Swarm for Ocean Dynamics Project

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Overview

Satellite magnetic field observations have the potential to provide much needed information on changes in ocean dynamics and heat content that are key components in the Earth system. It is well established that the oceans produce a time-varying magnetic field by motional induction and that its amplitude is measurable at satellite altitude. However it remains a major challenge to efficiently extract the small signal of ocean variability from the magnetic measurements made by the *Swarm* mission.

In the **Swarm for Ocean dynamics** project, over the next 18 months we aim to retrieve the Ocean-Induced Magnetic Field (OIMF) by

- A dedicated pre-processing scheme for *Swarm* magnetic field data including corrections for known magnetospheric and ionospheric signals
- High resolution global modelling of the time-dependent internal field at Earth's surface based on this processed dataset
- Spatio-temporal filtering to extract the OIMF in specific period bands, guided by advanced forward model using latest oceanographic information

Advanced forward modelling of OIMF signal

- Use ElmgTD time-domain numerical scheme [Velímský et al. 2019] for solving the magnetic induction equation

$$\frac{\partial \boldsymbol{B}_{\rm oi}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}_{\rm c}) - \frac{1}{\mu_0}\nabla \times \left[\frac{1}{\sigma}(\nabla \times \boldsymbol{B}_{\rm oi})\right]$$

- Includes both poloidal and toroidal parts of $\boldsymbol{B}_{\rm oi}$ (the OIMF) and includes self-induction effects

Example

- Daily-mean velocities $\boldsymbol{v}$ from ocean state estimate ECCOv4r4 [Fukumori et al., 2021]
- Main field $\boldsymbol{B}_{\rm c}(\mathbf{r}, t)$ from IGRF13 model
- Ocean conductivities from WOA 13 [Tyler, 2017], as monthly means
- Sediment conductivity model [Everett et al., 2003]
- 1D mantle conductivity below [Grayver et al. , 2017]

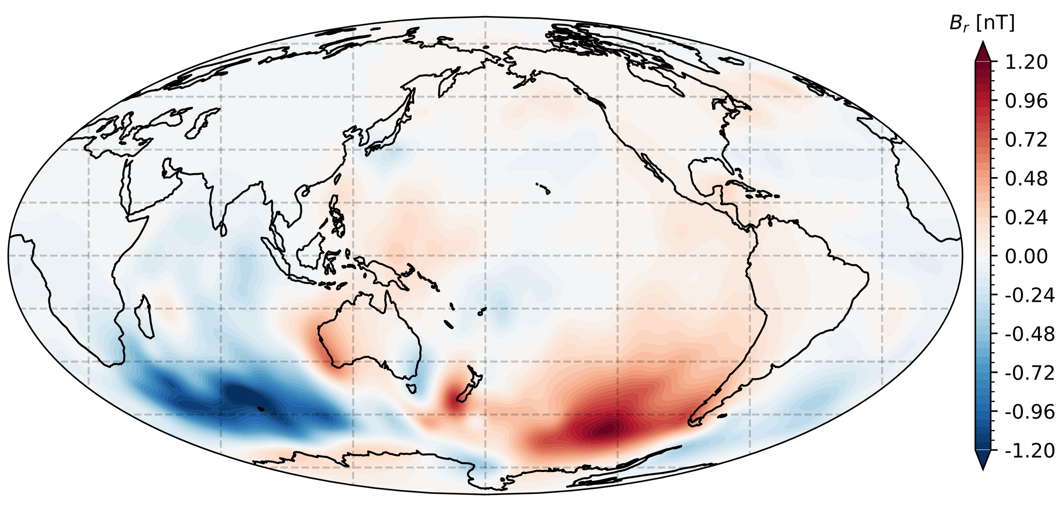

Fig. 1: Simulated radial magnetic field at 450km altitude in 2016.5, truncated at degree $N = 60$.

