Field-aligned Currents on Board of Intercosmos Bulgaria-1300 Satellite in Comparison with Modelled Large-scale Currents

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The large-scale field-aligned currents (FACs) are well examined experimentally and described by different models, but the small scale FACs are less investigated and there exists a controversy about their intensity and dimensions. A possible source for the discrepancy is the assumption of infinite homogeneous current sheet which allowed their deriving from one-satellite measurements. We present a new method for identification of finite size current sheets, which we applied to derive FACs from magnetic field measurements aboard the INTERCOSMOS BULGARIA-1300 satellite. Then we compare one case of FAC, detected on 22 August 1981, with empirical (Tsyganenko'2001) and a magneto-hydrodynamic Block-Adaptive-Tree-Solar-wind-Roe-Upwind-Scheme (BATS-R-US) model of large-scale currents. We discuss the possible reasons for the observed discrepancy between the measured and modelled FACs.

Introduction

The existence of significant field-aligned currents (FACs) in the auroral region was demonstrated more than thirty years ago when Armstrong and Zmuda [1] had measured for the first time transverse magnetic disturbance produced by sheets of field-aligned Birkeland currents. The statistical large-scale (LS) field-aligned current distribution has been examined for the first time by Iijima and Potemra [2]. In the ionosphere they introduce two concentric current regions: poleward Region 1 and equatorward Region 2 (hereinafter R1 and R2, respectively). R2 currents flow upwards on the morning side and downwards on the dusk side. R1 currents flow in the opposite directions. Nowadays several new empirical FAC models have been proposed – for example Tsyganenko [3], Papitashvili et al [4], etc. In these two models, the current density is less than 0.6 $\mu A/m^2$ and current sheet thickness is greater than 30. In Iijima and Potemra [2] model the FAC density is up to 1.5 $\mu A/m^2$.

FACs are part of the global magnetosphere circuit and should be closed in the ionosphere and linked to the magnetospheric source region. Auroral FACs can carry about 1 million *Amperes*. They can heat up the upper atmosphere resulting in increased drag on low-altitude satellites. A comprehensive description of all elements of this large-scale circuit remains to be worked out. The mechanism of FAC's generation is discussed in many publications. There are two approaches: kinetic (e.g. [5]) and magneto-hydrodynamic (MHD) (e.g. [6]).

Data set, method and models

Experimental data

We use data measured aboard the INTERCOSMOS BULGARIA-1300 (ICB-1300) satellite by the three-axial fluxgate magnetometer experiment IMAP-1 [7]. ICB-1300 was launched on 7 August 1981 and stopped operating on 17 February 1983. It was three-axially stabilized; its orbit was with parameters: perigee 825 *km*, apogee 906 *km*, inclination 81.2°, eccentricity 0.005. IMP-1 had a dynamic range of ±64000 *nT*, sensitivity 5 *nT* and time sampling 80 or 320 *ms*.

Our method to identify FAC sheets in magnetic field data

Investigations of the field-aligned current were limited by the assumption of the existence of infinite homogeneous current sheets. This allowed reducing the three-dimensional problem to one-dimensional one and deriving FAC's from one-satellite measurements. However, this assumption is valid when the width of the current sheet in longitudinal direction exceeds significantly its size along the meridian. To avoid possible errors resulting from the finite currents sheet size, we use the following method to identify current sheets in magnetic field (MF) data:

A. Process the telemetry and obtain three magnetic components in satellite coordinate system;
B. Subtract the model International Geomagnetic Reference Field (IGRF) geomagnetic field from the measured field;
C. Transform the magnetic vector to three components in spherical Solar Magnetic (SM) coordinate system;
D. Analyze the graphs of these components to identify the sheets (the interval with possible currents). Proceed further only if the following conditions are satisfied:
   - The graph of the longitudinal component B_φ is linear;
   - ΔB_φ between both edges of the linear interval is greater than 50 *nT*;
   - $\Delta = \max(B_\Theta) - \min(B_\Theta) < 50$ *nT* (for the meridional component).
E. The value (and sign) of the current density is evaluated by a simple program in the following steps:
   1. Calculate $\sigma(B_\varphi)$ and $\sigma(B_\Theta)$ with their confidential intervals (i.e. $\sigma(B_\varphi)\pm\varepsilon_1$ and $\sigma(B_\Theta)\pm\varepsilon_2$; ε_1 and ε_2 must be less than 10% with probability greater than 0.9, i.e. we will have a current in the interval only if $\sigma(B_\varphi) - \varepsilon_1 > \sigma(B_\Theta) + \varepsilon_2$);
   2. The correlation coefficient $\boldsymbol{\rho}$ between B_φ and Θ is greater than 0.9 (i.e. $0.9 \leq \boldsymbol{\rho} \leq \mathbf{1}$ *with probability greater than 0.9*);
   3. The current density is estimated in spherical components as *curl* of the measured $\vec{B}$.

