Swarm 10 Year Anniversary
& Science Conference 2024

A Swarm of jerks

Using the spatial gradient tensor for core-surface flow modelling

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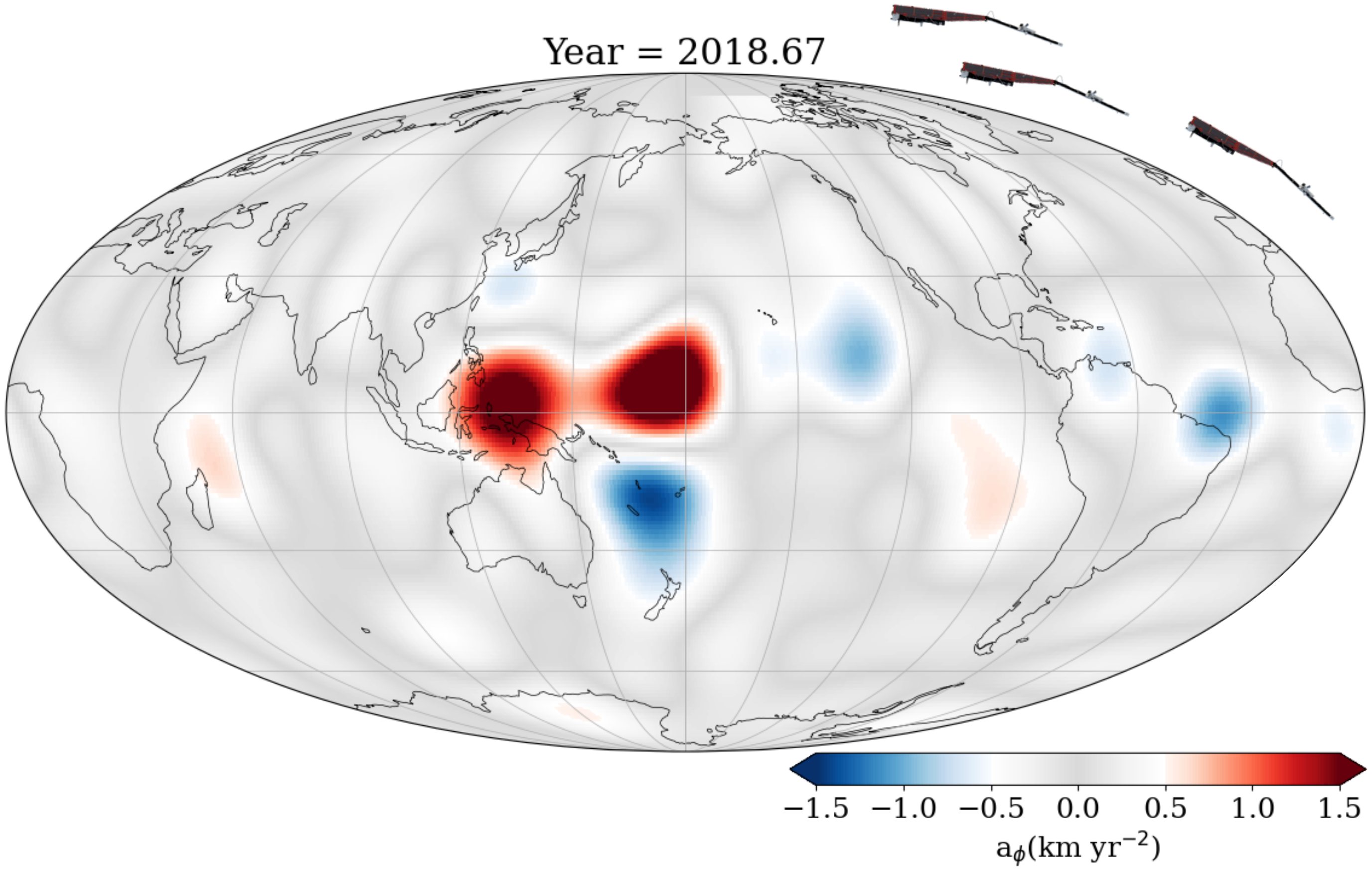
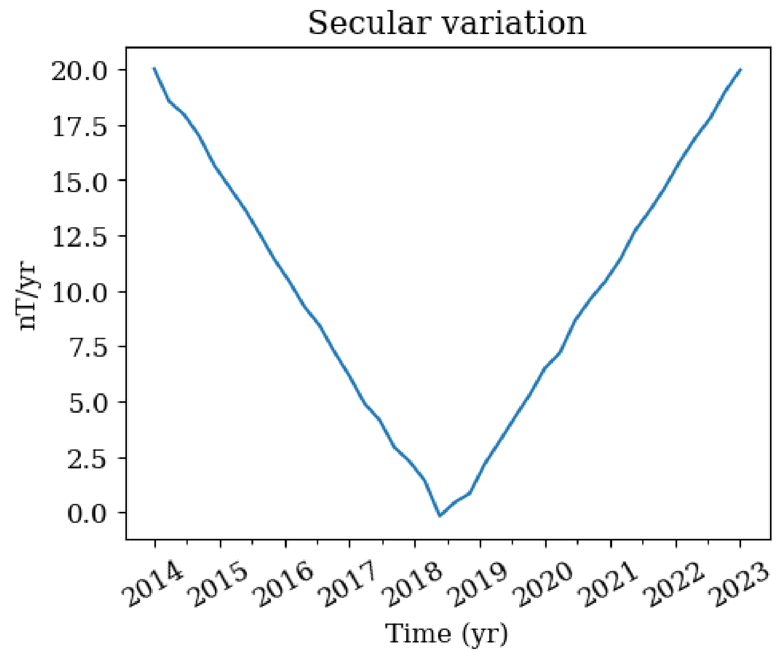


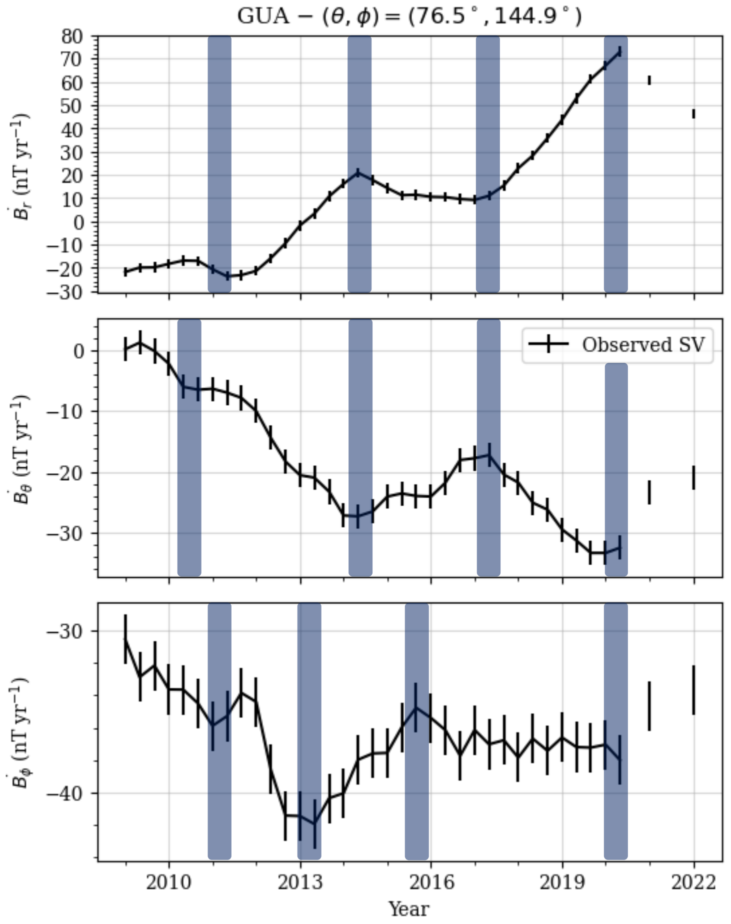
1. THE UNIVERSITY of EDINBURGH School of GeoSciences
2. British Geological Survey
3. UNIVERSITY OF LIVERPOOL

What are geomagnetic jerks?

- The internal magnetic field from the outer core is highly dynamic.
- Geomagnetic jerks: **abrupt*** **changes** in **secular variation** (**SV**), often V or Λ shaped.