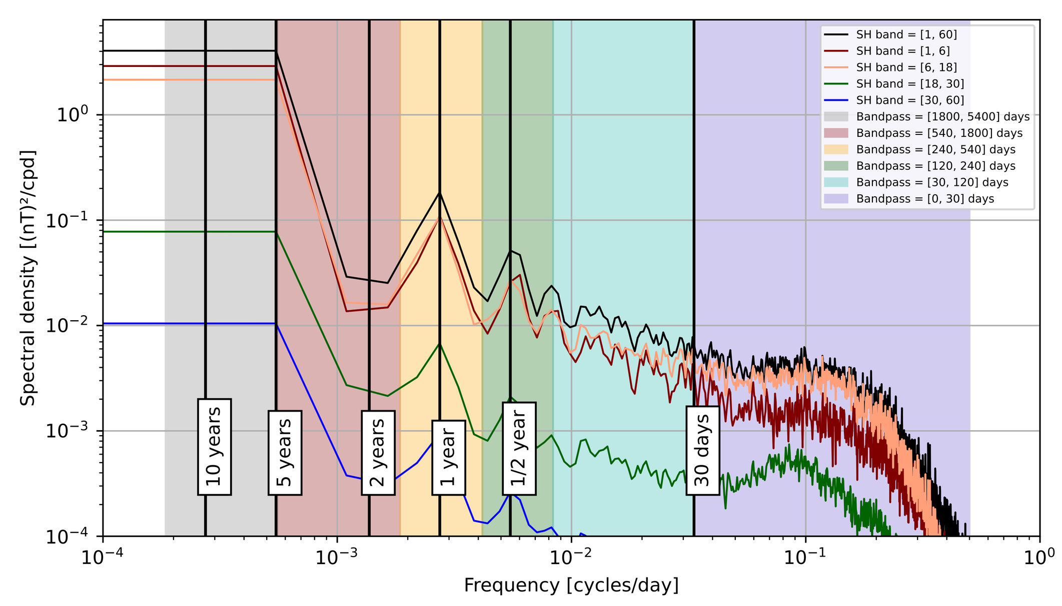

Fig. 2: Median temporal power spectra of simulated radial magnetic field altitude 450km, truncated at degree $N = 60$.

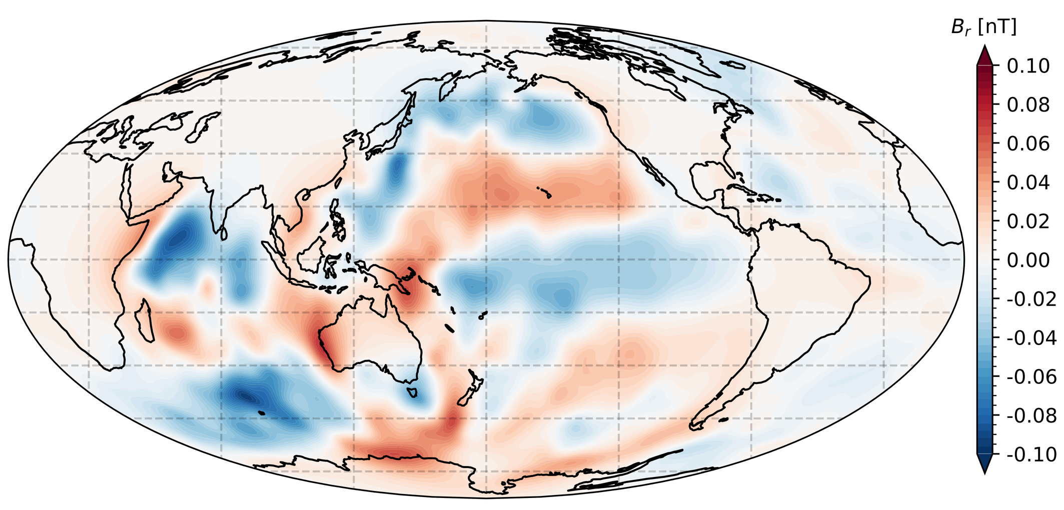

Fig. 3: Simulated radial magnetic field at 450km altitude in 2016.5, 1 yr period band, truncated at degree $N = 60$.

