British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

Reporters Review
Results from the decade of geopotential research and beyond: Session A13.2

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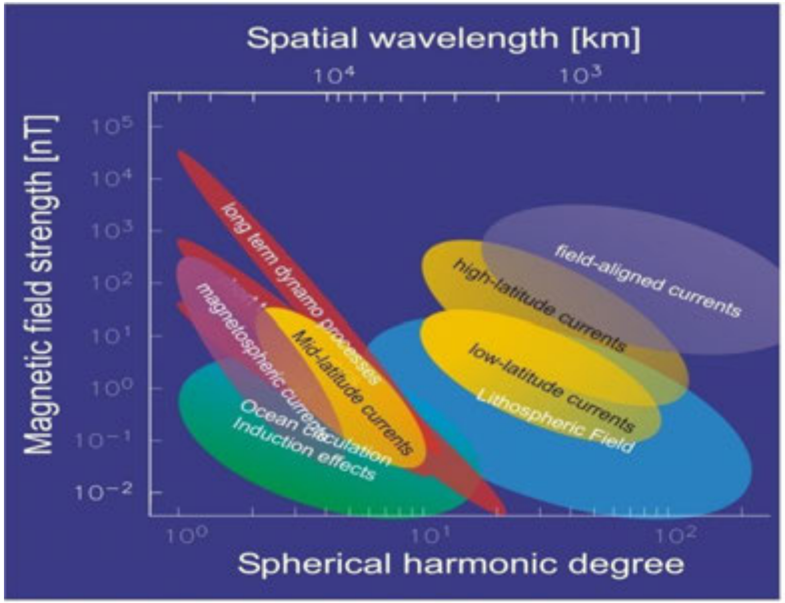
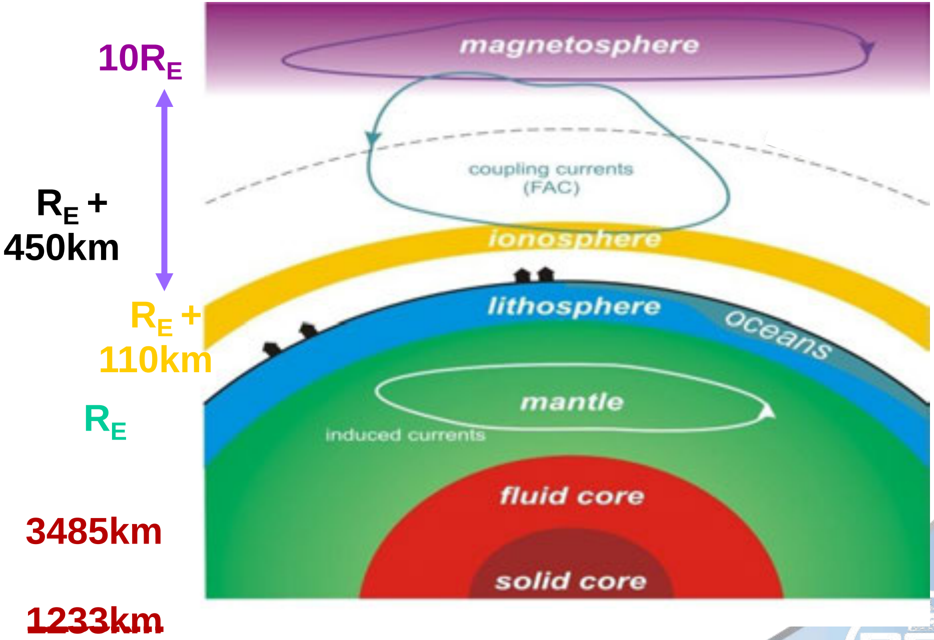
Sources

Field is very complex in time and space





Decade of Geopotential Research

- Officially started in February1999 with launch of Ørsted
  - Altitude 650-800km;
  - Vector and scalar initially; scalar only (since 2005)
- CHAMP (July 2000 – September 2010)
  - Altitude 450km → 300km; 4 month repeat period
- SAC-C launched (November 2000 – end-2004)
  - Altitude 700km; scalar only
- GRACE (2002) & GOCE (2009) gravity missions
- Next generation: ESA Swarm (July 2012)

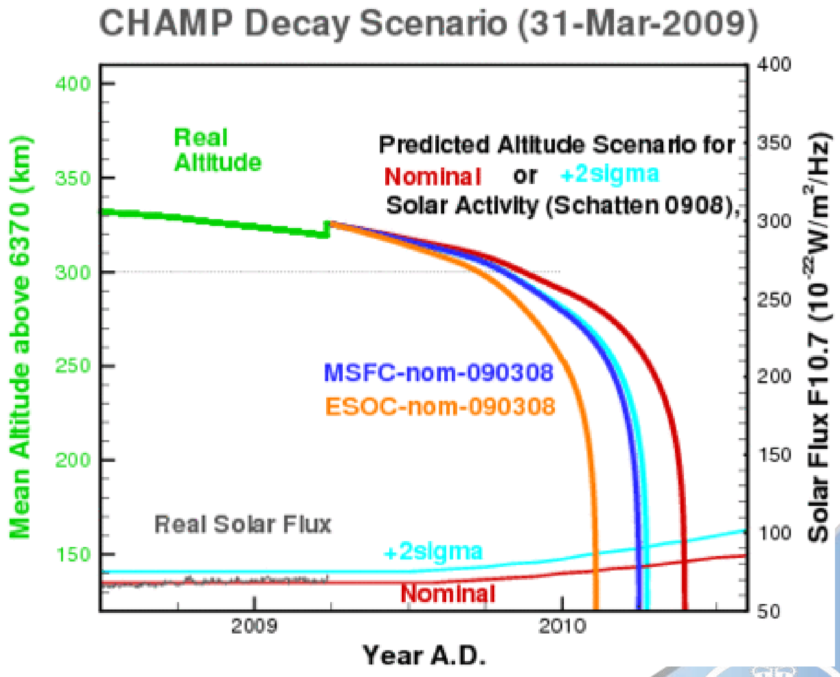
Decade of Geopotential Research (DoGR)

- In ~12 years there has been a vast improvement in:
  - Data collection
  - Communication
  - Collaboration

- DoGR has seen improvements:
  - Modelling and theory of main field and SV
  - Treatment and processing data
  - Understanding of processes throughout the geospace (i.e. Core to magnetosphere)

Satellite data

- High quality data:
  - Global coverage
  - Improved Euler angle estimation
  - Precise orbit determination (GPS)
  - Extremely low solar activity from 2005 – 2010
  - Long-lasting missions
- Dedicated managers & scientists:
  - Data-driven experiments now possible



Other factors

- Improved ground observatory network and data availability (e.g. INTERMAGNET, WDC)
- The Internet (plus other communication technologies)
- Large-scale computing readily available:
    - PC and HPC for handling large datasets and inverse problems
- International collaborations on many projects now truly possible
- Willingness of funding agencies to invest in research programmes on geopotential fields

