Using weighted averages of satellite secular variation for investigating dynamics of flow at the top of the outer core

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Motivation:

Satellite magnetic readings can be related to flow at the top of the outer core. However, we want to gain the most information possible from the satellite readings to go into our core surface flow inversions. We aim to incorporate a weighted averaging technique, called SOLA, into our core surface inversions to investigate short-period wave dynamics.

Methodology:

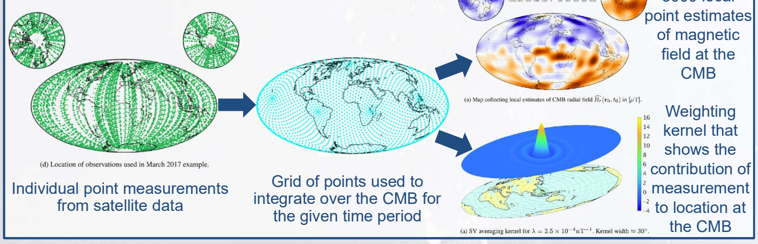
We use two main methodologies – **SOLA** and **pygeodyn**

SOLA (Subtractive Optimally Localised Averages) is a weighted averages technique that allows us to produce point estimates of the magnetic field (or its time derivatives) at the core-mantle boundary. We ingest point data taken directly from the satellite and integrate over a known grid for the given time period.

The output of this method is twofold: 1) point estimates of the main field (or its time derivatives) and 2) the averaging kernel that describes the contribution of each measurement to the approximation at the CMB. To maximise the benefit of the SOLA data, we want to incorporate the spatial weighting from the averaging kernel into our flow inversions

A spatio-temporal trade-off is achieved by editing the λ parameter, which affects the width of the averaging kernel. This allows us to push towards shorter periods and provides insight into wave dynamics.

Summary of SOLA methodology:



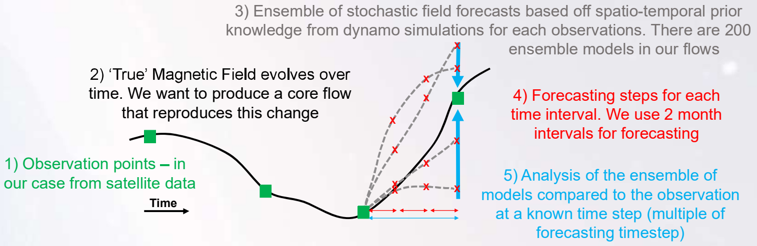
Individual point measurements from satellite data

Grid of points used to integrate over the CMB for the given time period

3000 local point estimates of magnetic field at the CMB

Weighting kernel that shows the contribution of measurement to location at the CMB

Pygeodyn is a python package for time-dependent stochastic flow inversion model with a Kalman filter



3) Ensemble of stochastic field forecasts based off spatio-temporal prior knowledge from dynamo simulations for each observations. There are 200 ensemble models in our flows

2) 'True' Magnetic Field evolves over time. We want to produce a core flow that reproduces this change

4) Forecasting steps for each time interval. We use 2 month intervals for forecasting

1) Observation points – in our case from satellite data

5) Analysis of the ensemble of models compared to the observation at a known time step (multiple of forecasting timestep)

The first derivative of the Earth's magnetic field (Secular Variation, SV) can be related to the motion of packets of outer core liquid at the top of the core by neglecting diffusion, which is known as the frozen flux approximation. This means that we can relate SV change to core surface flow by:

$$\dot{\mathbf{g}} = \mathbf{A}(\mathbf{g})\,\mathbf{v} + \mathbf{e}$$

$$\hat{\mathbf{v}} = \mathbf{v}^b + \mathbf{C}_{vv}\mathbf{H}^T\left(\mathbf{H}\mathbf{C}_{vv}\mathbf{H}^T + \mathbf{C}_{ee}\right)^{-1}\left(\dot{\mathbf{g}} - \mathbf{H}\mathbf{v}^b - \mathbf{e}^b\right)$$