- Plan: systematic numerical experiments exploring uncertainties in simulated ocean signal resulting from specific choices of $\boldsymbol{v}$ and σ

Pre-processing of Swarm data

Corrections for the magnetospheric field

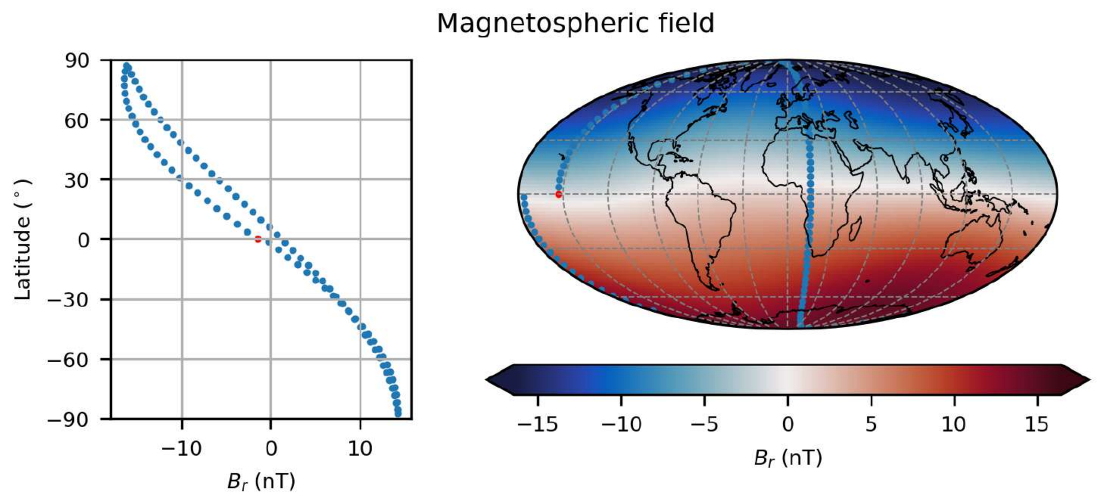

Fig. 4: Radial field corrections due to the magnetospheric field along an example orbit of a *Swarm* satellite.

- Subtract CHAOS-type magnetospheric field model [Olsen et al., 2014], degree 1 in SM coordinates with time-dependence from ground-based RC index plus degree 1-2 in GSM coordinates.
- Includes magnetospheric and Earth-induced parts
- Improvements to time-resolution of RC (towards 1 minute)

