CHAMP Observations of Multiple Field-Aligned Current under Quiet Geomagnetic Conditions

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We analyze Field-Aligned Current (FAC) measurements on board the CHAMP satellite, conducted on days 30.06-02.07.2008, under quiet geomagnetic conditions. In general, there are 91 crossings over polar regions (46 in the Northern and 45 – in the Southern hemisphere). The data are gathered under quiet geomagnetic conditions (Kp < 1, Vsw < 450 km/s, and IMF Bz is within ± 3.5nT). On these days most of the FAC measurements fall in Mlat = 55^0-85^0 and noon (MLT =10-14) or midnight (MLT =22-02) sectors.

Our analysis reveals a multitude of alternating medium-scale (at least 1-2 degrees) FAC sheets of reverse sign and with increasing amplitude. There are no regions where the sign of current remains unchanged, therefore, it is not possible to discriminate regions similar to R1/R2. We were unable to find a relationship between Solar Wind (SW)-parameters and observed FAC structures.

We discuss the possible errors arising from single satellite magnetic field measurement.

Introduction

CHAMP is LEOs (Low Earth Orbiter satellite), at the start the orbital parameters ware semimajor axis=6830km, inclination=87.27^0 and eccentricity=0.004. interaction with the atmosphere leading their change over time. CHAMP remains low apogee (ALT~600km) satellite with a circular, polar orbit.

We analyze FAC measurements on board the CHAMP satellite, conducted on days 30.06-02.07.2008, under quiet geomagnetic conditions. In general, there are 91 crossings over Polar Regions (46 in the Northern and 45 – in the Southern hemisphere). All orbits are in NOON-MIDNIGHT sector. A typical picture of measurements is shown on Fig.1.

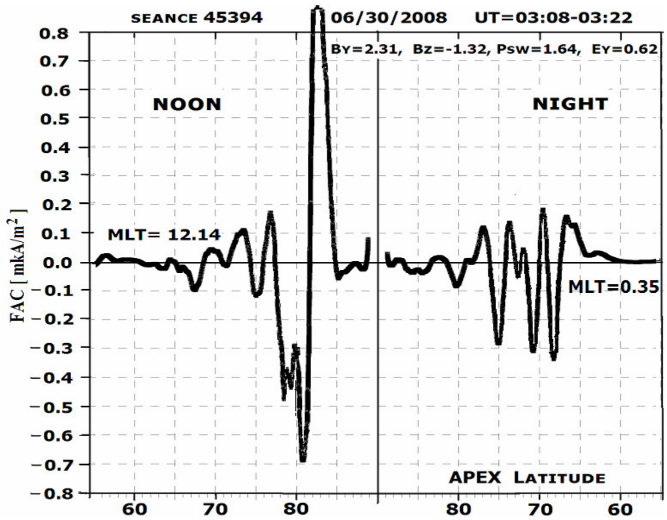


Figure 1. FAC measured by CHAMP, positive - from Earth. Quiet geomagnetic conditions Kp <1. B_Y=2.31nT, B_Z=-1.32, P_{SW}=1.64nP. APEX latitude is similar to INVLAT, taken into account the height of the satellite and model of the main magnetic field.

Multiple FAC at the night side have been measured several times in rocket magnetic field experiments [9] while, they were only noted rarely from satellite magnetometer measurements. In the 90s some prominent cases of multiple current sheets within the auroral oval were reported by [8] from AKEBONO satellite, [7] from FREJA satellite, [4] from MAGION satellite.

Figure 2 shows multiple FAC sheets measured from MAGION.

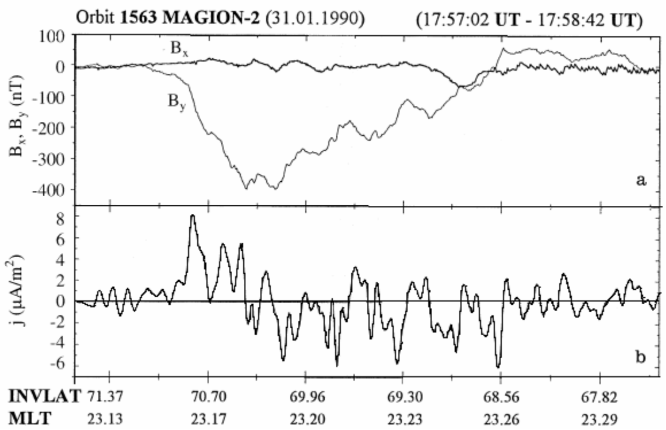


Figure 2. FAC measured by MAGION, positive - from Earth

It seems then the number of reported cases of small-and medium-scale stratifications of FAC is enough to believe in its existence.