Current Observatories

World Data Centre Data Holdings

Presented Research in A13.2

- Improved modelling techniques for field and SV
  - Jackson; Lesur; Whaler

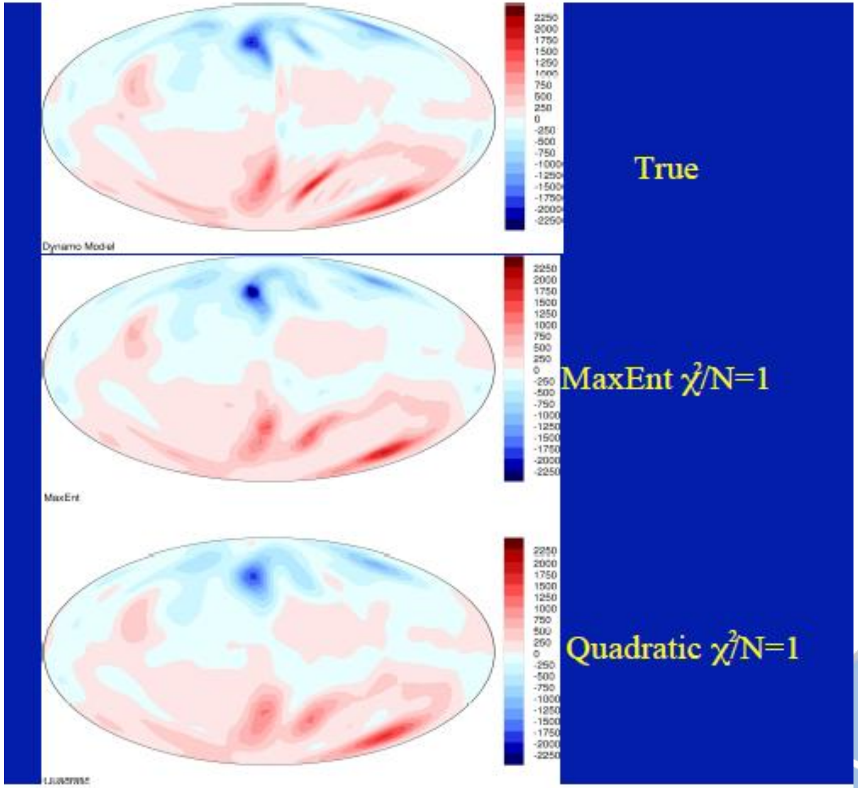
- Data selection methods and treatment
  - Holme; Kelly

- Understanding of magnetic field processes and implications
  - Shore; Penequec‛h; Rajaram

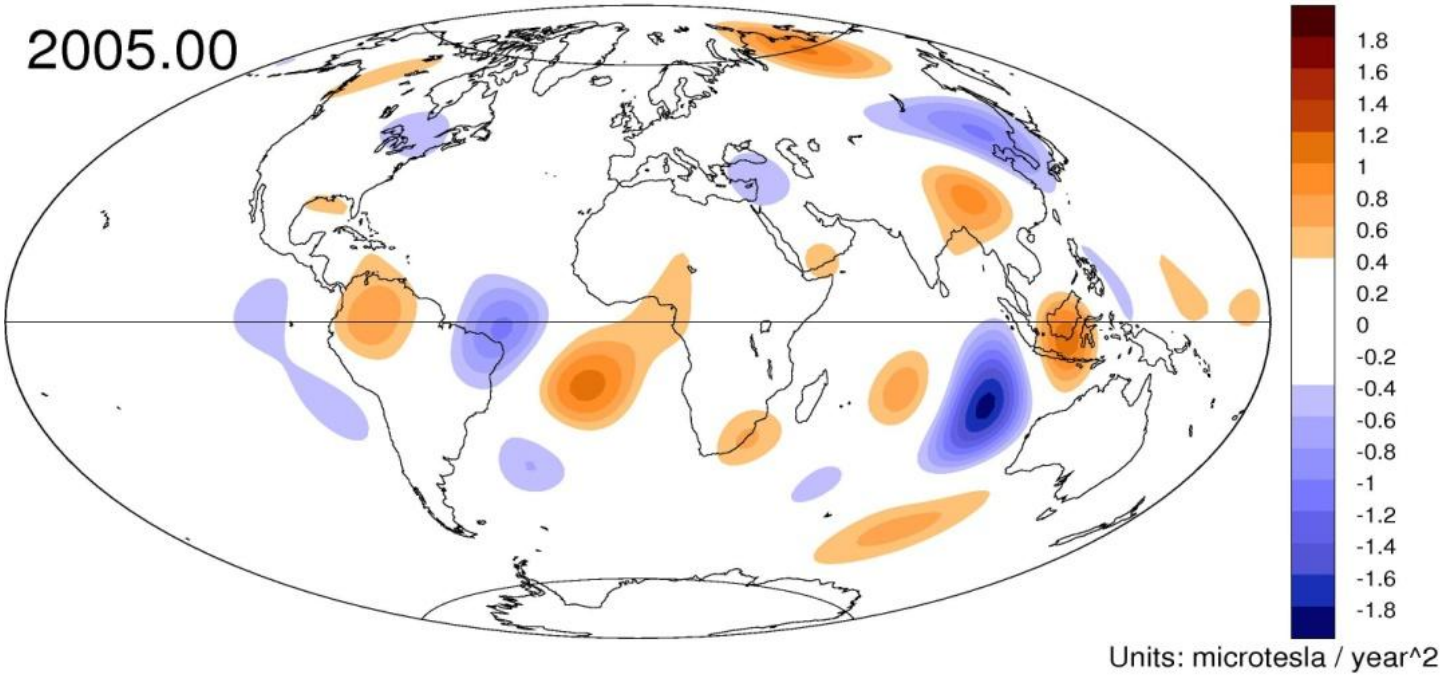
- Swarm Mission
  - Fratter; Haagmans

Modelling I

- Updated GUFM-type model for 2000-2010
    - Imaging of the field at the core-mantle boundary
    - „Blurred" due to the Green"s function
- Maximum Entropy approach
    - Allows solutions with „sharp" features and boundaries
    - Image processing heritage



Core Mantle boundary



Modelling II

GRIMM-3:

- Magnetic field covering the full CHAMP data time span.
- Improve the time behavior of the model:
    - Fitting the rapid evolution of the observed SV (Jerks)
    - Avoiding spurious oscillations
- Solve for field using different constraints

$$B = -\nabla(V_i + V_e)$$

$$V_i(\theta,\phi,r,t) = a\sum_{l,m}\left(\frac{a}{r}\right)^{l+1}\left(g_l^m(t)\cos m\phi + h_l^m(t)\sin m\phi\right)P_l^m(\cos\theta)$$

$$V_e(\theta,\phi,r,t) = a\sum_{l,m}\left(\frac{r}{a}\right)^{l}\left(q_l^m(t)\cos m\phi + s_l^m(t)\sin m\phi\right)P_l^m(\cos\theta)$$

