Satellite magnetic field observations as a tool for studying the Earth's core:

Opportunities and Challenges

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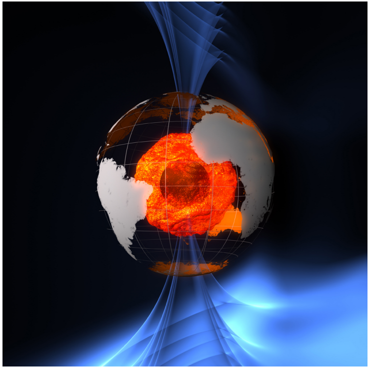

DTU Space
National Space Institute

Outline

1. Satellite magnetic data as a tool for studying the core: state of the art
2. Opportunities
3. Challenges
4. Conclusions and outlook

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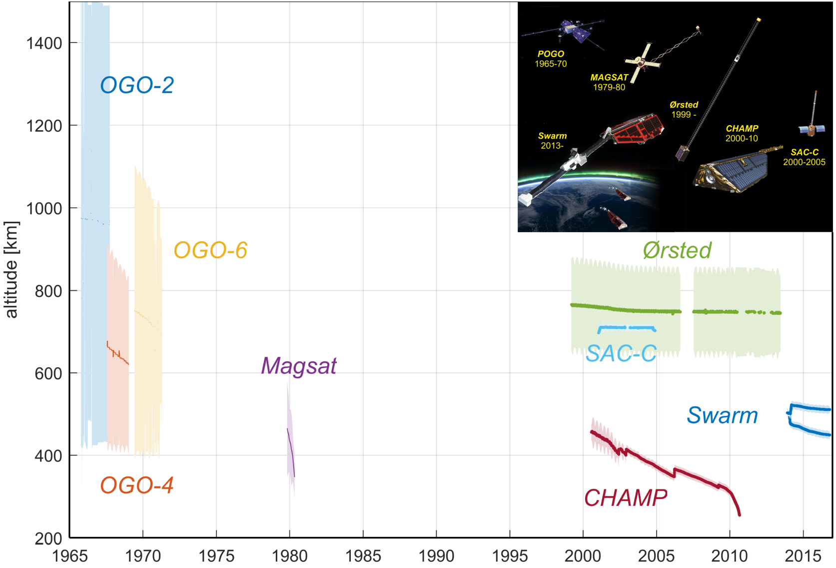
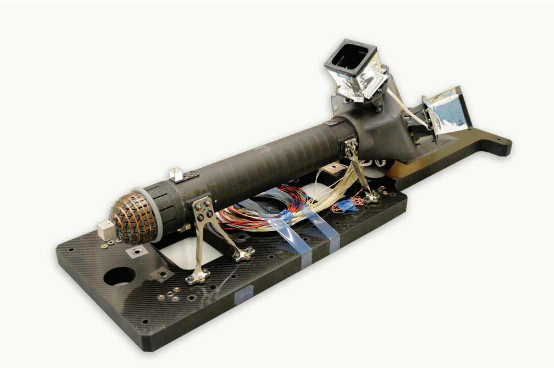
1.1 Satellite magnetic field observations for studying deep Earth processes



1.2 The Swarm satellite trio

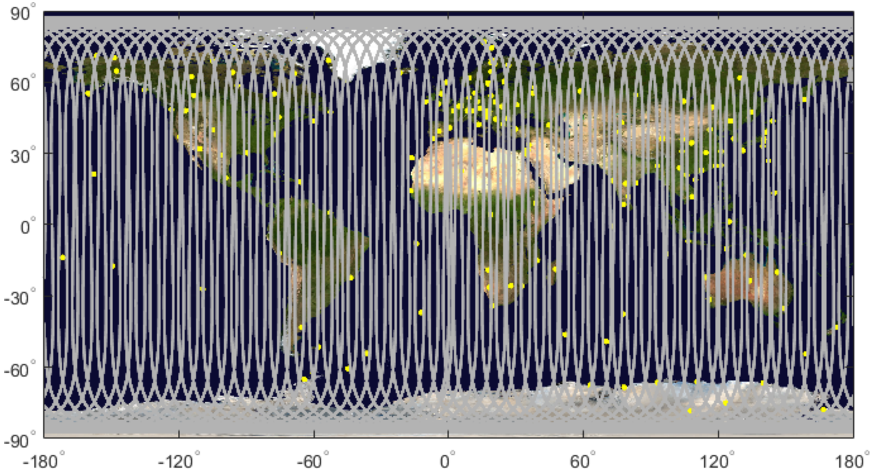
- Multi-point constellation, launched in November 2013
- Aim: To carry out the best ever survey of the Earth's magnetic field
- Lower pair, altitude approx. 450 km, separated by 150 km East-West -> "gradiometer"
- Plus a higher satellite at altitude approx. 500 km: Different local time, potentially very long lifetime