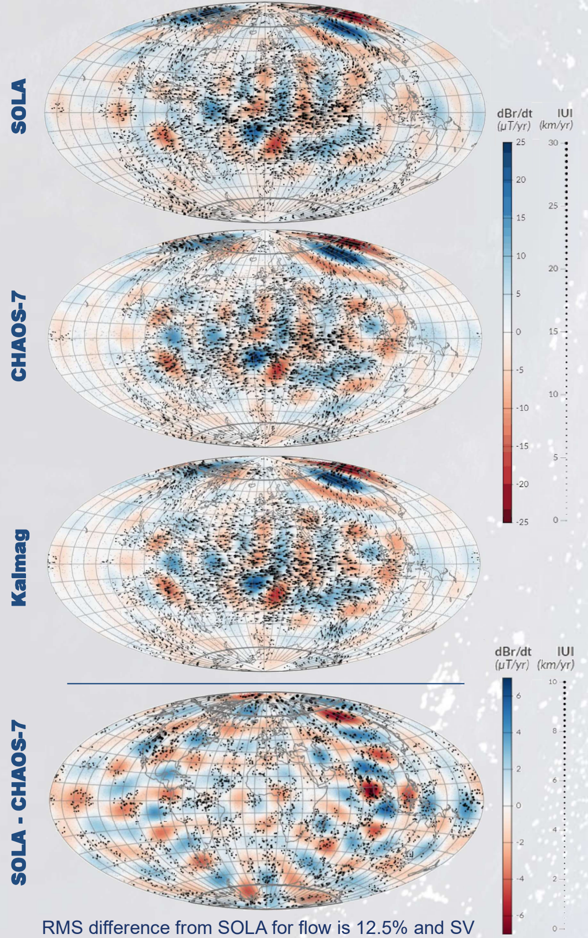
where $\dot{\mathbf{g}}$ is the SV model, $\mathbf{A}(\mathbf{g})$ is the Gaunt-Elsasser matrix (which relates field to flow coefficients), $\mathbf{v}$ is the Spherical Harmonic (SH) coefficients associated with the radial main field, core surface flow and its error terms, and $\mathbf{H}$ is the observation operator. $\mathbf{C}_{vv}$, $\mathbf{C}_{ee}$, $\mathbf{v}^b$ and $\mathbf{e}^b$ are the expected values from a numerical dynamo for the covariance matrices (for flow and error), core surface flow and the error associated with core surface flow.

Results:

We compare our **SOLA** solutions to those from the **CHAOS-7** (Finlay et al, 2020) and **Kalmag** (Baerenzung et al, 2020) field models

Flow Maps:

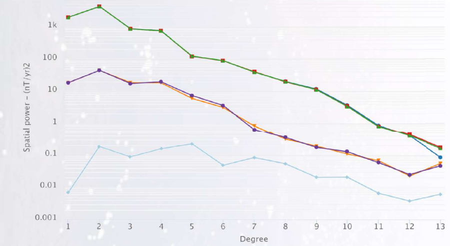
Snapshot from January 2018



RMS difference from SOLA for flow is 12.5% and SV

SV Spectra:

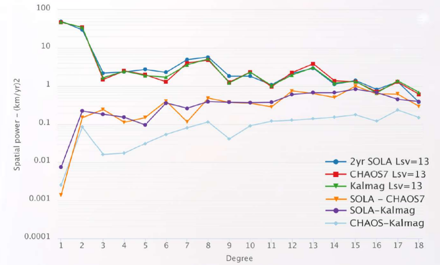
The SV models are incredibly similar except at largest SH degrees but the difference between SOLA and other field models is larger than the difference between field models



Flow Spectra:

Snapshot from January 2018

Flow models show more difference compared to SV but the difference between the different field models is still small smaller than SOLA

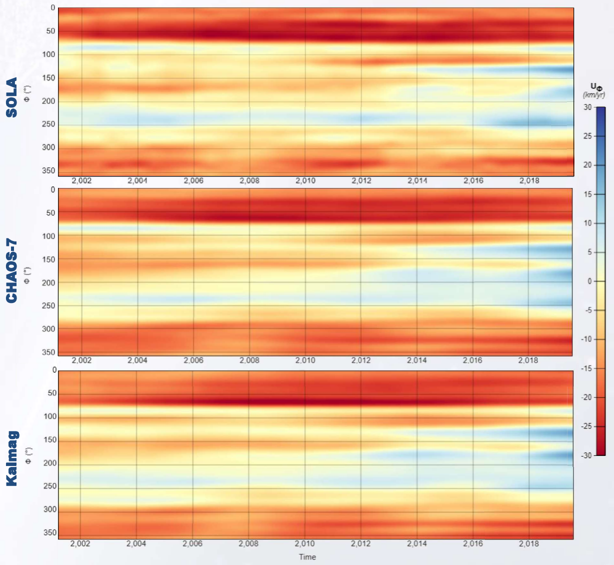


E-W (ϕ) flow at Equator:

Time-Longitude plots (right) show the magnitude of the eastward flow over time for all longitudes located at the equatorial cross-section.

SOLA appears to replicate the overall structures of CHAOS-7 and Kalmag. However, the better spatio-temporal resolution indicates that there may be additional complexity within these structures (e.g. 2017 over the Pacific – 200 degrees).

We can bandpass these results to investigate dynamics occurring at different periods such as the 7-year wave structure investigated by Gillet et al (2022).



Conclusions:

We can now incorporate weighted satellite data measurements at the core surface into our core flow inversion scheme. SOLA flow solutions are comparable to other magnetic field models but other magnetic field flow models are more similar to each other than to SOLA. Ongoing investigations are taking place into high resolution models of core surface flow.