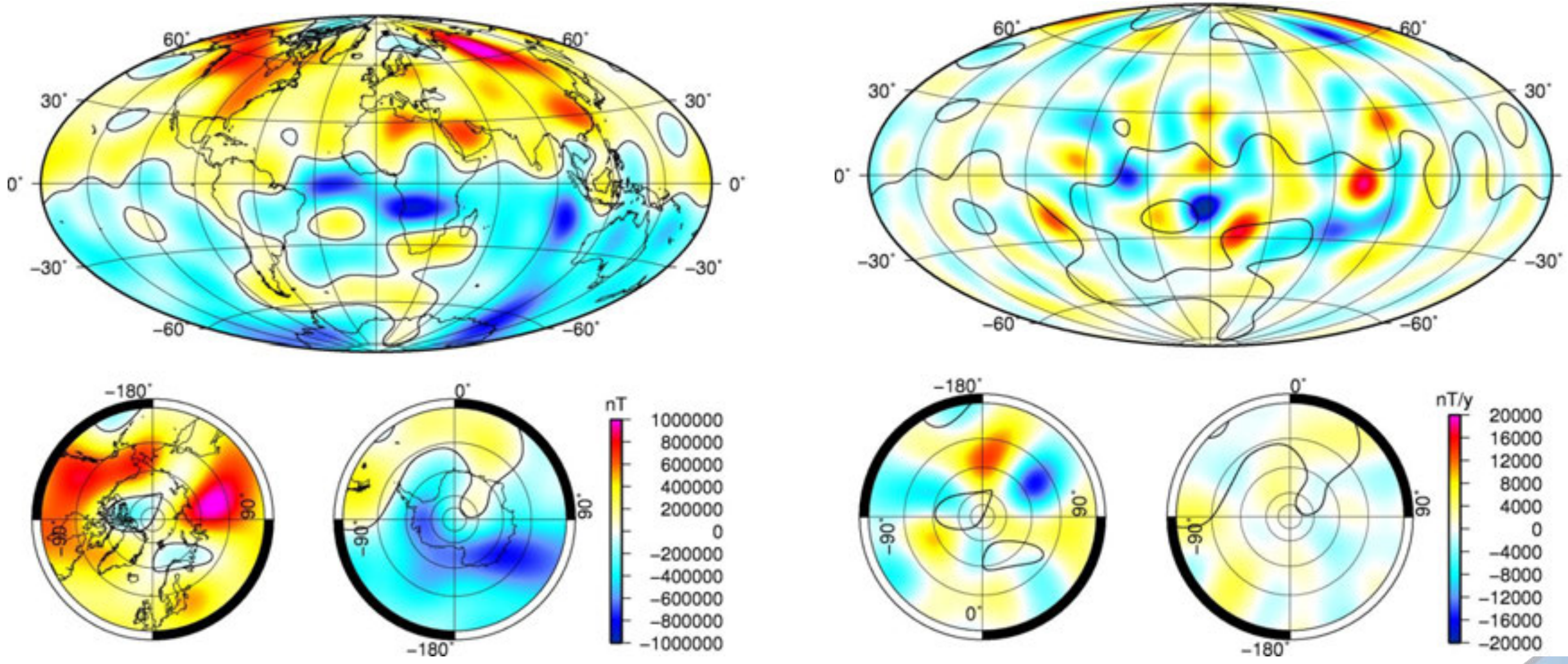
$$\Phi = \Phi_0 + \lambda_1\,\Phi_1 + \lambda_2\left\{\Phi_2(2000) + \Phi_2(2011.5)\right\}$$

$$\Phi_0 = \sum_i w_i\left[d_i - B(\theta,\phi,r,t)\right]^2$$

$$\Phi_1 = \sum_{l,m}\frac{(l+1)^2}{2l+1}\sum_{t_i}\alpha_{lmi}[\partial_t^3 g_l^m]^2 + \beta_{lmi}[\partial_t^3 h_l^m]^2$$

$$\Phi_2(t) = \sum_{l,m}\frac{(l+1)^2}{2l+1}\tilde{\alpha}_{lm}[\partial_t^2 g_l^m]^2 + \tilde{\beta}_{lm}[\partial_t^2 h_l^m]^2\,\Big|_t$$

Field & SV at CMB



Vertical down component of GRIMM-3 and its SV at the CMB for year 2005.0.
The model has been truncated at SH degree 13

Observations about the past decade

Jackson *et al.*

- At low latitudes the current geodynamo possesses a series of intense westward drifting flux concentrations.
- Satellite observations have enabled us to image the formation of the newest member of this sequence under the eastern Indian ocean.
- Bursts of equatorward flow stripping flux from the high latitud lobes may be responsible.
- Decay of the dipole is almost entirely controlled by southern hemisphere.
- The Pacific hemisphere has very low secular variation (c.f. palaeomagnetism); coincidence with edge of continents is remarkable.

Lesur *et al.*

- The smoothing constraints applied allow for large/sharp variations of the acceleration, consequently the Gauss‟s coefficient third time derivatives behave “step-like” in time.
- “Jerks” are localized both in time and space. They are identified in :
  - 2003.7 at the magnetic equator under South-East Asia
  - 2007.3 at the magnetic equator under South-West Atlantic Ocean

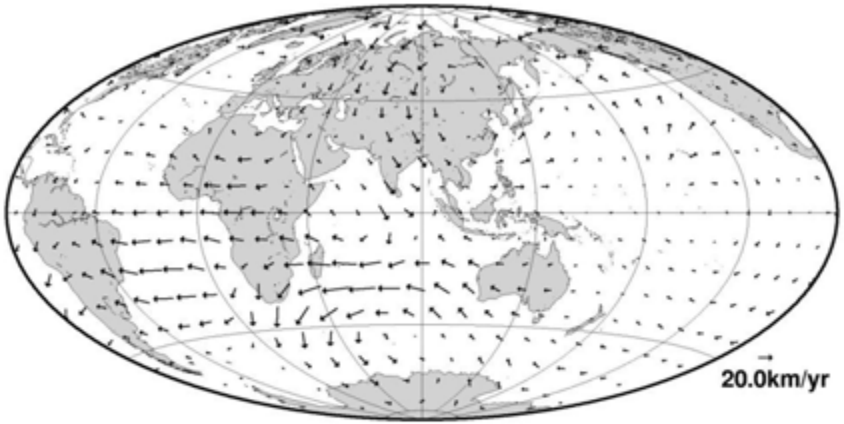
Core Flow Models

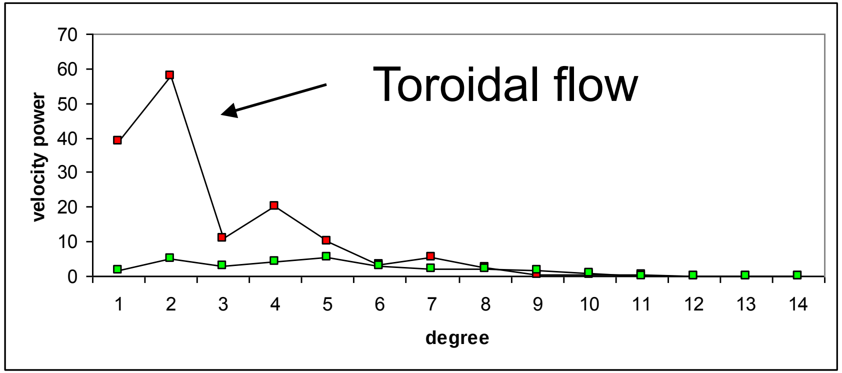
- Steady core surface flows fit gross features of secular variation (SV) data over long periods with a small number of parameters
- Provide a better SV forecast than extrapolation
- But cannot follow details of SV variation
- Can we do better if we allow flow acceleration too?
  - small increase in the number of parameters

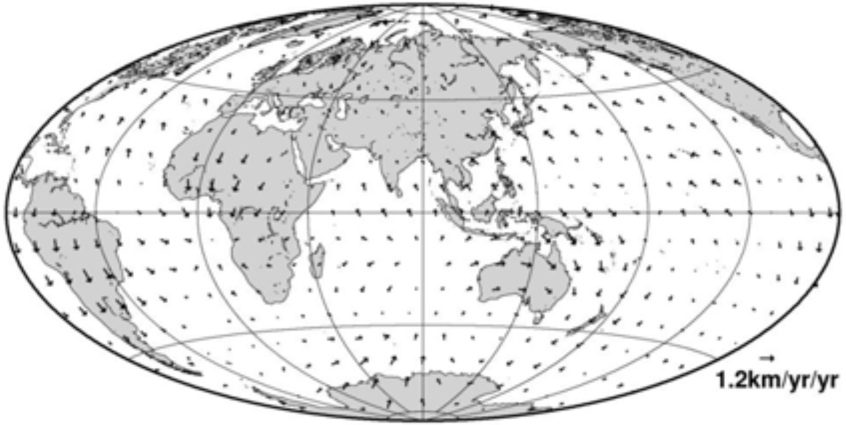
- *Jointly* invert SV and SA data for flow and flow acceleration coefficients
- Flow truncated at degree 14, flow acceleration at degree 8
- Regularise using „strong‟ norm (weighting ~ ℓ^5), applied to both flow and flow acceleration

