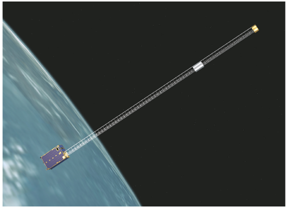
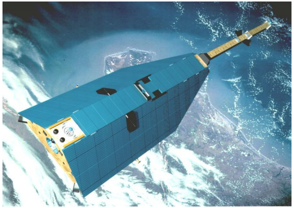
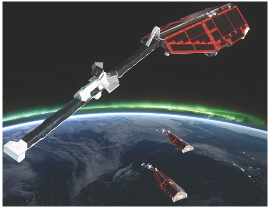
Exploring the Earth's Magnetic Field Using Satellites – From Ørsted to Swarm

Nils Olsen
DTU Space
Technical University of Denmark

Bullard Lecture 2016







Exploring Earth's Interior Using Satellite Magnetic Field Observations – From Ørsted to Swarm

Nils Olsen
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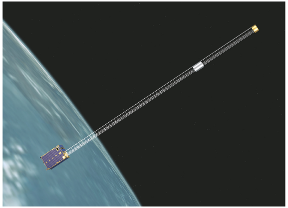
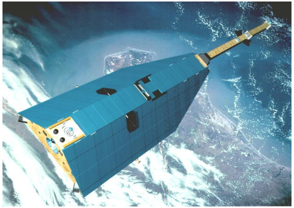
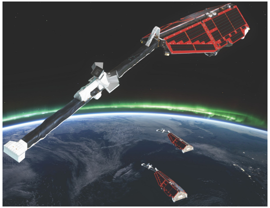
Bullard Lecture 2016







Thanks to the Ørsted, CHAMP and Swarm teams

Sir Edward Bullard

PROFILE Sir Edward Bullard

Chairman of Britain's space projects

New Scientist, 21 June 1959

Sir Edward Bullard

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"Interests centres on the variations in the magnetic field at different heights, at different times of day and in different states of the Sun. Satellite measurements . . . may give the data from which the variable effects can be eliminated – by comparison with simultaneous measurements on the ground.

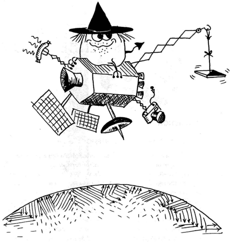
It should then be possible to confirm or deny the present belief that the Earth's magnetic field is in some way distorted."

Nigel Calder: Some exciting possibilities
New Scientist, 21 May 1959

Outline of Talk

1. Satellites for Measuring Earth's Magnetic Field
2. *Swarm* Satellite Trio
3. The Recent Geomagnetic Field and Core Field Dynamics
4. The Lithospheric Field
5. Conclusions and Outlook

Outline of Talk



Credit: C. Barton

Satellites for Measuring Earth´s Magnetic Field

POGO
1965-70

Satellites for Measuring Earth´s Magnetic Field

POGO
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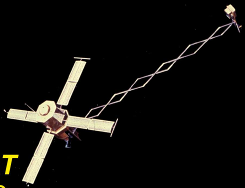
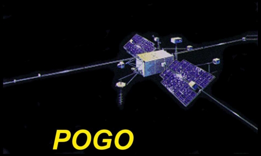


MAGSAT
1979-80

Satellites for Measuring Earth´s Magnetic Field



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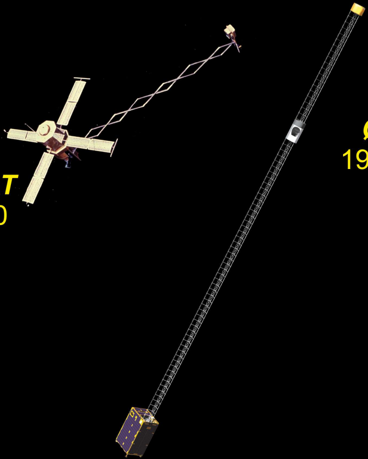