1.3 Magnetic field measurements



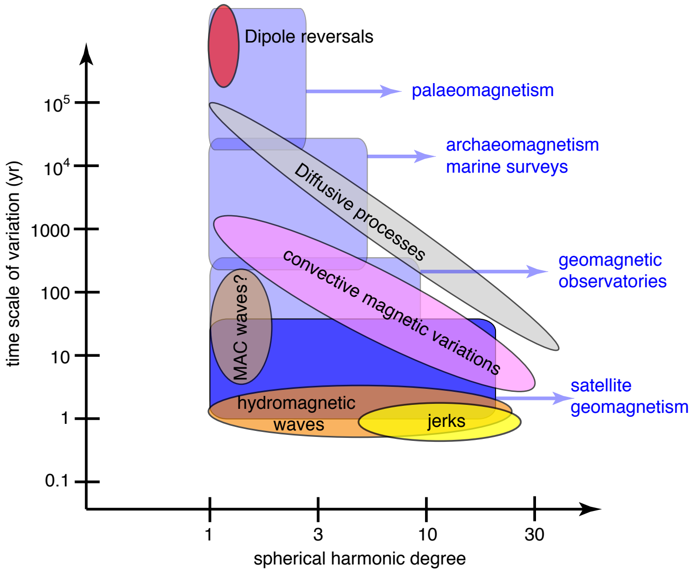
- Vector Field Magnetometers plus star trackers (3 on each satellite)
- In-flight Calibration using Absolute Scalar Magnetometers
- Absolute accuracy: under 0.3 nT, alignment at arc-sec level

1.4 Global coverage within a few days

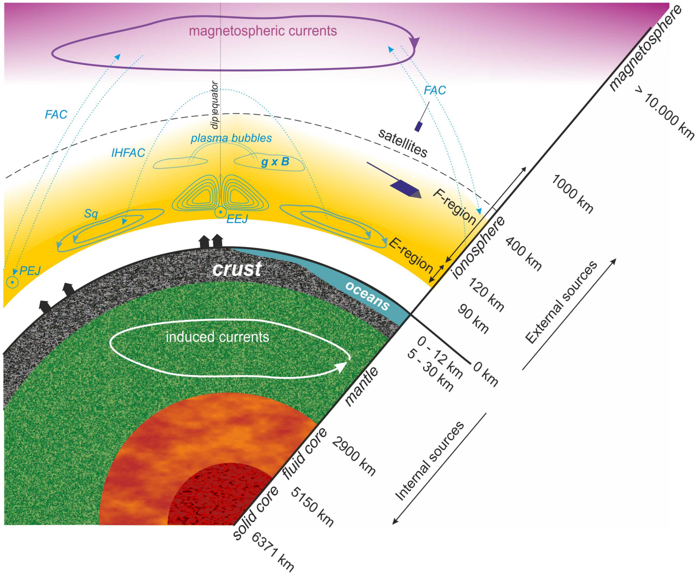


- Coverage from 4 days of *Swarm* data compares well to that from ground network
- Hope is for a long mission !

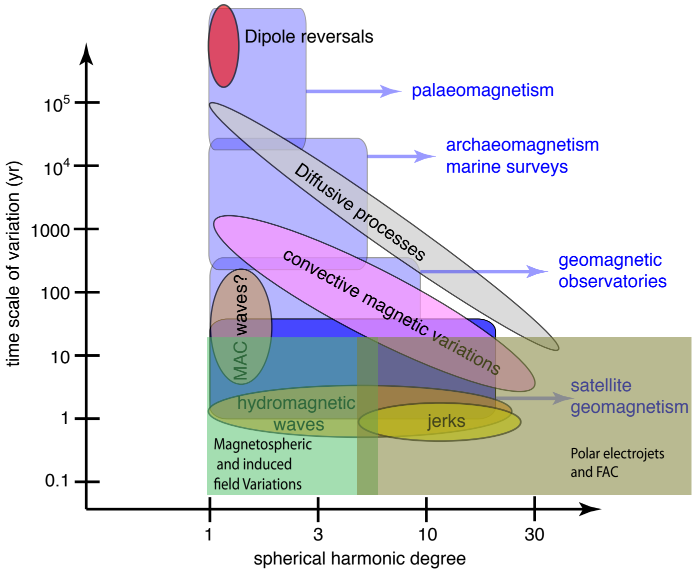
1.5 What 4D deep Earth process can we hope to probe?



