The origin of core field secular acceleration pulses

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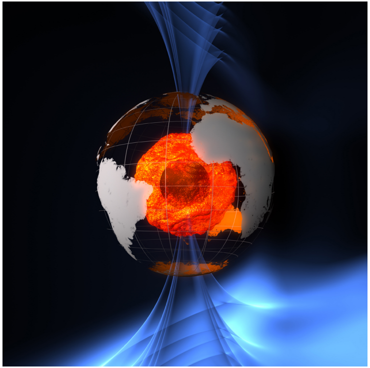
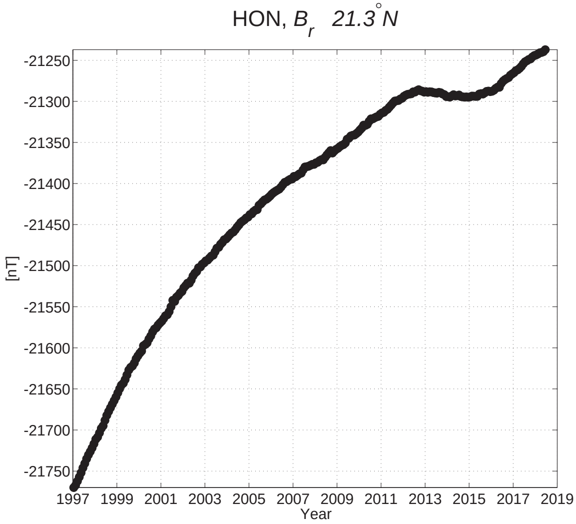
J. Aubert (IPGP)



Secular acceleration pulses



- Core field change is not linear
- Observe 'pulses' of enhanced secular acceleration
- Duration of pulses are short, typically 1-2 years
- Recurrence times and amplitudes are unpredictable
- Geomagnetic Jerks occur between consecutive acceleration pulses of opposite sign

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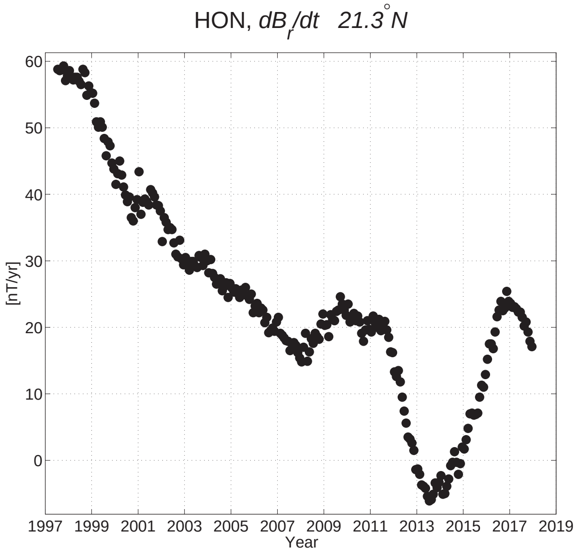

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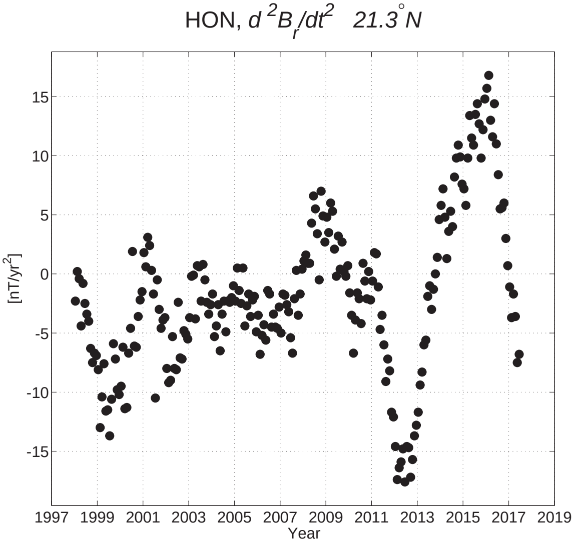

