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Large Scale Field Aligned Current derived from Intercosmos-Bulgaria-1300 Satellite. Comparison with Empirical Models

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Abstract. Large Scale (LS) Field Aligned Currents (FAC) distribution at high latitudes is studied on the base of Intercosmos-Bulgaria-1300 satellite observations. It is shown that observed LS-FAC strength and thickness as a whole do not coincide with predictions of well-known empirical LS-FAC models. Possible reasons of this non-coincidence are suggested. Among them are: (a) errors due to identification of FAC regions with respect to satellite position; (b) incorrect selection of model input parameters; (c) smoothing of Magnetic Field (MF) measurements done in models' construction processes. To check some of the reasons mentioned, time intervals of nearly constant or slowly varying Solar Wind (SW) and Interplanetary Magnetic Field (IMF) parameters, when large-scale FACs can be considered in steady-state conditions are selected. We analyze the non-coincidence between the measured and modeled FACs both in magnitude and position and conclude that the smoothing of the MF measurements during model construction is the most probable source of the discrepancies found.

Keywords: Field Aligned Currents (FAC); empirical model; satellite measurements

Introduction

The high-latitude *field-aligned current* (FAC) system is a ubiquitous manifestation of the solar wind-magnetosphere – ionosphere coupling processes and includes large-, medium-, small-scale and filamentary FACs. The large-scale (LS) FACs have dimensions of ~500–1000 km, the medium-scale currents ~ 50–200 km, small-scale are less than 50 km [1].

LS FACs known also as Birkeland currents [2] represent a substantial part of the electric current systems that support the Earth's magnetosphere structure during its dynamic interaction with the solar wind. Large-scale magnetospheric FACs are closed at ionosphere heights (~100-120 km) by ionospheric current systems such as DP2, DP1, DPY, etc. FACs and associated particle precipitations are responsible for heating, excitation and ionization processes in the thermosphere/ionosphere system and therefore can influence our environment. Further, the ionospheric current systems induce electric currents and magnetic fields within the Earth's subsurface known as geomagnetically induced current (GIC) system.

Historically, based on TRIAD magnetometric data two belts of upward and downward FACs have been statistically discovered in the polar regions and referred to as Region 1 (R1) - higher latitude belt and Region 2 (R2) FAC - lower latitude belt [3]. Another FAC situated poleward of R1 was observed and named Cusp or Region 0 (R0) current [3]. When the interplanetary magnetic field (IMF) component *Bz* is northward, a pair of FACs of inversed polarity has been found in the polar cap region [4]. The latter is referred to as Northward Bz (NBZ) FAC system. The NBZ-FAC system has initially been observed in the southern polar cap region and then sequence of LS FAC structures of inverse polarity both in the polar cap and in the auroral region has been revealed [5]. A three-sheet FAC system that includes simultaneously R0, R1 and R2 currents on the dayside can exist.

The structure of the LS FAC has been studied using satellite and/or ground-based data. Several empirical LS FAC models have been proposed: IZMEM model [6] is based on ground observations, models [7, 8] are based on satellite measurements, and model [9, 10] – on ground and satellite data. The current density in these models (estimated at ionosphere heights) is less than 0.8μA/m^2 and the average current sheet thickness is greater than 30 km, so they describe LS and medium scale currents. It is worth mentioning that the measured FAC density varies up to 1.5μA/m^2, e.g. satellite (TRIAD) measurements used by [3].

The Intercosmos-Bulgaria-1300 (ICB-1300) satellite magnetic field measurements have revealed also multiple medium scale (MS) FAC sheets inside the polar regions and sometimes outside regions predicted by the models. Such MS FACs have often been encountered by satellites in the night-side polar ionosphere [11]. Examples of FACs outside of "classical" regions R1, R2, R0 and NBZ have been observed by Papitashvili in [9] and [10] as well.

In this study, we compare some cases of "one satellite" measurements with predictions of two empirical models ([7] and [8]). These models give different description of high-latitude FAC system. In the Tsyganenko's model [7] only R1 and R2 current systems are presented. The Weimer model [8] reveals conventional R1 and R2 FAC belts (under southward-directed IMF) and clear NBZ current system surrounded by the R1 and R2 currents (under north-directed IMF).