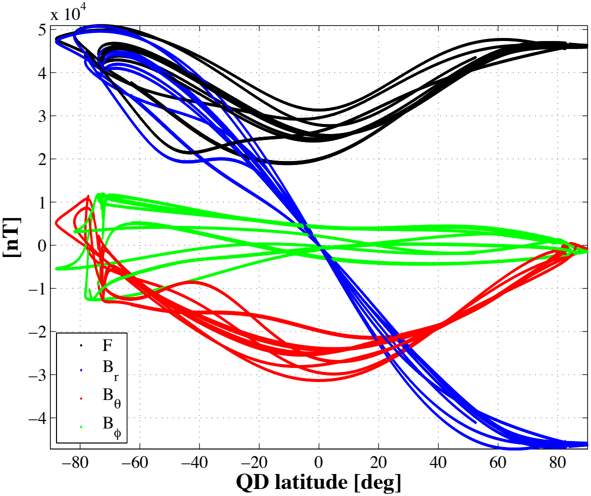
1.6 Other field sources



1.7 Overlap of external signals with core processes

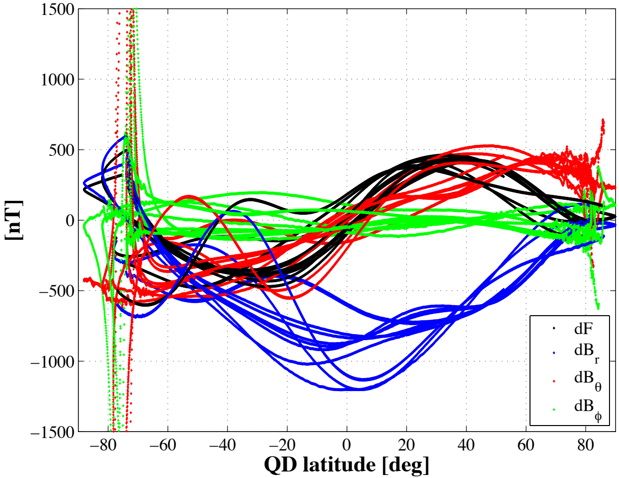


1.8 Example vector field data from quiet orbits



- 12 example geomagnetically quiet orbits from Sw-A in 2014

1.9 Example field differences (gradients) from quiet orbits



- 15 sec along-track differences of same 12 Sw-A orbits

1.10 Isolating the core signal: Potential field modelling

- **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

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

- Expand external potential in SM and GSM coordinates, with θ_d and T_d being dipole co-lat. and local time

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

1.11 Isolating the core signal: Potential field modelling

- Model estimation by robust non-linear least squares including regularization, iteratively minimizing

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

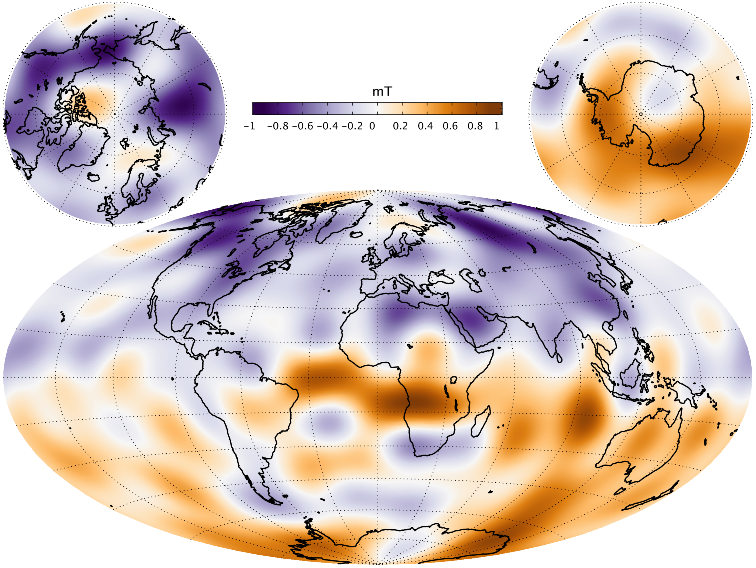
$\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are temporal regularization matrices

[Olsen et al., 2006; Olsen et al., 2014; Finlay et al., 2016]

- DTU's latest field model, spanning 1999 - 2017.5, is **CHAOS-6-x4**
- Based on 8,533,432 data (satellite and ground observatory)
- Weighted rms misfit to non-polar, dark *Swarm* scalar data is **2.14 nT**,
For scalar field differences, **0.25 nT** along-track and **0.4 nT** cross-track.

