Using OpenGGCM Simulations to Separate Earth's Internal and External Field in SWARM Observations

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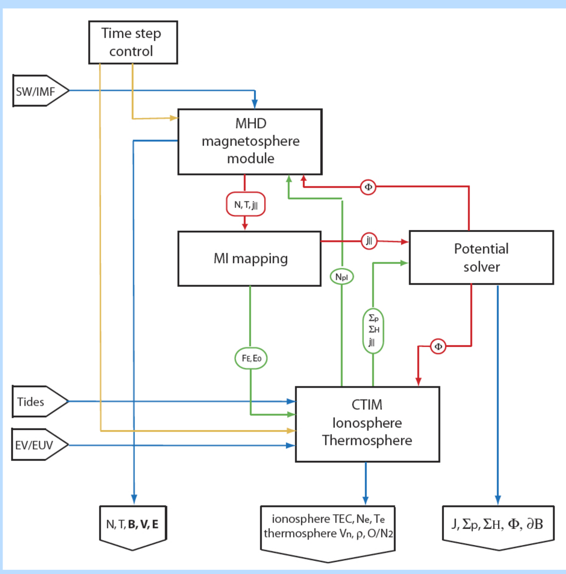
Abstract

We use Open Geospace General Circulation Model (OpenGGCM) simulations to predict magnetic field perturbations at Low Earth Orbiting (LEO) satellites such as SWARM, at high latitudes. The simulations allow us to separate three different major contributions to the observed perturbations, i.e., the perturbations caused by currents in the outer magnetosphere, field-aligned currents (FACs), and the currents flowing in the ionosphere. We find that at an altitude of 500 km the strongest contribution comes from FACs, followed by the perturbations caused by the ionospheric currents, while the magnetospheric currents make only a minor contribution. The high latitude perturbations do not average out over extended quiet time periods. There are significant variations in the patterns; however, on a large scale, the basic shape of the pattern remains stable. Thus, without explicitly removing the perturbations from the data, any spherical harmonics fit is expected to incur a bias. Although the predicted OpenGGCM perturbations do not compare particularly well with SWARM data, the simulations reproduce the overall pattern. However, they may still be useful to reduce the bias of the ensemble and produce better global spherical harmonic fits, by producing an ensemble whose external field contributions average out. Since this paper only scratches the surface of the role that models of the external field can play in producing unbiased internal field models, much progress is still possible, for example by improving the external model, investigating larger ensembles, and by considering data from geomagnetically disturbed times.

OpenGGCM Model



The Open Geospace General Circulation Model (OpenGGCM) is a coupled model of the magnetosphere, ionosphere, and thermosphere. It consists of modules that solve the outer magnetosphere (MHD based), the inner magnetosphere (essentially the Rice Convection Model, RCM), NOAA's Coupled Thermosphere Ionosphere Model (CTIM), and a ionosphere potential solver. OpenGGCM is a community model housed at UNH and at NASA's Community Coordinated Modeling Center (ccmc.gsfc.nasa.gov). References: Raeder, J., Global Magnetohydrodynamics – A Tutorial, in: Space Plasma Simulation, Lecture Notes in Physics, 615, Springer, 2003. (DOI:10.1007/3-540-36530-3_11); Raeder, J., et al., OpenGGCM Simulations for the THEMIS Mission, Space Sc. Rev., 141, 535-555, 2008. (DOI: 10.1007/s11214-008-9421-5).

Calculating Perturbations

At the altitudes of low Earth orbiting satellites like SWARM, we consider three contributions to the magnetic field perturbations:

1. From currents flowing in the ionosphere (labelled CIO). These currents are assumed to flow on a spherical shell at 110 km altitude.
2. From Field-Aligned Currents (FACs, labelled FAC). These currents flow along field lines from the outer magnetosphere into and out of the ionosphere.
3. From currents flowing in the magnetosphere, i.e., outside of 4.5 R_E. These include the Chapman-Ferraro currents, tail currents, etc. (labelled MAG).

For each of the currents we compute the field perturbation using Biot-Savart's law:

$$\delta\mathbf{B}(\mathbf{x}) = \frac{\mu_0}{4\pi}\int_V \mathbf{J}_{\{\mathrm{MAG,FAC,CIO}\}} \times \frac{\mathbf{x}-\mathbf{x}'}{|\mathbf{x}-\mathbf{x}'|^3} d^3x'$$

The integrals are calculated numerically using the gridded values from the OpenGGCM output.