Synthetic geomagnetic jerk



Geomagnetic jerks at GUA

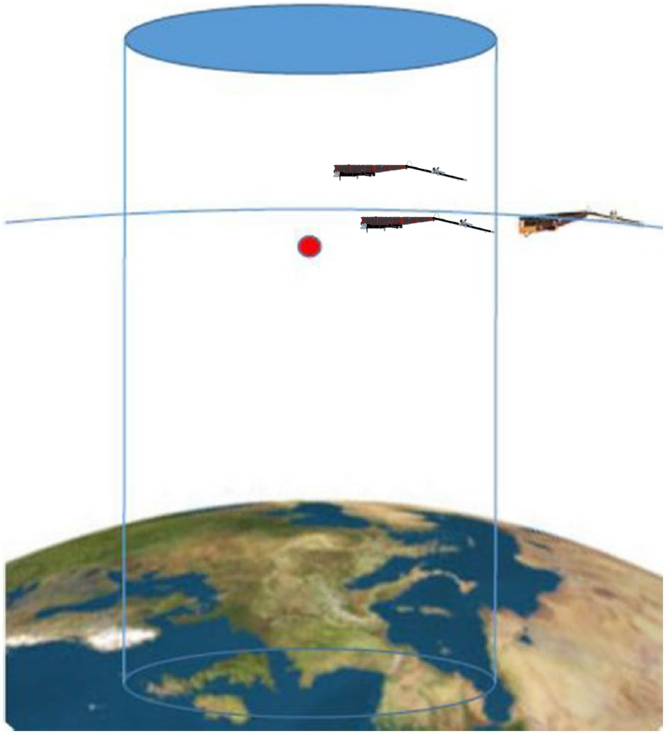
*< 1 year

Geomagnetic virtual observatory (GVO) gradients

- Bin satellite data onto a semi-regular grid on a sphere,
  - Each grid point is the centre of a cylinder (radius = 700 km)
- This is the **GVO**
- By taking along- and across* track differences of the data, we can estimate the **spatial gradients tensor** (Hammer et al. 2022)

$$\begin{pmatrix} [\mathbf{B}]_{rr} & & \\ [\mathbf{B}]_{r\theta} & [\mathbf{B}]_{\theta\theta} & \\ [\mathbf{B}]_{r\phi} & [\mathbf{B}]_{\theta\phi} & [\mathbf{B}]_{\phi\phi} \end{pmatrix}$$

- We can obtain gradients from **Swarm** and **CHAMP**

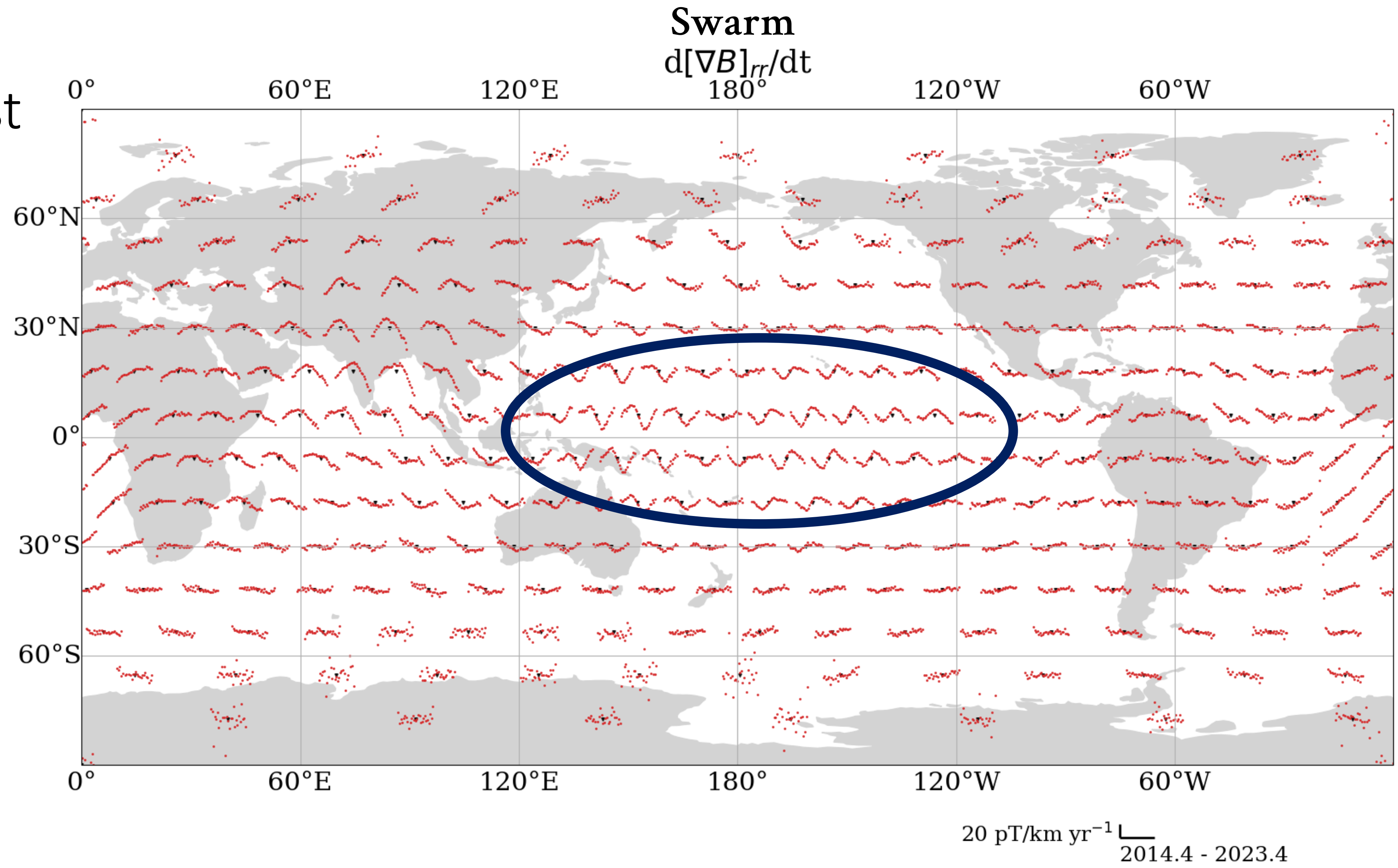


Hammer et al. (2021), EPS

*Across track differences only available with Swarm

GVO gradients from Swarm

- We obtain **SV** from first annual differences
- We use **4-monthly** mean gradient tensor SV
- For **Swarm**, this gives 28 epochs, from **2014.4—2023.4**
- For **CHAMP**, this gives 27 epoch, from **2001.4—2010.0**



Thanks to Jonas Bregnhøj Lauridsen and Chris Finlay at DTU for these data.

Flow inversion – inverting the induction equation

- Assume that **magnetic field** is **“frozen”** into the **fluid flow** → Neglect diffusion
  →i.e. “When the **field moves, it is moved by flow** in the outer core”

- This leads to **reduced induction equation:**

Horizontal surface flow

$$\dot{B}_r + \nabla_{\mathbf{H}} \cdot (\mathbf{u}_{\mathbf{H}} B_r) = 0 \quad \equiv$$

Radial secular variation

Radial magnetic field

Secular variation is driven by the interaction between **flow** and the **magnetic field**

- By **decomposing the flow** into **poloidal** ($\mathcal{S}$) and **toroidal** ($\mathcal{T}$) **components**, we expand data and flow components into **spherical harmonics** (SH)

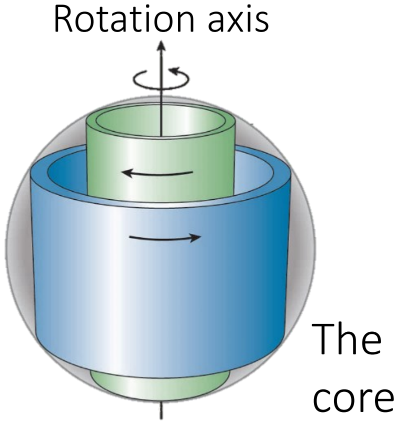
- We **obtain our model** with a **damped** least squares inversion.
  - Our models are damped: to **minimise acceleration** between epochs, and to **minimise spatial complexity.**