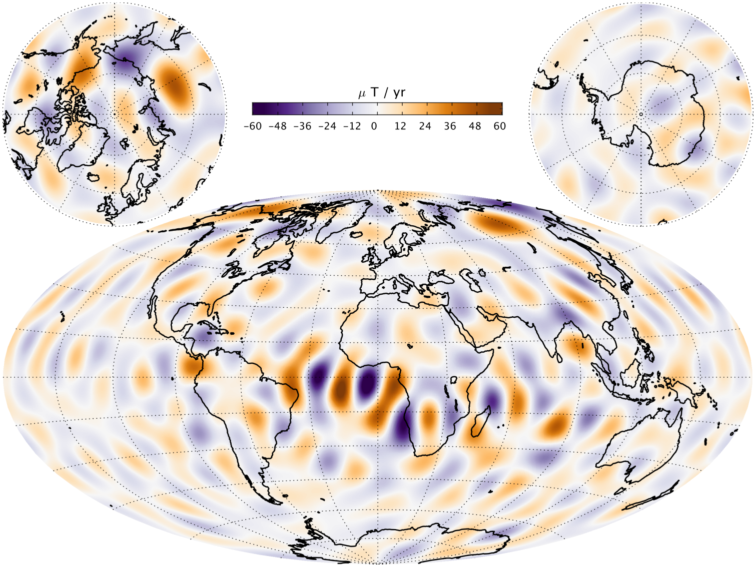
`http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/`

1.12 Core surface field in 2017



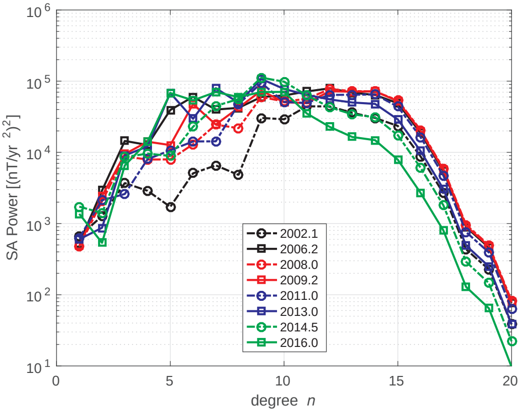
[CHAOS-6-x4, 2017, truncated degree 13]

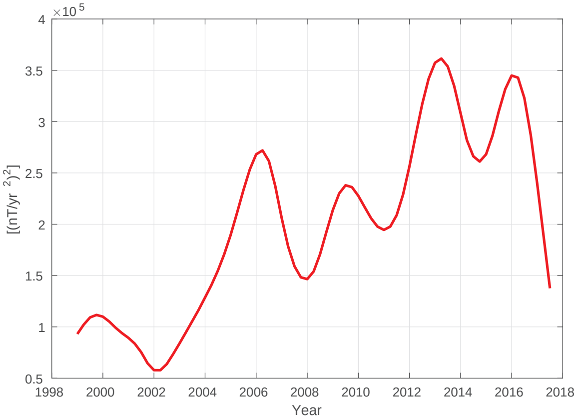
1.13 Core surface field variation (SV) in 2017



[CHAOS-6-x4, 2017, truncated degree 20]

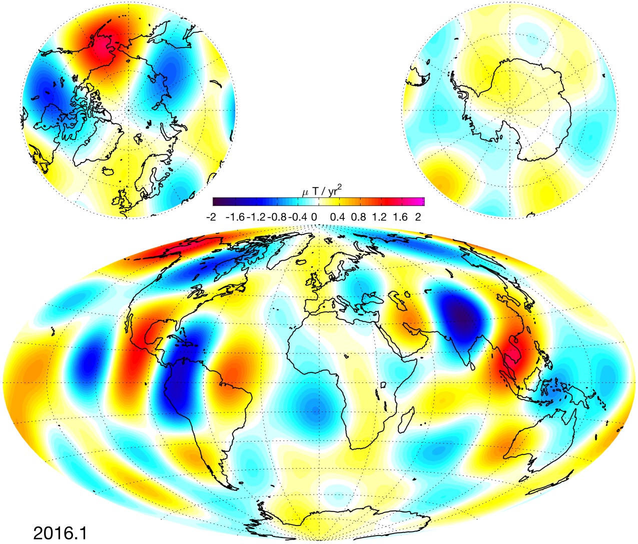
1.14 Core surface field acceleration (SA)





- Time changes in SA resolved up to degree 9
- Oscillations seen in SA energy, period 3-4 years
- Above degree 9 the applied temporal regularization has a strong influence
- Regularization is required to control spurious interannual oscillations, especially in polar regions