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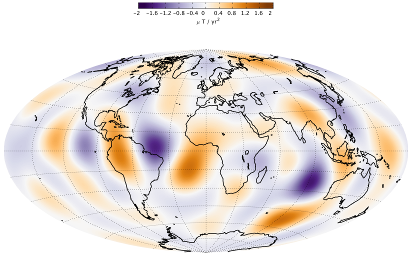
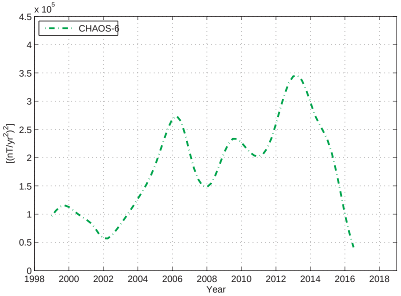
Secular acceleration pulses at the core surface

- Acceleration pulses localized in space
  [Lesur et al., 2008, Olsen and Mandea, 2008]
- Prominent signature at low latitudes
- Series of pulses over the past two decades
  [Chulliat et al. 2010; Chulliat and Maus, 2014]



- Wish to better characterise pulses at the core surface
- And to understand the physical process responsible
- Longer time series are essential



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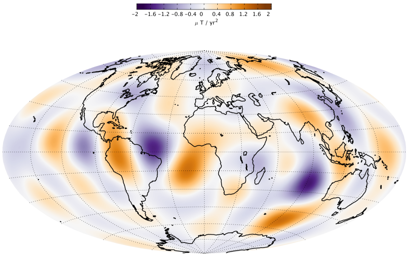

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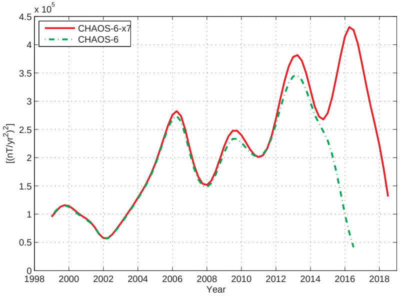


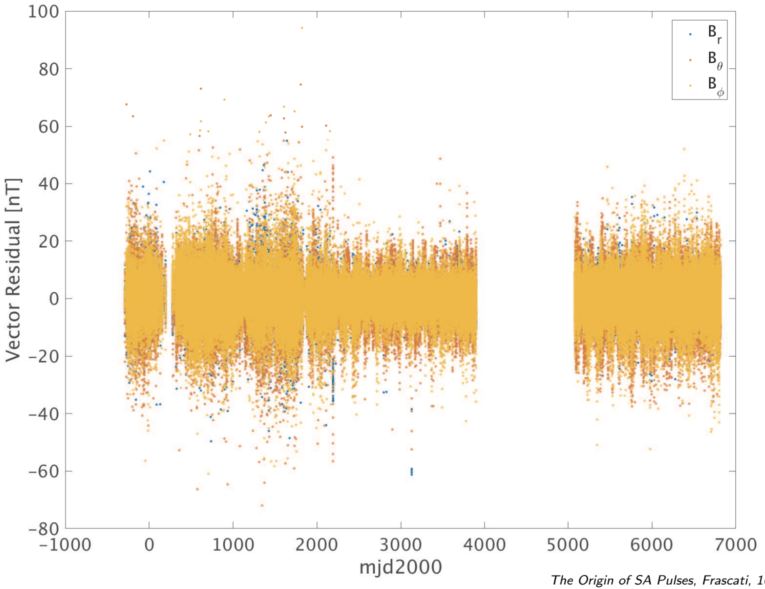
Tool 1: CHAOS-6-x7 global geomagnetic field model

- Latest update of CHAOS field model *[Olsen et al., 2014; Finlay et al., 2016]* is **CHAOS-6-x7**, see