We compare the measured FAC values with Weimer model [Weimer, 2002] (averaged per sheet measurements). We did not get good agreement (with the exception of individual case). A similar result was obtained for measured FAC onboard of ICB-1300 [3].

Using the potentiality of Community Coordinated Modeling Center (CCMC, BATS-R-US model [10],[5]) we did modeling with actually measured SW parameters again , no good agreement with measurements.

This discrepancy with the models and the fact that all reported splitting of FAC sheets are from single satellite passes over the polar region led us to investigate the possible sources of false current sheets.

Possible sources of false FAC sheets

Associated with calculations

The formula used in CHAMP FAC estimations (Wang at.al, [11]) is:

$$j_{II} = \mu^{-1}(\Delta B_T / \Delta X_N) = \mu^{-1}(\Delta B_T / V\cos(\alpha)\Delta t) \quad (1)$$

where j_{II} -is the current density in the sheet; ΔB_T -is the change (between two measurements) in the MF component parallel to the sheet; ΔX_N - is the change in the coordinate of the satellite, in a direction normal to the layers; V -satellite velocity; α - the angle between vectors of the normal to the sheet and satellite velocity;

To reduce the possible error, twenty consecutive j_{II} measurements are averaged.

This formula was used as well by Danov [2] and Higuchi [6]. The difference comes from the method of averaging and the method for determining the direction of normal. They averaged ΔB_T, and V before applying the formula above. There are more differences in the determination of the angle α.

Wang [11] (CHAMP FAC) assumes - the current sheets are parallel to Auroral Oval. The position of the oval is determined from model with conformity of measurements. [Wang at.al, 2005]

Danov [2] fixed the minimum of Variance in the magnetic component directed towards the magnetic poles.

Higuchi [6] use more sophisticated methods for determining the normal - so called MVA (Minimum and Maximum Variance Analysis) [1]

When calculating by formula (1) the error is highly dependent on accuracy in the determination of α. When values of $\alpha > 45^0$, the error is unacceptably large.

Errors independent of the instrument

Suppose that in the coordinate system **Oxyz** the current density is determined by

$$\vec{j}(x_0, y_0) = \begin{cases} j_c \; if\,(-a \le x_0 \le a \; and \; -b \le y_0 \le b) \\ 0 \qquad else \end{cases}$$

from Biot–Savart law it follows that:

$$\vec{B}(x, y) = \int_{-b}^{b} dy_0 \int_{-a}^{a} dx_0 \frac{\mu . j(x_0, y_0)}{2.\pi.\sqrt{(x - x_0)^2 + (y - y_0)^2}} \quad (2)$$

If denote $B_N = B_y$ and $B_T = B_x$, in the case of $a = \infty$ we obtain $B_N = 0$ for all (x,y)

$$B_T = \begin{cases} -\mu . j_c . y \quad if\,(-b \le y \le b) \\ -\mu . j_c b \quad if\,(b \le y) \\ \mu . j_c b \quad if\,(y \le -b) \end{cases} \quad (3)$$

Obviously, formula (1) is a consequence of formula (3).

The solution $\vec{B}(x, y, a, b, j)$ of (2) can be written in elementary functions. However it has so many elements that are not worth it to write all of them explicit here.

The dependence of the solution of (2) on x, y, a and b is not linear. We can only say that:

a) when $a \to \infty$ (or $b \to \infty$), disappears dependence on x (or on y) infinite and flat current sheet

b) the condition $r = \sqrt{x^2 + y^2} >> \sqrt{a^2 + b^2}$, leads to

$$\left|\vec{B}\right| = \frac{\mu .}{2\pi . r} \int_{-a}^{a} dx_0 \int_{-b}^{b} dy_0 j \quad \text{infinite wire}$$

This is known from the textbooks of physics, is cited here only to show that the solution of (2) found by us is true.