1.15 Core surface field acceleration (SA) to degree 9



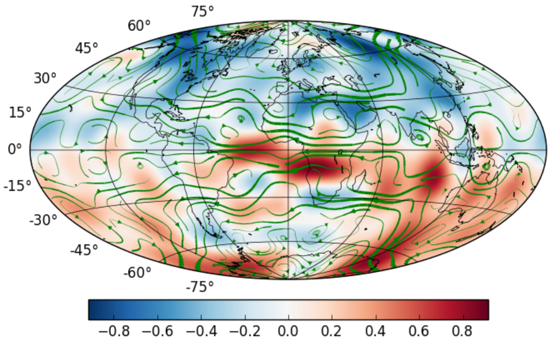
[CHAOS-6-x4, truncated degree 9]

1.16 Application - Inversion for core flow

- Invert for flow producing observed field changes, using the frozen flux induction eqn:

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

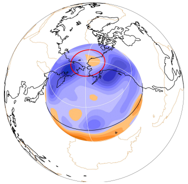
- Example: rotation dominates the core flow i.e. quasi-geostrophy (QG)
- Ensemble approach, random realizations of unknown small scale field



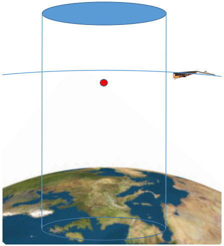
- Planetary scale anticyclonic gyre, westward at mid/low latitudes under Atlantic
- Regions of intense flow, for example at high latitude under Alaska/Siberia
- Oscillations in azimuthal flow at sites of SA pulses

[Gillet et al., 2015; Finlay et al., 2016]

1.17 Alternatives approaches



- **Use Green's functions or correlation functions** to link core field estimates to data [Gubbins and Roberts, 1983; Jackson et al., (2007) Holschneider et al., (2016); Hammer and Finlay (2017)]



- **Grids of monthly point estimates (Virtual Observatories)** [Mandea and Olsen, 2006; Whaler and Beggan, 2015]
    - Take all data within cylinder of chosen radius
    - Remove estimates of crustal, magnetospheric and S_q fields
    - Robust fit of local (cubic) potential model
    - Convenient for use in data assimilation schemes (regular grid, manageable size, can account for covariances) [Barrois et al., 2017]
- **Direct use of observations in data assimilation schemes** ?

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What does Swarm bring to the table?

- Longer time span of magnetic field observations with global coverage
- Higher spatial resolution of field time derivatives (SV, SA)

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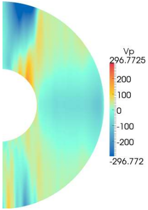
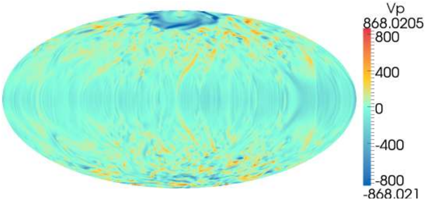
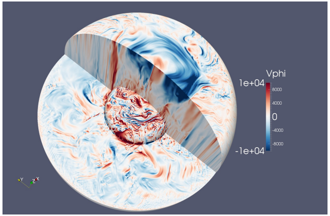
2.1 Structure of geodynamo and its decadal fluctuations

Recent highly-driven, low viscosity, dynamos simulations suggest:

- Striking differences inside vs outside the tangent cylinder
- Regions of strong shear and jets may play an important role in the geodynamo process?





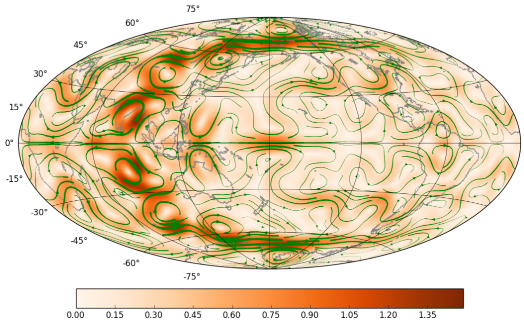


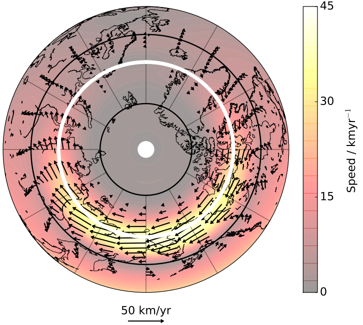
[Sheyko (2014, 2017), Schaeffer et al., (2017)]

- Can such structures be identified and their evolution tracked using high resolution SV?

