J., and Korth, H. (2016): Filamentary field-aligned currents at the polar cap region during northward interplanetary magnetic field derived with the Swarm constellation, Ann. Geophys., 34, 901-915. doi:10.5194/angeo-34-901-2016.

2.3 Abbreviations

Acronym ***or abbreviation***	***Description***
Cat-1	Level-2 Products that are processed by the Swarm SCARF Consortium
Cat-2	Level-2 Products that are processed by PDGS
DISC	Data, Innovation, and Science Cluster
doi	digital object identifier
DTU	Technical University of Denmark, Copenhagen, DK
EO	Earth Observation
ESA	European Space Agency
ESL	(Swarm) Expert Support Laboratories
FAC	Field-Aligned current
GFZ	Helmholtz Centre Potsdam - German Research Centre for Geoscience, Potsdam, DE
GLon	Geographic Longitude
IHFAC	Interhemispheric Field-Aligned Current
IRC	Ionospheric Radial Current
LR	Low Resolution
L1	Level 1 (satellite data)
L1b	Level 1b (satellite data)
L2	Level 2 (satellite data)

Acronym ***or abbreviation***	***Description***
MAG	Magnetic
MLat	Magnetic Latitude
MLT	Magnetic Local Time
NaN	Not a Number
SCARF	(Swarm) Satellite Constellation Application and Research Facility
Swarm	Constellation of 3 ESA satellites: http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm
Swarm DISC	Swarm Data, Innovation, and Science Cluster
UTC	Coordinated Universal Time
VFM	Vector Field Magnetometer

3 Product Description

3.1 Scientific relevance

The Swarm constellation mission is the fifth Earth Explorer mission approved in ESA's Living Planet Programme [AD-2] and provides among other products the Field-Aligned Currents. FAC is the dominant mechanism by which energy and momentum are transported from the magnetosphere to the high-latitude ionosphere-thermosphere. 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, also related to space weather, e.g. ionospheric conductivity.

3.2 Algorithm description

The ionospheric radial currents can be calculated [RD-1] using the differential form of Ampère's law for $\boldsymbol{B}$-field and total current:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j}, \qquad \text{Eq. 3.2-1}$$

where μ_0 is the magnetic permeability of free space. Focusing on the vertical component, Eq. 3.2-1 can be rewritten as:

$$j_z = \frac{1}{\mu_0}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right], \qquad \text{Eq. 3.2-2}$$

where the z-axis is pointing vertically downward, x-axis northward, y-axis eastward, and j_z is the current density. Here, B_y and B_x are the residual field components. The residual field is defined as difference between the 1 Hz magnetic field readings of the Vector Field Magnetometer (VFM) as provided by the Level-1b MAGx_LR_1B product [AD-3] and the main field, which is the sum of the geomagnetic field from the Earth's core, lithospheric field, and magnetosphere field. For the actual calculation of IRC density Ampère's law in integral form is used (for more details see [RD-1]):

$$\boldsymbol{j} = \frac{1}{\mu_0 A}\oint \boldsymbol{B} \cdot d\boldsymbol{\ell}\,, \qquad \text{Eq. 3.2-3}$$

where $d\boldsymbol{\ell}$ is the path element along the closed contour, A is the encircled area, and $\boldsymbol{j}$ is the mean value of the current density component normal to the plane. Measurements from four points (Figure 3.2.1) are considered to calculate the closed line integral. Then, Eq. 3.2-3 can be written in discrete form:

$$j_{IRC} = \frac{1}{2\mu_0 A}\left[\left(B_x^{t_1} + B_x^{t_2}\right)d\ell_1 + \left(B_y^{t_2} + B_y^{t_3}\right)d\ell_2 - \left(B_x^{t_3} + B_x^{t_4}\right)d\ell_3 - \left(B_y^{t_4} + B_y^{t_1}\right)d\ell_4\right], \qquad \text{Eq. 3.2-4}$$

where $B_x^{t_{1(3)}}$ and $B_x^{t_{2(4)}}$ are along-track components derived at two subsequent measurements points 1 (3) and 2 (4) with time difference of 5 s, which corresponds to a distance of about 38 km, $d\ell_{1(3)} = 38$ km. $B_y^{t_{2(4)}}$ and $B_y^{t_{3(1)}}$ are cross-track components separated by 1.4° in geographic longitude (GLon) that corresponds to a distance of about 50 km at 70° geographic latitude. A is the area encircled by the four line elements $d\ell$ (Figure 3.2.1).