MAGSAT
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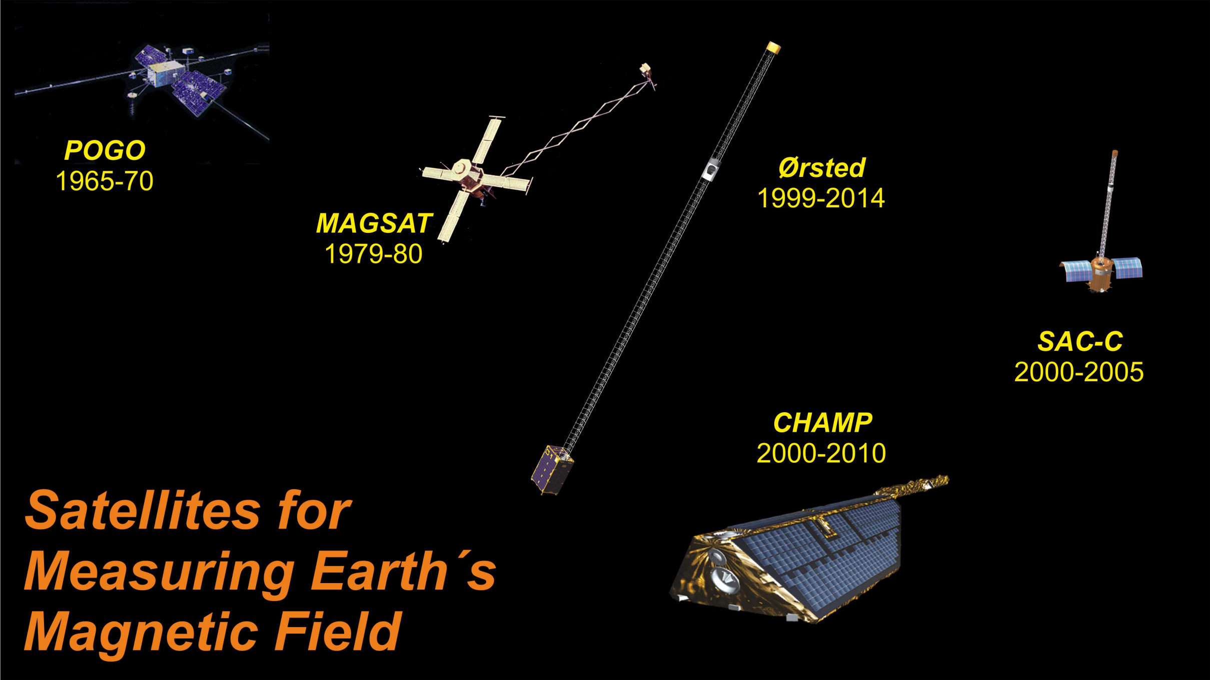
Ørsted
1999-2014