2.1 Structure of geodynamo and its decadal fluctuations

- Flow inversions indicate preferred regions of strong (decadal) flow acceleration

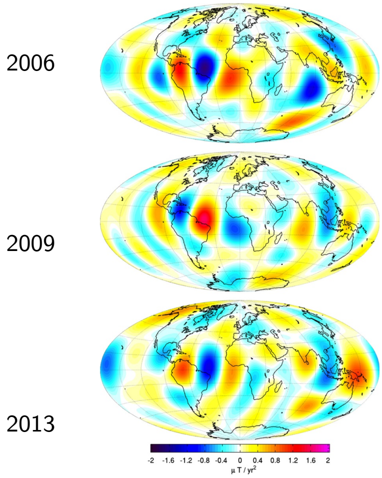


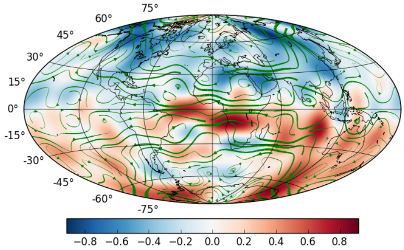


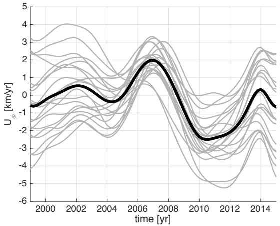
[Gillet and Finlay (in prep), Livermore et al., (2017)]

- Can we map the detailed structure of the flows driving the geodynamo?
- Inferences within the core require additional information (data-assimilation approaches?)
- Can older data sources be utilized to reconstruct decadal variations in these structures?

2.2 Rapid core dynamics: Jerks, pulses and waves







- Localised secular acceleration pulses *[Lesur et al., 2008, Olsen and Mandea, 2008]*
- Compatible with non-axisymmetric azimuthal flow fluctuations *[Gillet et al., 2015]*

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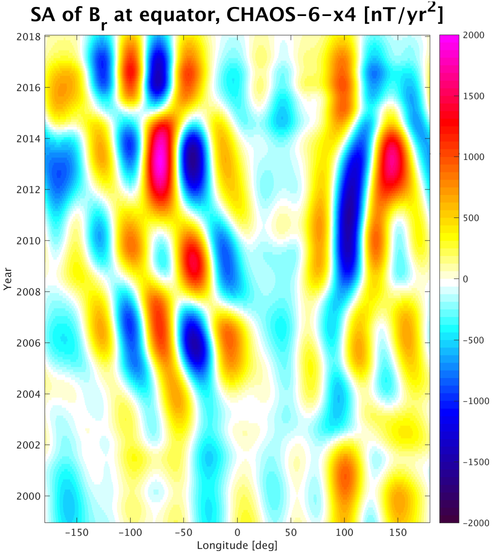

- Opportunity to test hypotheses regarding **rapid core dynamics**!
- Hydromagnetic wave arriving at core surface?
  [Aubert and Finlay, under review]
- MAC wave propagating in stratified layer ?
  [Chulliat et al., 2015]
- Dynamics give information on underlying physical properties (stratification, elec. conductivity)
- Progress requires:
  (i) Suitable forward models
  (ii) Higher spatial and temporal resolution of core field changes

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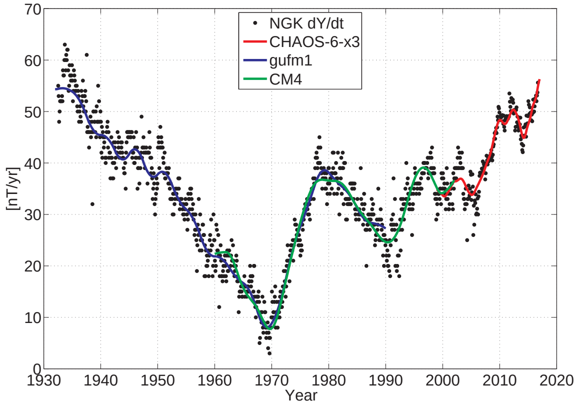
3.1 How best to exploit older datasets?



