Changes in Earth's core-generated magnetic field, as observed by Swarm

Chris Finlay, Nils Olsen, Stavros Kotsiaros, Lars Tøffner-Clausen, Magnus Hammer

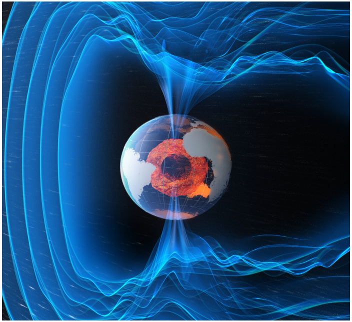
DTU Space, Technical University of Denmark

Nicolas Gillet

ISTerre, Université Grenoble 1 and CNRS

The Earth's core-generated magnetic field

- $> 98\%$ Earth's $\mathbf{B}$ field originates in the core
- Provides protection from the solar wind
- Generated by **dynamo action** in the core
- Not steady; continuously changing



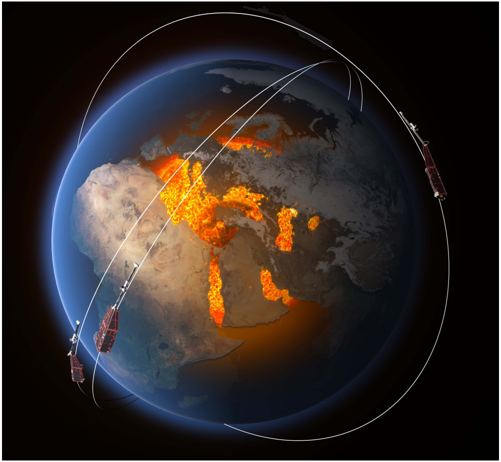
[Image credit: ESA]

Investigating Earth's core: the least understood place on the planet

- Core field changes on timescales shorter than decades?
- Structure of flows responsible for generating, and driving the evolution, of the field?

This talk: What have we learnt about the core field from recent *Swarm* data?

The *Swarm* satellite trio: a new era in geomagnetism

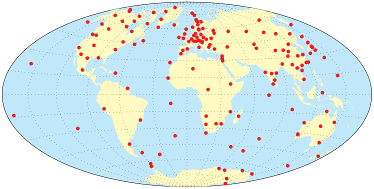


[Image credit: ESA]

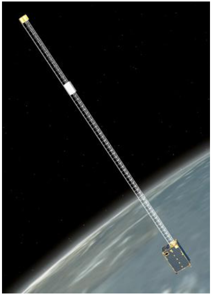
- A pair of satellites (*Alpha*, *Charlie*), flying close together at altitude approx. 460 km
- A third satellite (*Bravo*) higher up at approx. 500 km, separated in longitude

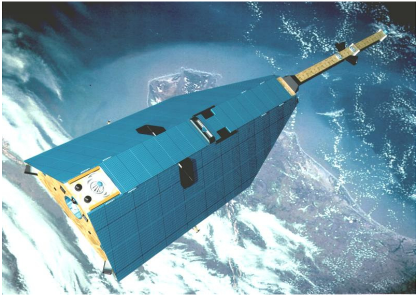
Other data sources

- **Ground observatories:**



- **The Ørsted and CHAMP missions:**





Global field modelling: Forward scheme

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.

- The internal part of the potential takes the form

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

- For $n \leq 20$, expand in 6th order B-splines

$$g_n^m(t) = \sum_{k=1}^{K} {}^k g_n^m B_k(t). \tag{1}$$

- For the external potential, expand in SM and GSM co-ordinate systems, with θ_d and T_d being dipole co-lat. and dipole local time

$$\begin{aligned} V^{\text{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d\right) \left(\frac{r}{a}\right)^{n} P_n^m(\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\text{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

- Degree-1 coefficients in *SM* coords dependent on the RC disturbance index

Global field modelling: Estimation

- Work with vector data in **magnetometer frame**, co-estimating Euler angles
- Use **vector and scalar field** data
  AND **field spatial differences**, along-track and cross track btw *Swarm* A and C
- Select data from **geomagnetically quiet times** using geomagnetic activity indices and (for high latitudes) Interplanetary Magnetic Field and solar wind speed data
- 7,481,013 data in all (3,449,233 from *Swarm*).