The FAC density is calculated from IRC by mapping the vertical current onto the field direction:

$$j_{FAC} = -\frac{j_{IRC}}{\sin I}\left[\frac{\mu A}{m^2}\right], \qquad \text{Eq. 3.2-5}$$

where j_{FAC} is FAC density, and I is the magnetic inclination angle. At high latitudes, where the magnetic field approximately has a vertical direction, FAC density is nearly the same as the IRC density [RD-1]. The dual-satellite method does not depend on the assumption that vertical current sheets are elongated infinitely in the zonal direction. This robustness is an advantage that the dual-satellite method has over the single-satellite method.

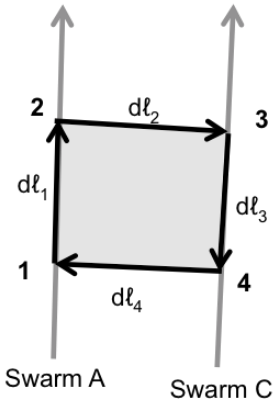

Figure 3.2.1 Sketch of a quad of 4 measurements points and route elements needed for the calculation of current density. Points 1-4 are positions on the orbit tracks of satellites Swarm A and Swarm C connected by the route elements $\boldsymbol{d\ell}$.

Note that the magnetic field data used for the dual-satellite method is low-pass filtered with a 3-dB cutoff period of 20 s (corresponding to a wavelength of 150 km). This step is indispensable because the lateral distance between Swarm A and Swarm C has to be taken into account. FACs come at a wide range of spatial scales. In order to avoid spatial aliasing any signals with horizontal scales smaller than the integration quad have to be suppressed. This filtering is not applied to the single-satellite solutions. As a result, current density from the single-satellite method contains fine-scale details while that from the dual-satellite method does not (e.g. Figure 3.2.2). That is why the single-satellite method is used beside the dual-satellite method.

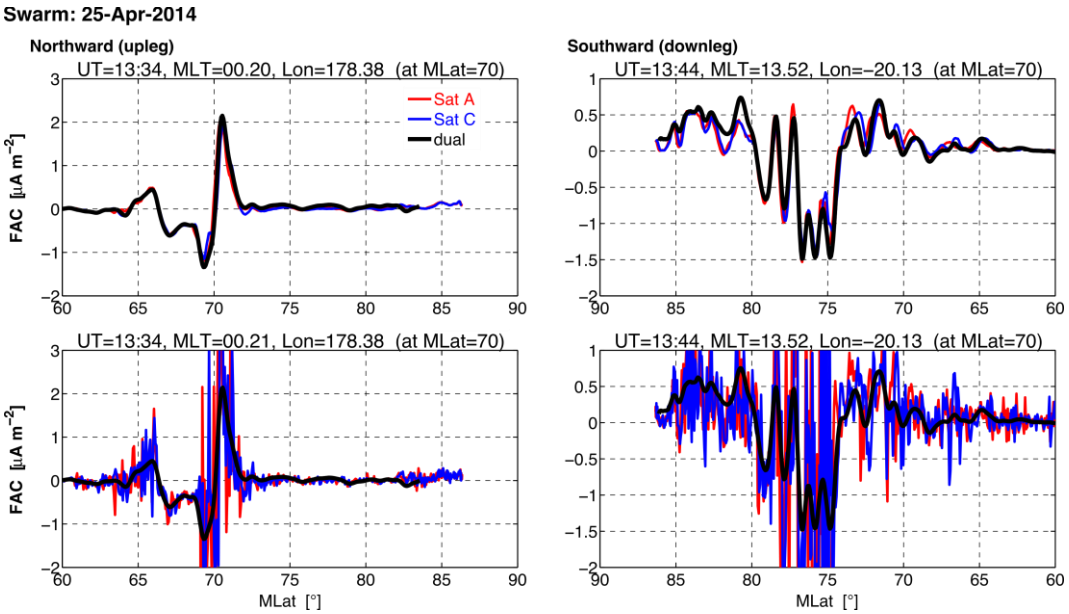

Figure 3.2.2 Comparison of FACs with and without low-pass filtering. Top panel shows dual and single (low-pass filtered) FACs at high-latitudes. Bottom panel shows the same case, but without low-pass filtering of single FACs [RD-2].