Flow inversion – minimum acceleration and TO-like

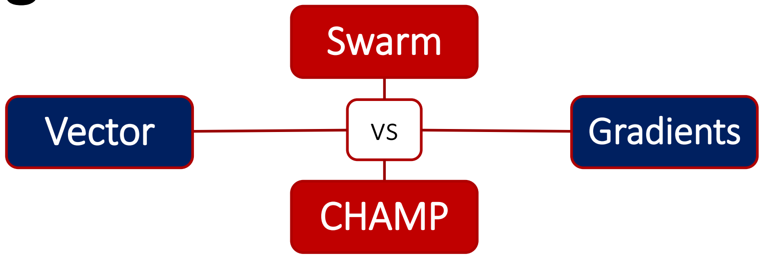
- We **obtain our model** with a **damped** least squares inversion.
  - Our models are damped: to **minimise acceleration** between epochs,
    and to **minimise spatial complexity.**
  - **No use** of **numerical** or **stochastic models**, and **without enforcing** any **flow-geometry** (such as **quasi-geostrophy or equatorial symmetry**)
- We create two types of models:

Model	Damping
Minimal acceleration	Damp **all** flow coefficients
Torsional oscillation (TO)-like	**No temporal damping** on equatorially symmetric **zonal** flow coefficients

Torsional oscillations:



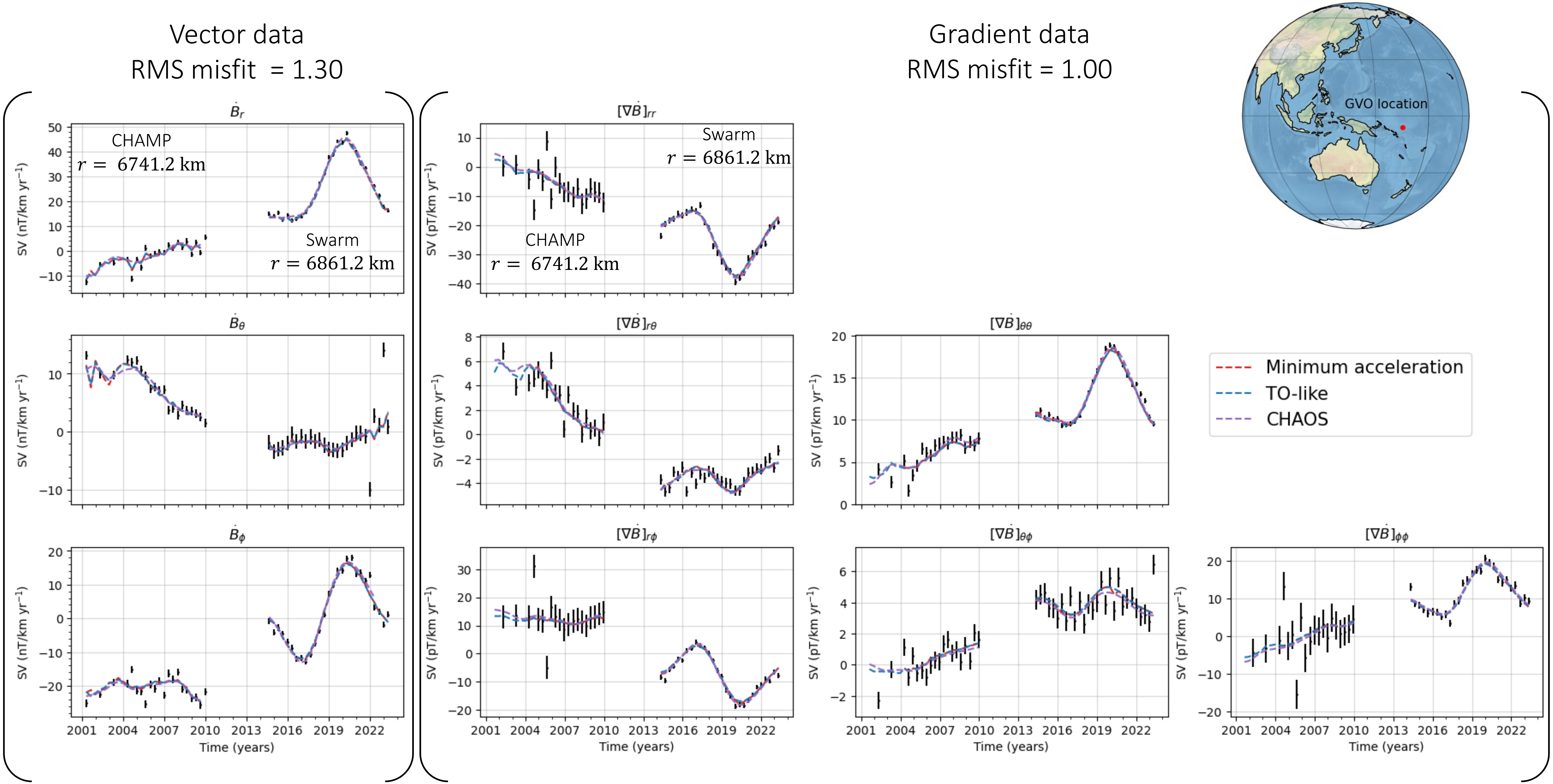
We **create** (and **compare**!) flow models from **vector** and **spatial gradient** data from **CHAMP** and **Swarm**



Model performance – good agreement with data

Vector data
RMS misfit = 1.30

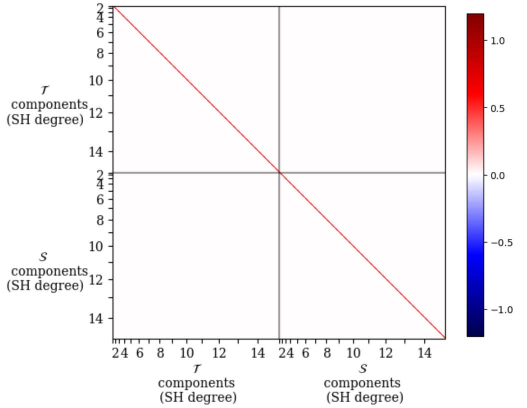
Gradient data
RMS misfit = 1.00

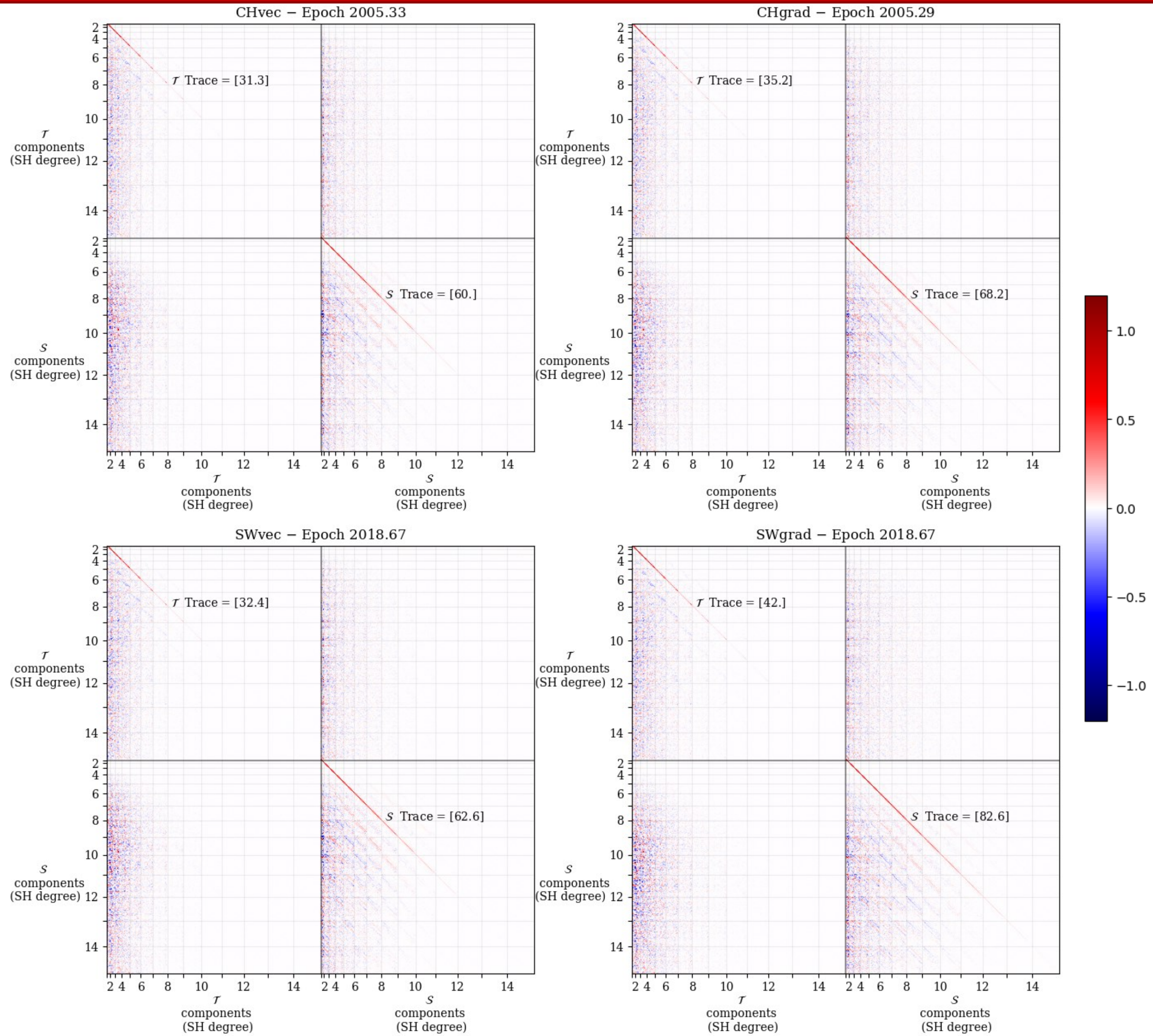


Model resolution – gradients resolve more flow coefficients

- **Resolution matrix** shows **how well** the **velocity coefficients** are **resolved** by **data**
- **Trace** = sum of diagonals
- **Ideal trace** for flow of maximum SH degree 14 = 224