- Combine with long ground series e.g. AUX_OBS database now back to 1957
- Earlier satellite missions (Magsat, POGO) and ground surveys e.g. gufm1, COV-OBS, CM4

PROBLEM:

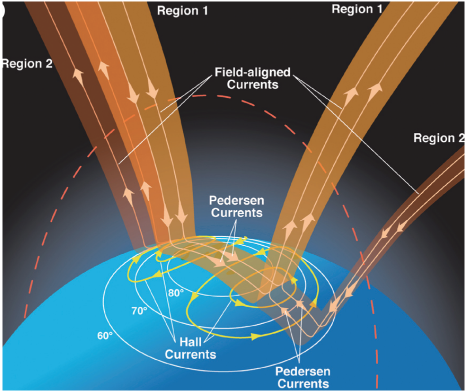
- Model parameterization (external field, regularization) designed for specific data quality

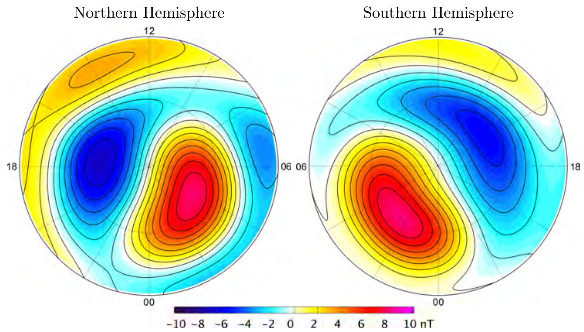
OUTLOOK:

- Might it be possible to propagate information back from *Swarm* era?

  Requires physics-based constraints and data assimilation techniques....

3.2 How to handle signatures of polar ionospheric currents?





- Olsen et al. (2016) made first co-estimation of poloidal potential field due horizontal ionospheric currents

$$V^{\mathrm{MLT}} = a \sum_{n=1}^{20} \sum_{m=1}^{n} \left(g_n^{m,\mathrm{MLT}} \cos m\tau + h_n^{m,\mathrm{MLT}} \sin m\tau \right) \left(\frac{a}{r} \right)^{n+1} P_n^m(\cos \theta_{QD})$$

- Need to co-estimate FAC's and their far-field effects
  And include time-dependence (seasonal, solar-cycle variations) [e.g. Laundal et al., 2016]

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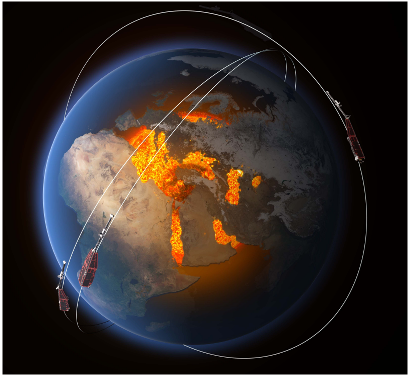
Thinking bigger, where do we want to be in 15 yrs?

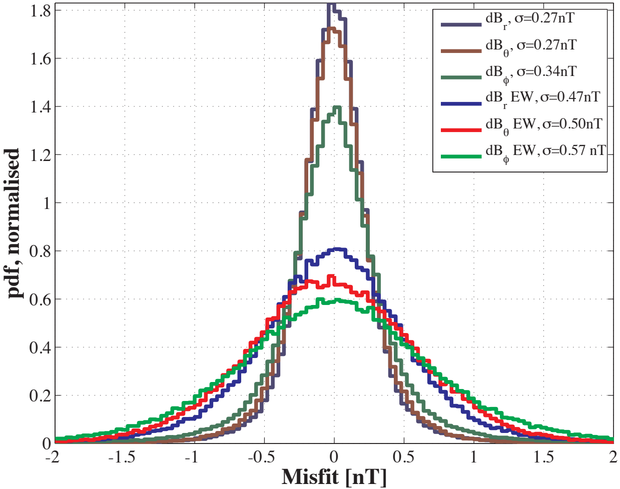
Which forward models, data processing, assimilation/inversion schemes ?