Measurements and models

Estimating experimental FAC densities

Our method to identify field aligned current sheets in the Earth's magnetic field data is based on analysis of both the meridional and the zonal components of measured magnetic field (MF) on board ICB-1300 satellite. The method consists of:

- Presenting the MF vector by spherical components ($\boldsymbol{B_R, B_\varphi, B_\Theta}$) in solar magnetospheric (SM) coordinate system. Then, the IGRF field is subtracted from the measured field. The ($\boldsymbol{\Delta B_R, \Delta B_\varphi, \Delta B_\Theta}$) components are obtained (*later cited as* ($\boldsymbol{B_R, B_\varphi, B_\Theta}$);
- Analysis of the graphs of these components in order to identify the current sheets, i.e. determination of specific turns between which the magnetic field changes linearly (FAC region localization). The distance between these turns must be greater than 0.5^0, and the change in $\boldsymbol{B_\varphi}$ component must be no less than 150 nT;
- Linear regressions $\boldsymbol{B_\varphi(\Theta)}$ and $\boldsymbol{B_\Theta(\varphi)}$ is estimated simultaneously with the standard error (**errBφ**). The ratio **errBφ/ΔBφ** has to be less than 10%;
- Error minimization procedure is applied: the two components $\boldsymbol{B_\varphi}$ and $\boldsymbol{B_\Theta}$ of measured vector are rotated until the minimum of the ratio **errBφ/ΔBφ** is obtained;
- The current density is $\boldsymbol{j=\mu^{-1}R^{-1}[B\varphi(\Theta_1)-B\varphi(\Theta_2)]/(\Theta_1 - \Theta_2)}$, where ***R*** is distance to the Earth centre and ***μ*** is the magnetic permeability.

The current is assumed to be in the form of planar sheet with a thickness much smaller than the width, i.e. we use the ''infinite current sheet approximation'', adopted by many authors. Magnetic disturbances with spatial scale less than 0.5^0 are neglected, thus ignoring the small-scale variations of the current density inside the sheet.

We use magnetic field data measured aboard the ICB-1300 satellite by the three-axial fluxgate magnetometer experiment IMAP-1 [12]. The ICB-1300 satellite orbit had inclination 81.21^0 with a perigee of 825 km and apogee - 906 km, (i.e. its eccentricity was 0.005). The magnetic field measurements had a dynamical range of 64000 nT, sensitivity 5 nT and time sampling 80 or 320 ms.

Tsyganenko and Weimer models

We compare the FACs obtained from the measurements with Tsyganenko-2001 [7] and Weimer [8] models. Both models are empirical models. They are based on a large amount of satellite measurements. Both models have as input parameters the dipole tilt angle, IMF B_Y and B_Z, (in GSM coordinate system), the solar wind (SW) particle density and SW plasma velocity magnitude. Parameters specific in the models are Dst index in the Tsyganenko model and AL index in the Weimer model. The Weimer model depends on the parameters at the time of interest. The Tsyganenko model depends on the evolution of the parameters in the preceding two hours. Only R1 and R2 current systems are modeled by Tsyganenko-2001 [7]. Weimer model reveals conventional R1 and R2 FAC sheets as well as clear NBZ current system surrounded by the R1 and R2 currents (when IMF has northward direction). Grounds for our choice of FAC models are:

a) the possibility to calculate the external magnetic field (MF) at satellite heights, using the original Tsyganenko-2001 program, and hence the corresponding FAC in the Tsyganenko model;
b) An easy access to numerical Weimer FAC data computed on WEB site of Community Coordinated Modeling Center (CCMC) <http://ccmc.gsfc.nasa.gov >;

FACs in Weimer 2005 model are computed at ionospheric heights ($1.017R_E$). Experimental FACs and Tsyganenko model FACs are estimated at $\sim 1.2R_E$. For comparison purposes, the measured and Tsyganenko (Tsy-2001) FACs are projected to ionospheric heights along the MF lines ignoring the negligible change of the flux tube cross section.

Analysis

We processed the magnetic field measurements during the period 23 September 1981–14 January 1982. We searched for measurements performed under quiet geomagnetic conditions ($Kp < 2$) and IMF $B_Z > 0$ nT, that settled at least three hours prior the measurements. Ten orbits of ICB–1300 satellite satisfying these criteria were selected. Forty six FAC sheets were identified: 15 in the southern hemisphere, the rest – in the northern one.

Our results are summarized in Table 1 as follows: column 1 yields the position of measurement /models estimation/ at ionospheric height (in parentheses the latitudinal "thickness" of measured sheets is given); column 2 – the measured FAC density (radial component) in μA/m^2; columns 3 and 4 – the FAC density component estimated from models. Note that plus sign (+) corresponds to FAC from the ionosphere, the minus sign (–) corresponds to FAC toward the ionosphere. Model values are estimated for the central point of the measurements. When the measured FAC direction coincides with the FAC direction for at least one of the models, then the relevant cell (column 2) is darkened. The same is done for the corresponding "model" cell (column 3 or/and 4). The time of measurements and the SW parameters used in model calculations are shown below the corresponding measurements in the "long" rows.

In all examined cases the measured FAC density (the absolute error of the measurements is ±0.02μA/m^2) differs from the models prediction.