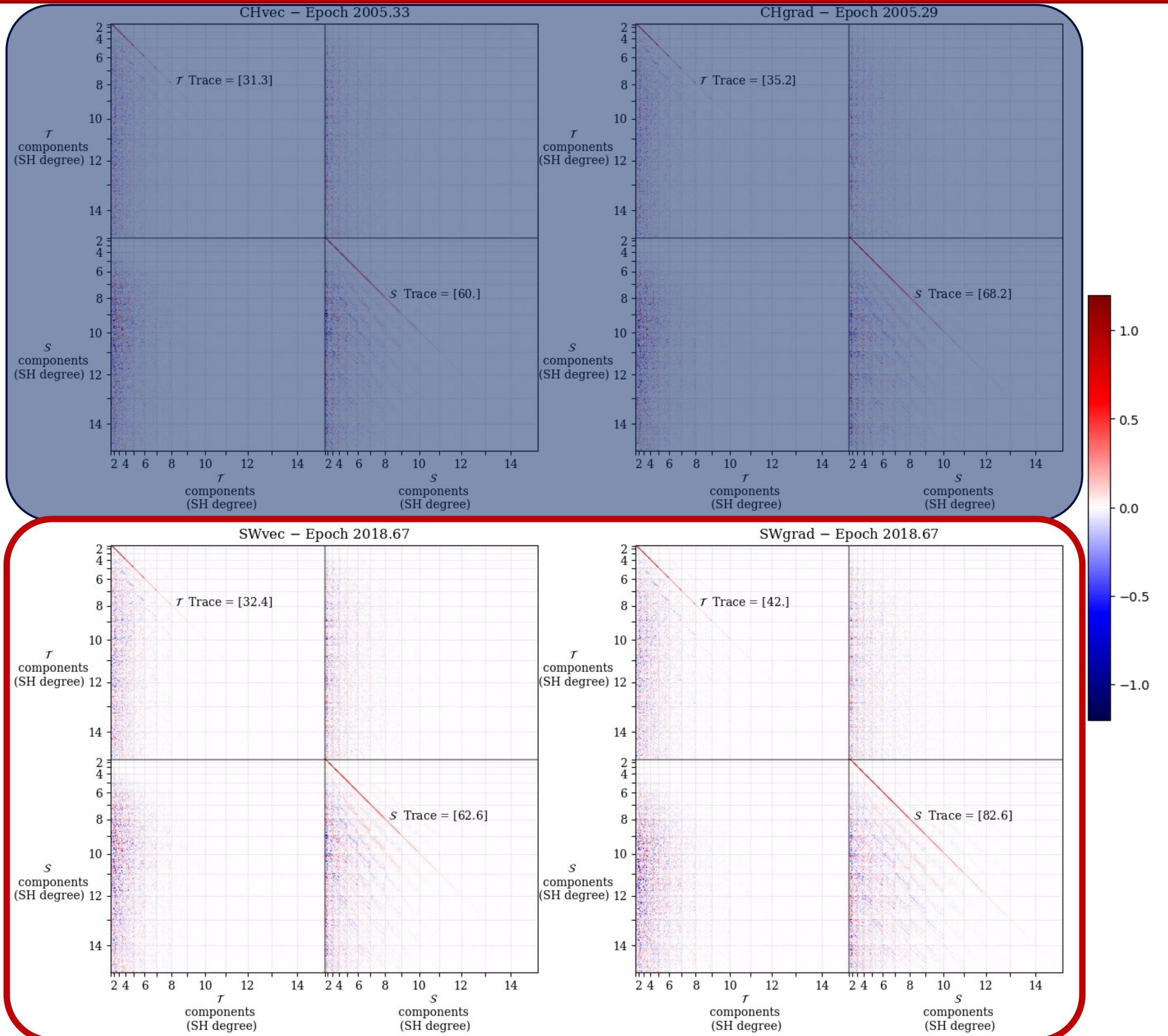
Perfect resolution matrix



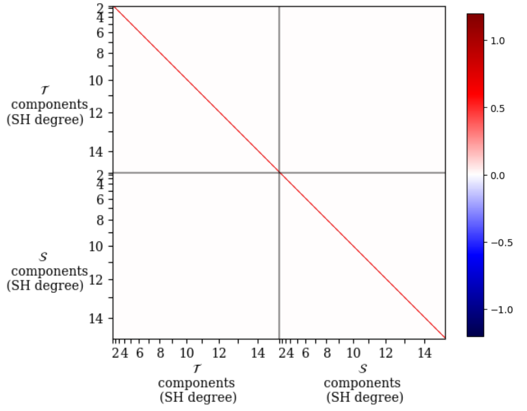


Model resolution – gradients resolve more flow coefficients

- **Gradient** based models **resolve ~133%** of that of the vector derived models **for Swarm**