Corrections for the ionospheric field

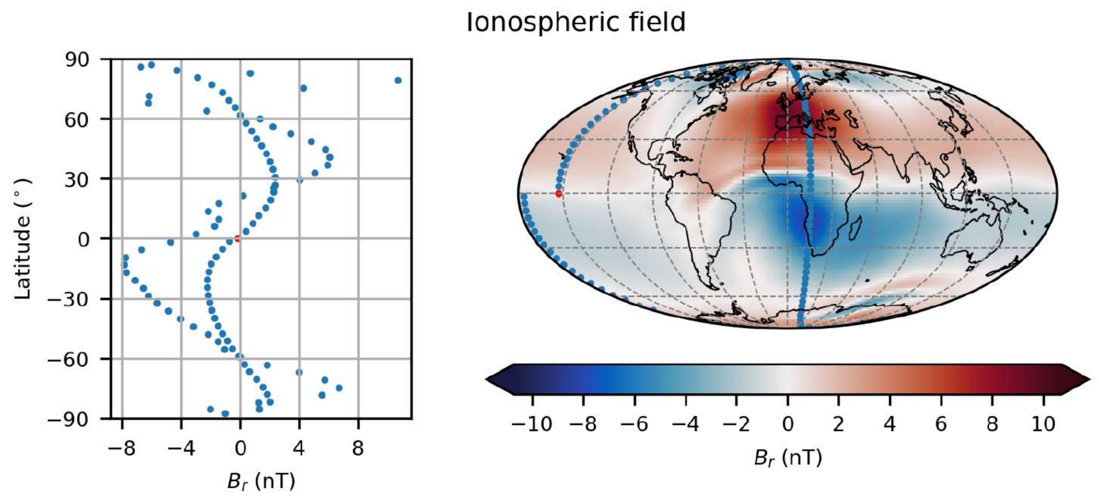

Fig. 5: Radial field corrections due to the ionospheric field along an example orbit of a *Swarm* satellite.

- Subtract CI-9 Ionospheric field model [Sabaka et al., 2018]
- Includes Ionospheric plus Earth-induced parts
- Scaling of model track-by-track for better corrections

Corrections for the lithospheric field

- Subtract LCS-1 model [Olsen et al., 2017], based on low altitude CHAMP data, for SH degrees 14 - 160.

Proposed data selection

- 10 years of data from *Swarm* A, B and C
- Vector data and gradients at mid and low latitudes
- Scalar intensity data in polar region
- Scalar intensity gradients at all latitudes

- Only data from dark regions at mid and low latitudes
- Data from local times 20.00 to 04.00 in polar regions
- Geomagnetically quiet times according to Kp and $d|RC|/dt$ thresholds

High resolution time-dependent field modelling

Potential field approach

- $\mathbf{B} = -\nabla V$ with $V = V^{\rm int} + V^{\rm ext}$
- The internal part takes the form

$$V^{\rm int} = a\sum_{n=1}^{N_{\rm int}}\sum_{m=0}^{n}\left(g_n^m(t)\cos m\phi + h_n^m(t)\sin m\phi\right)\left(\frac{a}{r}\right)^{n+1} P_n^m(\cos\theta)$$

- Internal coefficients further expanded in time as

$$g_n^m(t) = \sum_l g_{n,l}^m \cdot M_l(t) \quad \text{for } n = 1 - 30$$

with $M_l(t)$ cubic B-splines, 0.2 yr knot spacing.

Model estimation

- Robust regularized non-linear least squares. Minimize:

$$\mathbf{e}^T \underline{C}^{-1}\mathbf{e} + \lambda_0 \mathbf{m}^T \underline{\Lambda}_0 \mathbf{m} + \lambda_2 \mathbf{m}^T \underline{\Lambda}_2^{end} \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\Lambda}_3 \mathbf{m}$$

- $\mathbf{e}^T \underline{C}^{-1}\mathbf{e}$ is the (Huber-weighted) data misfit
- $\underline{\Lambda}_0$ penalizes B_r integrated over Earth's surface
- $\underline{\Lambda}_2^{end}$ penalizes d^2B_r/dt^2 integrated over Earth's surface, only at model endpoints
- $\underline{\Lambda}_3$ penalizes d^3B_r/dt^3 integrated over Earth's surface