- **Robust non-linear least squares including regularization**, iteratively minimizing

$$[\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}}^{-1} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}$$

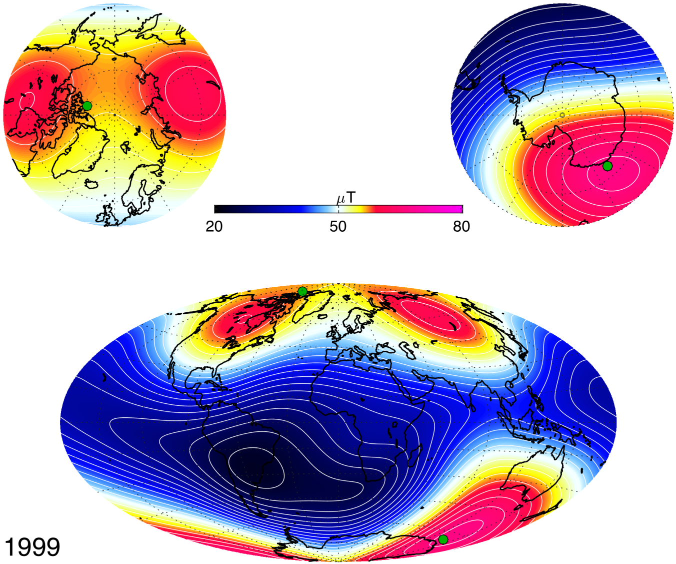
$\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are regularization matrices

- **Resulting field model, spanning 1999 - 2016.5, is CHAOS-6**

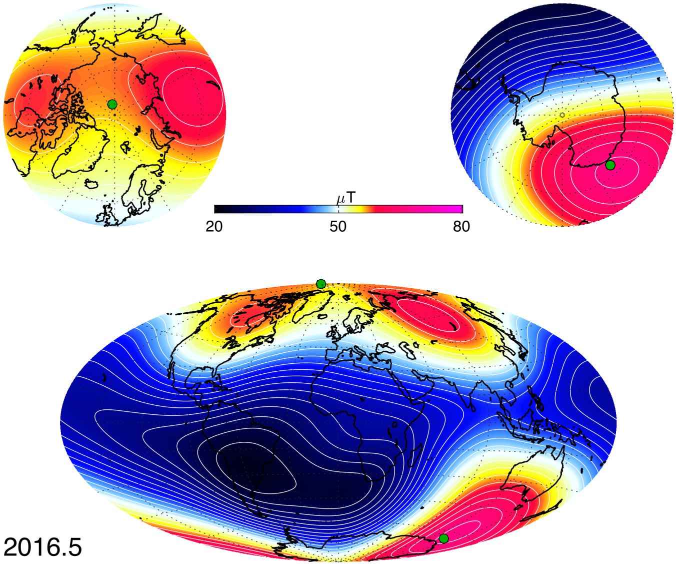
  `http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/`

- Weighted rms misfit to non-polar, dark *Swarm* scalar data is **2.19 nT**,
  For scalar field differences, **0.27 nT** along-track and **0.43 nT** cross-track.

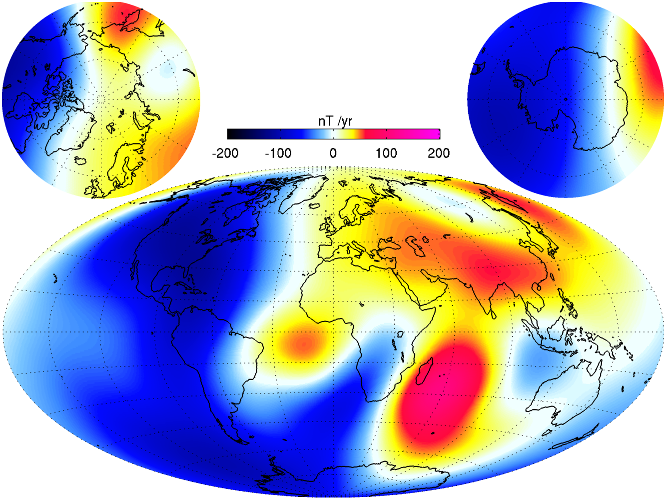
Field strength and magnetic pole position in 1999



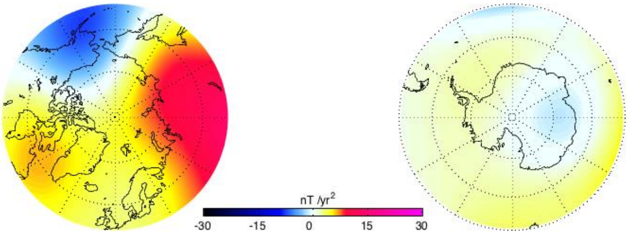
Field strength and magnetic pole position in 2016.5