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Reference

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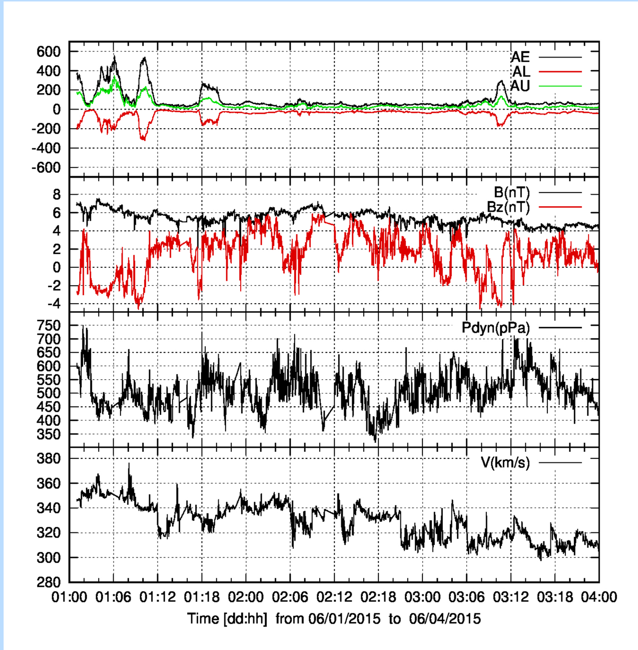
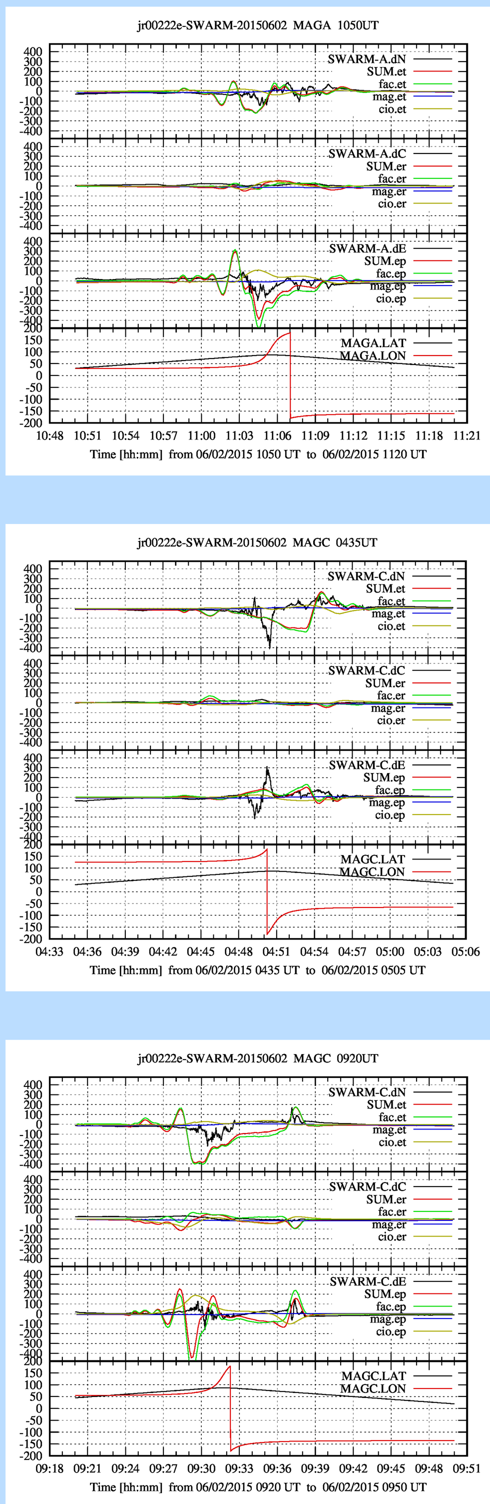
Quiet Day Example