4 Description of the output data

4.1 Data product

One data file of Level 2 (L2) FAC_TMS_2F product is produced per day for the lower satellite pair Swarm A and Swarm C. A daily file is produced only when the Level 1b (L1b) 1 Hz magnetic field data for both satellites Swarm A (MAGA_LR_1B) and Swarm C (MAGC_LR_1B) of the corresponding date are available.

The cadence of the L2 FAC-dual data (FAC_TMS_2F) is 1 Hz (1 s). The time stamp for the dual-satellite FAC value is halfway [AD-4] between the time stamps of the L1b 1 Hz magnetic field data at the measurement points 1 and 2 (Figure 3.2.1) of Swarm A (MAGA_LR_1B).

4.2 List of variables in the data product

The Table 4.2.1 presents the list of variables in the L2 FAC-dual data product (FAC_TMS_2F), where IRC and FAC densities are calculated using Eq. 3.2-4 and Eq. 3.2-5, respectively.

Table 4.2.1 The list of variables in the L2 FAC-dual data product (FAC_TMS_2F).

Variable Name	Description	Unit
Timestamp	Time stamps in Coordinated Universal Time (UTC)	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-dual 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 Table 4.2.2 presents the list of 10 individual and independent digits, characterizing the L2 FAC-dual 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 dual FAC processing N can equal to 1, 2, 3, or 4, because 4 measurement points are involved (Figure 3.2.1).

Table 4.2.2 Flags characterizing the L2 FAC-dual product (FAC_TMS_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/N	A long (> 5 seconds) data gap occurred, which cannot be interpolated linearly, in the vicinity (for the single-satellite method this digit is always zero because no filtering is done)
3	0/N	No *EST* (external part of *DST* [RD-3]) data were available, and a default value was used for the magnetospheric field model
4	0/N	No *IST* (internal part of *DST* [RD-3]) data were available, and a default value was used for the magnetospheric field model
5	0/N	No solar radio flux (*F*10.7) 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 E_m (merging electric field [RD-4]) 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	0/1	For dual FAC, this digit is equal to 1 if latitude $\lvert\theta\rvert > 86°$ (IRC = NaN and FAC = NaN).
10	0/1	This digit is equal to 1 if inclination $\lvert I\rvert < 30°$ (FAC = NaN).

4.3 NaN values used in the data product

The Table 4.3.1 lists the cases when IRC and FAC densities are set to NaN. This information is provided for both L2 FAC products single (FACxTMS_2F) [AD-1] and dual (FAC_TMS_2F).

Table 4.3.1 Overview of NaN values in the L2 FAC data products.

	L2 FAC-single [AD-1] **(FACxTMS_2F)**		**L2 FAC-dual (FAC_TMS_2F)**	
	IRC	**FAC**	**IRC**	**FAC**
Near the poles for latitudes greater than 86°			NaN	NaN
Near the magnetic equator for magnetic inclination angles, $\lvert I \rvert$, smaller than 30°		NaN		NaN

5 Scientific validation

5.1 Approach of the scientific validation

The scientific publications are the basis of the scientific validation. The plots are used as scientific products, which are produced after applying scientific analysis, methods, or just directly presenting the data, for comparison between old and new publications. The statistical distributions of data is also used to compare the new obtained results against the existing results based on other data sources (e.g. satellites, ground observations, etc.) and prove the quality of the agreement.

All Swarm data products are presented on yearly Swarm data quality workshops, where the analysis and validation of data produced by the Swarm constellation mission is the main topic:

https://earth.esa.int/web/guest/missions/esa-eo-missions/swarm/activities/conferences.

