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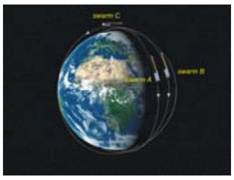
Curl-B technique applied to Swarm constellation for determining field-aligned currents

Patricia Ritter and Hermann Lühr

GFZ Potsdam, Telegrafenberg, D-14473 Potsdam, pritter@gfz-potsdam.de



Abstract

The multi-satellite mission Swarm is conceived to investigate the dynamics of the Earth's magnetic field and its interaction with the Earth system in unprecedented detail. For a further improvement of the main field and lithospheric field models it is vital to understand and reduce the influence of ionospheric currents. The constellation of the Swarm satellites provides for the first time the opportunity to determine field-aligned currents (FACs) in the ionosphere uniquely. This is achieved by employing the curl-B relation of Ampere's law directly to measurements of a satellite pair flying side-by-side. The new technique is applied to a set of consistent magnetic field and current data generated by a global magnetospheric model. Using a realistic Swarm constellation the current distribution is determined along the orbit from the synthetic magnetic field data. The resulting currents are tested against the input currents. The agreement between input model and recovered field-aligned currents is excellent and much improved compared to the single-satellite estimates.

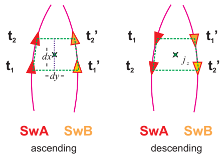
Calculation of Field-Aligned Currents (FACs)

The basic equation for determining the electric current density ***j*** from magnetic field observations ***B*** is Ampere's law. If two satellites are moving side-by-side, the FACs may be computed from the spatial gradients of the horizontal magnetic field:

$$\operatorname{curl}\mathbf{B} = \mu_0\,\mathbf{j}$$

$$j_Z = \frac{1}{\mu_0}\left(\frac{dBy}{dx} - \frac{dBx}{dy}\right)$$

To use this equation on measured data, the following configurations are employed:



The field differences in x-direction are obtained from measurements taken from each satellite (**SwA** and **SwB)** at subsequent positions (Δt=5sec). The differences in y-direction, however, are taken at orbit-simultaneous positions of the two satellites. As there are 4 measurement points available for the gradients the mean value of each difference pair goes into the above equation:

$$j_Z = \frac{1}{\mu_0}\left(\frac{dBy_{\mathbf{A}} + dBy_{\mathbf{B}}}{dx_{\mathbf{A}} + dx_{\mathbf{B}}} - \frac{dBx_{t_1} + dBx_{t_2}}{dy_{t_1} + dy_{t_2}}\right)$$

Parameters of the different processing steps and their contributions to the retrieved radial current density for one polar crossing are shown in Fig. 2. Due to the spatial separation of the sampling points only the large-scale FACs can be determined.

In the single satellite approach only one the along-track derivative is available. The resulting amplitude deviations can be seen in the comparison plots of Fig. 3b and 4 (bottom).

An alternative way to estimate the FACs from the quad can be performed by using Ampere's integral law along the closed path around the encircled area *A* (in our case the trapezoid):

$$\mathbf{j} = \frac{1}{\mu_0 A}\oint B\,d\ell$$

$$\begin{aligned} j_Z = \frac{2}{\mu_0 A}\Big[& \left(B_{v\mathbf{A}}(t_1) + B_{v\mathbf{A}}(t_2)\right) d\ell_{v\mathbf{A}} + \left(B_{t\mathbf{B}}(t_2) + B_{t\mathbf{B}}(t_2')\right) d\ell_{t_2} \\ & - \left(B_{v\mathbf{B}}(t_2') + B_{v\mathbf{B}}(t_1')\right) d\ell_{v\mathbf{B}} - \left(B_{t\mathbf{A}}(t_1') + B_{t\mathbf{A}}(t_1)\right) d\ell_{t_1}\Big] \end{aligned}$$

where d$\boldsymbol{\ell}_v$ and d$\boldsymbol{\ell}_t$ are the path elements parallel to the flight direction and aligned with the connection line of the spacecraft, respectively. The area A is given by $A = \left(d\ell_{v\mathbf{A}} + d\ell_{v\mathbf{B}}\right)\left(d\ell_{t_1} + d\ell_{t_2}\right)$. As it yields practically the same results as the curl-B method, we don't apply Ampere's integral law in this study.

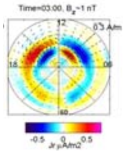


Fig.1 *Ionospheric currents (arrows) and field-aligned currents (colour coding) of the MHD model for a moderate activity level (IMF Bz=1nT).*

Application to synthetic magnetic fields

In order to test this approach, magnetic field components were calculated from a model ionospheric current distribution which was made available for different IMF conditions (Vennerstrøm et al, 2004, and posters by Moretto and by Vennerstrøm, here) and provided on a 3D grid in the magnetic local time (SM) coordinate system. The ionospheric current and FAC distributions for a moderate activity level are displayed in Fig.1.

The magnetic field given in the synthetic data set is the disturbance field caused by the currents. No geomagnetic main field has been added to it. Thus it can be used directly in the current retrieval. The B-field is given in spherical components (B_r, B_θ, B_ϕ) in the SM frame. The horizontal components at both spacecraft are rotated locally about the radial axis into the VZ frame giving (Bx, By).