We have tested this method on modeled data in two cases - a rectangular current sheet [8] and sheets as a part of cone surface [9]. In distinction from Lukianova

[10] we use analytical expressions for the magnetic field. In the case of rectangular current sheet we directly integrate the Maxwellian equations, in the second case we construct a vector potential similar to that in [3].

Empirical magnetosphere magnetic field simulation

We calculate the magnetospheric magnetic field according the Tsyganenko'2001 model (hereinafter Tsy'2001) [3], which depends upon solar wind (SW) conditions in the preceding two hours and accounts for FACs. We use the original subroutine "T01_01", retrieved from http://modelweb.gsfc.nasa.gov. SW parameters for the model are retrieved from OMNI-WEB database. As the time sample in that database is one hour, we interpolate quadratically SW parameters for the period prior our measurements, to obtain the necessary for the simulation parameters. Tracing along the MF lines is done by means of program TRACE (from same WEB source).

We examined all magnetic field measurements aboard ICB-1300 in the period August-December 1981. They represent 185 data sets in which 107 current sheets were identified (using the method described above).

In many cases we observe small-scale current sheets located within the regions of large scale FACs, defined according the Tsy'2001 model [3]. More than 60% of the observed current sheets have thickness less than 1.5^0. The most intensive FAC have sheet thickness within 0.25^0-1.5^0 (inward FAC) and 0.25^0-2^0 (outward FAC). Sometimes, if we neglect the small-scale structure, the magnetic field measurements exhibit an overall trend, which could be identified as a large-scale current. In all cases the density of an individual small-scale current is greater (more than 10 times) than the density of the corresponding LS FAC in Tsy'2001 [3] or Papitashvili [4] models.

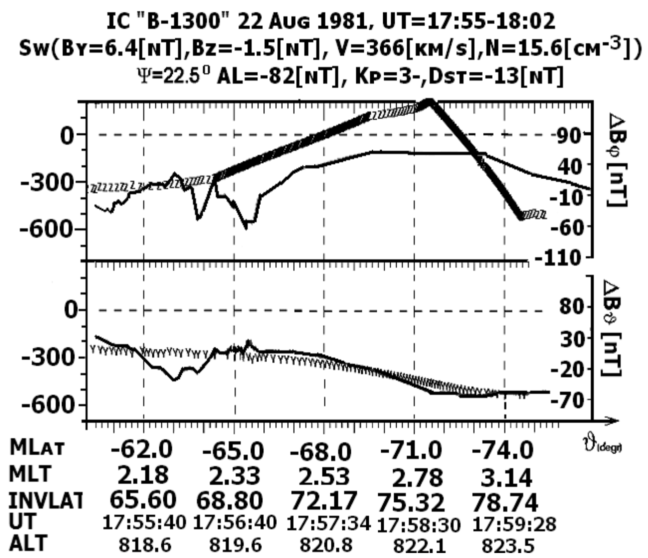

Fig.1.Case of 22 August 1981. Two components of the measured MF (after subtracting the IGRF MF) are shown. The model MF (calculated from Tsy'2001) is plotted with symbols. X-axis is polar angle; Y-axis for each panel denotes the MF-component amplitude (left for measured field, right-Tsy'2001 model). Vertical dashed lines mark intervals of 3°.

The MHD simulation

For the purpose of this study we performed an event global magnetospheric MHD simulation for the event on 22 August 1981. The MHD simulation results have been provided by the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC) through their public Runs on Request system (http://ccmc.gsfc.nasa.gov). The CCMC is a multi-agency partnership between NASA, AFMC, AFOSR, AFRL, AFWA, NOAA, NSF and ONR. Used was the Block-Adaptive-Tree-Solar-wind-Roe-Upwind-Scheme (BATS-R-US) [11], developed by the Computational Magneto-hydrodynamics Group at the University of Michigan, now Centre for Space Environment Modeling (CSEM). The finest grid resolution was 1/8 R_E near the Earth. The Earth's magnetic field is approximated by a dipole with updated axis orientation and co-rotating inner magnetospheric plasma. The simulation run included the Rice Convection Model (RCM) in the inner magnetosphere [12] in addition to the BATS-R-US MHD module of the global magnetosphere and the ionospheric electrodynamics potential solver. The RCM modifies the plasma pressure distribution in the inner magnetosphere and changes resulting FAC in the ionosphere (yields more realistic R2 currents).