5.2 Swarm data quality workshops

The status and new developments of the Swarm L2 FAC-dual product (FAC_TMS_2F) data have been presented and discussed at all ESA's Swarm Data Quality workshops starting from June 2014. Spatial distributions of dual IRCs presented at the ESA's 6th Swarm Data Quality Workshop [RD-2] (the most recent one) are shown on Figure 5.2.1.

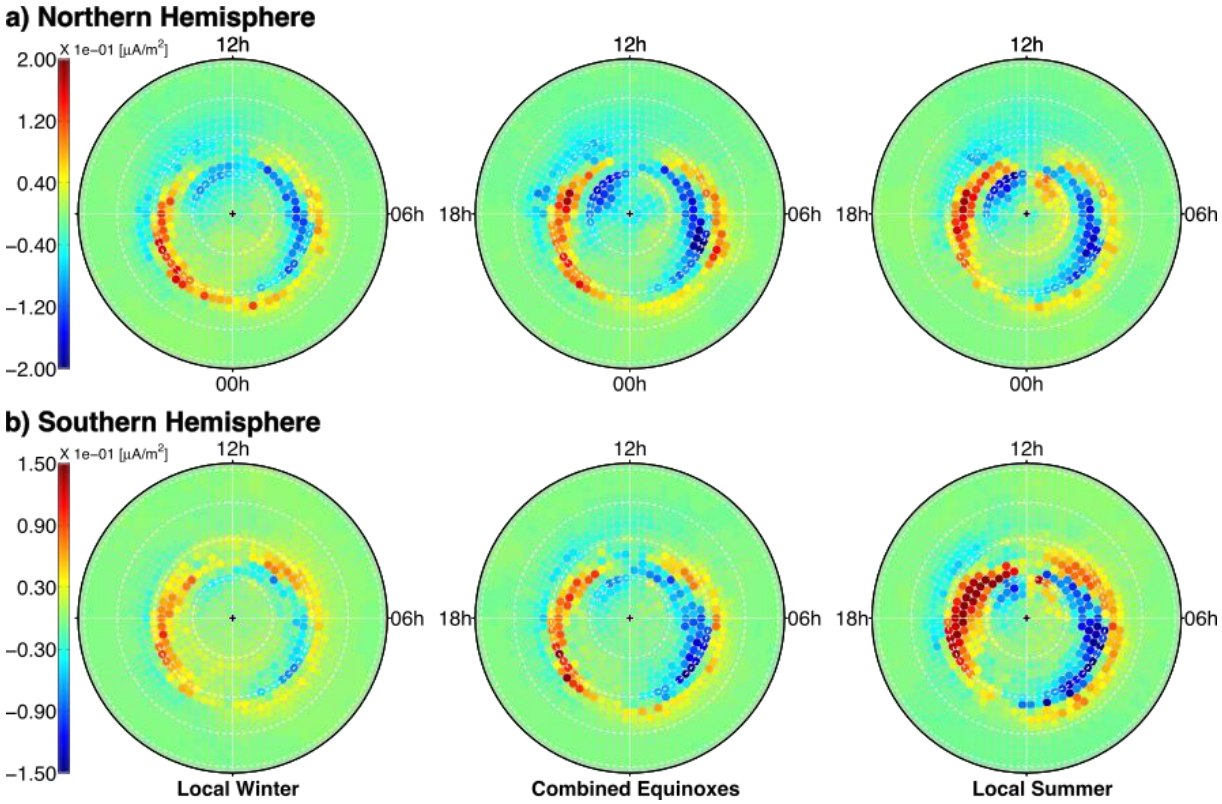

Figure 5.2.1 The bin-averaged median values of dual IRCs for local winter, combined equinoxes, and local summer, from left to right, respectively: (a) northern and (b) southern hemispheres. The data are presented in the MLat-MLT coordinate frame, where the white circles mark the 10° latitude spacing starting from 50°.

