Rapid core field variations: New insights from magnetic spatial gradients and Swarm data

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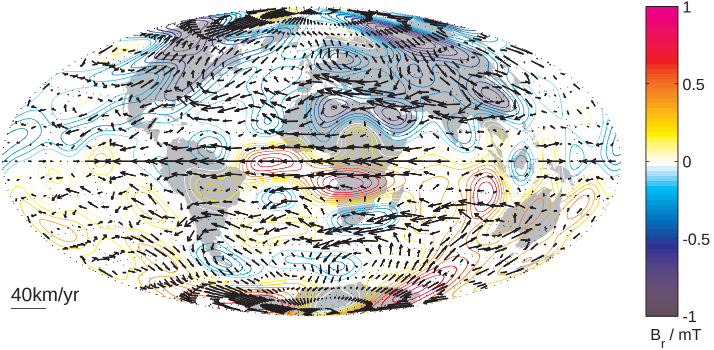
SV as a window into the dynamics of the core

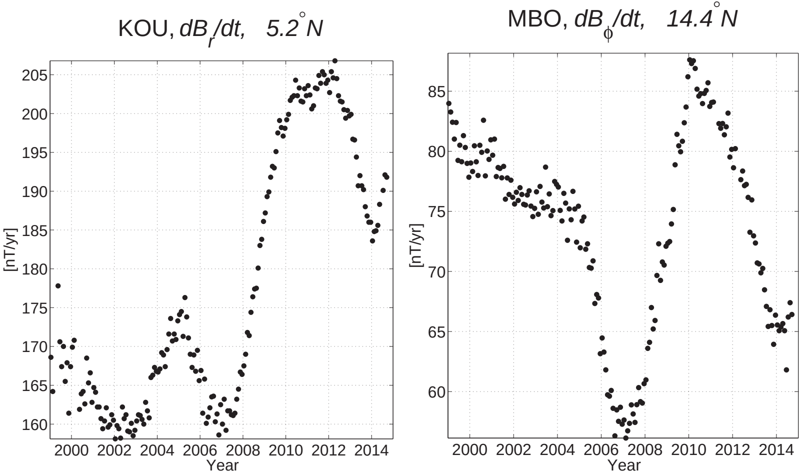
- Secular variation (SV) is the gradual change of the Earth's main magnetic field due to MHD processes in the Earth's core:

$$\underbrace{\frac{\partial \mathbf{B}}{\partial t}}_{\text{Secular variation}} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Advection \& stretching by core flow}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{Ohmic diffusion}}$$



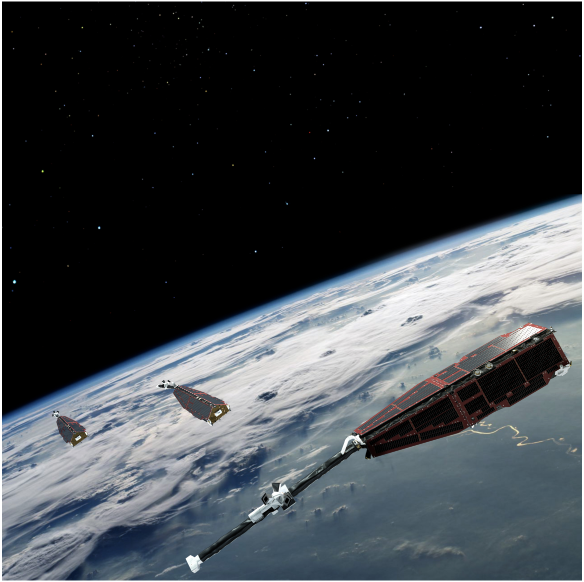
[Example Quasi-Geostrophic core flow, Gillet et al. (2015)]