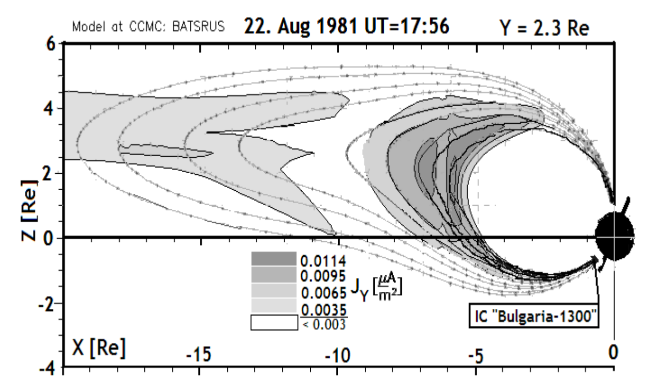

Fig.2. Y-component of total magnetosphere current according to BATS-R-US MHD modeling [11]; Jy =0.0114, corresponds to the Ring Current. XZ-projections of MF lines (Tsy'2001) with starting point on satellite orbit are shown in grey. With black are marked lines connected to points with measured strong MF perturbations (FACs).

Comparison between simulated magnetospheric field-aligned currents and FACs registered aboard ICB-1300 on 22 August 1981

Observations and empirical simulation

Fig.1 represents magnetic field measured aboard ICB-1300 on 22 August 1981 and the corresponding Tsy'2001 model MF. In the modeled magnetic field R2 (left side) and R1 (right side) field aligned currents are well defined. The R2 current density is +0.26 $\mu A/m^2$ and the thickness is 3^0. For R1 these parameters are 0.16 $\mu A/m^2$ and 5^0 respectively. We observe very fast changes in the MF and group of up/down FACs, located in the area of the modeled R2 large scale FAC. The changes in the measured MF are more than 10 times greater than in the model. Neglecting the fast changes, we obtain one upward R2 current with +0.39 $\mu A/m^2$ density and thickness ~6^0. Further poleward the Tsy'2001 model predicts a downward current, not observed in our data.

Experimental data in comparison with the BATS-R-US

BATS-R-US is not valid for distances from Earth less than 3 R_E. So we used the Tsy'2001 and IGRF models to project to the magnetosphere the field lines on which FACs are observed. Fig.2 is a picture of the Y_{GSM} -component of the total magnetospheric current density contours received in the BATS-R-US model with the projection of Tsy'2001 MF lines crossing the part of ICB-1300 orbit, shown in Fig.1. FACs registered on board ICB-1300 are bound up (or connected) with the Ring Current (black field lines). This confirms our assumption that we observe small-scale structures within the LS R2 current. In Tsy'2001 model R2 FACs are set to connect with the ring current and night-side R1 currents are set to connect with the neutral sheet current [3]. Concerning the location of R2 upward current, experimental data, Tsy'2001 model and BATS-R-US model are in good agreement. The field lines on which Tsy'2001 predicts R1 current along ICB-1300 orbit really connect with the BATS-R-US neutral sheet current, but the fact that R1 FACs are not observed aboard ICB-1300 could mean that these field lines do not cross the neutral sheet in the regions where its current is diverted Earthwards to form R1 current system.

In Fig.3 the intensity of BATS-R-US FACs together with ICB-1300 orbit in two planes are shown.