Satellites for Measuring Earth´s Magnetic Field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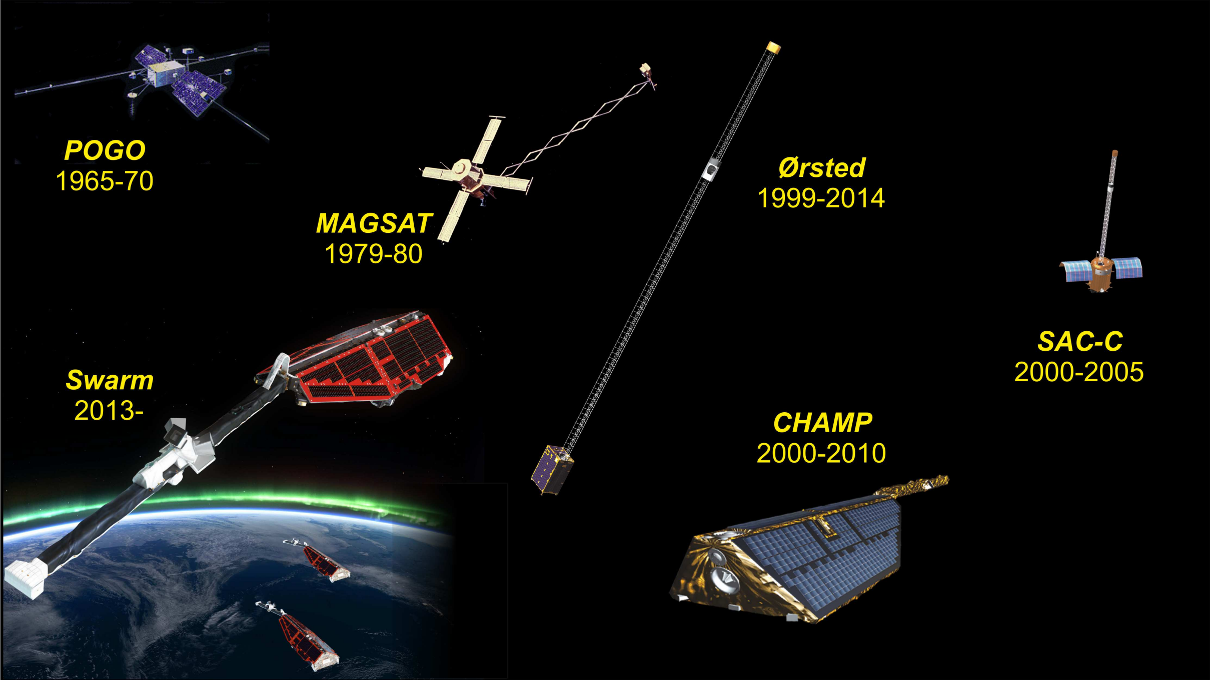
POGO
1965-70
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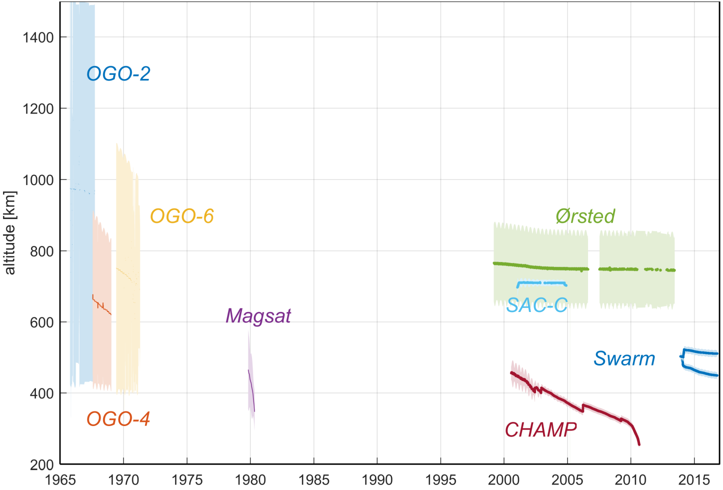
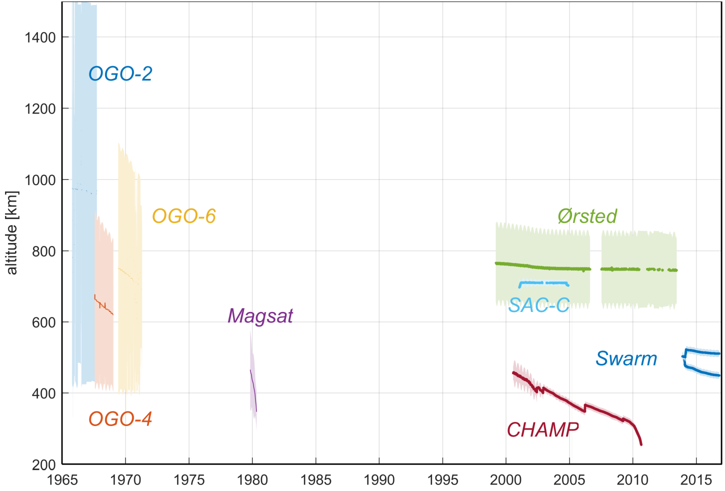
Satellites for Exploring Earth's Magnetic Field



- POGO satellites (OGO-2, OGO-4, OGO-6) only scalar field *F*
- Magsat (1979 – 1980) first satellite to measure vector **B**

Satellites for Exploring Earth's Magnetic Field



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Continuous measurements since 1999

- Ørsted (1999 – 2014)
- SAC-C (2000 – 2005)
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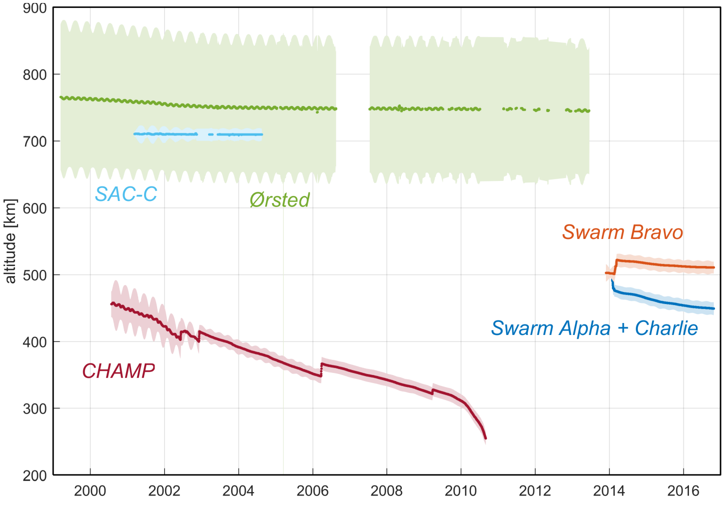
- . . . and now *Swarm* satellite trio