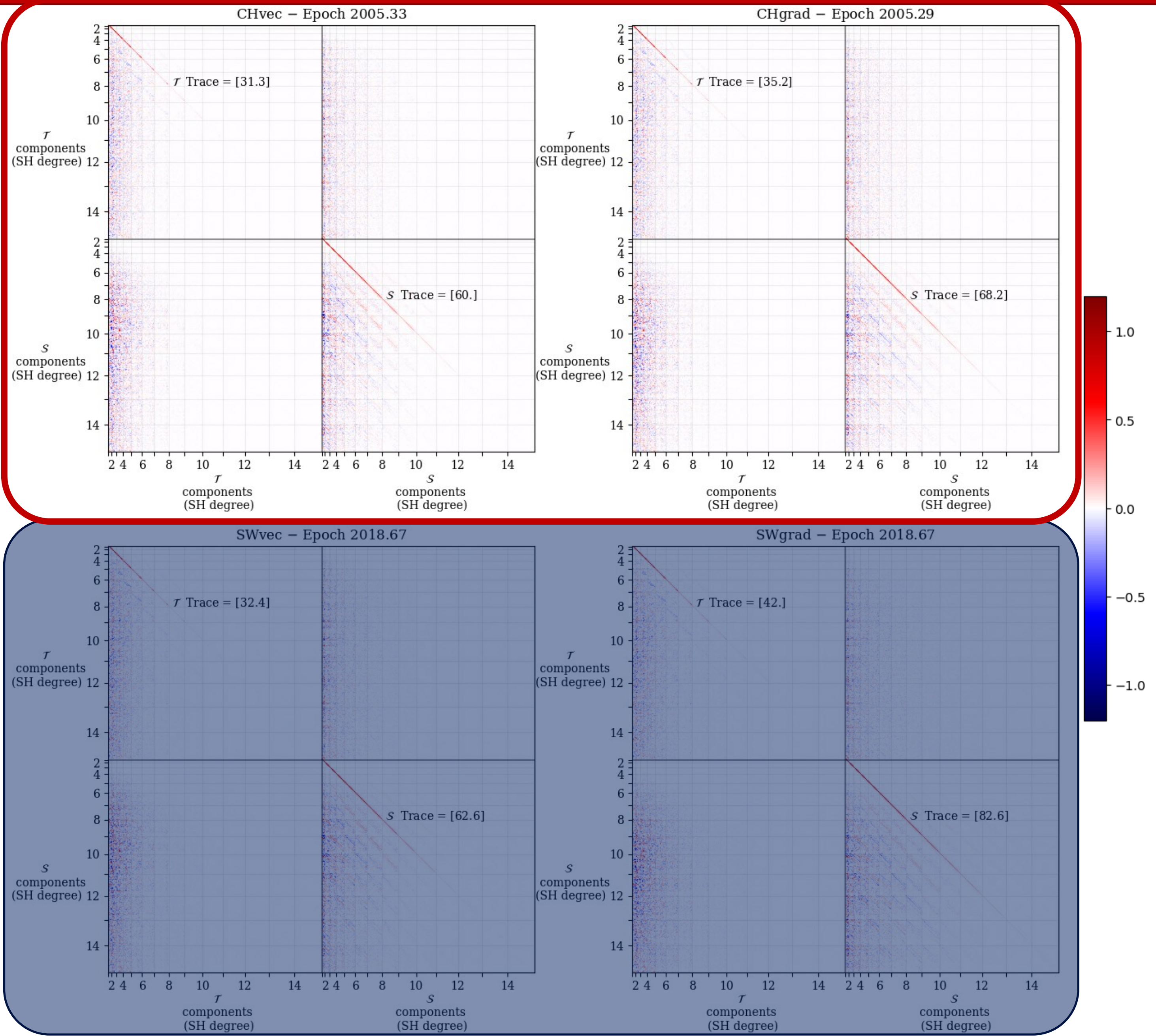


Perfect resolution matrix

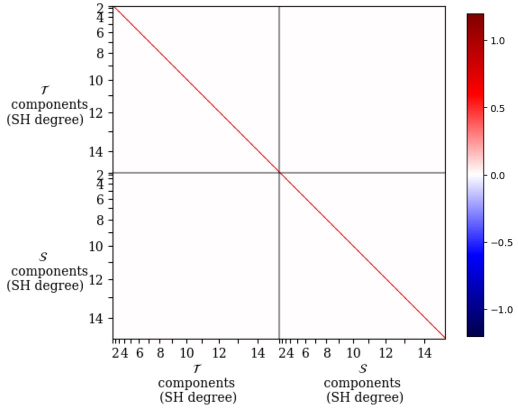


Model resolution – gradients resolve more flow coefficients

- **Slight improvement** when using **gradient data** for flow-modelling in **CHAMP** era



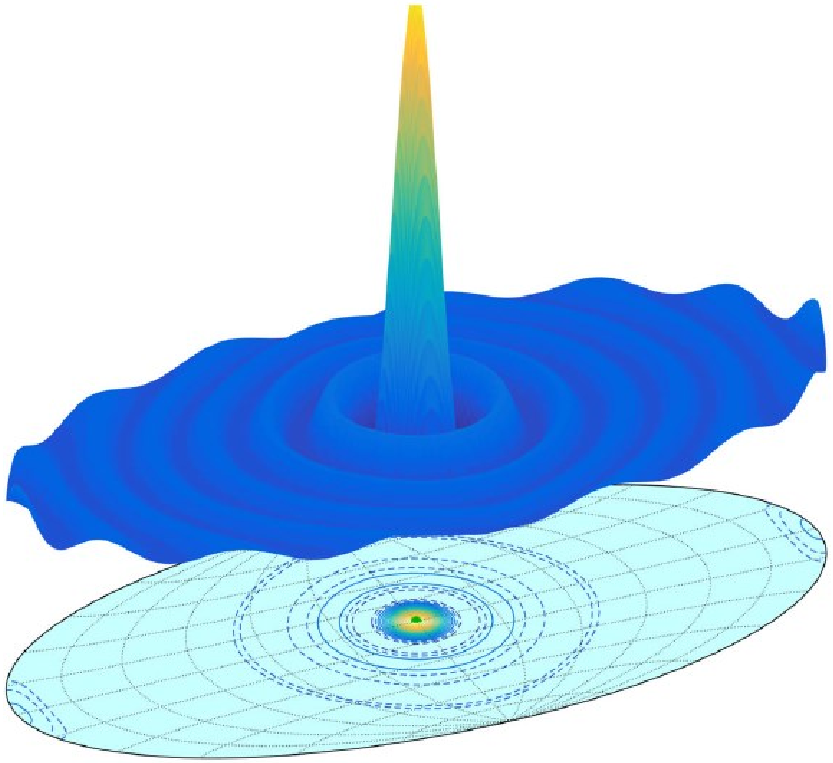
Perfect resolution matrix



Averaging functions

- Averaging functions (AF) are great way to **visualise spatial resolution**
- They indicate **how well** a model estimate **is localized** at a **given point**

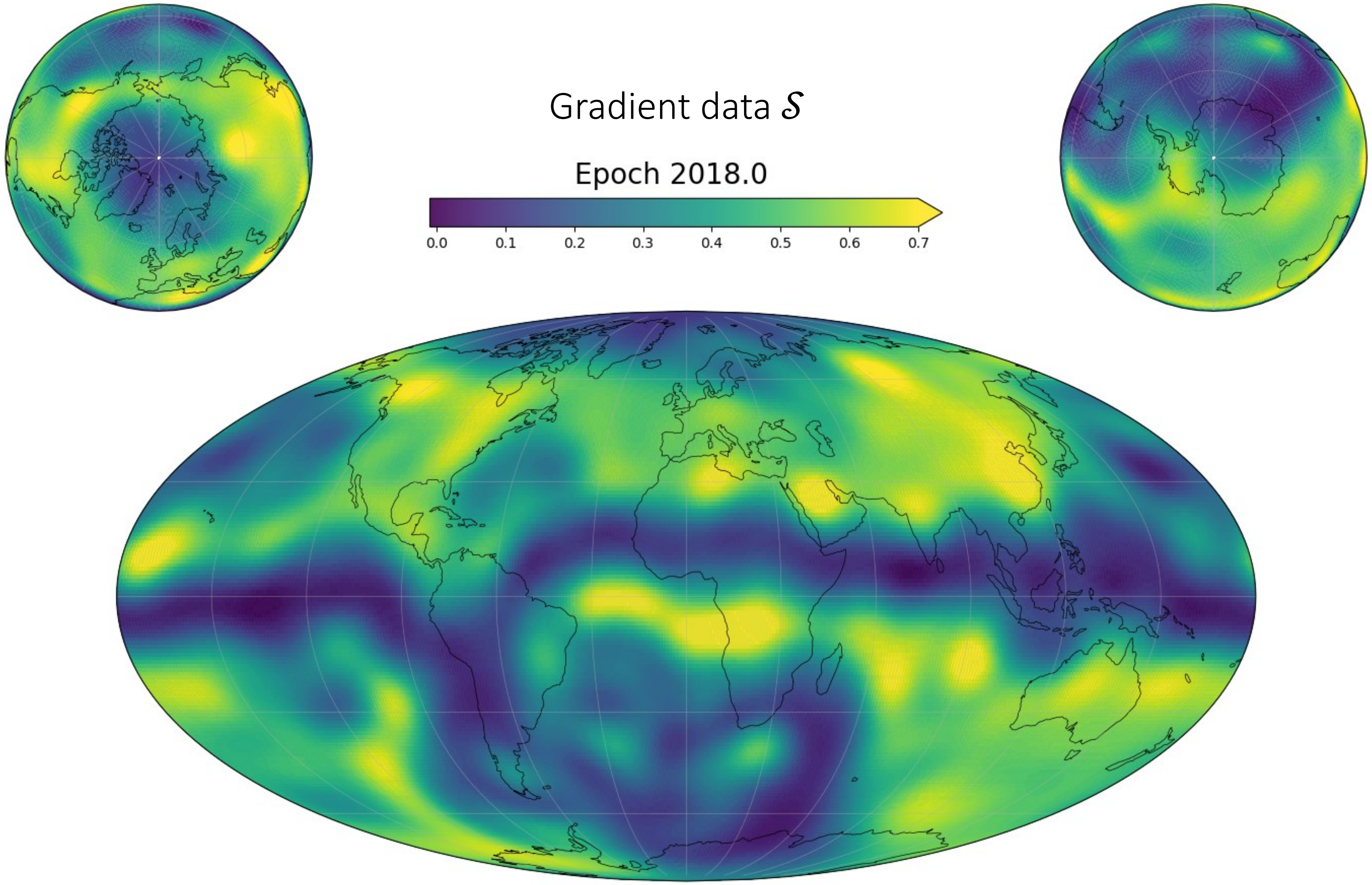
- We calculate AFs **across the core-mantle boundary** (and normalise values), in order to **evaluate model resolution in space**



Example of perfect averaging function at a point with max. spherical harmonic degree 14. From Whaler, Olsen, and Finlay (2016), GJI.