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

- Uses MAG L1B LR 0505 *Swarm* data (scalar field, vector field, field differences) until end of Aug 2018
- Model spans 1999 - 2018, also using CHAMP, Østed and SAC-C satellite data, from 'quiet' times
- Plus revised monthly means from AUX_OBS ground obs. hourly means as available in August 2018
- 10,777,772 data in all
- Weighted rms misfit to *Swarm* non-polar, dark scalar data is **2.39 nT**,
  For scalar field differences, **0.25 nT** along-track and **0.41 nT** cross-track.
- CHAOS forward code has been translated to Python: the **chaomagpy** package (see CHAOS-6 webpage)

CHAOS-6-x7: Residuals to 0505 Swarm data



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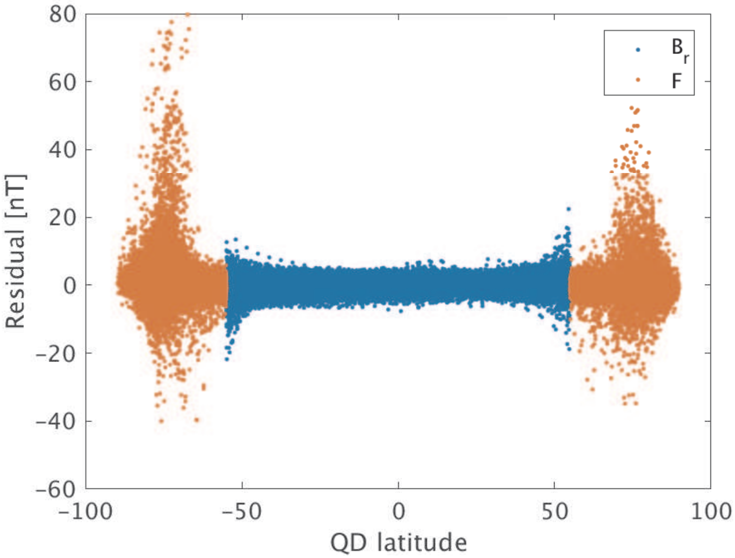
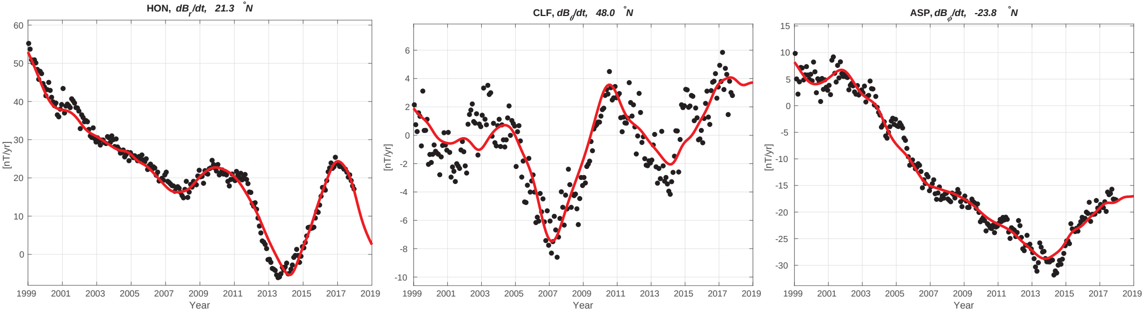


CHAOS-6-x7: example comparisons with updated ground observatory data



Core surface secular acceleration pulses in CHAOS-6-x7

[Finlay et al., 2018, CHAOS-6-x6, to degree 9]

Tool 2: Optimized Local Analysis of Core Field (SOLA)

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- Forward scheme:

$$d_n(\mathbf{r_n}) = \int_S G_n(\mathbf{r_n}, \mathbf{s}) B_r(\mathbf{s}) dS$$

where G_n is the Green's function for the Neumann boundary value problem relating $B_r(\mathbf{s})$ on S to data d_n.