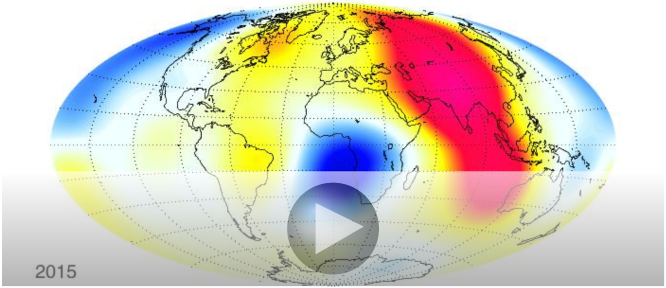


Field strength strengthening and weakening in 2015

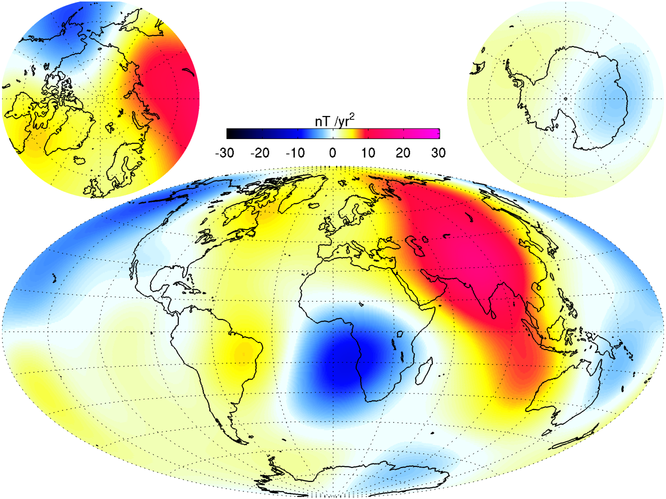


Rate of change of field strengthening/weakening

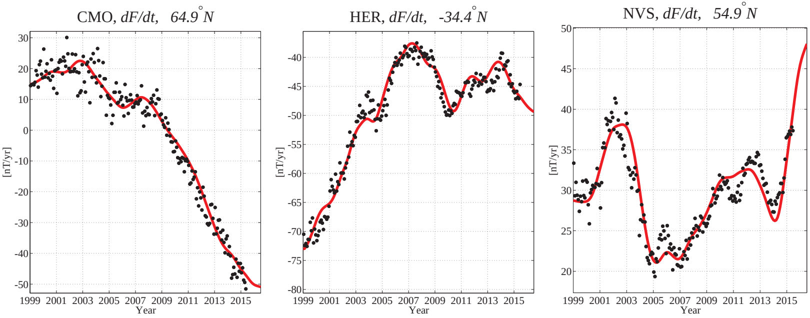




Rate of change of field strengthening/weakening 2015

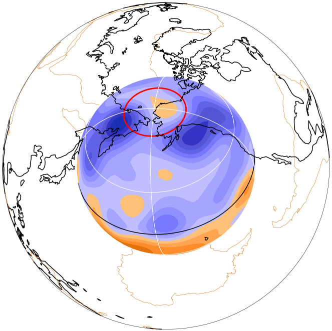


Ground observatory series of field strength change



Downward continuation of field to the core surface

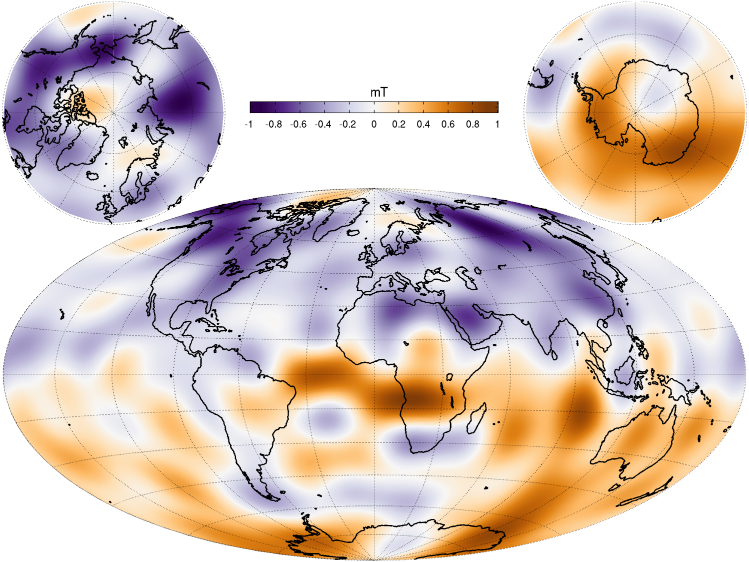
- Wish to understand origin of changes
  -> need to descend to core
- Possible to downward continue through mantle
  (Neglecting currents there on these timescales)
- Small scales amplified as approach source
- Field at core surface stable to degree 13
  (above this crust dominate)
- Field change (SV) stable to degree 18