Rapid (sub-decadal) secular variation

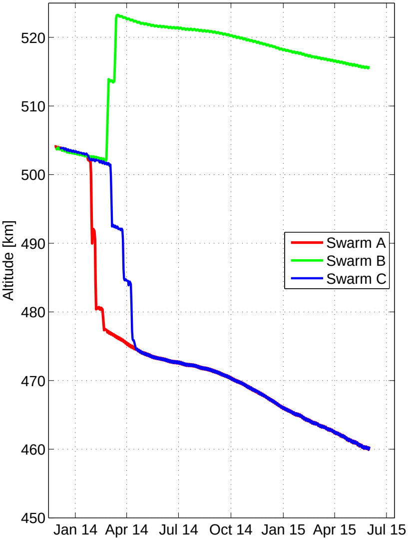


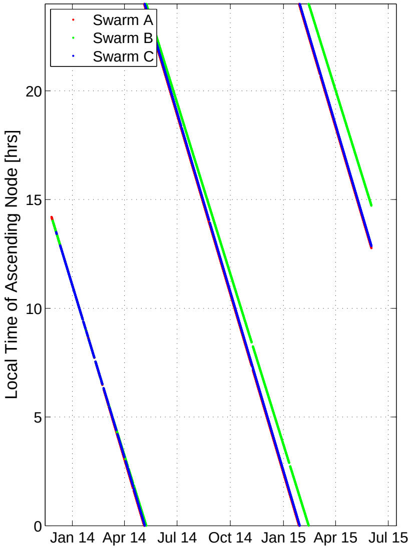
- Field change is not linear on sub-decadal timescales!
- Punctuated by changes in slope called 'jerks'
- Due to localized pulses of field acceleration at core surface (Chulliat et al., 2010)

The Swarm mission: a new era in geomagnetism

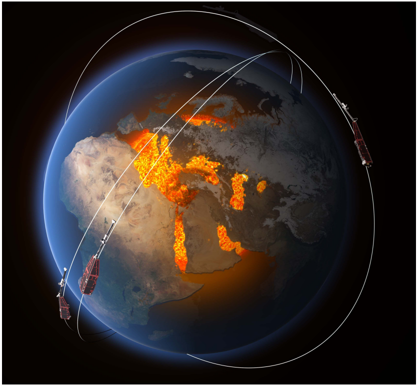


Evolution of the Swarm constellation





Field differences as spatial gradient estimates

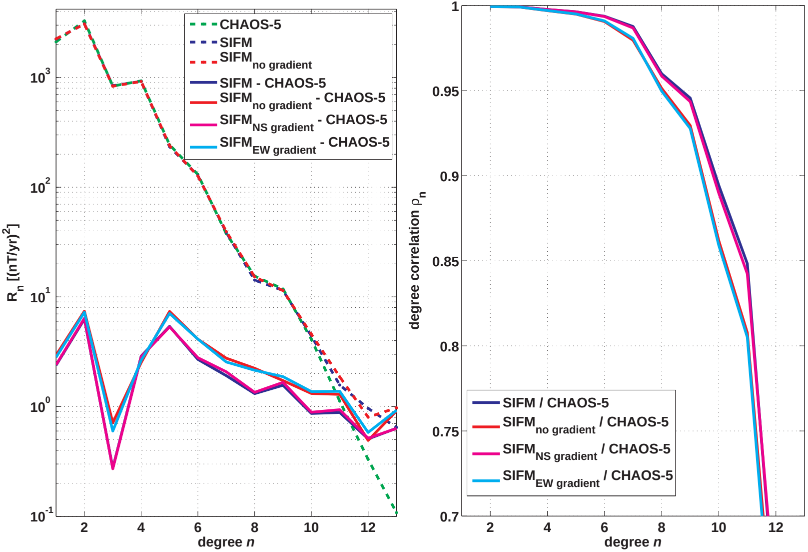


- **NS gradients: approx by along-track differences**
  Assumption: Unwanted disturbance field changes little between sample pts

- **EW gradients: approx by EW inter-satellite differences**
  Assumption: In short time-delayed to align EW disturbance field changes little

[For further details see Kotsiaros et al. (2015) and Olsen et al. (2015)]

Example: Impact of gradients on SV determination



[From Swarm Initial Field Model: Olsen et al. (2015)]