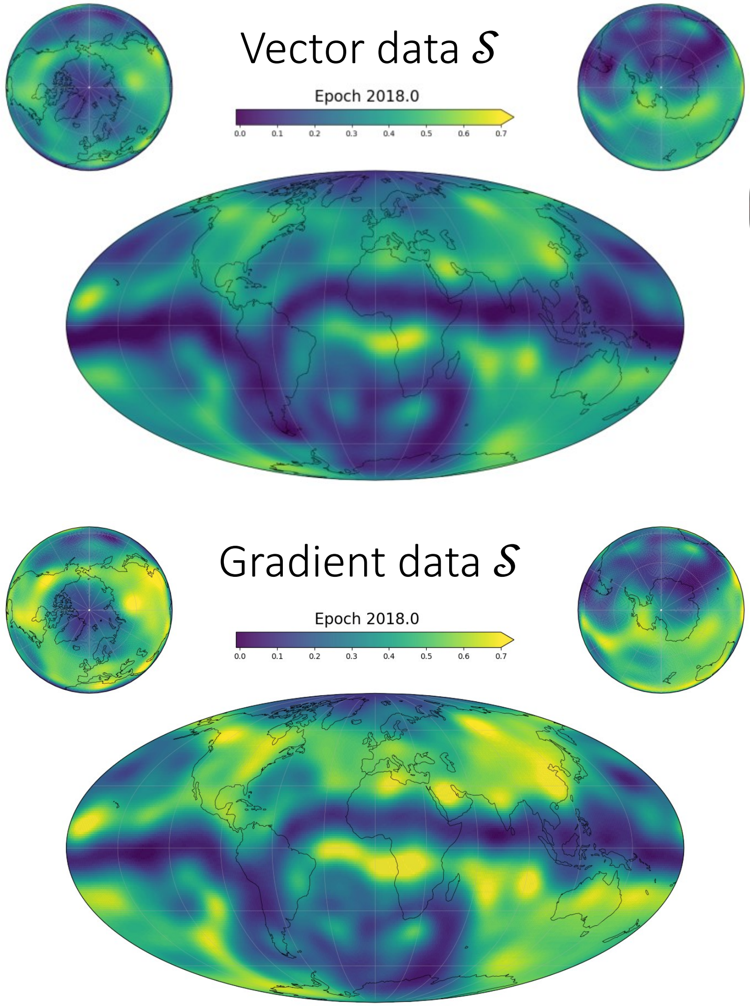
Averaging functions reveal regions of improved resolution

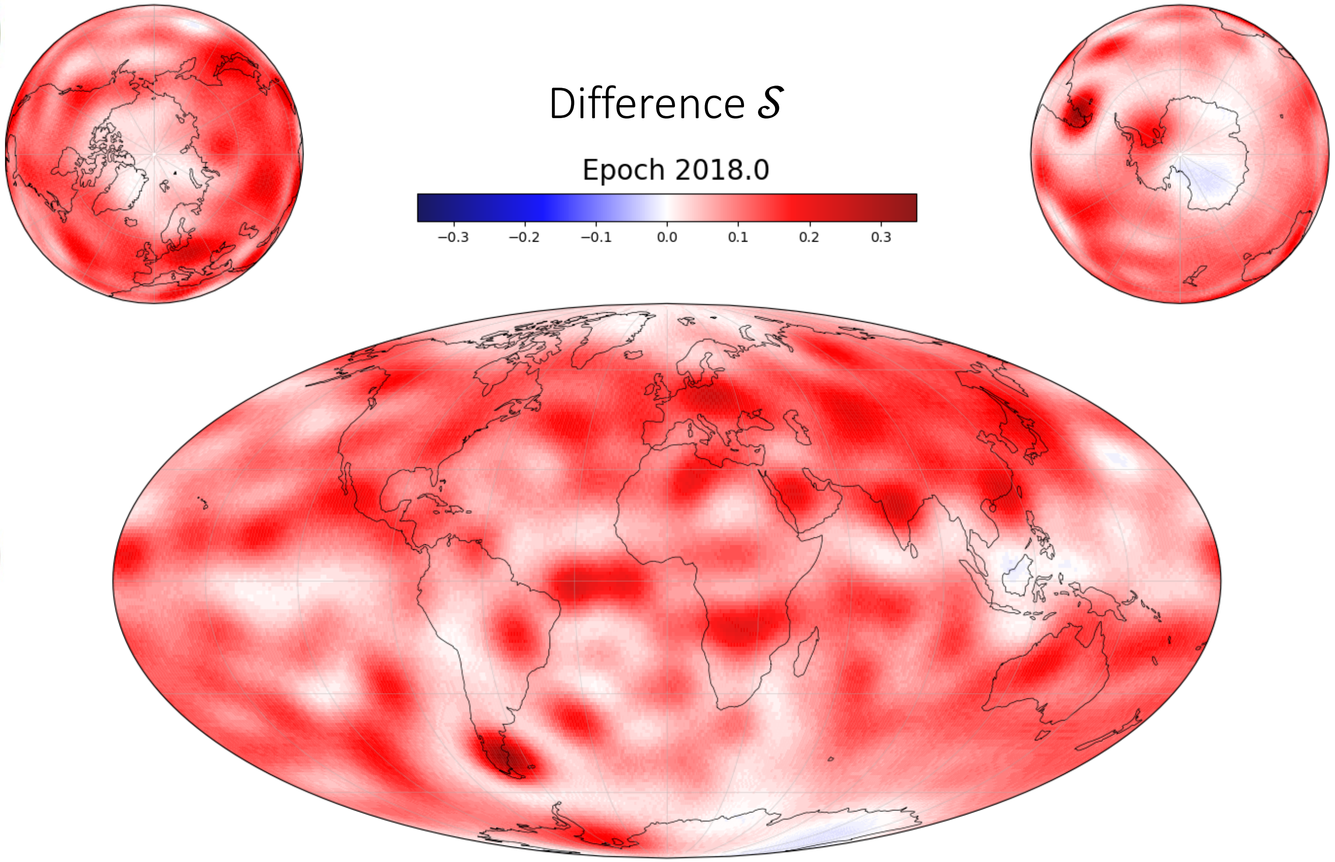
- **Poloidal flow**, $\mathcal{S}$, appears well resolved most locations
- Pronounced '**ambiguous' band** along magnetic equator?
- **Weak resolution** in **South Atlantic**, **North Pacific**, and **North Polar region**



Averaging functions reveal regions of improved resolution

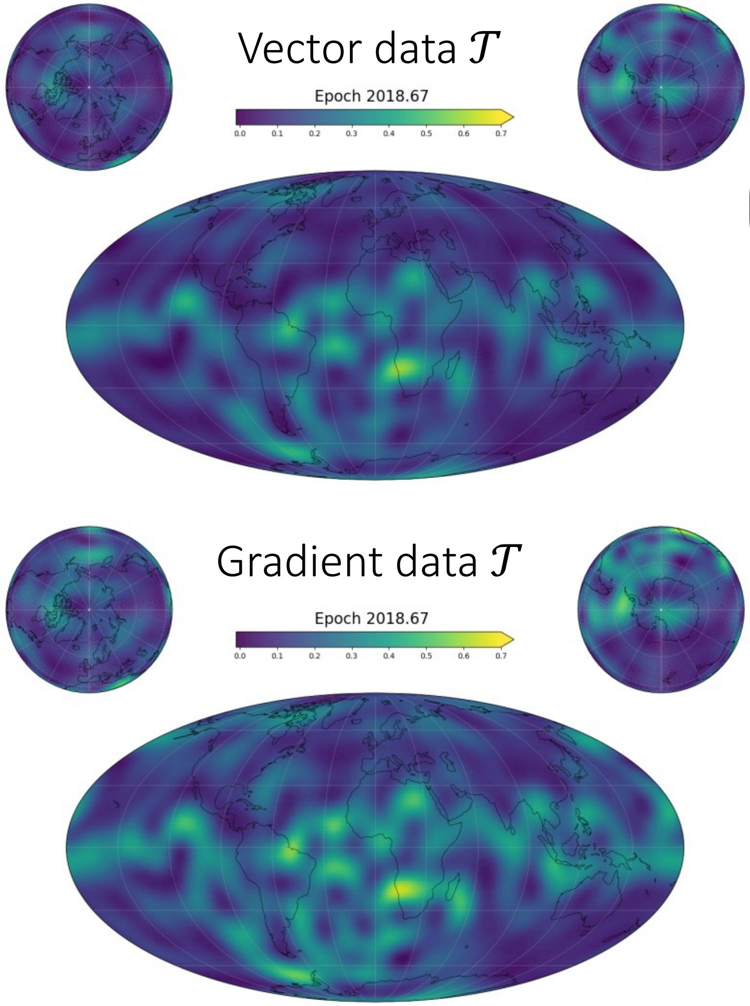
- Strong increase in AF (nearly) **everywhere** when using **gradients**
- Increased spatial resolution confining ambiguous patches?