[Image credit: A. Jackson]

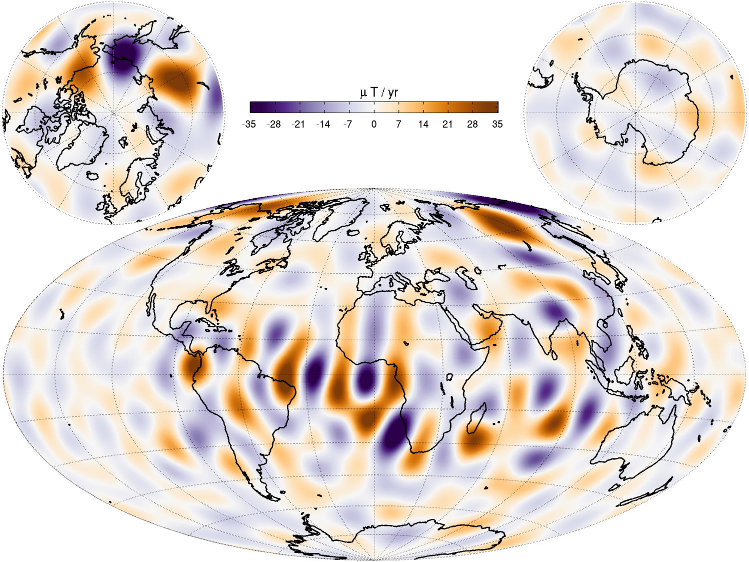
$$B_r = \sum_{n=1}^{N} \sum_{m=0}^{n} (n+1)\left(g_n^m \cos m\phi + h_n^m \sin m\phi\right)\left(\frac{a}{r}\right)^{n+2} P_n^m(\cos\theta)$$

Radial field at core surface in 2015



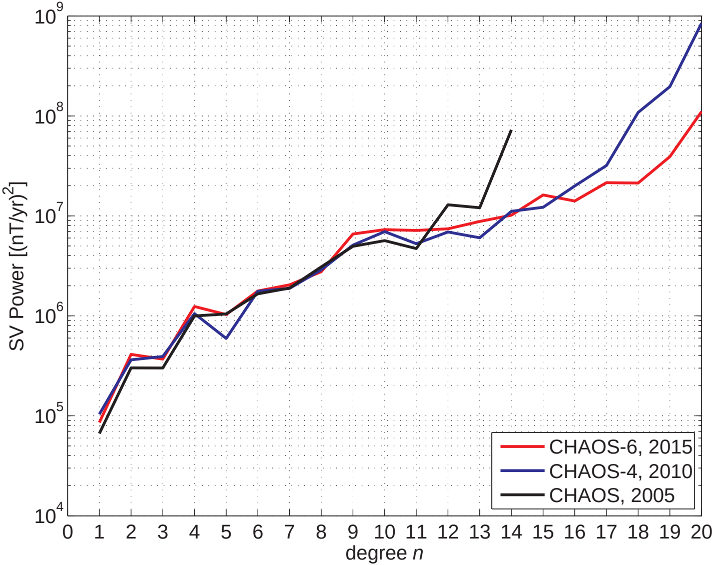
[CHAOS-6, truncated degree 13]

Radial field SV at core surface in 2015



[CHAOS-6, truncated degree 18]