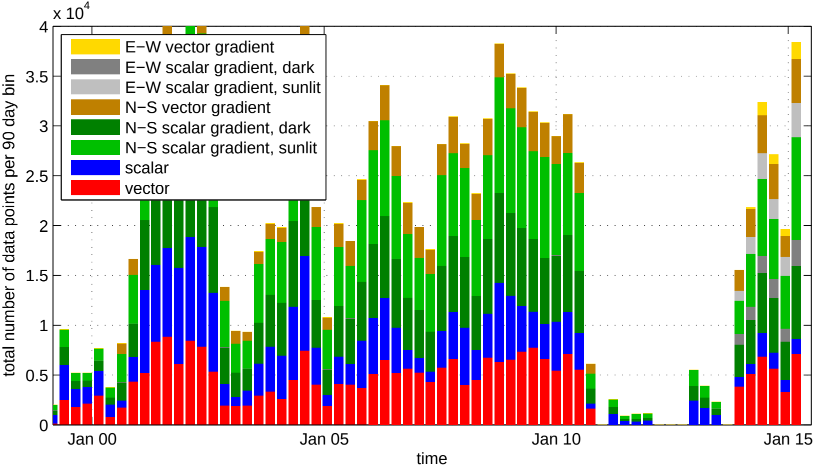
Extension of CHAOS model to use gradient estimates

- Extend CHAOS-5 (Finlay et al., 2015) to include:
  - Latest Swarm vector and scalar data & observatory data available in mid-2015
  - Use Swarm scalar and vector along-track and EW gradient estimates
  - Along-track gradients of Ørsted (scalar) and CHAMP (scalar & vector) data

  - **Selection criteria for field data**
    - *Kp* $\leq$ 2o, $|dD_{st}/dt| \leq$ 2nT/hr
    - Only data from dark regions, Sun at least 10 deg below horizon
    - Use only scalar intensity data in polar regions $> \pm$55 deg quasi-dipole latitude
    - Only if E_m averaged over preceding 2hrs ≤ 0.8mV/m and IMF $B_z > 0$
    - And only if $|dE_m/dt| < 5$ nT/min during the preceding 2 hours.

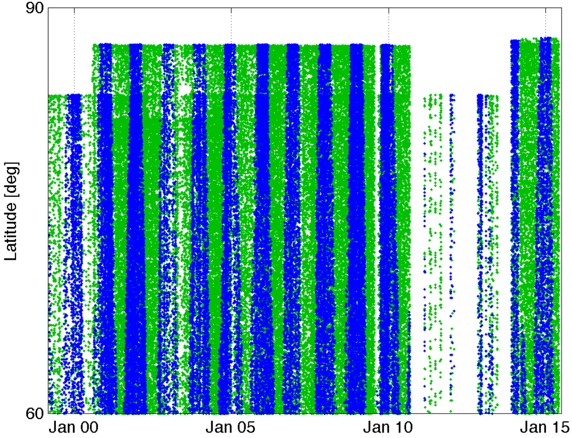
  - **Selection criteria for gradient data**
    - *Kp* $\leq$ 3o, $|dD_{st}/dt| \leq$ 3nT/hr
    - Vector gradients only for dark, non polar regions
    - Scalar gradients also dayside, except $< \pm$ 10deg of mag. equator

Data selection: Dependence on time



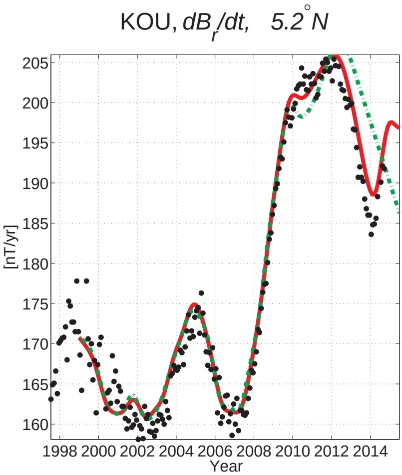
Data selection: Sampling at high latitudes