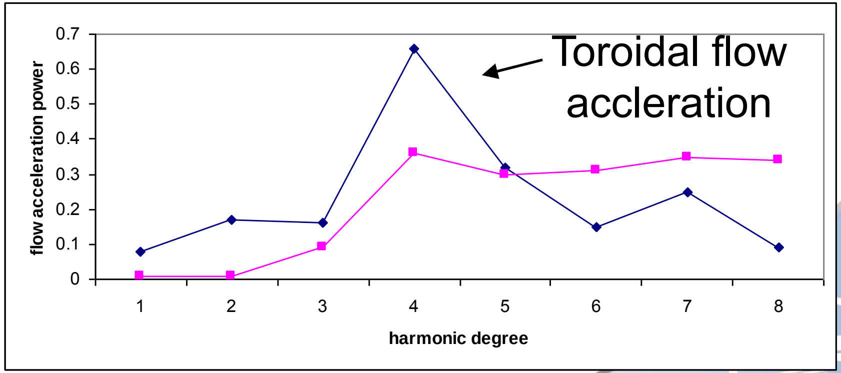
- Data VO + Ground Obs (2000-2010)

VO data 2002-7







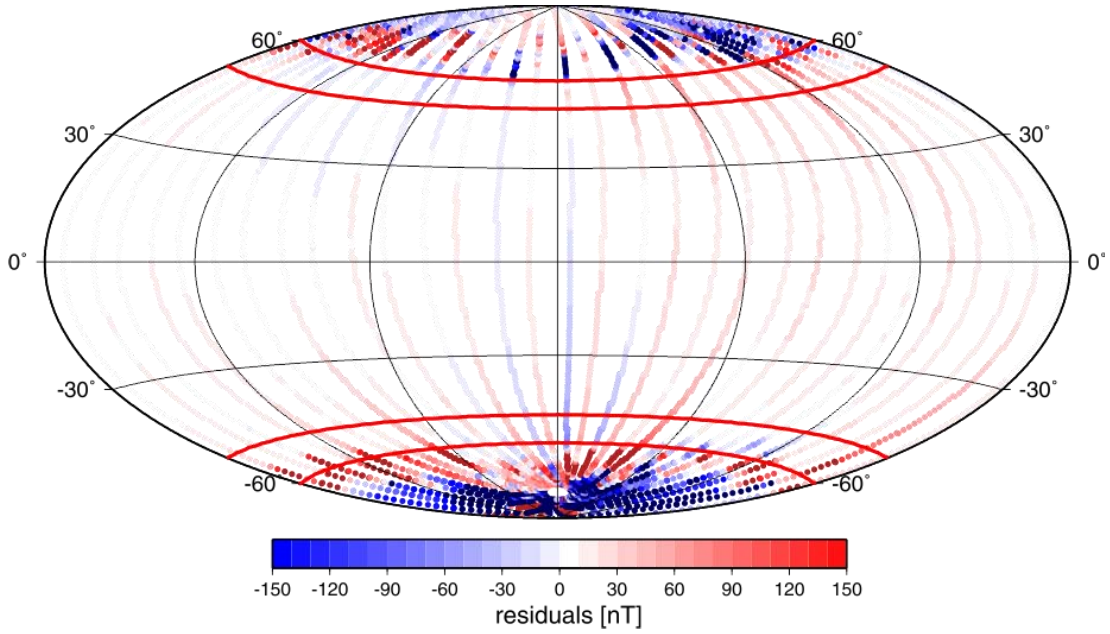


Presented Research in A13.2

- Improved modelling techniques for field and SV
  - Jackson; Lesur; Whaler
- Data selection methods and treatment
  - Kelly; Holme
- Understanding of magnetic field processes and implications
  - Shore; Penequec'h; Rajaram
- Swarm Mission
  - Fratter; Haagmans

Data selection High Latitude: Ovation auroral model

- Many existing models exclude all data at dip latitudes > either |50°| or |60°|
- Use of Ovation may allow more data to be included whilst still avoiding the "noisy" auroral region



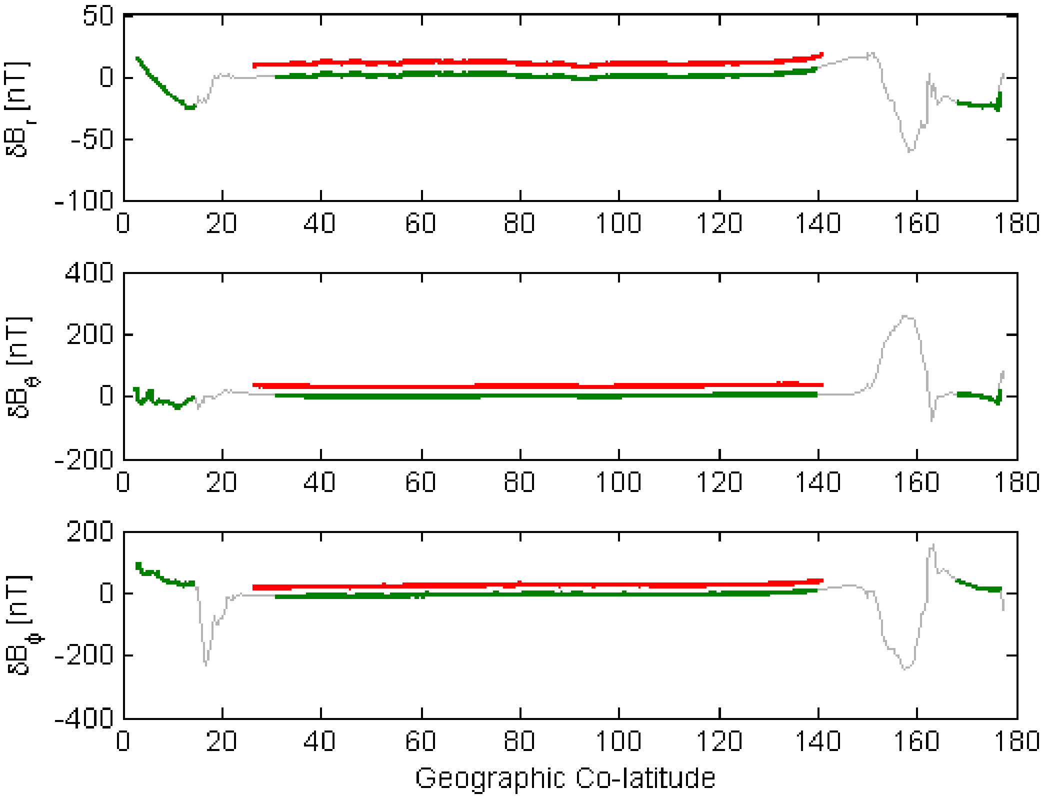
Residuals between CHAMP and CHAOS-2 for 11/12 Dec 2001 in Geomagnetic coordinates (ϕ component)

G. Kelly: Univ. of Liverpool

Data selection: Standard deviation approach

- A single orbit for 8th Sept 2001 (CHAMP-CHAOS2)
- Dark green line is data selected with Ovation
- Red line (plotted with an offset) data that would be selected using standard deviation.