Satellites for Exploring Earth's Magnetic Field



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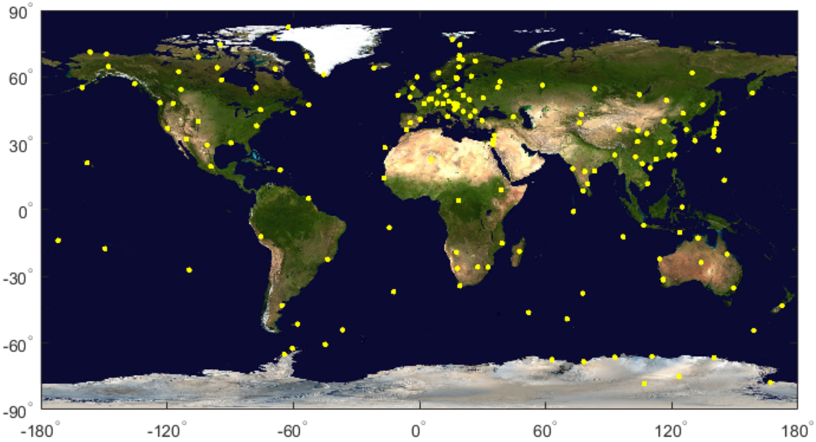
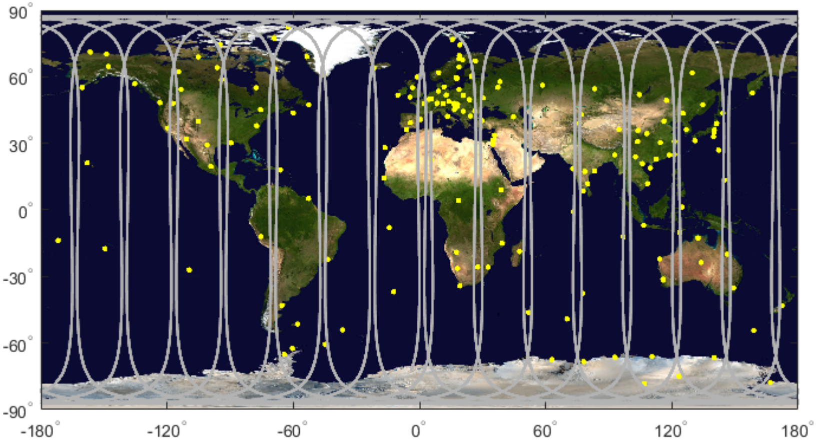
Global coverage ...



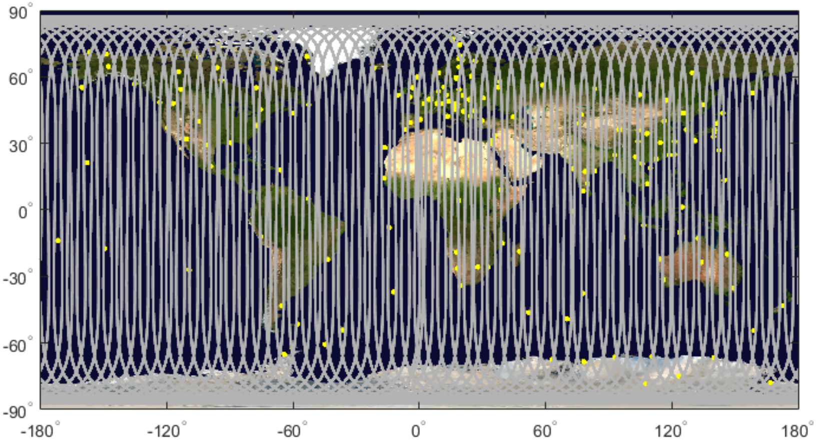
with ground observatories ...

Global coverage ...