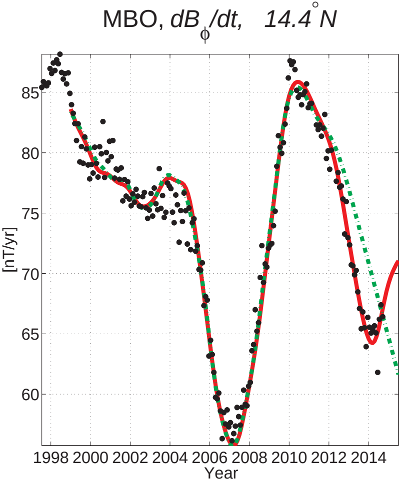
scalar gradients
scalar



Fit to ground observatory secular variation

CHAOS-5x
CHAOS-4 + linear extrapolation





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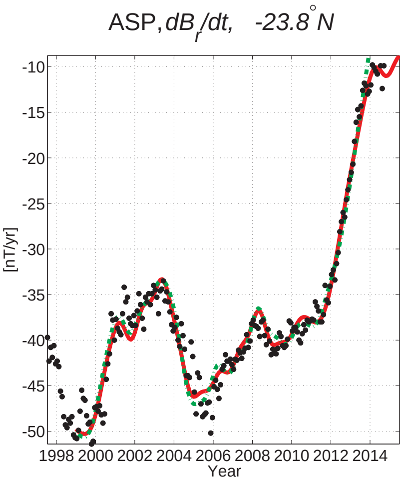
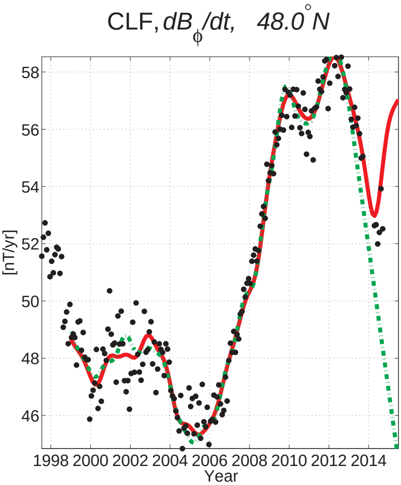
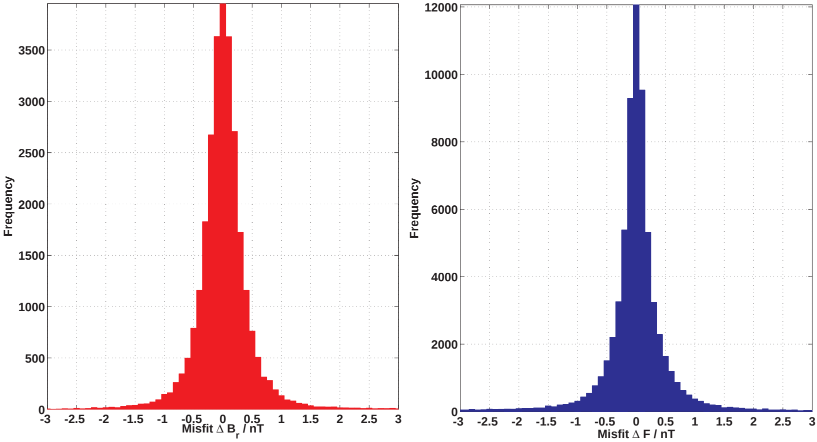