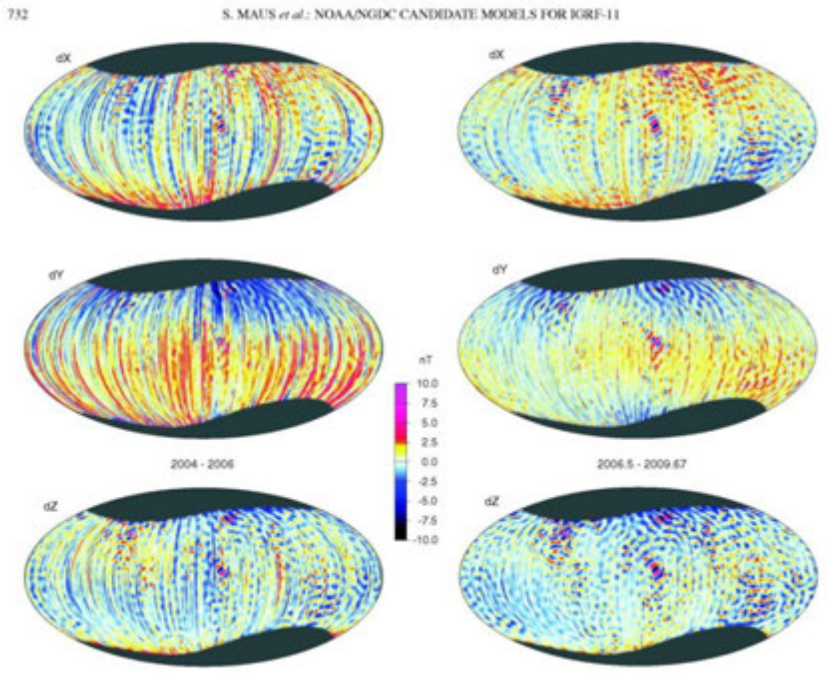
- Improved data selection gives more representative field models at high latitudes



Data selection Mid-latitudes: Removing along-track noise

Problem:

- Mid and low latitude data still show along-track structure in residuals
- Unmodelled external (and induced) field still dominant error source



Solution:

- Calculate initial field model from decimated data set. Use track residuals from model to estimate contamination from large-scale field signal
- Model this contamination with simple low-degree field model.
- Remodel from decimated data set downweighting data in direction of contamination

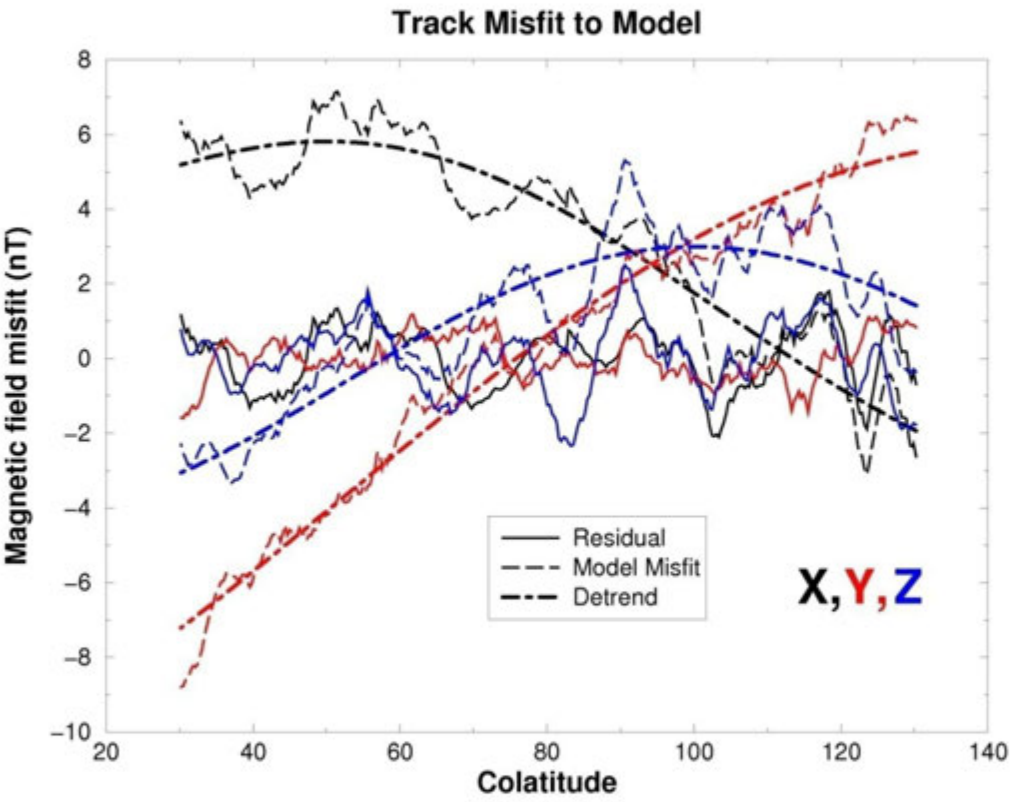
R. Holme: Univ. of Liverpool

Data selection Mid-latitudes: Correlation & Detrending

- Substantial remaining correlated residual
- Large Y component difficult to model deterministically

- RMS of tracks order ~4nT
- **After detrending, residual of order: ~1nT**

- Applications to:
  - Short wavelength field
  - Secular variation



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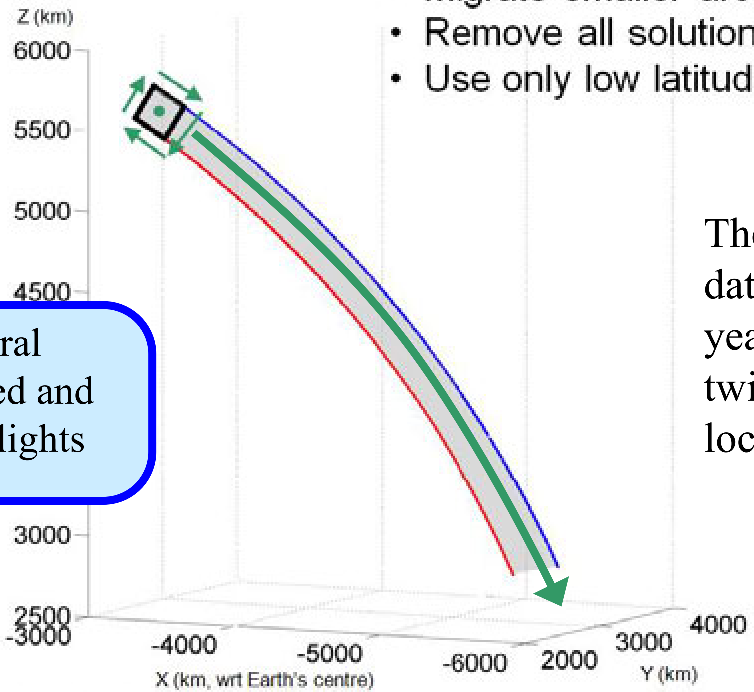
Dynamic fields: Ionospheric **E** systems

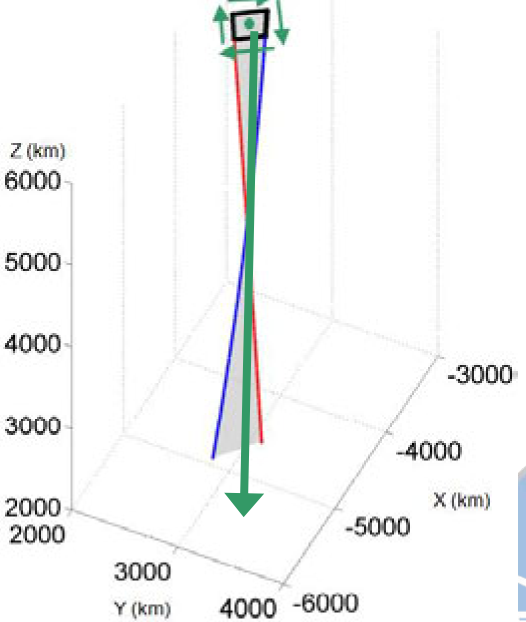
The Method

- Define wide-arc overflights in GEO coordinates
- Define smaller arcs and solve circuital integral $\oint B \cdot dl = \mu_0 I$
- Migrate smaller arcs along orbit
- Remove all solutions which exceed local time span criterion
- Use only low latitude data