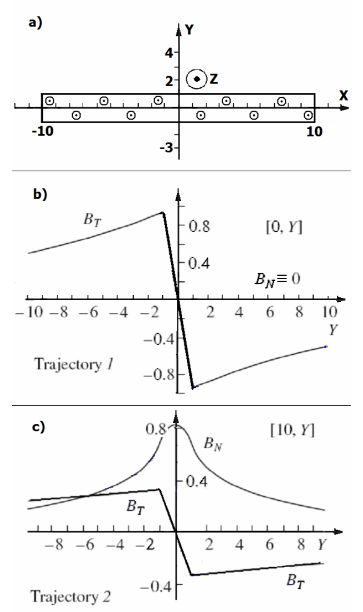
The properties of this solution, which are important for us, are illustrated in Figure 3 and Figure 4.

To make the graphs readable, we take $j = \mu = b = 1$. Under these conditions we get:

$$B_T(x, y, \infty, 1, 1) = \begin{cases} -y \quad if\,(-1 \le y \le 1) \\ -1 \quad if\,(1 \le y) \\ 1 \quad if\,(1 \le -b) \end{cases}$$

, see and compare with (3)

Assuming $j = const$, then (2) leads to a linear relationship between $\vec{B}(x, y, a, b, j)$ and j, μ. Therefore the values of B_T and B_N, shown in the graphs will differ with scale factor from those in $j \ne 1$, $\mu \ne 1$.



a) picture of the current layer. ***j=1*** *if* ***–a<x<a*** *and* ***-b<y<b****, otherwise* ***j=0****. The Normal is parallel to Oy*

b) the satellite is moving over line with coordinates [0, Y (t)] ie intersects the layer perpendicularly at its center.

c) the satellite is moving over line with coordinates [10,Y (t)] i.e. square to and at the edge of the layer

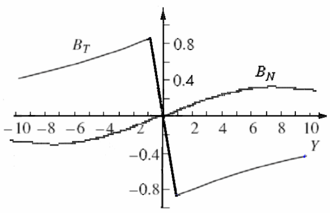
Figure 3. Satellite crossing square to finite current sheet

If we use formula (1) in the case of crossing the center of the layer (fig.3 b), we get: $j = \begin{cases} = 0.85 \; if\,(|y| \le 1) \\ \approx -0.07 \; if\,(|y| > 1) \end{cases}$. Inside the layer the 'measured' current is less than specified. Worse, outside the layer we will measure false currents with opposite sign. In this case, the MVA method will not improve the outcome because B_N remains zero. With the increase of the ratio b/a (ie narrow layers) results become worse (i.e. the amplitude of false currents increases, the amplitude of the current in the sheet decreases).

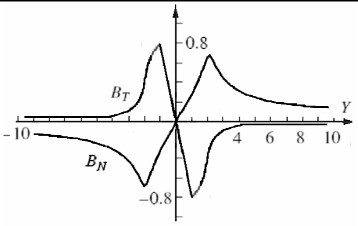
When the satellite is moving over line perpendicular to layer and at the edge of the layer, the formula (1) gives: $j = \begin{cases} = 0.38 \; if\,(|y| \le 1) \\ \approx -0.01 \; if\,(|y| > 1) \end{cases}$. - Again underestimate the current in the layer, but the amplitude of false currents is reduced. In this case $B_N \neq 0$ and its amplitude is even greater than the amplitude of B_T. This leads to significant errors in defining the normal to the layer, α become significant less than 45^0 and computational error becomes unacceptably large.

When the trajectory crosses the layer between its center and its edge, the graphs of B_T and B_N are among those shown in fig.3.b and fig.3.c. i.e. when the layer is finite, we underestimate the current inside the layer (and we always have two fake layers).

When the satellite crosses the layers at an angle to normal, once again confronted with the underestimation of the current in the layers and with false currents on both sides (look at Figure 4). When this angle is greater than 45^0, the magnitude of these currents increased rapidly (see fig.4.b)



a) the angle is 45^0



b) the angle $\alpha >> 45^0$

Figure 4. Graph of B_T and B_N components of the magnetic field when the satellite crosses finite layer at angle $\alpha \neq 0$

We can summarize: in case of finite layer we always have a systematic errors.

These errors do not depend on the accuracy in determining the magnetic field or the position of the satellite. They are independent of the chosen method of calculation.

They depend on the size of the sheet in azimuthally direction. (As greater ratio b/a, so the errors are larger.) Unfortunately, this ratio can be not determined by measurements from a single satellite.