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- Estimate the field at a location of interest $\mathbf{s_0}$ on S using

$$\widehat{B_r}(\mathbf{s_0}) = \sum_n q_n(\mathbf{s_0}) d_n = \sum_n q_n(\mathbf{s_0}) \int_S G_n(\mathbf{r_n}, \mathbf{s}) B_r(\mathbf{s}) dS = \int_S \mathcal{K}(\mathbf{s_0}, \mathbf{s}|\mathbf{r_n}) B_r(\mathbf{s}) dS$$

where $\mathcal{K}$ is a 'Resolution Kernel', describing how the estimate is a averaged version of the true $B_r(\mathbf{s_0})$

$$\mathcal{K}(\mathbf{s_0}, \mathbf{s}) = \sum_n q_n(\mathbf{s_0}) G_n(\mathbf{r_n}, \mathbf{s})$$

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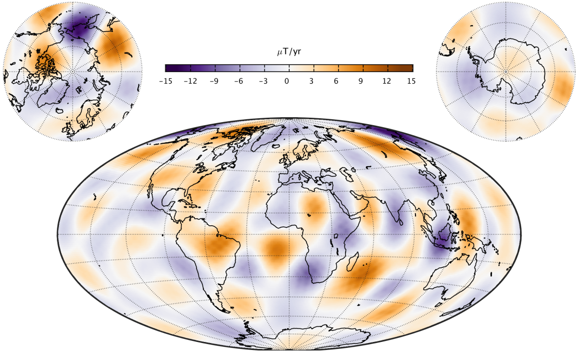
- SOLA: Subtractive Optimized Local Average: find q_n such that $\mathcal{K}$ is as close as possible to a target Kernel $\mathcal{T}$

$$\min \quad \oint_S [\mathcal{K}(\mathbf{s_0}, \mathbf{s}) - \mathcal{T}(\mathbf{s_0}, \mathbf{s})]^2 dS + \lambda \underline{\underline{E}} \quad \text{subject to} \quad \int \mathcal{K}(\mathbf{s_0}, \mathbf{s})\, dS = 1$$

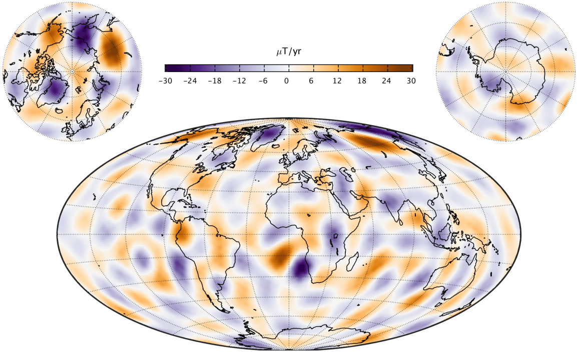
- Variance on the estimate is obtained as

$$\sigma^2(\mathbf{s_0}) = \mathbf{q}^T \underline{\underline{E}} \mathbf{q}$$

Core field SV in 2016.5, collections of SOLA local estimates



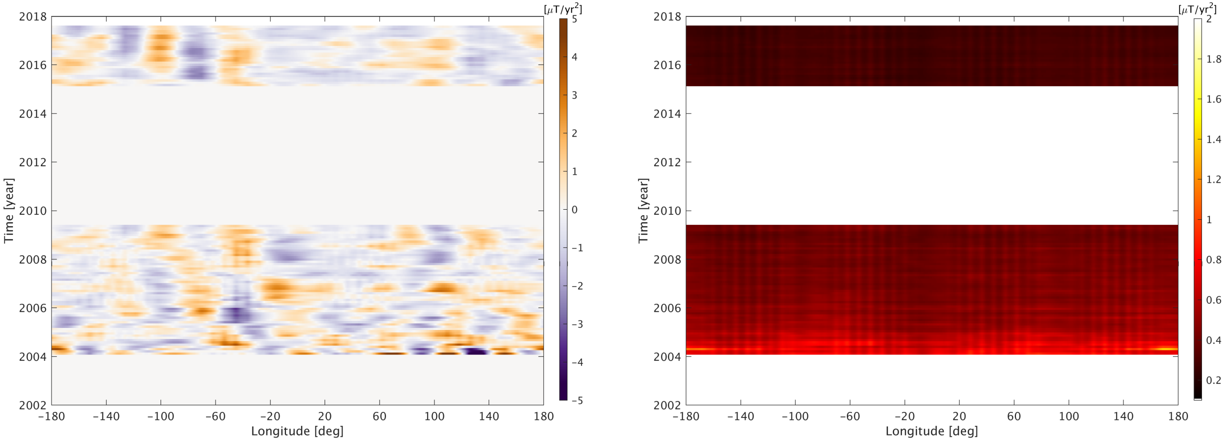
λ=5e-3, $\sigma = 0.25\mu T/yr$, Kernel width 42 deg