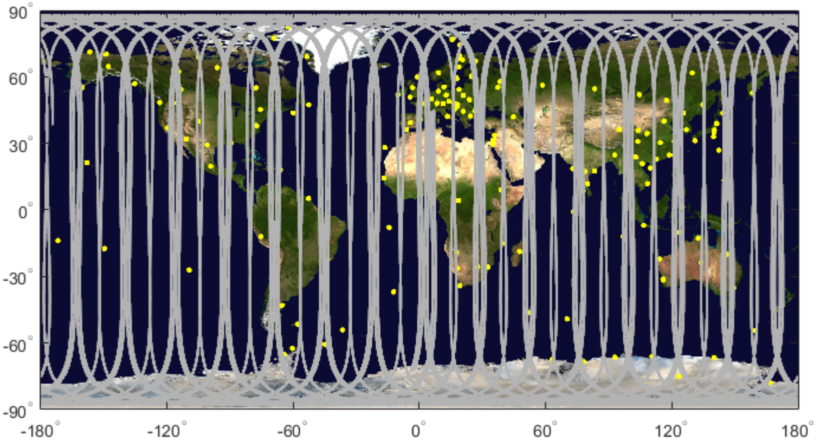
with ground observatories ...
... and 1 day of satellite data

Global coverage ...



with ground observatories ...
... and 4 days of satellite data (single satellite)

Global coverage ...



with ground observatories ...
... and 1 day of Swarm data (three satellites)

Ground vs. Satellite Magnetic Data

- Ground stations monitor time changes of Earth's magnetic field at fixed locations
- Satellites move (with 8 km/s): mixture of temporal and spatial changes

Ground vs. Satellite Magnetic Data

- Ground stations monitor time changes of Earth's magnetic field at fixed locations
- Use of time averaged values (hourly, monthly, annual means) to reduce rapid external field contributions

- Satellites move (with 8 km/s): mixture of temporal and spatial changes
- Time-averaging of observations is *not* possible: one has to work with (possibly down-sampled) instantaneous values

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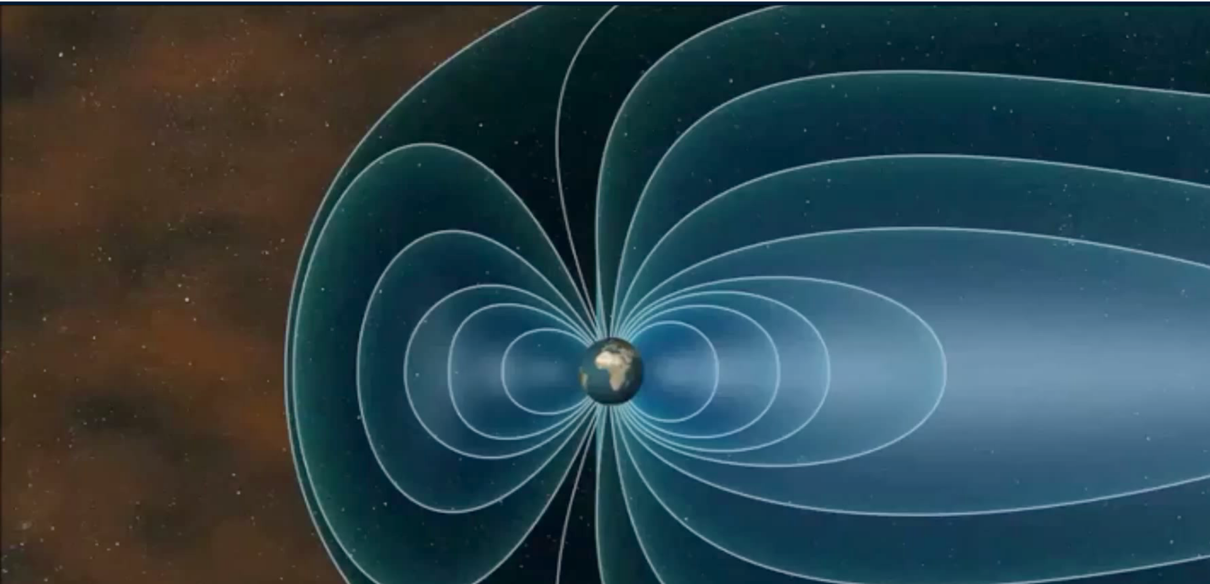
- Absolute measurements of **B** from High-precision Satellites

Ground vs. Satellite Magnetic Data

- Ground stations monitor time changes of Earth's magnetic field at fixed locations
- Use of time averaged values (hourly, monthly, annual means) to reduce rapid external field contributions
- Absolute measurements of **B** from Geomagnetic observatories
- External field studies using data from variometer stations; no (stable) baseline for **B**