Spatio-temporal filtering to isolate ocean signal

Ocean signal dominates core signal at high degree

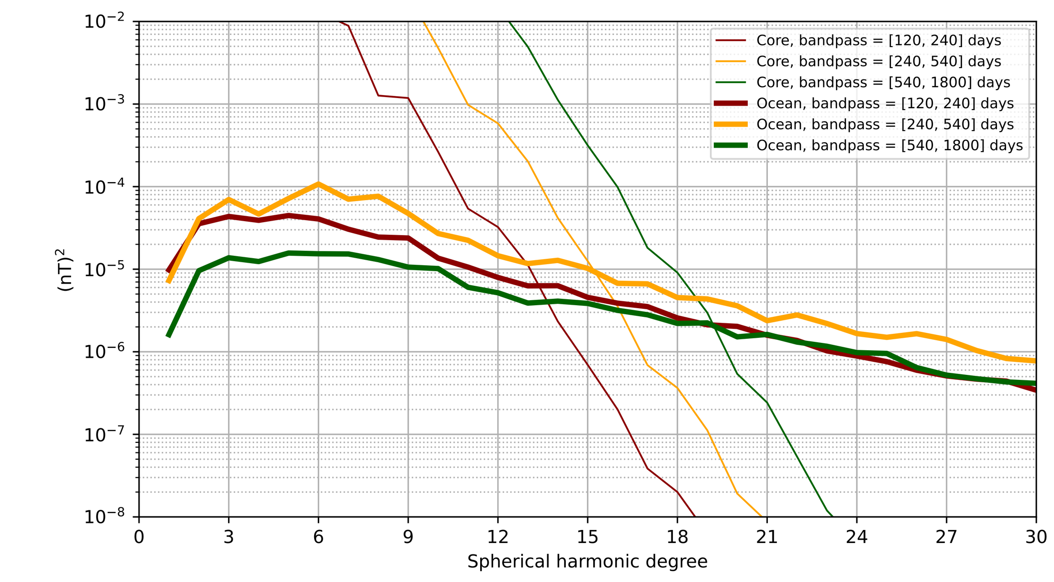

Fig. 6: Spatial power spectra of core and ocean signals at 450km.

- Spectra of core and ocean signals cross at degree 13-18 depending on period

Synthetic data: Recovered ocean signal

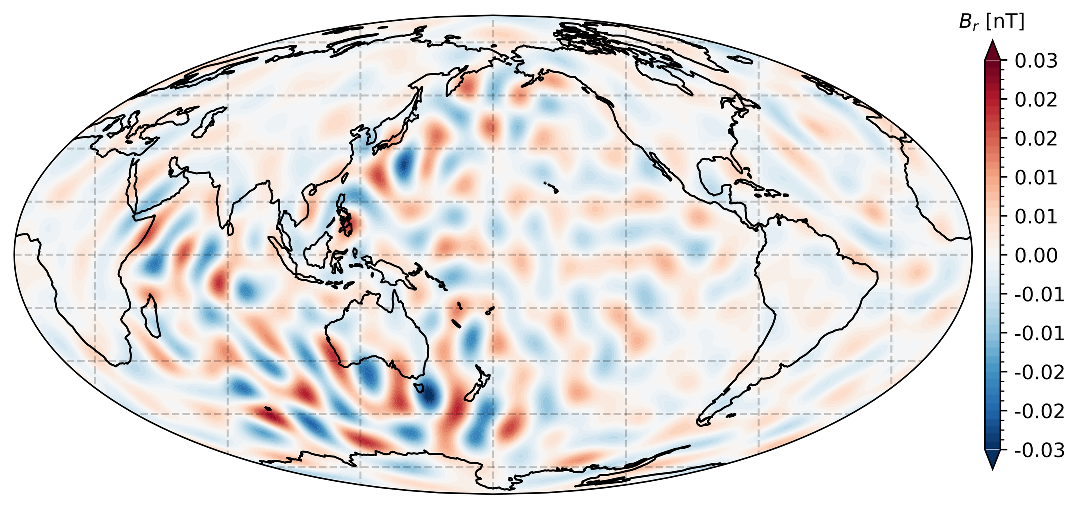

Fig. 7: Recovered radial magnetic field at 450km altitude in 2016.5, filtered to1 yr period band, degrees $17 - 30$, based on inversion of 10yrs of simulated Swarm satellite data including core and oceanic sources.