Power spectrum of SV at core surface

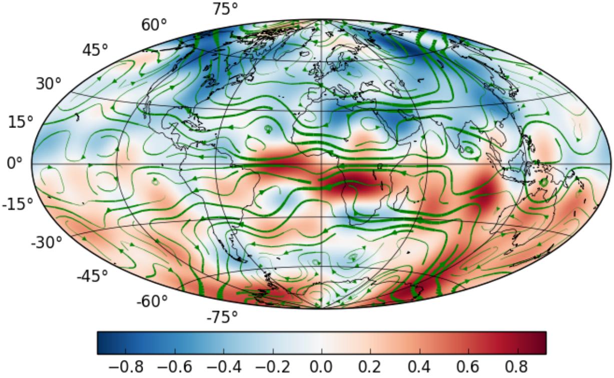


Inferred quasi-geostrophic core flow in 2015

- Assume rotation dominates the core flow (quasi-geostrophy)
- Invert for flow producing observed field changes, using the frozen flux induction eqn:

$$\frac{\partial B_r}{\partial t} = -\nabla_H \cdot (\mathbf{u}B_r)$$

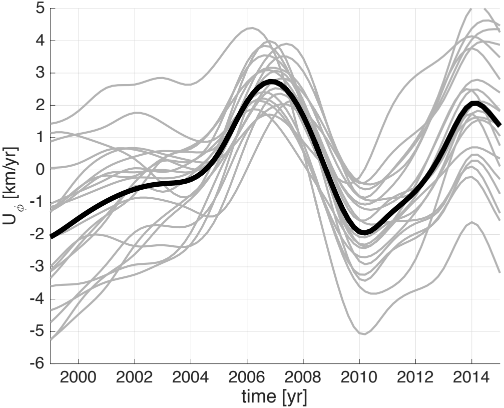
- Ensemble approach: random realizations of unknown small scale field



- Planetary scale anticyclonic gyre, westward at mid/low latitudes under Atlantic
- Regions of intense shear, for example at high latitude under Alaska/Siberia

Time-dependence of core flow

- Also find non-axisymmetric flow **oscillations** at low latitudes e.g. -15°N, 0°E



- Times of azimuthal flow acceleration, correspond to times of rapid field change
- Dynamical origin of oscillations presently unknown

Summary

(1) ***Swarm*** **is monitoring detailed changes in the core-generated magnetic field**

Summary

(1) ***Swarm*** **is monitoring detailed changes in the core-generated magnetic field**

(2) Find clear trends on a decadal time scales

- Weakening, N. America (3.5% in 17 yrs), Strengthening, N. Asia (2% in 17 yrs)
- South Atlantic Anomaly: Weakening (2% in 17 years) and moving westward
- Movement of north pole from N. America towards Asia

Summary

(1) ***Swarm*** **is monitoring detailed changes in the core-generated magnetic field**

(2) Find clear trends on a decadal time scales

- Weakening, N. America (3.5% in 17 yrs), Strengthening, N. Asia (2% in 17 yrs)
- South Atlantic Anomaly: Weakening (2% in 17 years) and moving westward
- Movement of north pole from N. America towards Asia

(3) Also able to track more rapid inter-annual field accelerations

- Large-scale field fluctuations on inter-annual time scale
- Foci of field acceleration rapidly grow and decay
- Foci with alternating sign e.g. near South Africa, with approx 3 years between

Summary

(1) ***Swarm*** **is monitoring detailed changes in the core-generated magnetic field**

(2) Find clear trends on a decadal time scales

- Weakening, N. America (3.5% in 17 yrs), Strengthening, N. Asia (2% in 17 yrs)
- South Atlantic Anomaly: Weakening (2% in 17 years) and moving westward
- Movement of north pole from N. America towards Asia

(3) Also able to track more rapid inter-annual field accelerations

- Large-scale field fluctuations on inter-annual time scale
- Foci of field acceleration rapidly grow and decay
- Foci with alternating sign e.g. near South Africa, with approx 3 years between

(4) Downward continuing to the core surface allows study of underlying processes

- Striking intense SV in northern polar region
- Quasi-geostrophic core flows characterized by:
  (i) planetary scale anticyclonic gyre
  (ii) strong shear of flow at high latitudes
  (iii) non-axisymmetric flow oscillations at low latitudes

Summary

(1) ***Swarm*** **is monitoring detailed changes in the core-generated magnetic field**

(2) Find clear trends on a decadal time scales

- Weakening, N. America (3.5% in 17 yrs), Strengthening, N. Asia (2% in 17 yrs)
- South Atlantic Anomaly: Weakening (2% in 17 years) and moving westward
- Movement of north pole from N. America towards Asia