- Satellites move (with 8 km/s): mixture of temporal and spatial changes
- Time-averaging of observations is *not* possible: one has to work with (possibly down-sampled) instantaneous values
- Absolute measurements of **B** from High-precision Satellites
- External field studies (mainly in polar regions and for active conditions) using satellites without absolute measurements

Sources of the Near-Earth Magnetic Field



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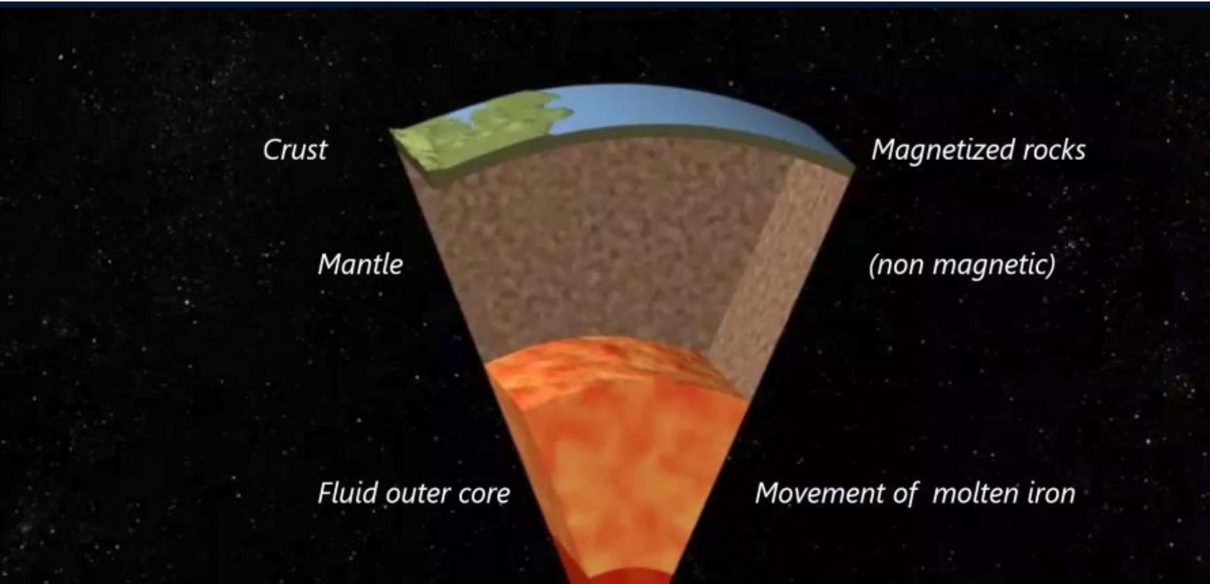

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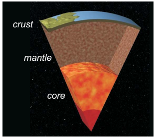
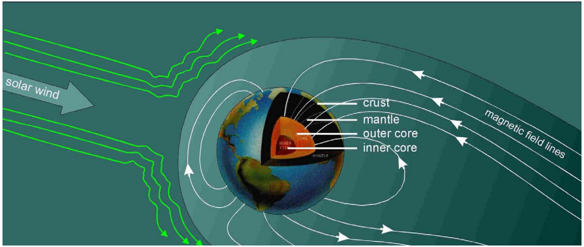
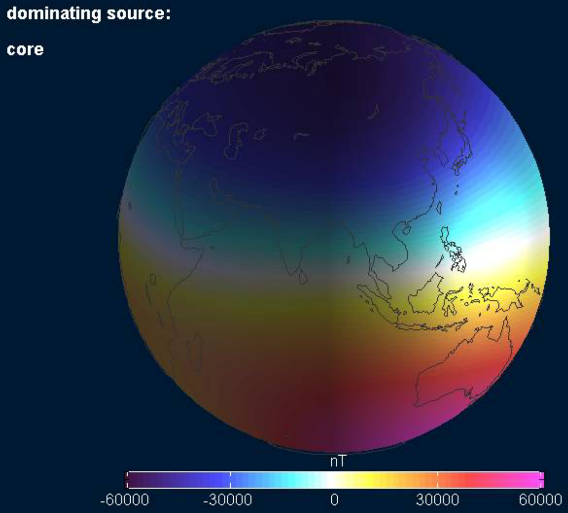
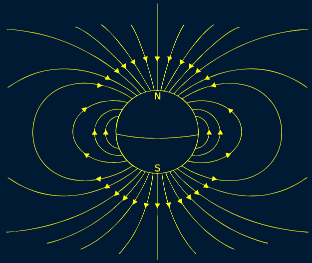


