Magnetic signals generated by ocean flow in Swarm satellite data: prediction and observation

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Motivation

Motion of sea water in the Earth’s main magnetic field generates the secondary induced field which can be decomposed into its poloidal and toroidal components. While the toroidal component is not directly observable outside the oceans, the poloidal magnetic field have already validated by CHAMP satellite magnetic observations, landbase magnetic measurements and sea surface magnetic field measurements, despite the poloidal field being rather weak, reaching an intensity of up to a few nT. New possibilities of observations of the ocean-induced magnetic field came with the launching of ESA’s Swarm mission satellites which have provided a valuable amount of high-precision and high-resolution measurements of the Earth’s magnetic field.

Ocean models

Two ocean flow models are incorporated:

DEBOT — a barotropic model of ocean tide flow

LSOMG — a baroclinic model of global ocean circulation

Magnetic induction models

The induced magnetic field is modelled by two different approaches:

TLAM — a thin-layer approximation is applied on the magnetic induction equation which leads to the steady-state equation for the stream-function $\psi$ of the Earth

$$\nabla \cdot \left( \frac{1}{\mu_0} \nabla \psi \right) = \nabla \times \left( \frac{1}{\mu_0} \int \sigma (\vec{u} \times \vec{B}_0) \, dr \right) \cdot \vec{e}_z,$$

$$\Sigma = \int \sigma \, dr \quad \vec{a} = (0, 1, 0, 0) \quad \vec{B}_0 = (B_0, 0, 0).$$

The stream-function is numerically solved by the finite differences method and the induced magnetic field is then given by

$$\vec{b} = -\frac{1}{2} \mu_0 \nabla \psi$$

ELMGIV — a 3-D time-domain electromagnetic induction model. The magnetic induction equation is solved by a spherical harmonic-finite element approach

$$\nabla \times \left( \frac{1}{\mu_0} \nabla \times \vec{b} \right) + \mu_0 \frac{\partial \vec{b}}{\partial t} = \mu_0 \nabla \times (\vec{a} \times \vec{B}_0)$$

1-D benchmark of the magnetic induction codes

Considering a global ocean of the constant depth $h$ and without continents and a 1-D conductivity profile of the globe, then the stream-function equation reduces to

$$\nabla \times (\vec{b} \times \vec{e}_z) = h \sigma \nabla \times (\vec{a} \times \vec{B}_0) \cdot \vec{e}_z,$$

This equation can be solved analytically by the spherical harmonics method. We compare the analytical solution with the solutions obtained by the TLAM and ELMGIV codes for three different velocity fields: 1) the field of the 1\textsuperscript{st}-4\textsuperscript{th} order of the spherical harmonics, 2) of the 10\textsuperscript{th} order and 3) of the 20\textsuperscript{th} order. The main magnetic field is a dipole. The comparison is shown in Figure below.

Magnetic field induced by ocean flow

Research in present and past has been mainly focused on the secondary magnetic field induced by barotropic ocean tides. However, baroclinic circulation also contributes to the induced magnetic field. Our modelling shows that wind-driven surface-ocean currents generates the magnetic signal of a similar intensity as the ocean tides. The strongest signal is in the Southern Ocean, however, a detection of this signals in Swarm data is very complicated due to polar magnetoicurrents.

Along-track analysis of Swarm data

Swarm data are analyzed along tracks of the satellites. The data are processed in several steps. First, the main and lithospheric field is subtracted and only night time (22:00-06:00) and magnetically quiet data are selected. Then, the data in polar regions, which are contaminated by field-aligned currents and polar electrojets, are removed and mid-latitude data (within the interval (20\textdegree, 150\textdegree)) of colatitudes) are represented by a series of Legendre polynomials to the degree 25. Finally, a 4\textsuperscript{th} order expansion into Legendre polynomials is fitted to the data and extrapolated to the polar areas. Synthetic data are processed identically.

Analysis of the expansion coefficients determines whether a source of the field is the only one and whether the source is purely internal or external or a combination of both. Desired ocean-induced signals have only one internal source, otherwise the data are biased by signals from the magnetosphere or ionosphere. The signals of the 1\textsuperscript{st} and 2\textsuperscript{nd} order have often an external source in the magnetosphere; hence, only the 3\textsuperscript{rd} and 4\textsuperscript{th} order signals are used for a comparison with the synthetic data (the bottom panel in Figure below).

Figure: Analysis of the observed (left) and predicted (right) data along one of Swarm B tracks. Top: Position and time of the track. Middle top: Original data, subtracted from the main field (thin lines) and a fitted expansion into Legendre polynomials to the 4\textsuperscript{th} degree (thick lines). Middle bottom: Amplitudes of the signal. A source of the magnetic field is the only one if the light blue and red dots lie on themselves and the source is internal if the purple dots lie on the 0\textdegree axis. Bottom: The 3\textsuperscript{rd} and 4\textsuperscript{th} order signals and residuals of the fitted data.

Figure: The comparison of the theoretical and numerical solutions of the 1-D benchmark test for the source velocity field of the 1\textsuperscript{st}-4\textsuperscript{th} order (left), 10\textsuperscript{th} order (middle) and 20\textsuperscript{th} order (right).