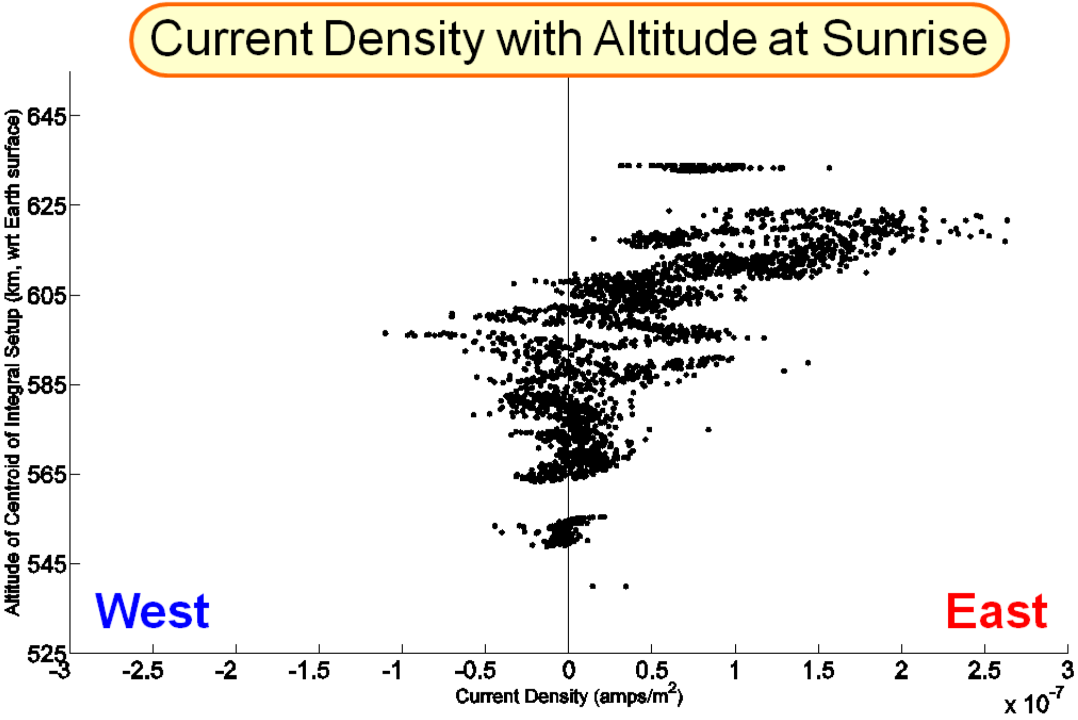
Ampère's Integral applied to Ørsted and CHAMP Overflights

The available data covers 6 years and runs twice through all local times



R. Shore: Univ. of Edinburgh

Summary of main results



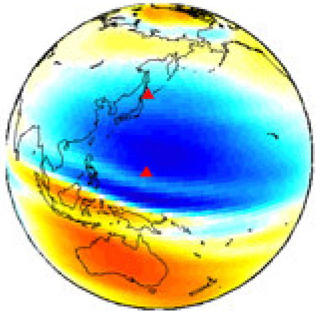
- Strong ionospheric current flow patterns resolved at a range of altitudes between the satellites Ørsted and CHAMP, throughout the span of local times

- Flow directions are systematic in local time or altitude, or both

- Gravity and pressure-driven currents both appear to affect solution

- Method should be suitable for use with ESA's *Swarm* constellation – lessening impact of ionospheric current flow on potential field models

Dynamic fields: Sq currents



- Sq varies daily, seasonally and with solar activity.

- Solar activity effect usually parameterised by a linear dependance with $f_{10.7}$ index : $1 + N f_{10.7}$ with N constant (for CM4 model)

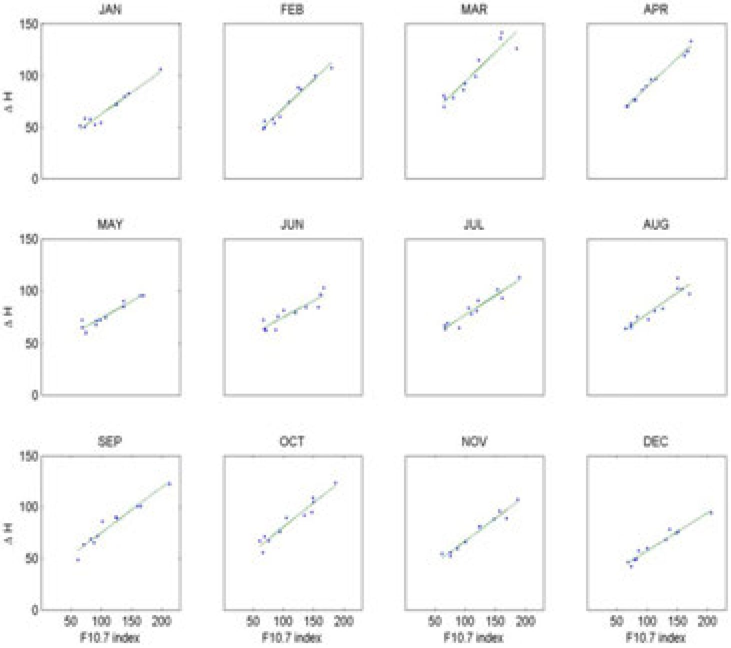
<u>However:</u>

- The proportionality factor between Sq and $f_{10.7}$ varies with seasons (larger during winter and equinoxes).
- Saturation effect observed for $f_{10.7} > 200$ for some ionospheric parameters.

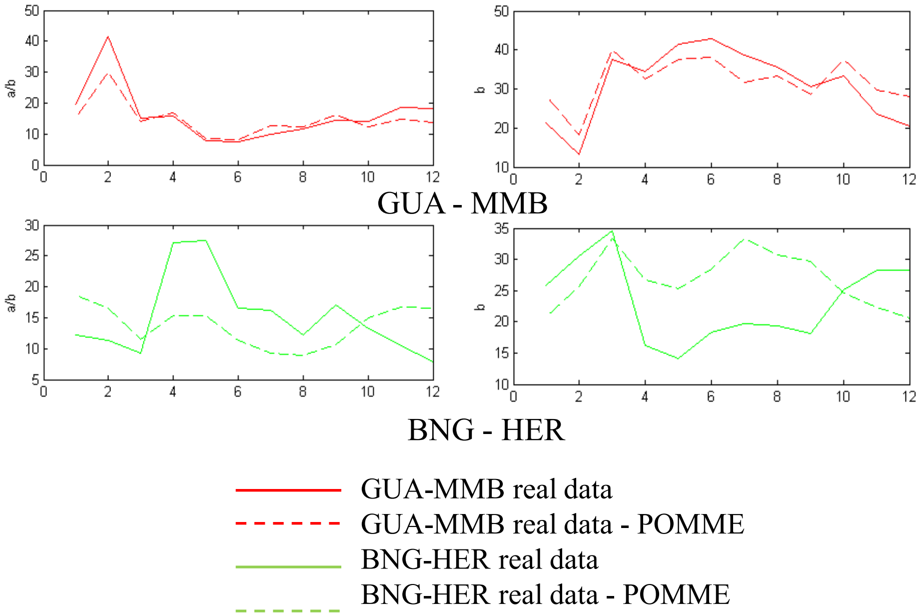
Taking difference ΔH of two stations located on the same meridian on both sides of the focus : => Disturbances removed.