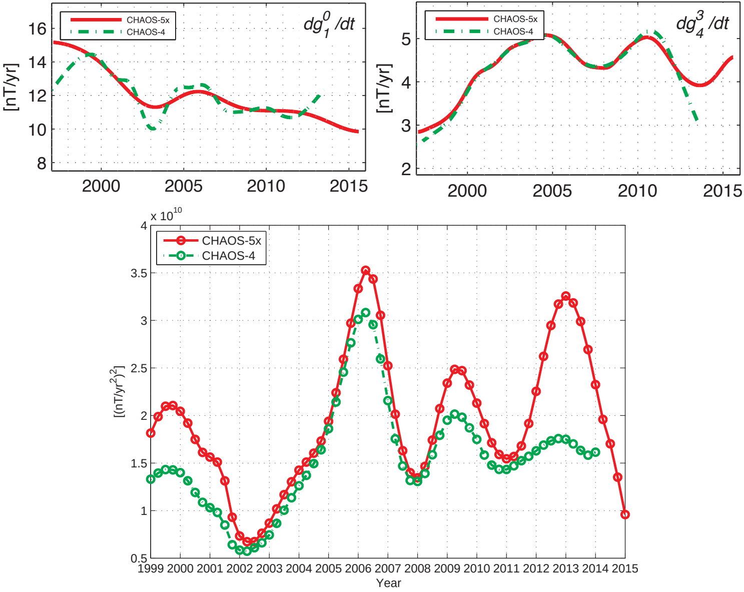


Fit to Swarm gradient estimates

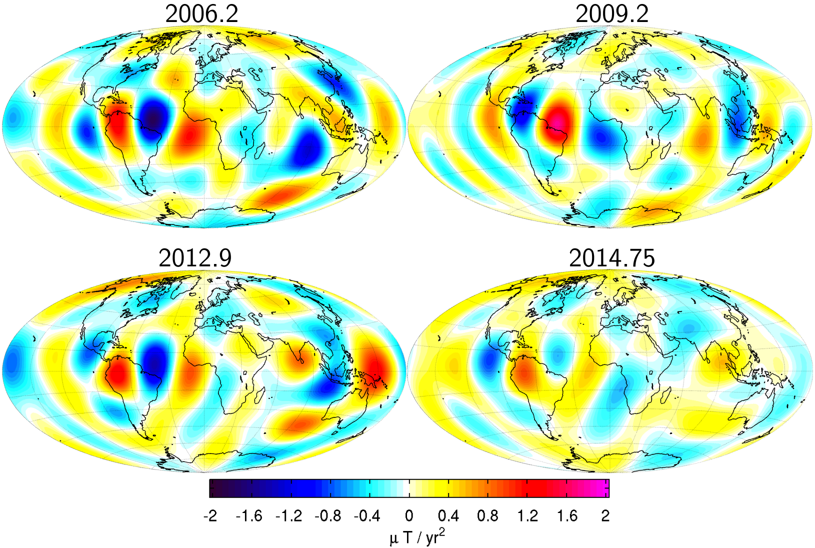


- Huber-weighted RMS Misfit between CHAOS-5x and *Swarm* data, units nT:
  - B_r grad: (AA: 0.29, BB: 0.28, CC: 0.30), **[AC: 0.47]**
  - F grad npol: (AA: 0.28, BB: 0.27, CC: 0.29), **[AC: 0.38]**
  - F grad pol: (AA: 0.87, BB: 0.78, CC: 0.89), **[AC: 0.75]**

Time-dependence of secular variation



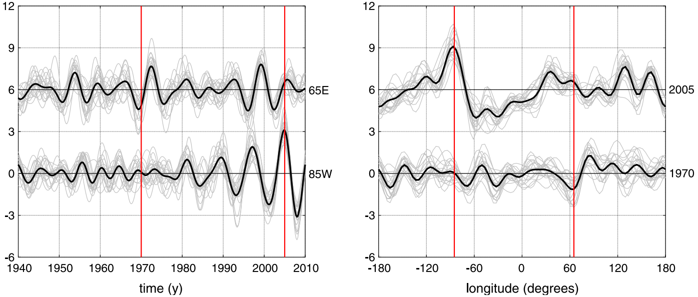
Core surface secular acceleration, up to degree 8



[c.f Chulliat & Maus (2014)]

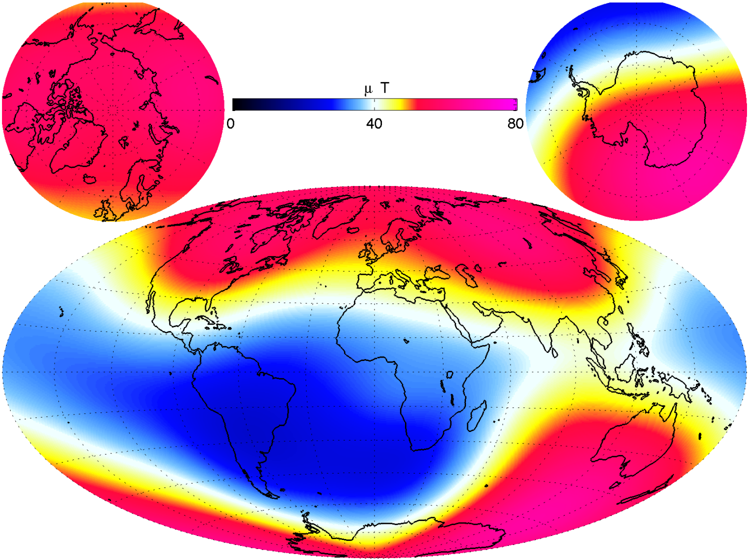
Origin of SA pulses?