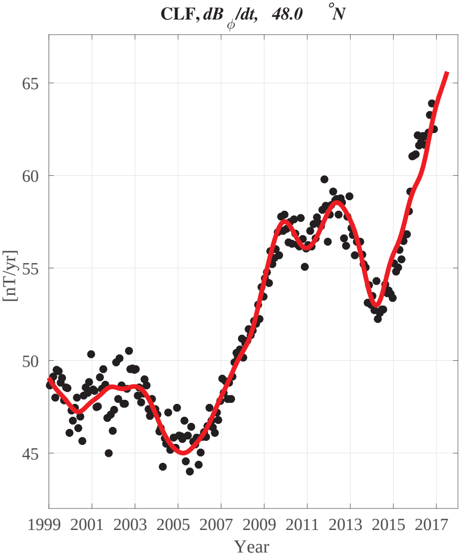
Approximate field gradients



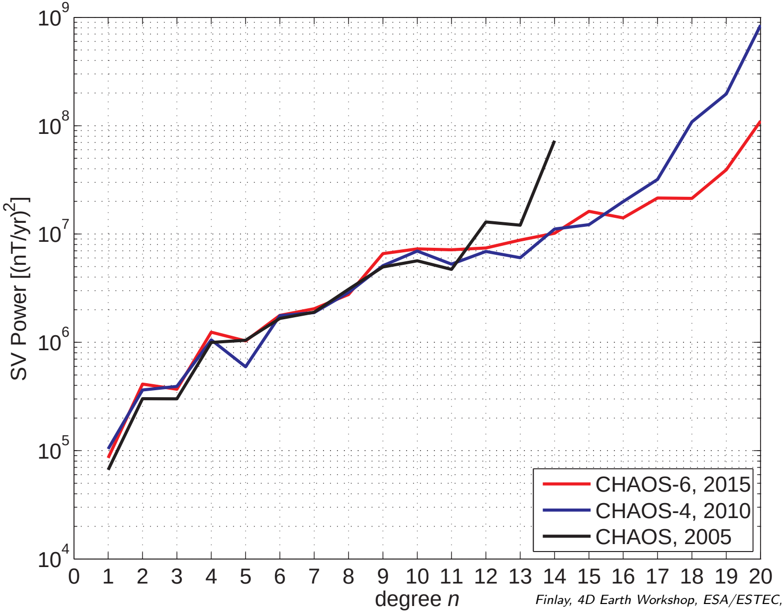
- EW gradients: Given Sw-A data, difference Sw-C data from same latitude, with short delay (typically 10sec)
- Along-track gradients: For a single satellite, difference data separated in time by 15sec
- Assuming fields are stationary over 15 seconds, then
- Large-scale magnetospheric signal cancelled, small-scale internal field signal enhanced

Fit to Swarm gradients and ground SV data

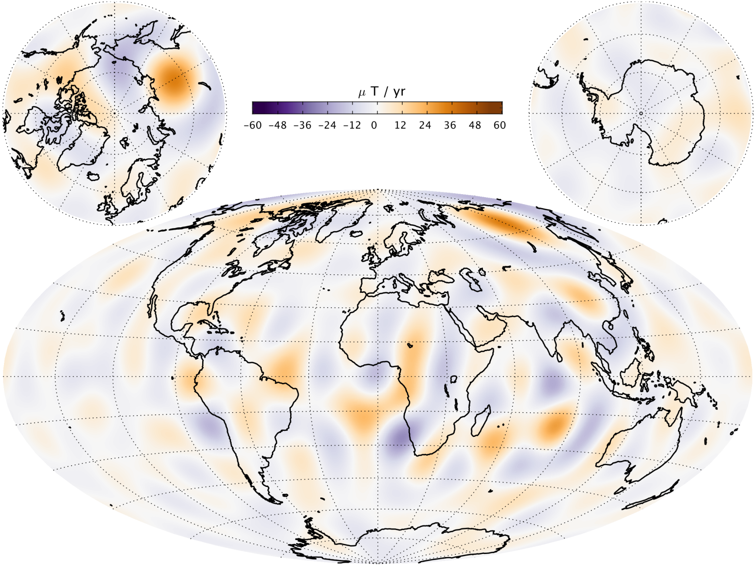




Improving in recovery of core surface SV

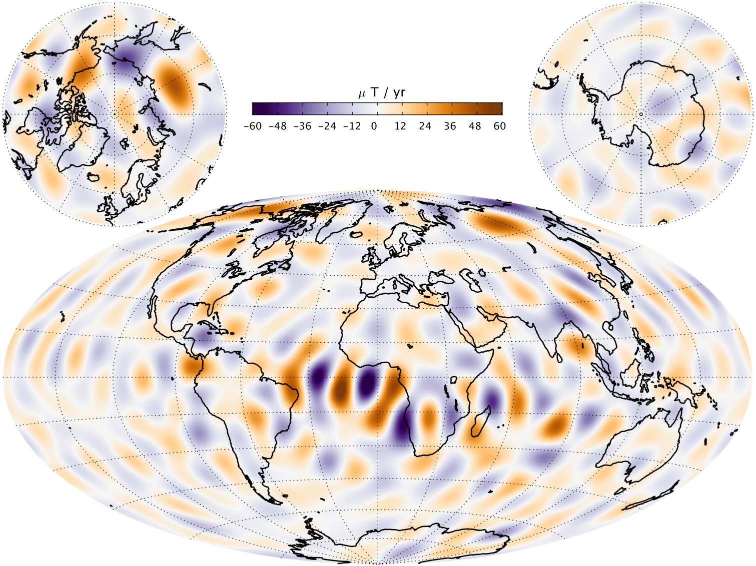


Contrast with pre-Swarm SV from CHAOS-4



[CHAOS-4, 2013, truncated degree 15]

Core field (SV) in 2017



[CHAOS-6-x4, 2017, truncated degree 20]