λ=2.5e-4, $\sigma = 5\mu T/yr$, Kernel width 30 deg

[Hammer and Finlay, 2018, under review]

Time-longitude plot of equatorial SA, from SOLA estimates



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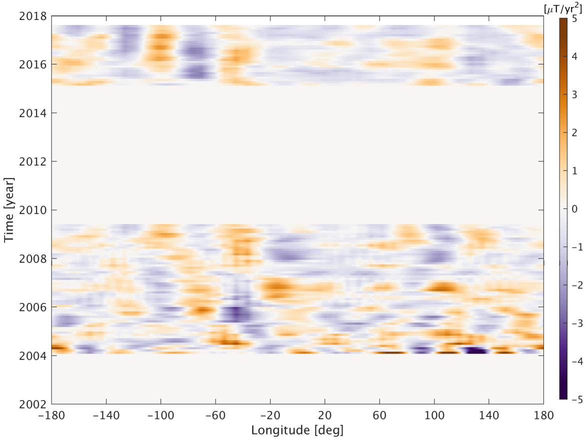
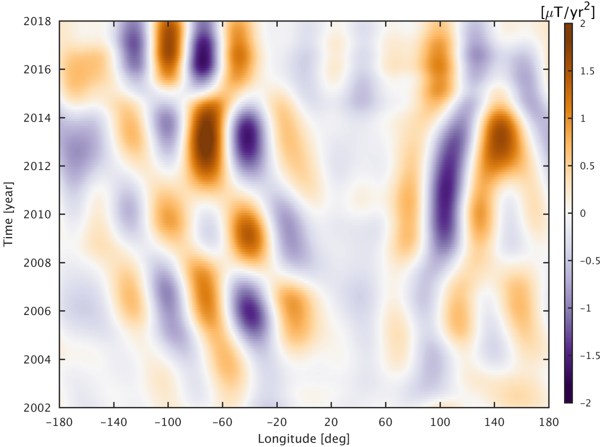


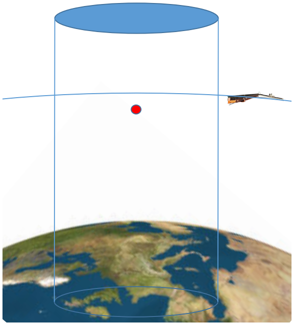
SOLA



CHAOS-6 to deg 9

Tool 3: Virtual Observatories: Localised point estimates at satellite altitude

- **Time series of monthly point estimates at satellite altitude**
  [Mandea and Olsen, 2006; Olsen and Mandea, 2007; Whaler and Beggan, 2015; Barrois et al., 2018]
- Take data within 700km of cylinder center, every 4 months
- Selection criteria: dark, quiet time data
  ($K_p < 3$, $|dRC/dt| < 3$nT/hr, IMF $B_z > 0$, $E_m < 0.8$ mV/m)
- Remove estimates of core, crustal, magnetospheric and S_q fields
- Work with sums and differences of data, along and across track