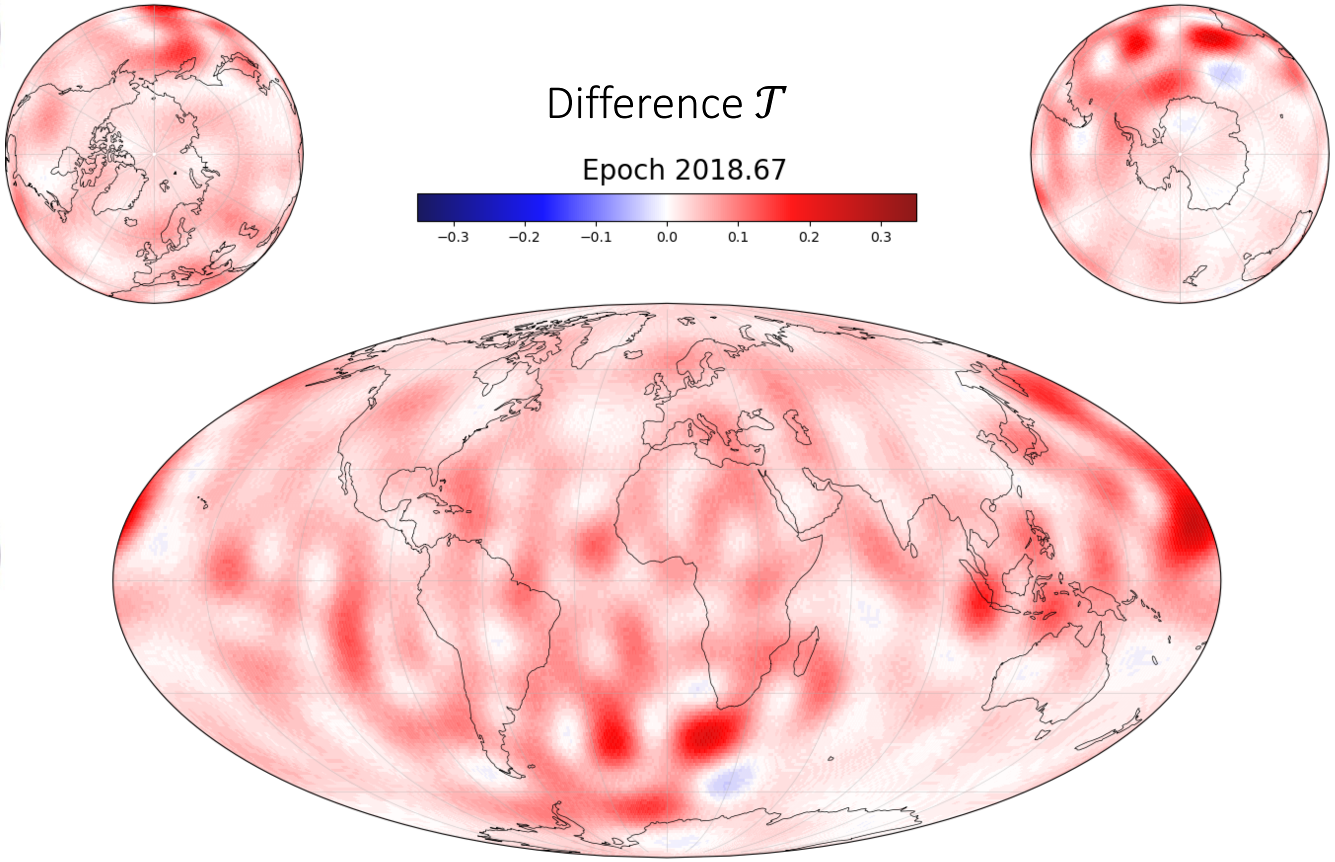




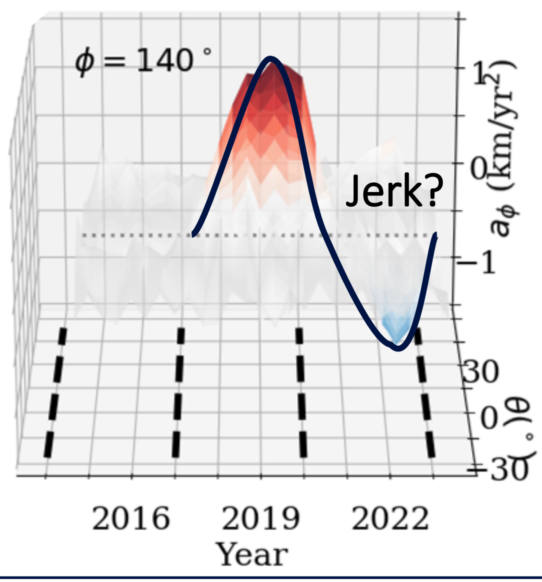
Averaging functions reveal regions of improved resolution

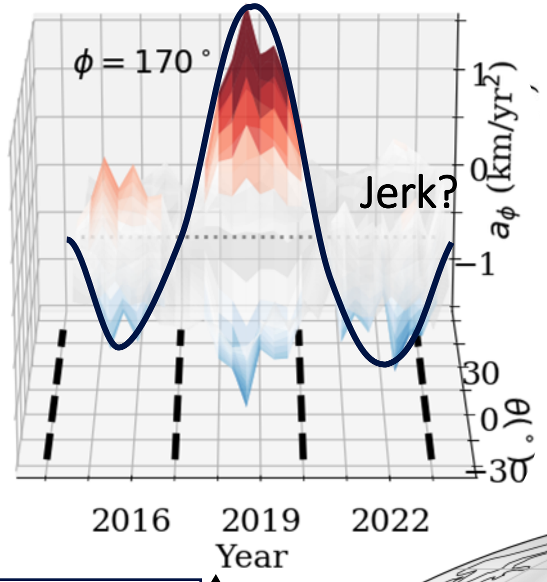
- Strong increase in AF (nearly) **everywhere** when using **gradients**
- Much weaker Afs for toroidal flow than poloidal