- Series of events at low latitude, alternating polarity
- Not axisymmetric torsional oscillations: need stronger $\mathbf{u}_\phi$ at particular locations
- Gillet et al. (2015): due to nonzonal, azimuthal, jets in QG flows.

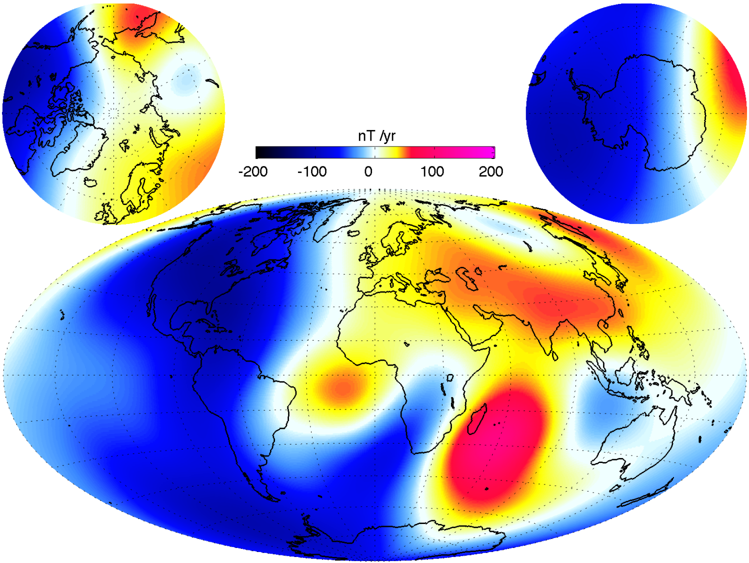


- Possibly a MHD wave e.g. in a stratified layer (Chulliat et al., 2015)?
  Or signature of intermittent convection, where meridional flows arrive/depart from equatorial regions?

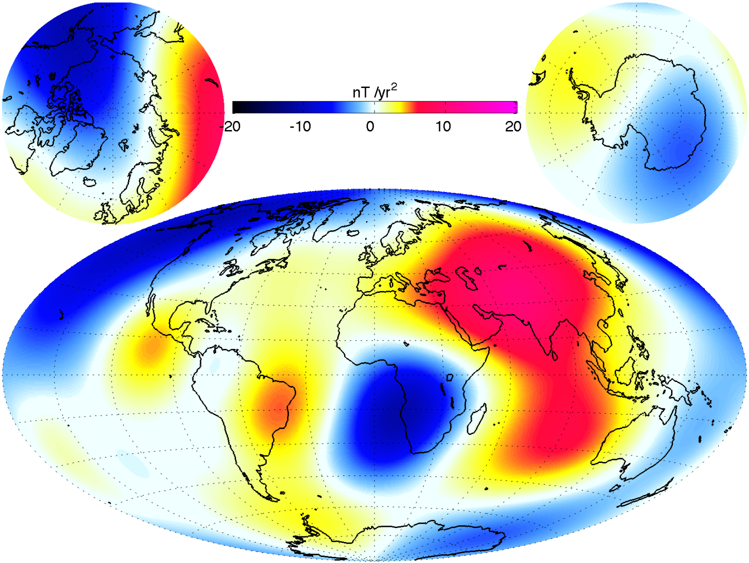
F at Earth's surface: 2015.5



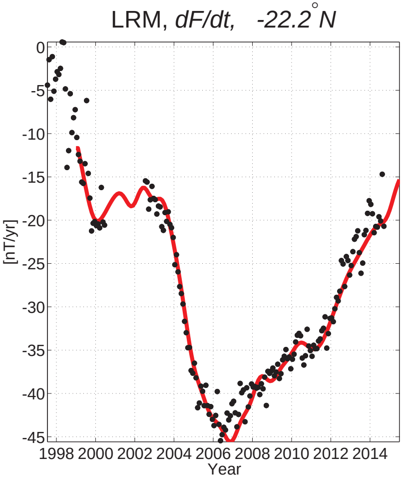
Averaged SV of F at Earth's surface: 2015.5 - 2014.0