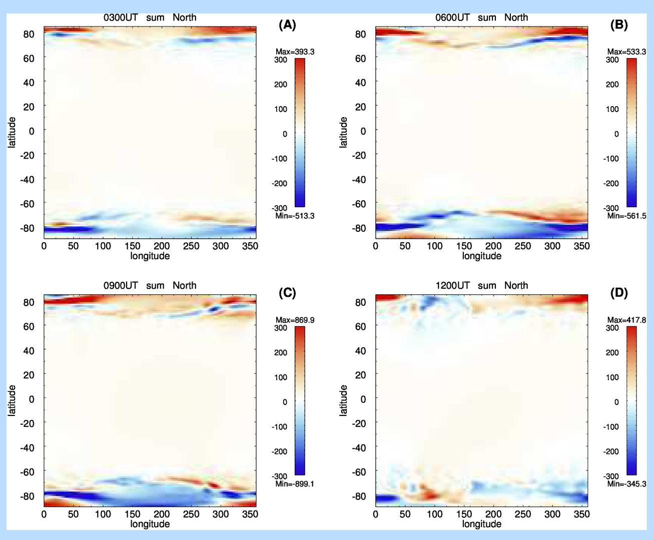
Solar wind, IMF, and geomagnetic activity between 2015-06-01 and 2015-06-04. The figure shows, from top to bottom the geomagnetic indices AL, AU, and AE, the IMF B_z and magnitude, the dynamic pressure, and the solar wind speed. During the period from 2015-06-01 2200 UT to 2015-06-03 0600 UT the magnetosphere is quiet, while the IMF B_z component is mostly northward, and both the solar wind speed and the dynamic pressure are comparatively low.

Comparison with SWARM Data



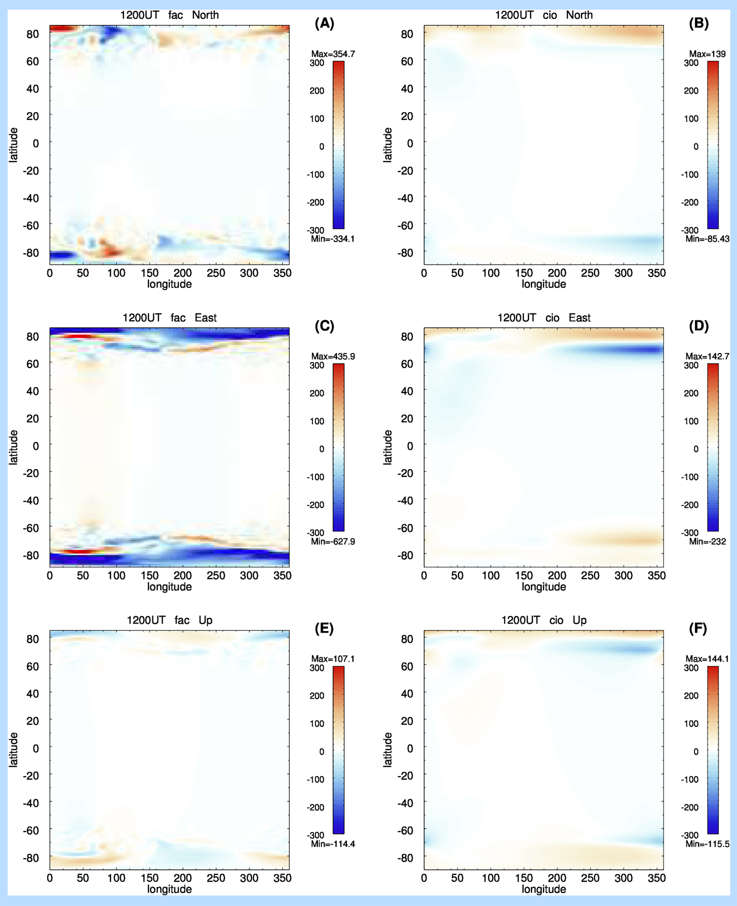
Comparison between SWARM observations and corresponding OpenGGCM predictions for selected passes over the polar cap. In each figure, the top three panels show the north, radial, and east components, respectively. Each of the panels shows the contributions due to Field Aligned Currents (fac), due to currents flowing in the outer magnetosphere beyond 4.5 R_E (mag), and the contribution from currents flowing in the ionosphere (cio). SUM denotes the sum of these contributions, i.e., the expected signal. The bottom panel shows the latitude and longitude of the track of the respective SWARM satellite.

