Derivation of the full current density vector in the Earth's ionosphere low- and mid-latitude F region using ESA's Swarm satellites

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Outline

Objective

This study investigates electric currents in the low- and mid-latitude F region ionosphere during quiet-time geomagnetic conditions. The three components of the current density are derived locally using the three satellites of the Swarm constellation and a new algorithm which allows for error propagation through the calculation.

- We demonstrate the method using a one-day dataset: February 15 2014.
- The accuracy of the method and the impact of errors and biases - which occur on the Swarm measurements - on the current density estimates are tested using the TIE-GCM model.
- We compute and analyse the three components of the current density derived during February 15 2014.

F region electric currents

In the F region, a complex electric current system is triggered by the interaction between the plasma and:

- the Earth's magnetic field
- winds in the neutral thermosphere
- gravity
- plasma pressure gradients
- electric fields.

The Swarm constellation

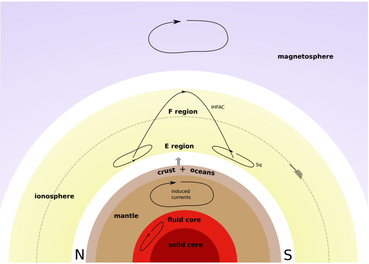
Three identical satellites orbit in the ionospheric F region on a near-polar orbit. They carry on board:

ESA image

- a scalar instrument (ASM) which measures the intensity of the magnetic field;
- a vector instrument (VFM) which measures the components of the magnetic field.

Data selection and pre-processing

We use L1 Swarm vector data version 0505 during February 15 2014:



Main magnetic field sources

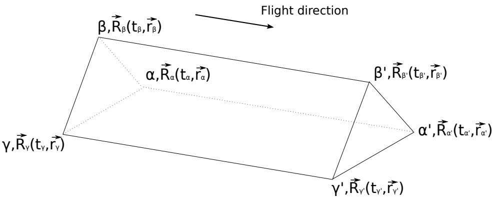
- To better isolate the F region signal, we remove the empirical representations of the core, lithospheric, E-region ionospheric and magnetospheric fields from the comprehensive model (Sabaka et al., 2018) version 0501
- We remove obvious outliers and low-pass filter the data
- We only consider geomagnetic quiet-time data (Ap ≤ 10).

Residual data

We call the resulting data **Residual data** and denote them $\vec{\boldsymbol{R}}$.

Formation of prisms

To estimate the local F-region current density, we take advantage of favorable configurations during the early mission when the satellites orbit close to each other:



- We build prisms using the three Swarm satellites denoted by α, β and γ at a time t and the same satellites ($\alpha\prime$, $\beta\prime$ and $\gamma\prime$) at a time $t\prime$

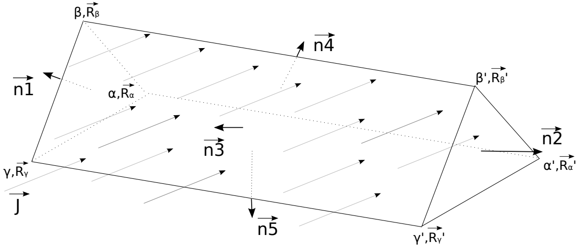
- There is a vector residual data $\vec{R}$ at each vertex of each prism

How many prisms?

During February 15 2014 and geomagnetic quiet time we could form **5135** prisms.

Estimation of the current density

We assume that the current density $\vec{J}$ flowing through each prism is uniform.



Principle

For each prism, we estimate $\vec{J}$ by fitting its projections on the normal vectors $\vec{n}_{1..5}$ to the current densities flowing through the 5 surfaces calculated with the curl-B technique (Ritter and Lühr, 2006). We can propagate the errors by modelling the uncertainties on the residual data $\vec{R}$ with a covariance matrix $\mathbf{C_R}$.

Data covariance matrix $\mathbf{C_R}$

The covariance matrix $\mathbf{C_R}$ is built using the following requirements:

- a residual data is affected by a bias supposed to be constant over a short period of time and a random error;
- two successive measurements from the same satellite share the same bias;
- position errors are assumed to be negligible.

How to deal with a bias in a covariance matrix?

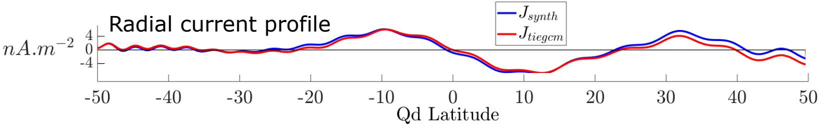
The bias shared by successive measurements of the same Swarm satellite is treated as two fully correlated random variables which in turn introduces non-zero non-diagonal elements in the $\mathbf{C_R}$ matrix.