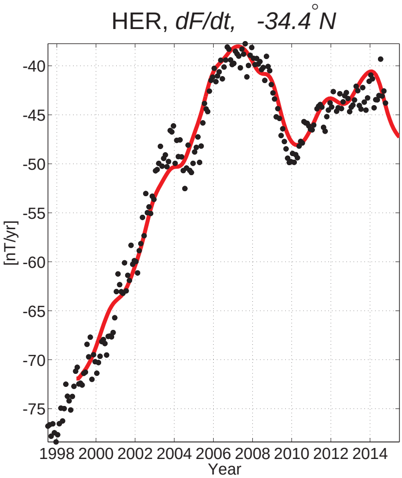


SA of F at Earth's surface: 2015.25-2014.25 (Preliminary)



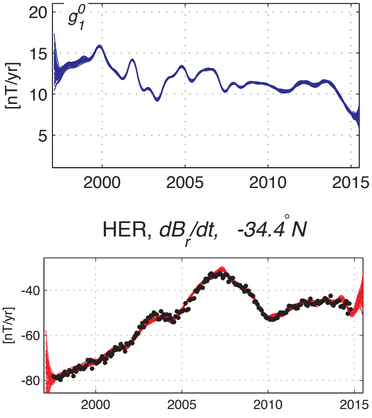
dF/dt at Ground Observatories





Towards imaging rapid changes at small length scales

- Wish to relax strong temporal smoothing at small length scales
- Adopt a model covariance matrix based on Gaussian process (AR-2) model compatible with observatory temporal spectra and jerks (Gillet et al., 2013)
- Derive models covariance matrix and use this to create an ensemble of field models compatible with the data and the temporal prior



- Still under development, esp. regarding unwanted oscillations at polar latitudes

Summary

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- Involve fluctuations of non-axisymmetric, azimuthal flow
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- Hints that field strengthening over Asia/Indian ocean and field weakening over Southern Africa may be accelerating (but more data need to confirm this!)

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- Rapid core field changes have occurred over the past decade
- Involve fluctuations of non-axisymmetric, azimuthal flow
  But underlying core dynamics unclear

- Observations from Swarm, including spatial gradients, allow improved models of SV and its time dependence
- Hints that field strengthening over Asia/Indian ocean and field weakening over Southern Africa may be accelerating (but more data need to confirm this!)

- Work ongoing on improved modelling/regularization schemes to better probe rapid time changes at short lengths scales

Chulliat, A. & Maus, S., 2014. Geomagnetic secular acceleration, jerks, and a localized standing wave at the core surface from 2000 to 2010, *J. Geophys. Res.*, **119**, doi:10.1002/2013JB010604.

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Model parameterization

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

- The internal part of the potential takes the form

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

- Define external potential 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* coordinates dependent on the the RC index

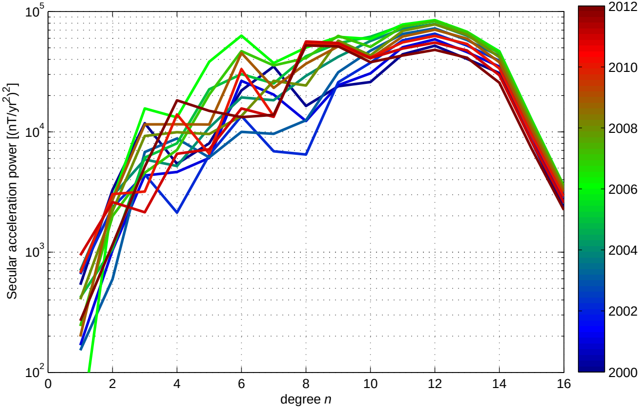
Model estimation

- Work with data in **magnetometer frame** co-estimating Euler angles
- **Robust non-linear least squares including regularization**, iteratively minimizing