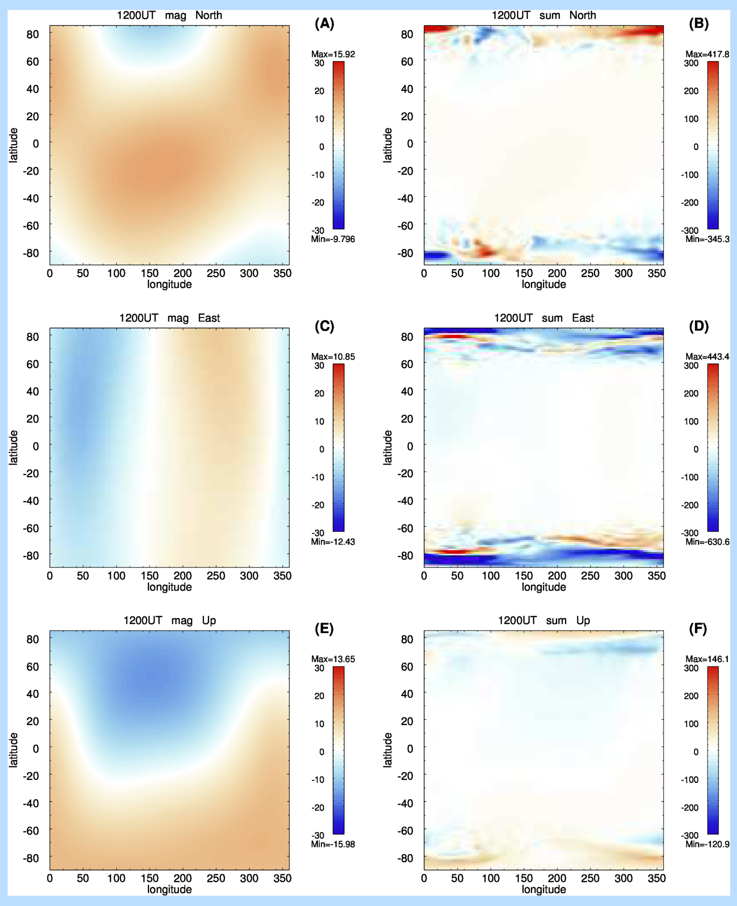
Time Changes



Maps of the northward component of the total field perturbation at 500 km altitude at 4 different times, 3 hours apart. The overall pattern of the perturbation does not change very much over time. Thus, these external perturbations do not average out in spherical harmonics fits and produce biases. Although not shown here, the perturbations during more active times may actually average out better.

Perturbation Maps





Upper panel: Latitude-longitude maps of the magnetic field perturbation at 500 km altitude. The left column shows the perturbations due to field-aligned currents. The next column shows the perturbations due to ionospheric currents. The top row shows the north-south perturbations, the middle row shows the east-west perturbations, and the bottom row shows the radial perturbations. The color scale is the same in all panels to illustrate the much smaller radial perturbations compared to the other two.
Lower panel: Same as the upper panel, except that the left column shows the perturbations due to the outer magnetosphere, and the sum of all perturbations is shown on the right side. The color scale for the magnetosphere perturbations is narrower by a factor 10, because these perturbations are much smaller than the others.

Summary

1. The strongest contribution comes from FACs. This contribution also has the highest spatial frequency, because the spacecraft traverse the highly structured current sheets.
2. The ionospheric currents also produce strong contributions at the satellites' altitude of about 500 km. Since these current are remote, they cause perturbations with spatial wavelengths that are comparable to the spacecraft distance from the currents, i.e., a few hundred km.
3. The currents in the magnetosphere (defined by a distance larger than 4.5 R_E from the Earth center) cause much smaller contributions. Also, because these currents are farthest for the observation points, their field perturbations should only affect the lowest order coefficients of a spherical expansion.
4. Even over an extended quiet time period, the perturbations do not average out. There are significant variations in the patterns; however, on a large scale, the basic shape of the pattern remains stable. Thus, without explicitly removing the perturbations from the data, any spherical harmonics fit will incur a bias.
5. The predicted OpenGGCM perturbations do not compare well with SWARM data. Although the location of the perturbation is a fairly good match, the predicted perturbations are often larger by a factor 2-3, although there are also times when they are smaller. The model also does not reproduce the highest frequencies seen in the data, due to insufficient resolution. Predictions might be improved by better precipitation models, or by better numerical resolution.
6. Even though the OpenGGCM predictions are not as good as one may wish, they may still be useful to reduce the bias of the ensemble. This will require further investigation.