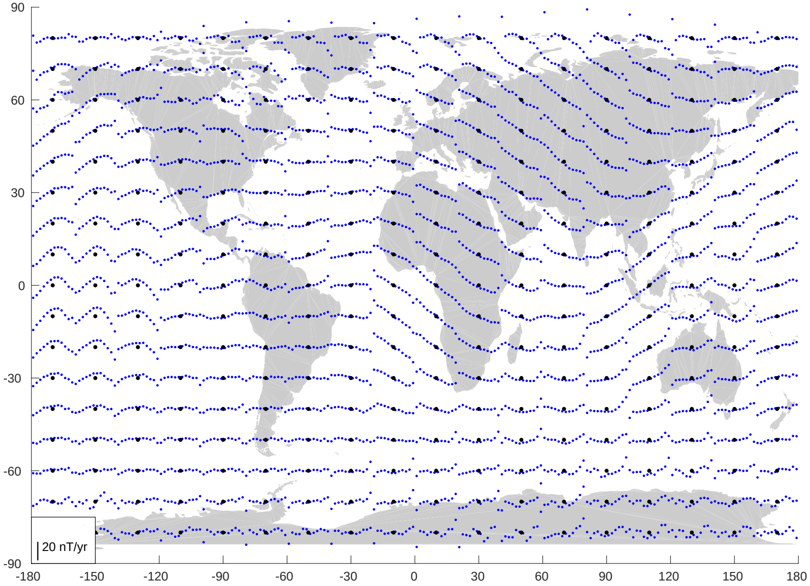


- Robust (Huber weighted) fit of **local cubic potential**

$$\begin{aligned}V(x,y,z) = {} & v_x x + v_y y + v_z z + v_{xx}x^2 + v_{yy}y^2 - (v_{xx}+v_{yy})z^2 \\ & +2v_{xy}xy + 2v_{xz}xz + 2v_{yz}yz - (v_{xyy}+v_{xzz})x^3 \\ & +3v_{xxy}x^2y + 3v_{xxz}x^2z + 3v_{xyy}xy^2 + 3v_{xzz}xz^2 + 6v_{xyz}xyz \\ & -(v_{xxy}-v_{yzz})y^3 + 3v_{yzz}y^2z + 3v_{yzz}yz^2 - (v_{xxz}+v_{yyz})z^3\end{aligned}$$

- Calculate prediction at chosen reference point using $\mathbf{B} = -\nabla V$

dB_r/dt during the Swarm era, as seen by VO's



Inversion for time-dependent core flow

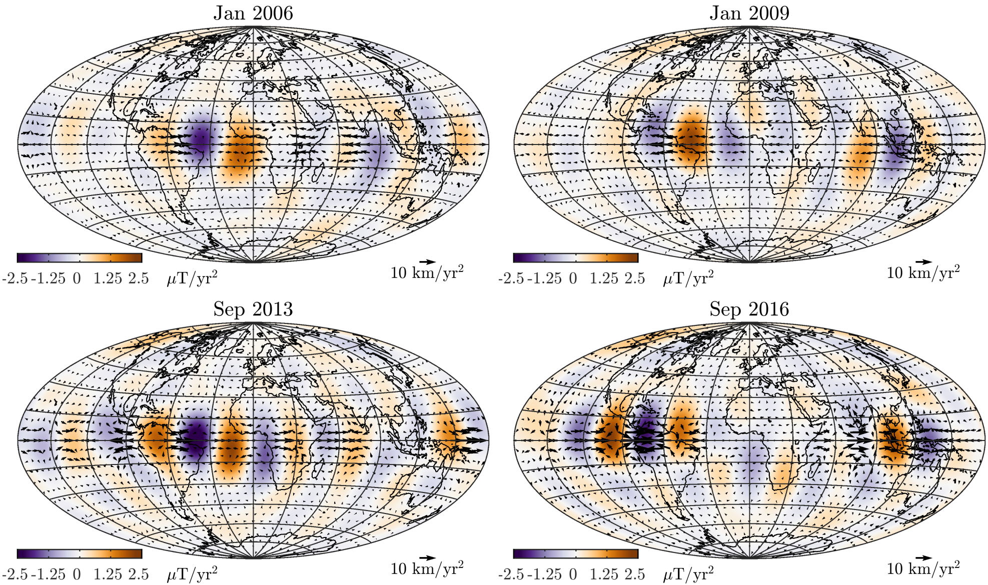
Under the frozen-flux approximation, at the surface of the outer core we have

$$\frac{\partial B_r}{\partial t} = -\nabla_{\mathrm{H}} \cdot (\mathbf{u} B_r),$$