Precisely these errors lead to the emergence of 'false' (fictional) current sheets.

Data processing

We define single current sheet, as measurements spacing between two zero crossings of the curve shown in Figure 1.

1084 sheets are numbered around the north pole and 1176 - around the south pole

We believe that an average of all measured FAC in the layer would presents layers better than the maximum value of the FAC in layer.

We assume that there is a 'false' FAC layers. We exclude such layers in the following three steps.

1/ the average density must be «significantly» different from zero (Student criterion)

- 56 sheets were removed in North, 76 – in SUD

2/ all FAC obtained at attack angles (the angle between the satellite trajectory and polar oval) less than 65^0 were discarded. (Table of these angles for all sessions we received from Dr Patricia Ritter, Geo Forschungs Zentrum, Potsdam, Germany)

- 136 sheets were removed in North, 720 – in SUD

- thus whole séances were omitted

- These conditions are sufficient to exclude all layers in the DAWN-DUSK sectors. (All satellite passes are in Noon-Night direction)

The third 'step' needs clarification. If we know the coordinates (LAT, MLT) of the points where the satellite encounters the boundaries of the layers, we can determine "thickness" δLat and "width" $\delta Long$=15*δMLT*cos(Lat) of the layer. The angle $\beta = \arctan(\delta Long / \delta Lat)$ is a good estimate of the angle α between the normal and the trajectory. (used in formula (1) and Fig. 3 and fig.4)

3/ all FAC obtained at $\beta > 25^0$ were discarded.

- 311 sheets were removed in North, 155 – in SUD

Unfortunately we are unable to connect δLat and $\delta Long$ (defined above) with the actual dimensions of the layers. Therefore we can not completely eliminate the 'false' FAC.

These three conditions are based on text as stated in the previous section.

We decided to discard FACs with density less than 0.03μA/m^2 and 0.2μA/m^2. The result is shown in Table 1 and Table 2.

Table 1 Distribution of FAC sheets with abs(<j>) > 0.03[μA/m^{-2}]

		NORD/NOON	NORD/NIGHT	SUD/NOON	SUD/NIGHT
	Number of sheets	104	129	48	36
	Min/max LAT	63.1^0÷84.7^0	62.8^0÷83.6^0	-60.3^0÷-82.4^0	-63.6^0÷-75.2^0
	Min/max MLT	10÷14	21.7÷01.5	9.6÷13.4	22.5÷01.1
mod	50% of them are less than	0.14[μA/m^{-2}]	0.14[μA/m^{-2}]	0.07[μA/m^{-2}]	0.18[μA/m^{-2}]
mod	10% of them are greater than	0.69[μA/m^{-2}]	0.42[μA/m^{-2}]	0.26[μA/m^{-2}]	0.62[μA/m^{-2}]
FAC	maximum	0.84[μA/m^{-2}]	0.53[μA/m^{-2}]	0.28[μA/m^{-2}]	0.87[μA/m^{-2}]
FAC	minimum	-0.91[μA/m^{-2}]	-0.69[μA/m^{-2}]	-0.36[μA/m^{-2}]	-0.78[μA/m^{-2}]
FAC	mean	-0.04[μA/m^{-2}]	-0.03[μA/m^{-2}]	0.000[μA/m^{-2}]	0.02[μA/m^{-2}]
FAC	upwards/downwards	51%/49%	48%/52%	50%/50%	48%/52%

Table 2 Distribution of FAC sheets with abs(<j>) > 0.2[μA/m^{-2}]

		NORD/NOON	NORD/NIGHT	SUD/NOON	SUD/NIGHT
	Number of sheets	46	43	7	18
	Min/max LAT	75.3^0÷84.7^0	66.2^0÷75.3^0	74.5^0÷79	-65.4^0÷-73.8^0
	Min/max MLT	10÷13.6	21.8÷00.7	9.9÷11.7	22.5÷01.1
mod	50% of them are less than	0.41[μA/m^{-2}]	0.33[μA/m^{-2}]	0.28[μA/m^{-2}]	0.33[μA/m^{-2}]
mod	10% of them are greater than	0.83[μA/m^{-2}]	0.53[μA/m^{-2}]	0.36[μA/m^{-2}]	0.78[μA/m^{-2}]
FAC	max/min not changed				
FAC	mean	-0.11[μA/m^{-2}]	-0.10[μA/m^{-2}]	-0.06[μA/m^{-2}]	0.04[μA/m^{-2}]
FAC	upwards/downwards	48%/52%	35%/65%	43%/57%	57%/43%

We compare the measured FAC values with Weimer model [Weimer, 2002] (averaged per sheet measurements).