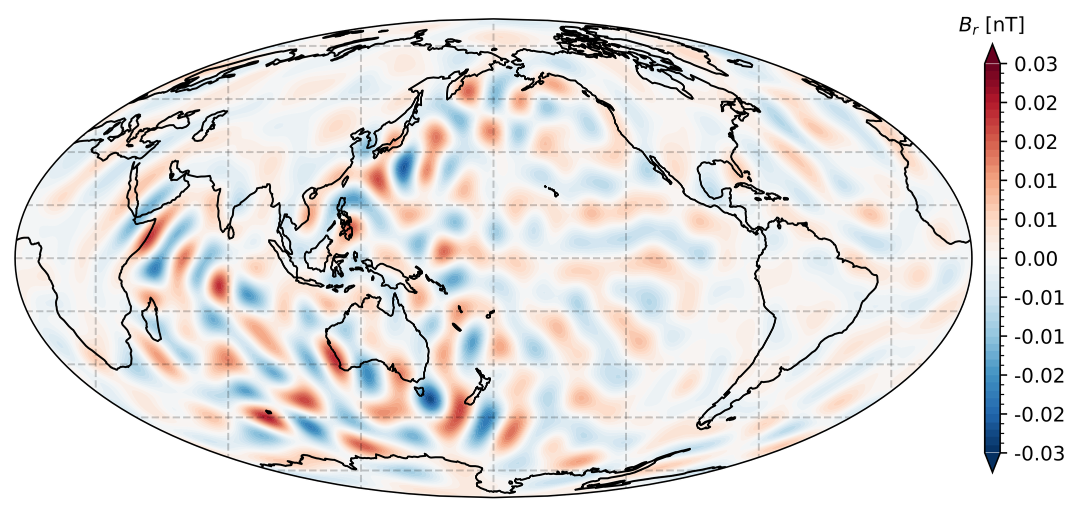

Fig. 8: Reference case: Simulated radial magnetic field at 450km altitude in 2016.5, filtered to1 yr period band, degrees $17 - 30$.

- Morphology of recovered ocean signal in 1yr period band matches well the input signal above deg 17
- Recovered ocean signal has slightly enhanced power, possibly due spectral leakage from higher degree input signals.

The challenge: Remaining ionospheric & magnetospheric signals

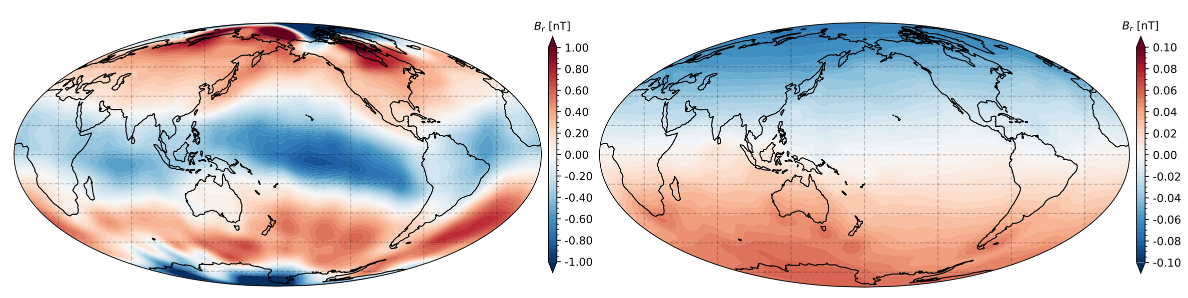

Fig. 9: Estimated internal fields driven by Ionospheric (left) and magnetospheric (right) currents, at 450km, 1 year period band.

Preliminary conclusions and project plan

- Ocean magnetic signal dominates over the core signal when one considers sufficiently small length scales and rapid time scales
- Oceanic signal can be recovered in inversions based on *Swarm* orbits i.e. signal amplitude is sufficient
- Major challenge is to separate the ocean signal from ionospheric and related induced fields

Project tasks:

1. Optimize data selection and corrections for magnetospheric and ionospheric fields
2. Carry out further high resolution simulations using latest oceanographic information to better characterize uncertainties in the expected ocean signal
3. High resolution internal field modelling with focus on timescales from 1 month to 5 years, including regularization at Earth's surface
4. Isolate the OIMF signal in these field models using filters based on the expected ocean signal and noise characteristics of external sources