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

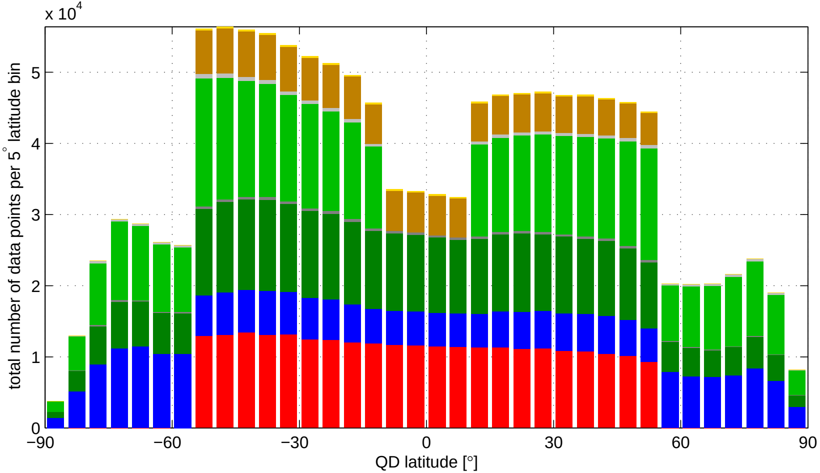
$\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are regularization matrices

Limitations of present observational techniques

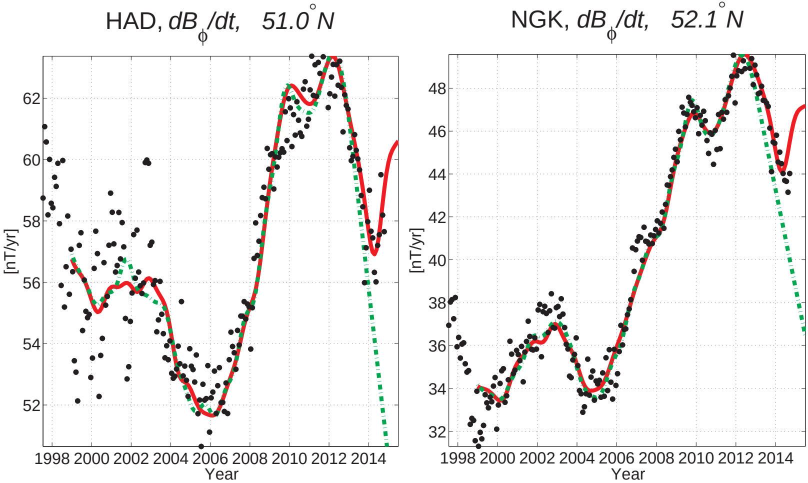


- Global field models are smoothed strongly in time, especially at small lengthscales e.g. SA power versus degree from CHAOS-4 (Olsen et al., 2014)
- Necessary to control leakage of unmodelled external field, especially at high latitude, and due to limitations of traditional data selection criteria

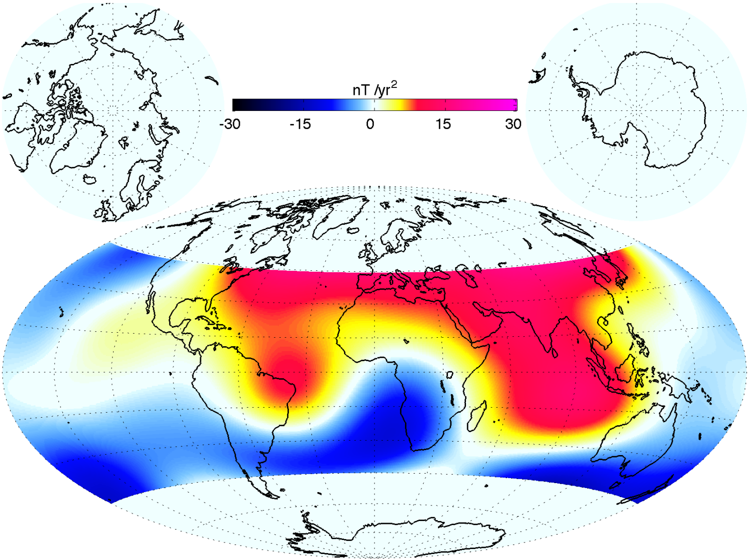
Data selection: Latitude dependence



A jerk in Europe in 2014?



SA of F at Earth's surface: 2015.25-2014.25 (Preliminary, SIFM+)



dF at Ground Observatories