The numerical non-coincidence found might be a consequence of possible error in determination the edges of the FAC sheet. To avoid this effect let us consider the FAC measurements that match model FAC in sign. We can thus produce Table 2. All measurements are separated in four sectors - noon, dawn, dusk and midnight (see columns in Table 2). In the first row the number of measurements in each sector is shown. In rows below the number of FAC that have the same direction as the FAC estimated from the respective model is given as well as their percentage from all measurements in this sector. In the bottom row FACs from both models are compared in the same manner.

TABLE 1

Measured FAC compared to FAC from models

Position MLAT/sector	IC1300 J_R	Weimer J_R	Tsy-2001 J_R
67.8÷69.2/dusk(1.4)	-0.43	-0.037	-0.080
60.÷65.2/dusk(5.2)	+0.26	-0.001	0.000
68.9÷71. /noon(2.1)	-0.68	+0.033	-0.010
65.÷68.7/noon(3.7)	+0.80	0.000	-0.034
59.8÷63.5/noon(3.7)	+0.22	0.000	-0.034
81-09-23, UT:06:4-06:5, Vx=318, N=12.2 By/Bz=-7.2/7.4			
-82÷-79.2/midnight(2.8)	-0.66	0.000	-0.010
-79.2÷-77/midnight(2.2)	-0.29	-0.035	-0.010
-82.4÷-74.9/down(1.4)	-0.17	+0.115	-0.118
-74.9÷-69.1/down(5.8)	+0.19	+0.020	
-69.÷-65.5/down(3.5)	-0.15	-0.045	0.027
-65.5÷-62.7/down(2.8)	0.20	0.000	0.027
81-09-23, UT=14:1 – 14:2, Vx=331, N=11.8, By/Bz=-8.8/4.7			
65.6÷71.0/dusk(5.4)	-0.01	+0.021	-0.087
60.7÷65.4/dusk(4.7)	+0.49	0.000	0.000
56.÷58.7/dusk(2.7)	-1.14	0.000	0.000
68.8÷71.8/noon(3.)	-0.29	0.014	-0.013
62.6÷68.5/noon(5.9)	+0.18	0.00	-0.013
81-10-06, UT=3:38 – 4:01, Vx=364, N=6.9, By/Bz=-0.9/0.7			
-71. ÷-68./midnight(3.)	+0.47	+0.062	+0.127
-68.÷-65. /midnight(3.)	-0.17	+0.087	-0.080
-71.÷-70.5/down(0.5)	+0.59	+0.251	-0.319
-70.6÷-69. /down(1.6)	+0.30	-0.170	+0.159
81-10-06, UT=4:38 – 4:46, Vx=362, N=5, By/Bz=-0.4/04			
-70.7÷-69/midnight(1.7)	+0.37	-0.068	+0.255
-68.5÷-64.8/dusk(3.7)	-0.33	+0.094	-0.111
-63.6÷-61.8/dusk(1.8)	+0.09	+0.007	0.000
-70÷-69/midnight(1.)	-0.46	+0.232	0.00
-69÷-62.4/midnight(6.6)	-0.27	-0.034	-0.116
81-10-26, UT=3:31 – 3:37, Vx=373, N=10.1, By/Bz=0./7.7			
83.1÷85.7/midnight(2.6)	+0.20	-0.000	0.00x
76.3÷79./midnight(2.7)	-0.57	-0.018	-0.199
73.4÷76./midnight(2.6)	+0.49	+0.074	+0.071
83.4÷85.2/noon(1.8)	+0.12	+0.079	0.00
82.4÷83.1/noon(0.7)	+0.89	+0.075	0.00
79.8÷81.5/noon(1.7)	+0.66	-0.001	0.00
74.9÷79.5/noon(4.6)	-0.22	-0.059	+0.021
71.2÷74.3/noon(3.1)	+0.21	+0.029	0.00
81-11-27, UT=14:16 – 14:24, Vx=381, N=3.6, By/Bz=0.4/1.8			
68.9÷69.9/down(1.0)	+1.30	-0.011	+0.074
64.4÷68.8/ down(4.4)	+0.30	+0.008	+0.074
65.5÷66.9/noon(1.4)	+0.77	+0.074	+0.066
81-12-23, UT=18:35– 8:42, Vx=360, N=20, By/Bz=-7.5/8.8			
71.8÷73./noon(1.2)	+3.68	+0.194	-0.198
68.1÷71.4/down(3.3)	-0.22	+0.182	+0.093
57.1÷61.7/down(4.6)	+0.40	0.00	0.00
72.4÷73.2/midnight(0.8)	-1.62	+0.224	-0.010
69.6÷72.3/midnight(2.7)	+0.97	-0.107	+0.127
65.3÷68.1/midnight(2.8)	-0.66	-0.044	-0.034
82-01-06. UT=15:26 – 15:48, Vx=373, N=11, By/Bz=7.2/7.6			
69.7÷70.8/midnight(1.1)	-0.72	+0.122	-0.112
63.8÷69./midnight(5.2)	+0.50	-0.139	+0.050
82-01-14, UT=17:06 – 17:10, Vx=290, N=31, By/Bz=4.3/5.9			
73. ÷75.8/down(2.8)	-0.61	+0.100	-0.196
64.5÷69.5/down(5.0)	+0.66	-0.018	+0.098
82-01-13, UT=22:25–22:28, Vx=205, N=15, By/Bz=-4.3/4.7			