An example of good agreement of measurements with this model is shown on fig.5.

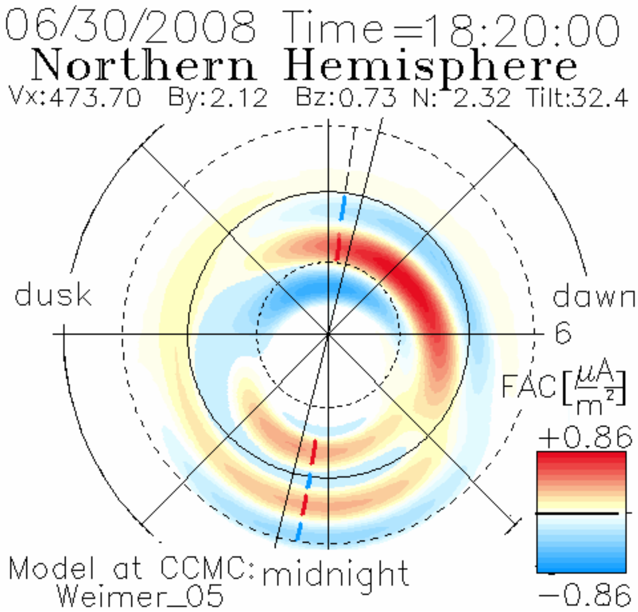


Figure 5 An example of good agreement of measurements with the model, perhaps because the satellite crosses the layers perpendicular and away from their edges.

In general, we did not get good agreement (with the exception of individual cases). A similar result was obtained for measured FAC onboard of ICB-1300 [3].

Empirical models, such as that of Weimer, were obtained by data from many satellites. That is why measurements in adjacent points were taken at different times (sometimes the time difference may exceed years). The method of LSq, leading to smoothing of data. Since we do not know with precision how a model describes the data on which it was obtained, we can not categorically say that it describes or not our measurements.

Using the potentiality of Community Coordinated Modeling Center (CCMC, BATS-R-US model [10],[5]) we did modeling with actually measured SW parameters on 30.08.2008. We could not find a good agreement.

Results

Most part of the measured FAC are weak. They are positioned equatorward or poleward from the main area of observation. Strong FACs (>0.5μA/m^2) were noted in the following intervals: [77^0;83^0] - NORD/NOON sector, [67^0;74^0] NORD/NIGHT and [68^0;73^0] SUD/NIGHT

The stronger ones are associated with open field lines on dayside, and prolonged (L > 7) on night side. (Checked by Tsyganenko GEOPAC2005)

The number of simultaneously measured FAC sheets is time dependent. It have a peak in the intervals (UT) 01:28÷06:25 and 16:48÷21:34 on 30 June, 00:28÷05:12 and 17:07÷21:51 on 01 July. Shortly before these times the B_z component in the Solar Wind changes its sign several times.

In other time intervals we measure 1÷3 sheets per sector. It exist passes with zero sheets in one sector and 2÷3 sheets in other.

Conclusions

In this work were analyzed multilayer FAC structures and was seek method to eliminate some of the layers in them.

One of the rules on disqualification is: If two FAC have a different sign and one of them is much weaker than the other, we can eliminate the weaker. This rule has helped to eliminate much of the FAC layers measured on CHAMP.

There is no rule of rectification at FAC with different sign and comparable amplitudes. In this case we need to know 'the real' sizes of FAC layer, but this is impossible from single satellite measurements.

Discussion

We were unable to find a relationship between SW-parameters and observed FAC structures. Possible reasons include:

1/ within the time resolution of SW-parameters data (1 min sampling rate in OMNI-WEB data base) the FAC changes its sign several times.

2/ Effects caused by the FAC structure crossings (especially after the manner of that crossing) distort the measurements in such a way, that the relationship of FAC with the solar wind parameters is lost.

We find multilayer structures only in times of frequently changing the sign of SW B_z.

Acknowledgments: The authors thank Dr Patricia Ritter and Dr Hermann Lühr for providing CHAMP data, consulting and their recent publications on FAC.

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