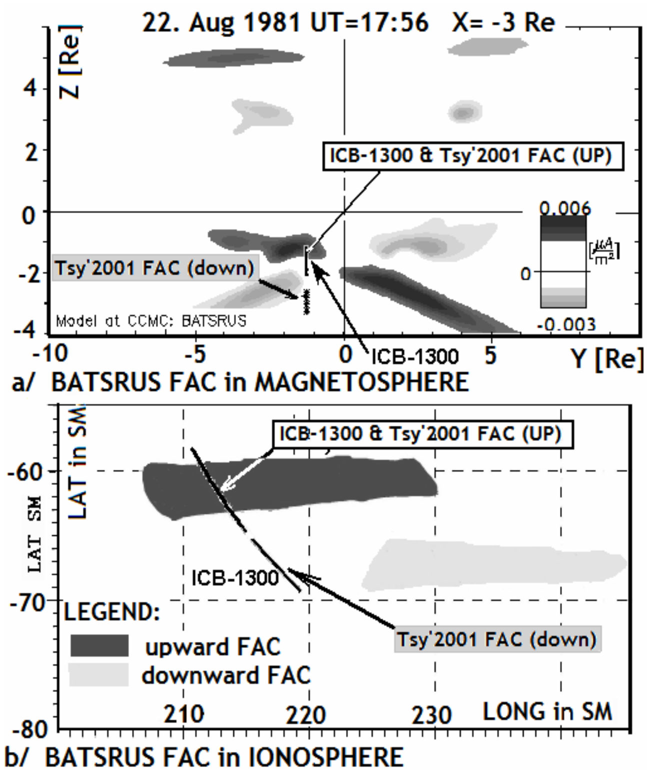

Fig.3. a) Cross section of FAC's (density in grey scale) at X_{GSM}=-3R_E. Positive is the outgoing from the ionosphere FAC. ICB-1300 orbit is projected along model MF lines;
b) Projection along model field lines to ionosphere of the main current bulges in the 3rd quadrant of (a).

Fig.3a is a cross-section of MHD current density (in grey-scale contours) in the plane X_{GSM} = -3 R_E, where the satellite's orbit is projected along the model Tsy'2001 field lines. Our measurements take place in the southern hemisphere where the MF vector points out of the ionosphere, so the positive (negative) current is upward (downward) flowing. Fig.3b is vice versa - the main MHD current bulges - those in the third quadrant in Fig.3a - are projected (as rectangulars for simplicity) to ionospheric heights along the corresponding Tsy'2001 field lines. In Fig. 3b part of the orbit where we register the upward R2 currents is depicted with an unbroken black curve; the part on which we do not observe the predicted by Tsy'2001 downward R1 FAC is drawn with asterisks. Our measurements map to the edge of the MHD upward FAC region. That part of the orbit, on which Tsy'2001 model predicts downward currents, not seen in the data, do not map to the MHD R1 downwards current. Thus the location of the observed FACs is in better agreement with the MHD model than with the empirical Tsy'2001 model. The MHD-modeled FACs, when projected to the ionosphere, have smaller longitudinal dimension than the empirical R1 and possibly R2 current bulges. A very rough estimation of MHD FAC density at ionospheric level shows that it will be less than in Tsy'2001 [3] and Papitashvili et al [4] models, and much smaller than the measured one.

Discussion and conclusions

We studied one case of MF measurements aboard the ICB–1300 on 22 August 1981, when FAC has been identified. We present our method for deriving FACs from one-satellite measurements, which allows us to avoid errors introduced by the assumption of infinite sized current sheets. We compared our observational results with the FACs, modeled in two ways – by the empirical Tsy'2001 [3] model and by the MHD BATS-R-US model, performing an event simulation provided by the CCMC. As BATS-R-US is not valid for distances from Earth less than 3R_E we used projection along modeled MF lines. Along ICB-1300 path we identified a series of small-scale FACs, embedded in a LS upward R2 current. The location of our measurements and the Tsy'2001 model R2 are in good agreement with the MHD model. The Tsy'2001 model predicts downwards R1 FAC along the poleward part of ICB-1300 orbit, which is not observed nor mapped by the MHD model to the satellite path. The observed FAC density is larger than that predicted by the empirical and MHD models. There could be several reasons for this discrepancy. We observe small-scale structures within the LS R2 currents, which possibly masks the LS FAC and makes its evaluation incorrect. Neither empirical models nor the used MHD model describe small-scale structures. As for the empirical models of LS FACs, they are obtained by averaging of big amount of data measured at different times and under different magnetosphere/ionosphere conditions, which could be the cause to obtain current sheets with greater thickness and smaller intensity than those of an individual measurement [9]. On the other hand, the intensity of FACs in theoretical models depends on the conductivity model of the auroral ionosphere accepted, thus leading to different results.

All FACs, identified and evaluated by the method presented here in the MF measurements aboard ICB-1300, could be found at: http://stil.acad.bg/mitko/katalog.html. In many cases we observe small-scale FACs, which sometimes are embedded, in a LS FAC. The observed FACs' density is greater and its thickness is usually smaller than those in Tsy'2001 [3] and Papitashvili [4] models. Data from Triad [2] exhibit current densities between ±2 $\mu A/m^2$, which is about 75% of our results.

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