In the noon sector six of the measured FACs (50%) correspond in sign to Weimer model and only 3 (25%) – to Tsyganenko model. In this sector the Weimer model reconciles better the satellite measurements. In the midnight sector 6 of the measured FACs (40 %) have the direction predicted by Weimer model and 13 (87%) – that predicted by Tsyganenko model. Hence, in the midnight sector the Tsyganenko model matches better the measurements. Moreover, the Tsyganenko model reconciles better the measurements in the dawn and dusk sectors as well. In general, the Tsyganenko model better corresponds to the direction of measured FACs (57% to 39% in percent).

The last row (Table 2) yields the percentage of coincidence in FACs' sign between the two models. Unexpectedly, the number of FACs with coinciding direction from both models proves to be less than the number of coincidences in sign between measured FACs and those in Tsyganenko model. Hence, the measured FAC directions favor the Tsyganenko model.

TABLE 2

Number of coincidences in FAC sheets' sign

Number of sheets	noon	dawn	dusk	midnight	ALL
	12	12	7	15	46
coincidence in sign Weimer	6	4	2	6	18
	50%	33%	29%	40%	39%
coincidence in sign Tsyg	3	7	3	13	26
	25%	59%	43%	87%	57%
Tsyg. equal in sign to Weimer	2	3	3	7	15
	17%	25%	42%	47%	33%

Discussion

In all cases of equal sign the measured FAC is situated inside the area of Weimer current. This area is many times larger [8] than the conceivable "area" of measured FAC. Therefore the measured and Weimer currents are not in conflict with respect to the total current limit.

The latitudinal thickness of Tsyganenko FACs' is less than 3^0 [7]. In some of the cases when model and measured FACs coincide in direction, the measured thickness is larger than in the model. To keep the total current limit we must presume that the azimuthal dimensions of measured sheets are less than the model.

The empirical models of LS FACs were obtained by averaging a large amount of data measured at different times and under different magnetosphere/ionosphere conditions. The statistical processing depends on the selection of the fitting function (chosen in advance according to the expected distribution). We suggest that the non-coincidences of the Weimer and Tsyganenko models are connected with the algorithms and aims of the model development. In this respect, the smoothing of magnetic field MF data in model construction appears to be more significant source of the observed errors that the non-coincidences we found. Observations indicate that FACs flow in much thinner and more confined sheets. This immediately implies smoothing functions of higher order than those used in the FAC models discussed.

In both models R1 and R2 FACs are presented by only one current sheet. Experimental data imply that FACs are composed by many narrower and thinner sheets. By using smoothing functions as in the Weimer and Tsyganenko FAC models these FAC sheets are undoubtedly cancelled. These narrower and thinner FAC sheets however are well presented in the first FAC-model done by Iijima and Potemra [3].

Conclusions

The discrepancy between modeled and measured FACs has already been discussed [13]. Possible reasons of the observed non-coincidence between observations and applied empirical FAC models could be: a) errors due to identification of the FAC region in respect to satellite position; (b) wrong selection of model input parameters; (c) smoothing of magnetic field measurements done in process of model construction. Our study was an attempt to avoid some of the mentioned reasons (in particular - model input parameters).

We compared several cases of FACs estimated from magnetic field measurements aboard ICB-1300 satellite with those calculated from two empirical models – Weimer-2005 and Tsyganenko-2001. The presented results show that in all analyzed cases the measured FACs densities are larger than the FACs magnitudes estimated in both models. More than twelve measured FACs sheets (24%) have intensities and even signs far from the model predictions (both models). The same non-coincidence between models and results from ICB-1300 satellite exists in all sectors (noon, midnight, dusk and down).

The measured FACs correspond better to the Tsyganenko model. An exception is the noon sector, where the correspondence is better with the Weimer model (the NBZ currents are not described in Tsyganenko model).

Observations indicate that FACs flow in thinner and more confined sheets. This suggests that smoothing functions of higher order than those used in the empirical FAC models are required.

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