(3) Also able to track more rapid inter-annual field accelerations

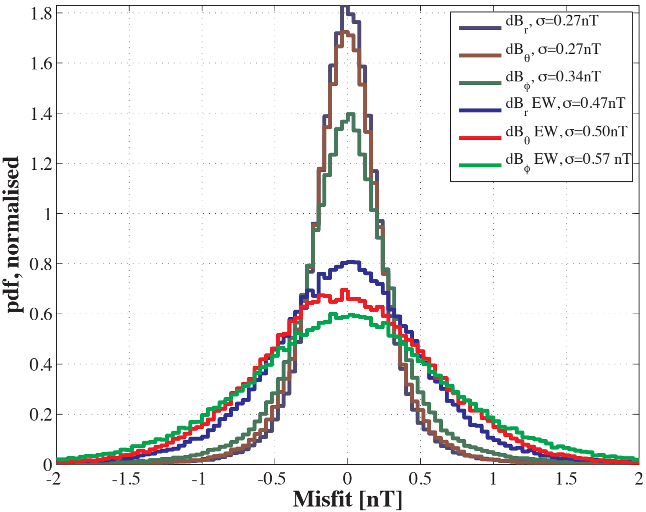
- Large-scale field fluctuations on inter-annual time scale
- Foci of field acceleration rapidly grow and decay
- Foci with alternating sign e.g. near South Africa, with approx 3 years between

(4) Downward continuing to the core surface allows study of underlying processes

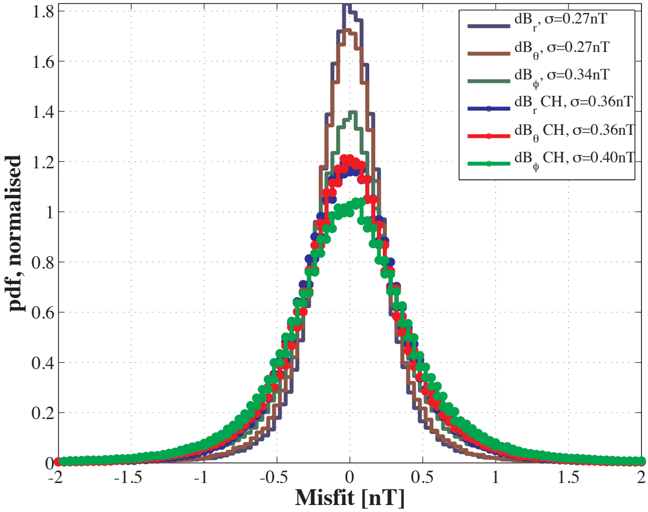
- Striking intense SV in northern polar region
- Quasi-geostrophic core flows characterized by:
  (i) planetary scale anticyclonic gyre
  (ii) strong shear of flow at high latitudes
  (iii) non-axisymmetric flow oscillations at low latitudes

(5) A long ***Swarm*** **mission is crucial to further progress**

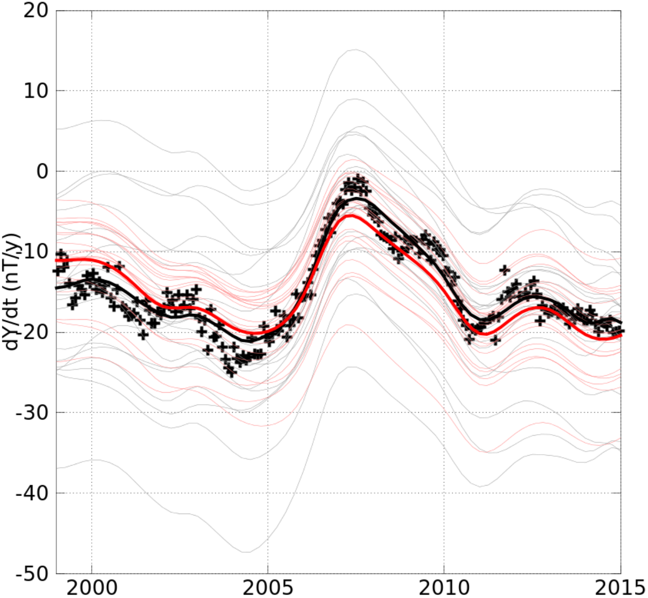
Swarm vector difference residuals, Along vs Cross track



Vector difference residuals, Swarm vs CHAMP



Example fit of flow to obs data: dB_ϕ/dt, HER



Time-dependence of core flow (another example)

- Also find non-axisymmetric flow **oscillations** at low latitudes e.g. 0°N, 40°W