Daily range : $\Delta H_{dr} = \Delta H_{12LT} - \Delta H_{24LT}$.

ΔH_{dr} vs. $f_{10.7}$



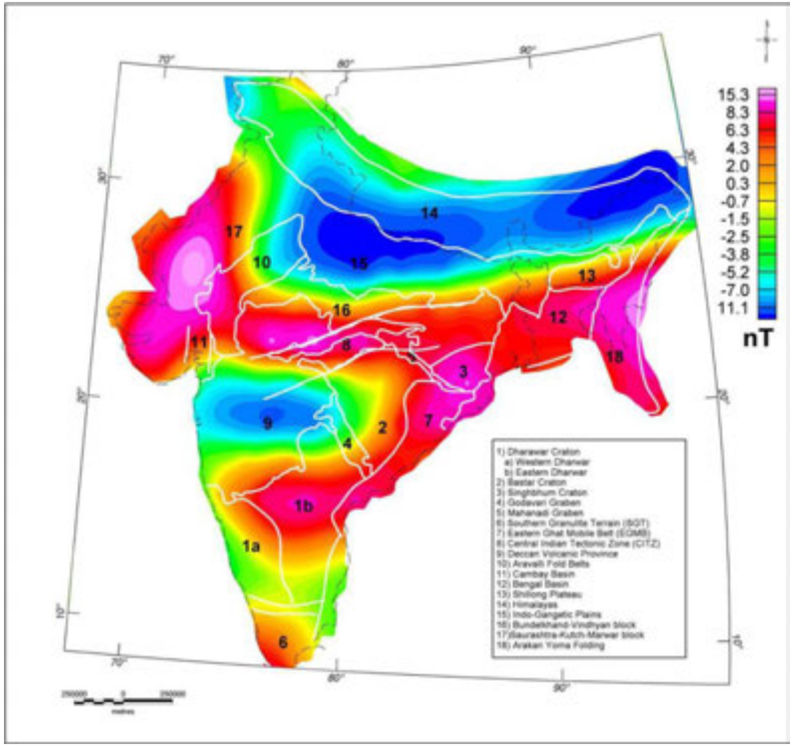
a/b ratio -> N : *b parameter:*



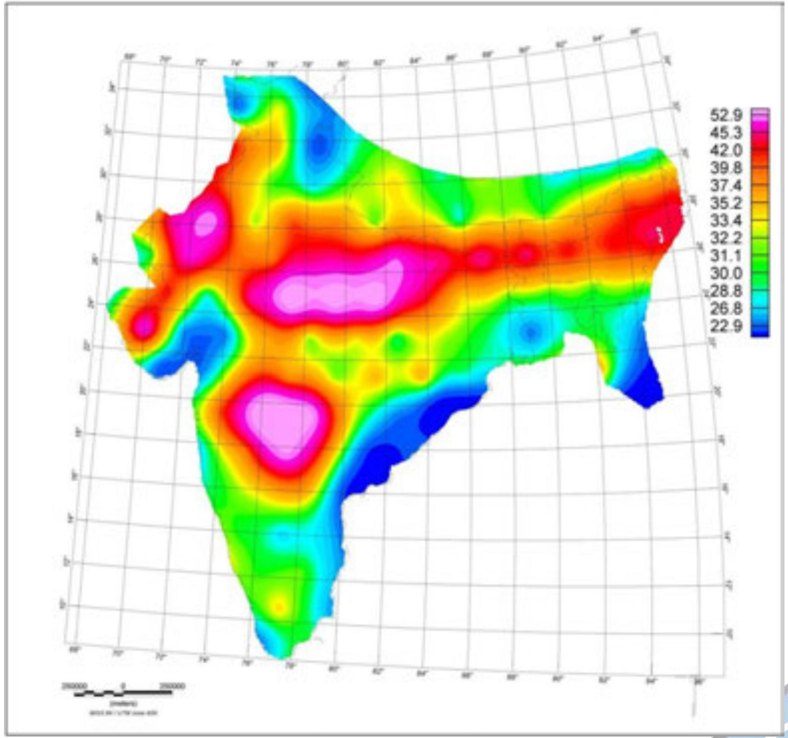
=> For each month : $\Delta H_{dr} = af_{10.7} + b$

Athough reduced, a seasonal variation is still visible after removal of the magnetospheric part of the POMME model (Maus, 2006)

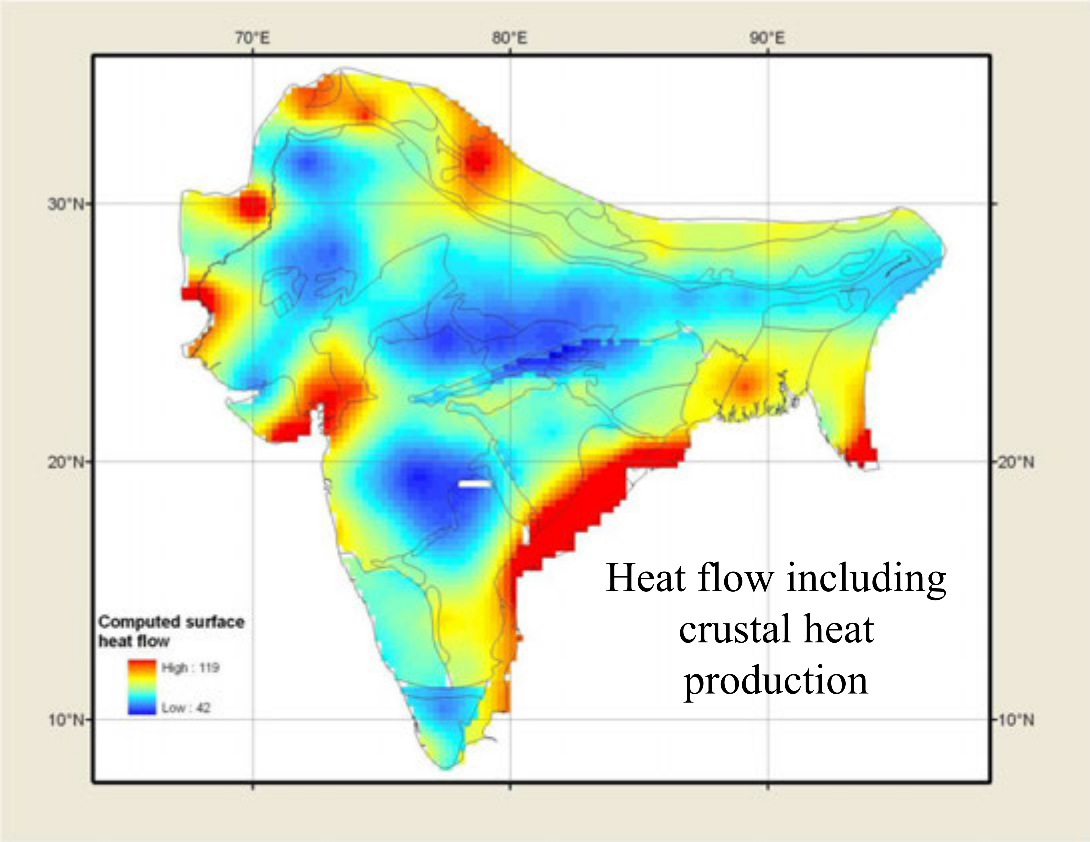
Heat Flow in India



MF5 Lithospheric Model from CHAMP



Lithospheric Crustal Thickness (km)