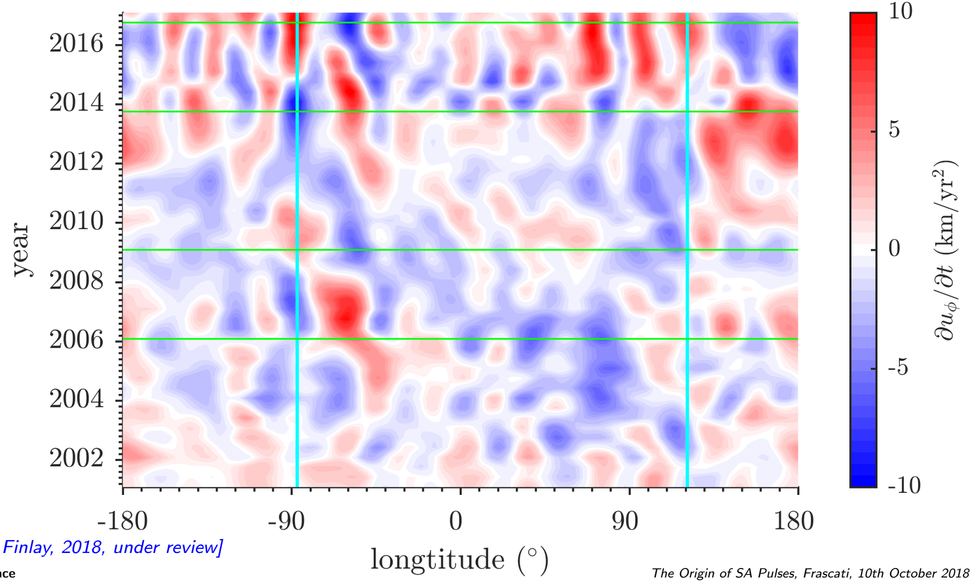
- Use Ground Observatories at Earth's surface and Virtual Observatories at satellite altitude, 4 month steps
- Separate responsible flow into steady and time-dependent parts
- Expand flow using basis of inertial modes plus geostrophic flow *[e.g. Zhang and Liao, 2017]*
- Assume time-dependent part is equatorially-symmetric, consisting of geostrophic and quasi-geostrophic parts
- Minimize L_1 norm of mode enstrophy, flow acceleration and account for error due to unresolved scales
- Solve iteratively using the scheme

$$\mathbf{m}_{k+1} = \left(\mathbf{G}^{\mathrm{T}}\mathbf{W}_d\mathbf{G} + \mathbf{R}(\mathbf{m}_k)\right)^{-1}\mathbf{G}^{\mathrm{T}}\mathbf{W}_d\mathbf{d}^{\mathrm{obs}}$$

Flow accelerations responsible for SA pulses



Azimuthal flow accelerations at low latitudes



[Kloss and Finlay, 2018, under review]