- Internal sources
  - fluid outer core: 94%
    electrical currents created by motion of a conducting fluid
  - lithosphere: 3%
    magnetized rocks
- External sources
  - current systems in ionosphere and magnetosphere: 3%, but highly time-variable!
    caused by solar particles, fields, and radiation



B_r at 400 km altitude





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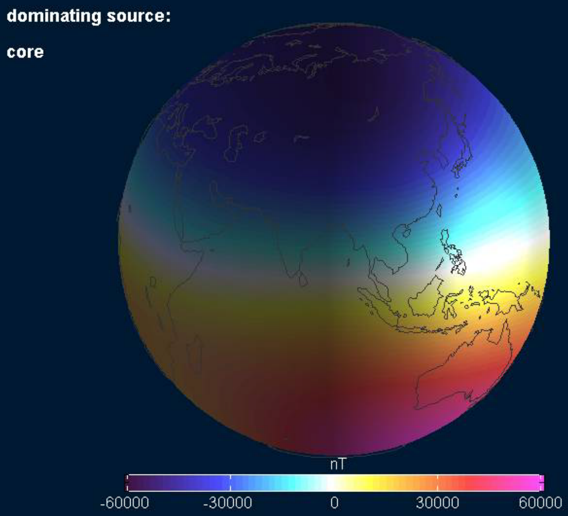
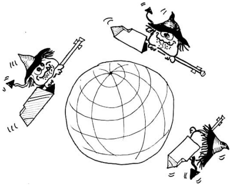


Outline of Talk



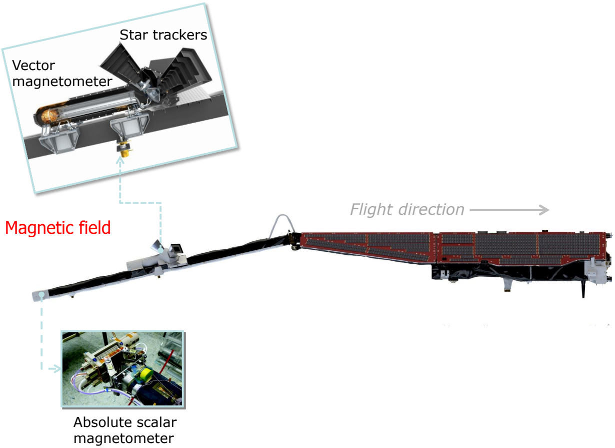
Credit: C. Barton

The *Swarm* Satellite Constellation Mission

Constellation of 3 satellites to explore
Earth's magnetic field and its environment

- launched on 22 Nov 2013
  10+ years lifetime
- two satellites (Swarm Alpha and Charlie)
  side-by-side ($<$ 150 km separation at equator)
  at 450 km altitude (Dec 2016),
  measuring East-West magnetic gradient
- third satellite (Swarm Bravo)
  at 530 km altitude (Dec 2016)
- See http://earth.esa.int/swarm

Swarm satellite payload and Level-1b Data Products

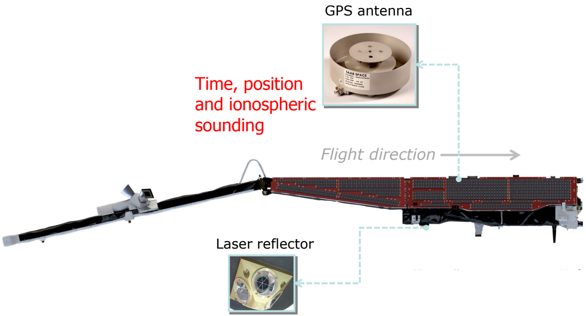


High-precision measurements of $\mathbf{B}$ (< 1 nT) and of $F = |\mathbf{B}|$ (< 0.3 nT)

Level-1b data product: Time series of $\mathbf{B}$ at 1 Hz (MAG-LR) and at 50 Hz (MAG-HR)

All Swarm data products are freely available at http://earth.esa.int/swarm

Swarm satellite payload and Level-1b Data Products



Precise positions (< few cm)