Depth to the bottom of the magnetic crust lies above the Moho depth - could represent a thermal boundary rather than a petrological or compositional boundary

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Swarm: ESA’s Magnetic Field Mission

1st dedicated Earth Observation Constellation

- ✓ 3 satellites:
  - 2 side-by-side in low orbit
  - 1 in higher orbit
- ✓ three orbital planes with two different near-polar inclinations (global coverage)
- ✓ Launch July 2012: 4 years operations

  (Potential overlap with Cluster)

Each Single satellite:

- ✓ Magnetic field magnitude and vector components
- ✓ Electric field vector components
- ✓ Electron density, Ion/Electron Temp.
- ✓ Air drag
- ✓ Position, attitude and time

Objectives: the Earth

- ✓ Studies of core dynamics, geodynamo processes, and core-mantle interaction, (*SV to degree 16-18*)
- ✓ Mapping of the lithospheric magnetisation and its geological interpretation, (*to degree 133-150*)
- ✓ Determination of the 3-D electrical conductivity of the mantle (*new complementing seismology and gravity)*
- ✓ Identifying the ocean circulation by its magnetic signature

Unique view "inside" the Earth from space for core, mantle & crust

Objectives: near-Earth EM Environment

- ✓ Investigation of electric currents flowing in the magnetosphere and ionosphere, (e.g. *Field aligned currents)*
- ✓ Quantifying the magnetic forcing of the upper atmosphere (*air density and winds*)

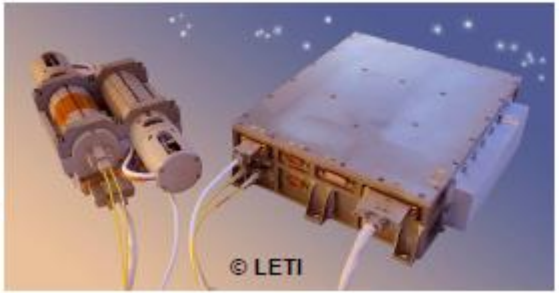
Sun's influence within Earth system

Expected Cal/Val Announcement of Opportunity summer 2011 (app. 1 year before launch)

www.esa.int/esaLP/LPswarm.html

Absolute Scalar Magnetometer (ASM)

- Built by CNES / LETI (France)
- **New technology :**
  - Optical pumping of 4He with careful control of the heading errors
  - Reduced susceptibility to magnetic gradients and to radiated H fields in the low frequency range
- **Improved performances with significant gains :**
- **New vector capacity :**
  - Synchronous absolute scalar and vectorial measurements are continuously delivered by the same instrument : **a world première**
  - Implemented on Swarm on an experimental basis



Performance

- **Scalar absolute accuracy :**
  - 32.5 pT @ 65 μT (Instrument error)
  - < 45 pT@ 65 μT (All errors)
- Stability :
  - demonstrated below 20 pT on a 15 days period @ 65 μT (All errors)
- **Vector mode:**
  - Expected performance :
  - Absolute accuracy ≤ 1 nT @ 50 μT
- Experimental mode, data not distributed by ESA : (let ESA know your interest)

Status:

• Six Flight Models delivered to ESA

• Best scalar precision and accuracy ever attained in space similar performances all along the orbit same point / same time vectorial measurements capability

• **In progress:**
Integration / tests on the 3 satellites
Characterisation / improvement of the vectorial performance

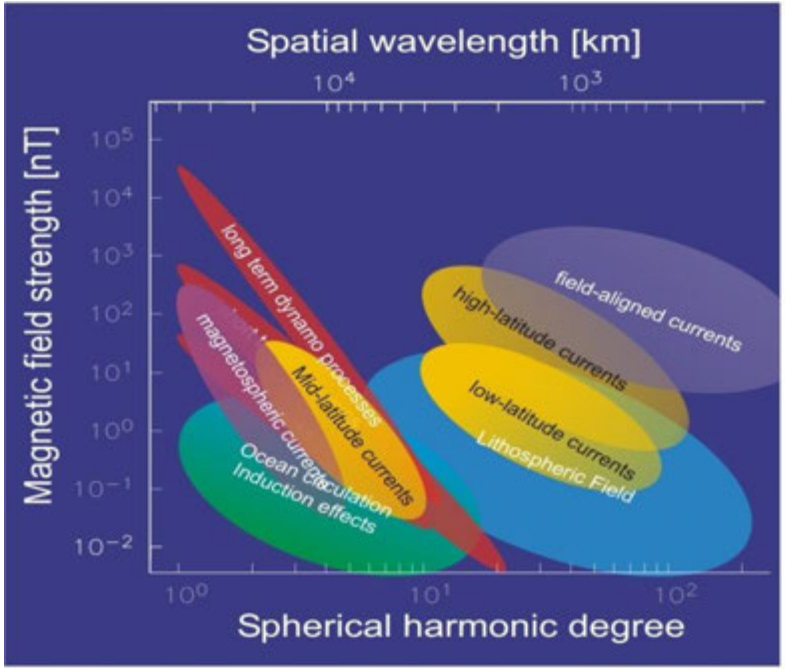
Decade of Geopotential Research: Part Deux?

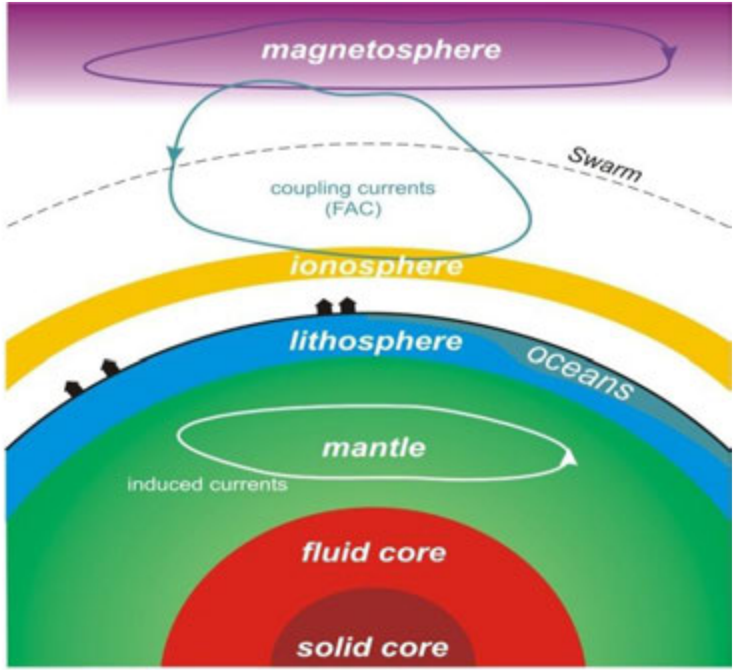
- Swarm (2012 – 2016 + extension)
- Swarm Follow-on (2019 - ?)
- Other opportunities?
  - Space weather
- Public interest too?

User applications...

Orientation of maps on smartphones using digital compass and magnetic declination model

'Augmented reality' e.g. Google Sky or Lonely Planet travel guides


Spatial wavelength [km]
10^4
10^3
Magnetic field strength [nT]
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
long term dynamo processes
magnetospheric currents
Mid-latitude currents
Ocean circulation
Induction effects
field-aligned currents
high-latitude currents
low-latitude currents
Lithospheric Field
10^0
10^1
10^2
Spherical harmonic degree


magnetosphere
Swarm
coupling currents
(FAC)
ionosphere
lithosphere
oceans
mantle
induced currents
fluid core
solid core

Thank You