For the estimation of the FACs the lower-flying satellite pair **SwA** and **SwB** is used. They orbit with an azimuthal distance of ca. 1.5°. At the poles their orbits cross each other. To retrieve the values of the magnetic field from the model grid, the orbit positions need to be transformed from Cartesian to cgm coordinates. We interpolate the synthetic magnetic components linearly between the grid points along the orbits to obtain a continuous, steady sampling with Δt=5s.

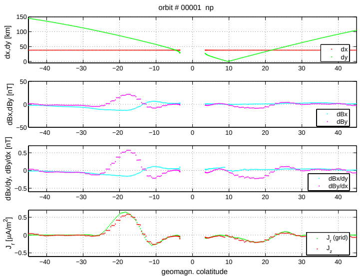


Fig.2 *Variations of the different terms in the curl-B calculation for a single path over the north pole.*

In Fig.2 the various terms of the FAC estimation are plotted versus magnetic colatitude, where negative angles represent the ascending and positive angles denote the descending parts of the track. dBx and dBy do not vary smoothly but step-like. This is a consequence of the linear interpolation process that was used to retrieve the magnetic field samples at the orbit positions from the grid points. To avoid problems with very small $|dy|$ at the cross-over points of the orbits near the poles, cross-track differences are omitted in their vicinity.

A comparison between determined FAC densities and the input model currents for one day (cf. Fig.3) and for different local times (cf. Fig.4) reveal a satisfying agreement in case dual-satellite measures are used.

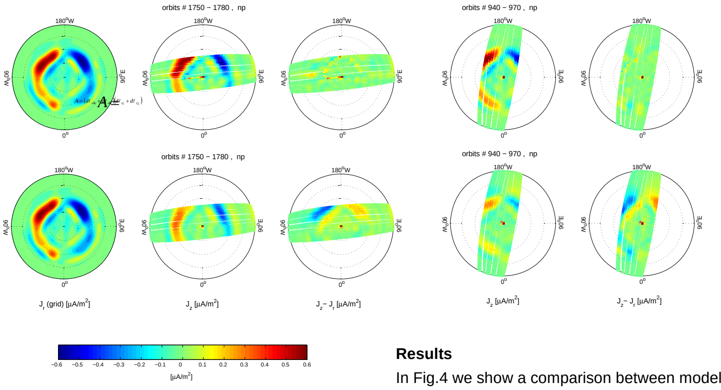


Fig.4 *Comparison between input currents and estimated FACs. IMF Bz=-2.5nT. 1st column (left): radial current component of the model grid; 2nd col.: derived FACs of 30 orbits (#1-30) at local time 17-18h; 3rd col.: difference between input and derived currents; 4th col.: derived FACs of 30 orbits (#940-970) at local time 11-12h; 5th col.: difference between input and derived currents. Top row : new multi-satellite method (curl-B), Bottom row: single satellite method.*

Results

In Fig.4 we show a comparison between model currents and the dual-satellite results for a number of subsequent orbits at different local times. The agreement is good in both cases and independent of the local time of the used orbits, and the characteristic FAC pattern is recovered clearly. Each frame contains also the single-satellite results of the same orbits in the second plot row. In these cases the descrepancies between input model and calculated currents are sub-stantial for both local times. The difference plots even reveal the characteristic pattern of the currents, implying that a good deal of the current is missed if the equation cannot be solved completely (ie. only dBy/dx is used).

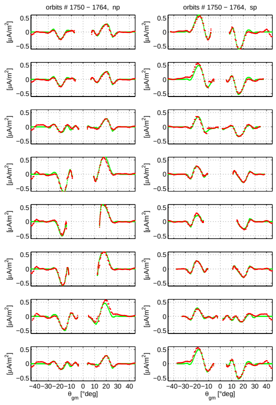


Fig.3a *Comparison of FACs of the model grid (green dots) and determined (red dots) along single tracks across the north (left) and south poles (right), activity level: IMF Bz = -2.5 nT.*

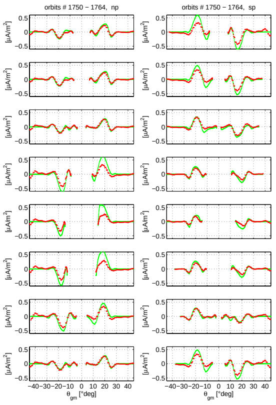


Fig.3b *FACs of the model grid (green dots) and single satellite results (red dots) of the same orbit segments as in Fig. 3a*

Conclusions

- The Swarm mission will allow for the first time to compute ionospheric field-aligned currents directly from the magnetic field readings of two azimuthally spaced satellites.
- The excellent agreement between computed field-aligned currents and input model is obvious.
- The observed phase shift and spurious bipolar signatures are probably due to systematically changing mapping conditions from the spherical to the local Cartesian frame near the poles.
- Due to the dimensions of spacecraft separations, only large-scale FACs can be recovered. They form the well-known local time pattern.
- As the formal resolution of the estimated FACs is very high, it might also be possible to detect mid-latitude current signatures of low amplitudes such as interhemispheric field-aligned currents.

References

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