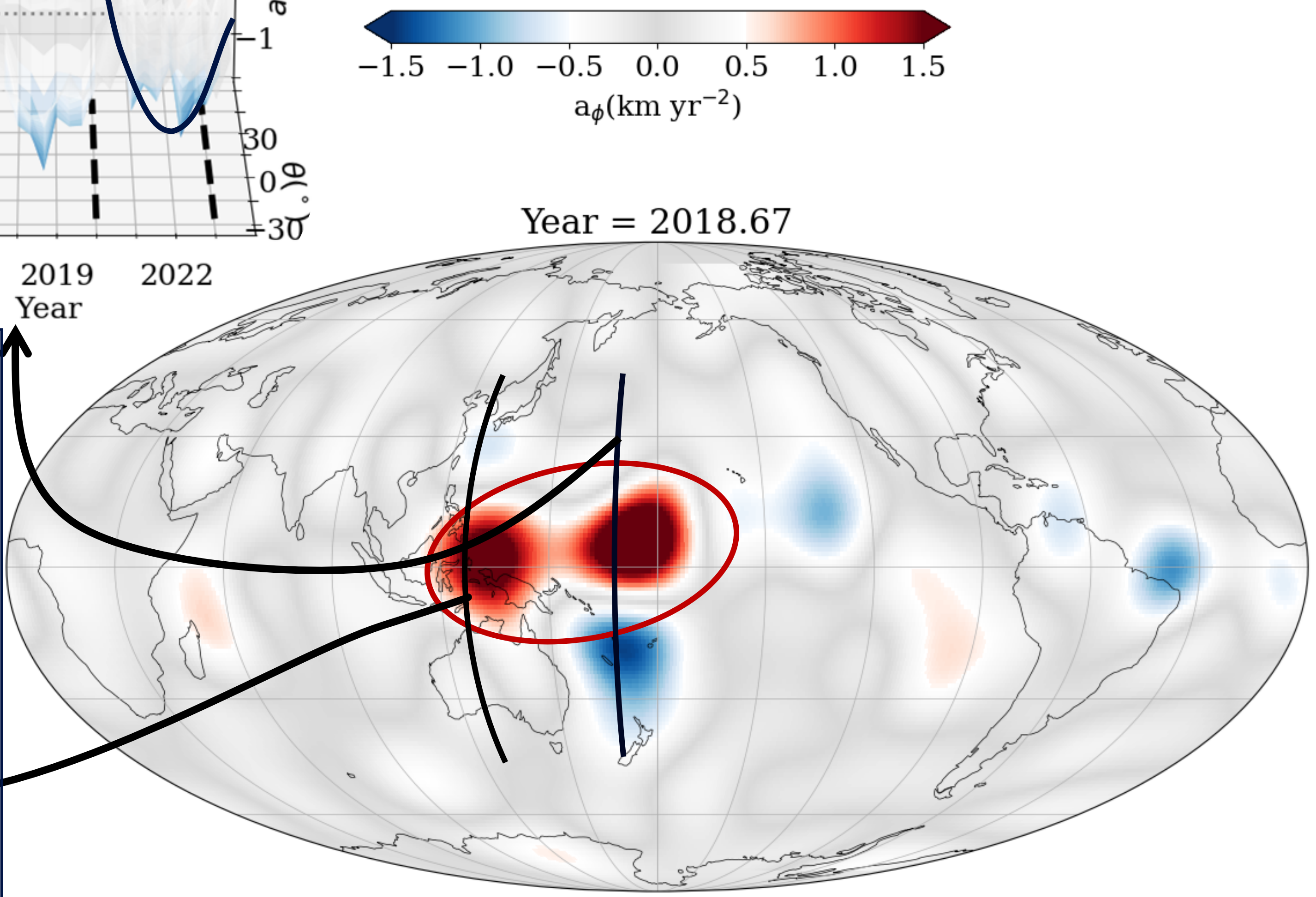


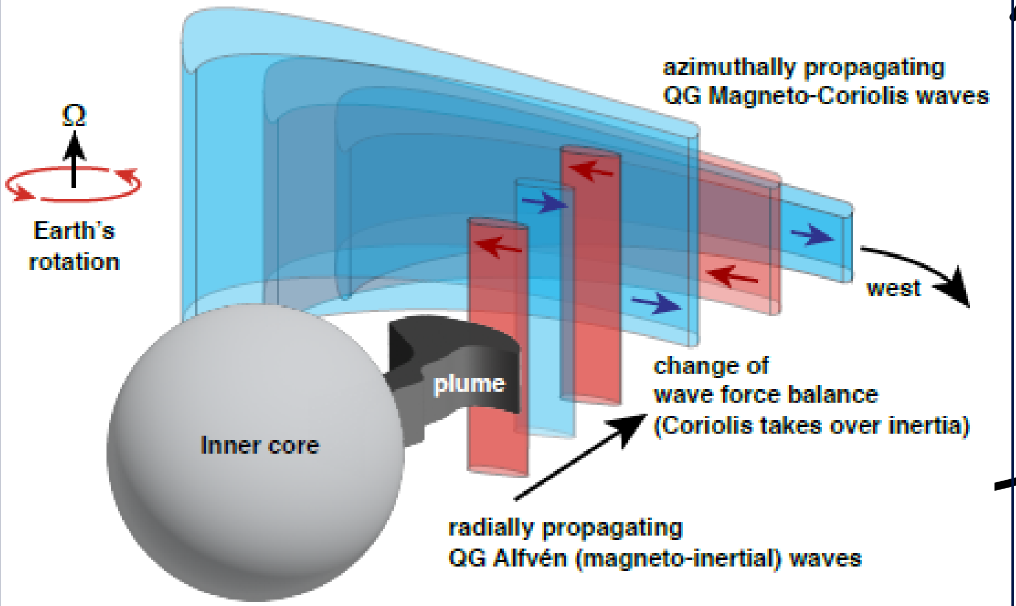


Result: Flow acceleration pulse in between jerks?





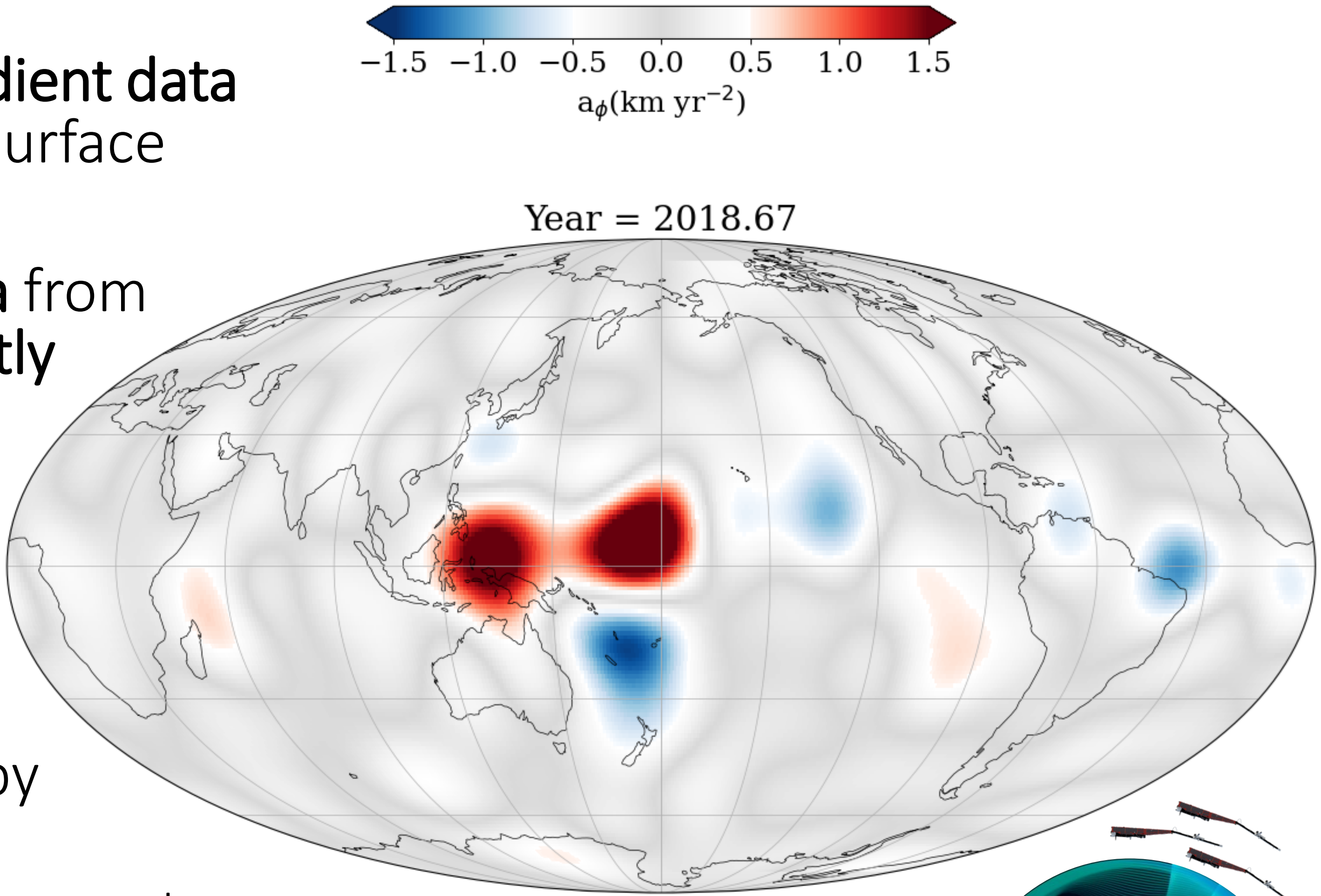




Finlay et al. (2023)

Conclusions

- We **inverted vector** and **spatial gradient data** from **CHAMP** and **Swarm** for core-surface flow
- We **found** that **spatial gradient data** from Swarm **resolved** the **flow significantly better** than vector data
- ...whereas **spatial gradient** and **vector data** from **CHAMP** performed **comparatively**.
- Our flow models **suggests** that the **2017** and **2020 jerks** were caused by a **wave-like pulse** in $\mathbf{a}_\phi$
  - This **suggests a new jerk** in the Pacific around 2023.



Happy birthday to Swarm!

Predicting variations in length-of-day (ΔLOD)

- The **minimum acceleration** models do **a poor job** at predicting ΔLOD variations
- **TO-like** models predict **better**
- **Equal performance** for **gradients** and **vectors**