- Setting appropriate numerical values to $\mathbf{C_R}$ allows to derive a realistic a posteriori covariance matrix $\mathbf{C_J}$ therefore providing error bars on the current density estimates.

Error-free synthetic test

The method is tested using the TIE-GCM model (Qian et al., 2014):

- The TIE-GCM provides predictions of the current density at the center of inertia of the prisms and of the magnetic field at the vertexes.
- The current densities predicted by the TIE-GCM model $\vec{J}_{tiegcm}$ are compared to the current densities $\vec{J}_{synth}$ calculated using our method and the magnetic field predictions at vertexes of the prisms.



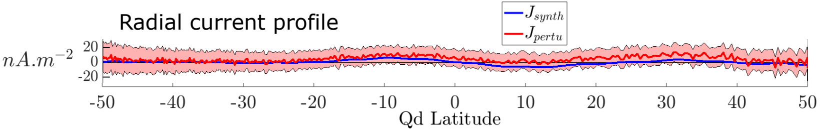
Results

We find that our method provides estimates to within 2 nA.m^{-2} on all three components during February 15 2014.

Impact of errors and biases

The impact of errors and biases on the current density estimates is assessed using again the TIE-GCM model:

- We use the TIE-GCM predictions of the magnetic field at the vertexes of the prisms to which we add a random error and a slowly varying bias.
- We compute with these data and our method a new current $\vec{J}_{pertu}$ and compare it to the error-free above-mentionned $\vec{J}_{synth}$ current.

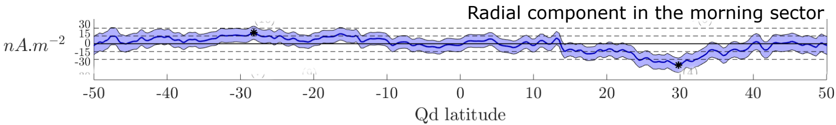


Results

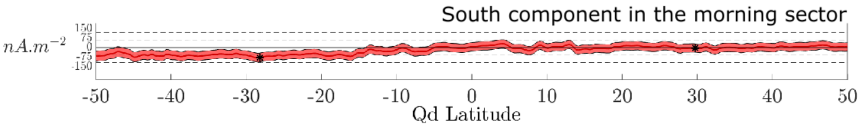
The slowly-varying biases introduce significant offsets of the order of 5 to 50 $nA.m^{-2}$. The error bars have proven to be reliable.

In the morning (0600-0800 LT) and evening (1800-2000 LT) sectors during February 15 2014 we identified:

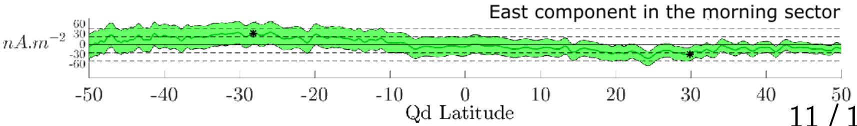
- interhemispheric field-aligned currents. For instance:



- potential F-region dynamo currents. For instance:



- potential pressure currents. For instance:



In conclusion:

- A new method which provides current density estimates in the low- and mid-latitude F-region ionosphere using the Swarm satellites is presented.
- The method is demonstrated using a one-day dataset: February 15 2014.
- A synthetic test performed with the TIE-GCM model showed that it provides robust estimates and error bars during that day.
- The method reveals some sensitivity to slow-varying biases.
- We identified interhemispheric field-aligned currents as well as potential dynamo and pressure currents in the morning and evening sectors on February 15 2014.

[1] Liying Qian, Alan G Burns, Barbara A Emery, Benjamin Foster, Gang Lu, Astrid Maute, Arthur D Richmond, Raymond G Roble, Stanley C Solomon, and Wenbin Wang. The NCAR TIE-GCM: A community model of the coupled thermosphere/ionosphere system. *Modeling the ionosphere-thermosphere system*, 201:73–83, 2014.

[2] Patricia Ritter and Hermann Lühr. Curl-B technique applied to Swarm constellation for determining field-aligned currents. *Earth, planets and space*, 58(4):463–476, 2006.

[3] Terence J Sabaka, Lars Tøffner-Clausen, Nils Olsen, and Christopher C Finlay. A comprehensive model of Earth's magnetic field determined from 4 years of Swarm satellite observations. *Earth, Planets and Space*, 70(1):130, 2018.