Figure 5.2.1 presents the statistical distribution of the bin-averaged median values of the dual FACs for the three Lloyd seasons: local winter, combined equinoxes, and local summer from left to right, respectively. Data used here cover more than 2 years of Swarm A and Swarm C observations in both hemispheres. The high-latitude spatial distributions are presented in magnetic latitude (MLat) versus magnetic local time (MLT) coordinate frames as dial plots. These dial plots are based on a binning procedure similar to the one used in [RD-5]. The Swarm dual currents generally agree with the results obtained from other satellite observations and on top of that also provide improved estimates of IRCs (FACs) at high latitudes, because the dual-satellite method does not depend on the assumption that vertical current sheets are elongated infinitely in the zonal direction (see subsection 3.2).

5.3 Scientific publications

The scientific validation of the Swarm L2 FAC-dual product (FAC_TMS_2F) is achieved in several recent peer reviewed publication, e.g. in [RD-1], [RD-6], [RD-7], and [RD-8]. Also, this product was successfully presented on a number of scientific and academic conferences such as European Geosciences Union General (EGU) Assemblies, American Geophysical Union (AGU) Fall Meetings, etc.

In [RD-6] the interhemispheric field-aligned currents (IHFAC) and F region dynamo currents have been deduced from dual-satellite observations for the first time using the Swarm L2 FAC-dual product. Figure 5.3.1 shows the initial results of MLT versus GLon distribution of IHFACs from the first half-year of final constellation flight (achieved on 17 April 2014). As it has been summarised by [RD-6], the Swarm L2 FAC-dual data, in general, confirms the expected and previously reported characteristics of IHFACs during local summer and equinox seasons. Moreover, the new dual-satellite approach has provided more detailed and promising results [RD-6].

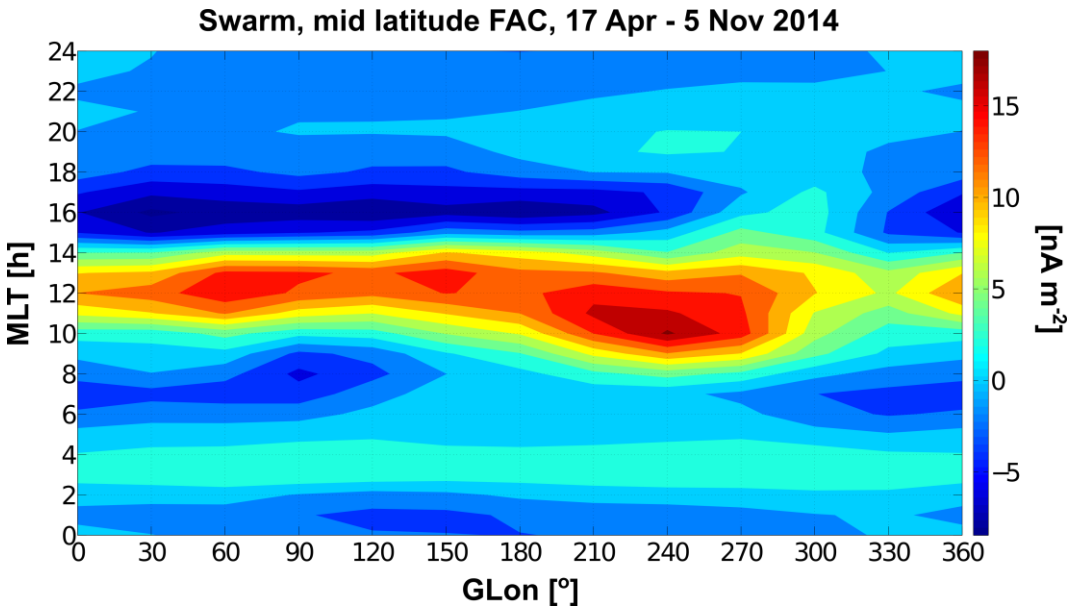

Figure 5.3.1 Figure 3 from [RD-6] shows MLT versus GLon distribution of IHFACs, where positive values represent currents flowing in the northward direction.

6 Summary and Conclusions

The results obtained confirm the scientific validity of the Swarm Level 2 product FAC_TMS_2F. More information about data quality of the Swarm constellation mission can be found here:

https://earth.esa.int/web/guest/swarm/data-access/quality-of-swarm-l1b-l2cat2-products.