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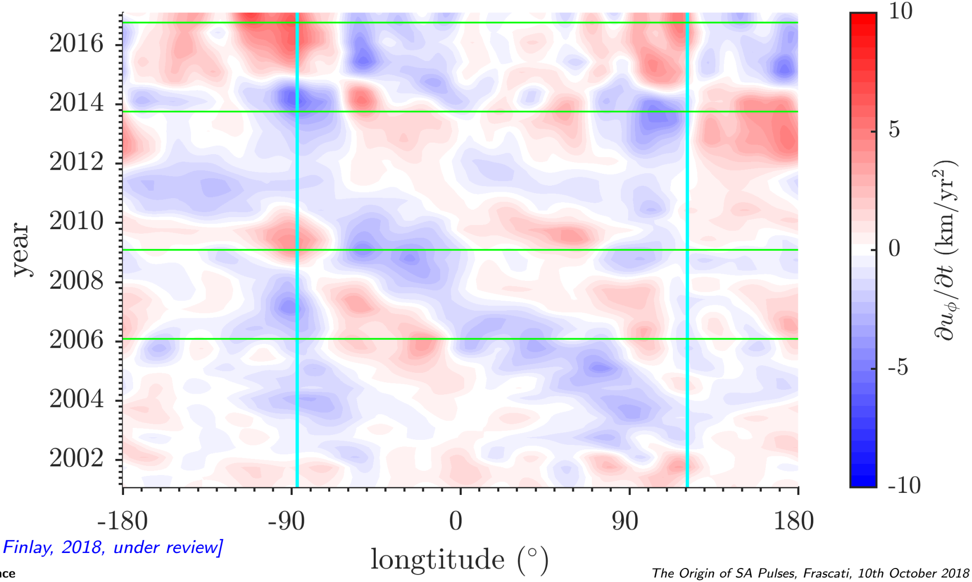

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Tool 4: Numerical geodynamo simulations

- Solve simultaneously eqn for:
  - **Conservation of momentum** in a rotating, electrically conducting, Boussinesq fluid
  - **Magnetic induction** under the MHD approx
  - **Heat/buoyancy transport**

- V. challenging to reach rapidly-rotating regime due to disparities of time and length scales

- *Aubert et al., (2017)* propose to follow a path through parameter space maintaining R_m
- Enhance viscosity at small length scales
- But achieve an Earth-like ratio of time scales:

  Convective timescale $>>$ Alfvén wave timescale $>>$ Rotation timescale

- Allows interaction btw slow convective processes and faster hydromagnetic wave dynamics to be studied

Bursts of buoyancy occur deep within the core

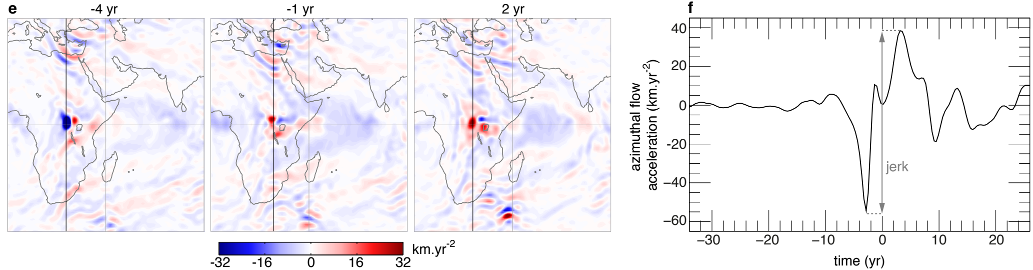
[Aubert and Finlay, under review]

Due to magnetic tension, these trigger (QG) Alfvén waves

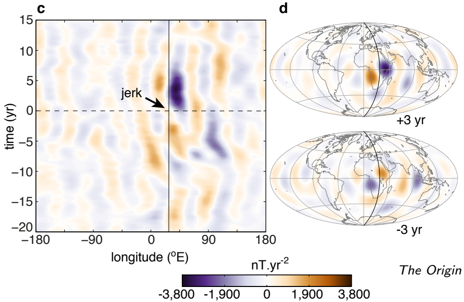
[Aubert and Finlay, under review]

Produce SA pulses and jerks as they arrive at the core surface

Simulated core surface flow acceleration



Simulated magnetic acceleration at core surface



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- **Can now invert data directly for local estimates of core surface field and derivatives (SOLA)**
  - Choose location of interest, time window, spatial averaging target function
  - Can produce regular estimates of the field (e.g. monthly) and SV/SA (e.g. annual)
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- **Numerical dynamo simulations beginning to show events relevant to pulse origin** *[Aubert, 2018]*
  - Arrival of QG Alfvén waves at core surface (much faster than convective processes)
  - Many features not yet fully understood, but v. intriguing dynamically consistent mechanism for pulses/jerks