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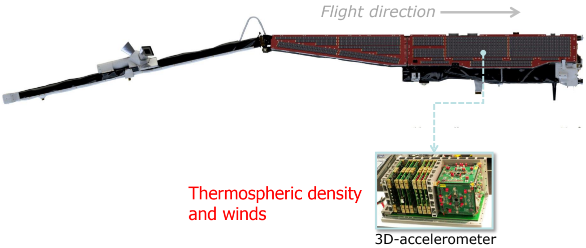
Swarm satellite payload and Level-1b Data Products



Thermospheric density and winds

Accelerometer data
(only for Swarm Charlie, reduced quality)

All Swarm data products are freely available at
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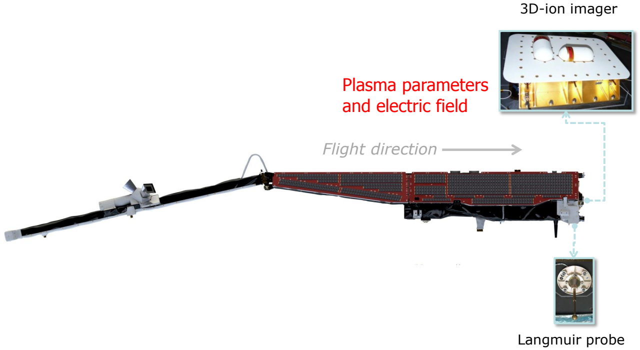
Swarm satellite payload and Level-1b Data Products



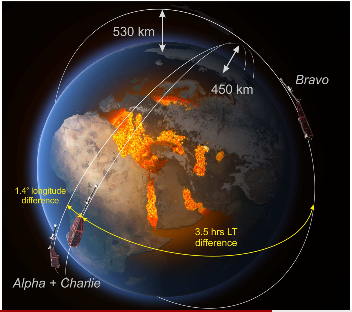
Electric Field, plasma density, ion and electron temperatures

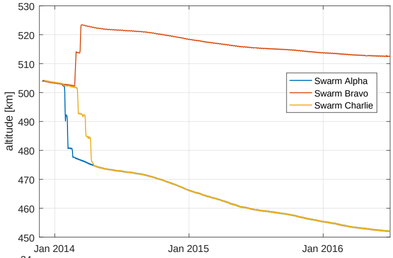
All Swarm data products are freely available at http://earth.esa.int/swarm

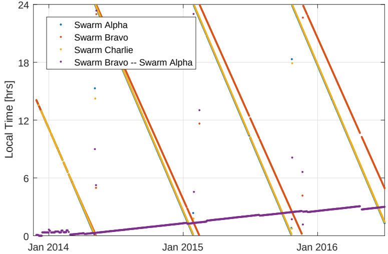
Evolution of the *Swarm* constellation

- Each spacecraft samples all Local Times within 9 months
- Present LT difference between Alpha/Charlie and Bravo is 4.5 hrs
- decaying altitude

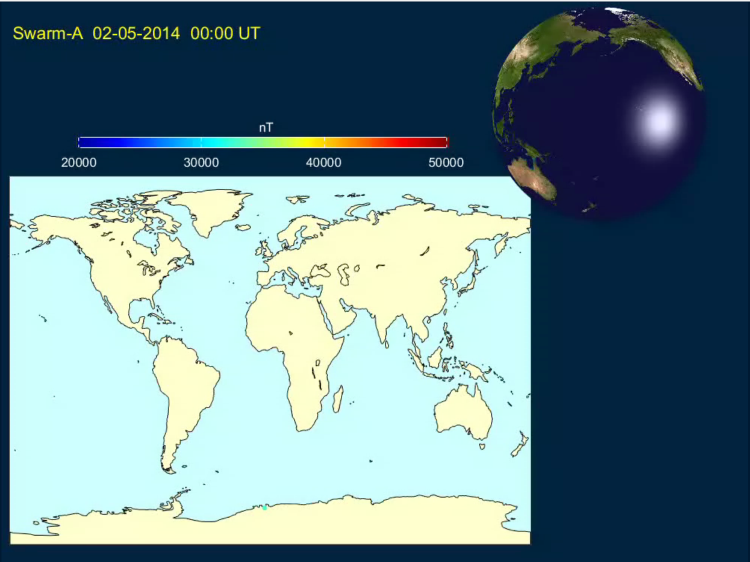
  re-entry of lower pair Alpha/Charlie in mid 2020 or even later?







Swarm Alpha, 2 May 2014, Quiet day (Kp $\leq$ 0+)



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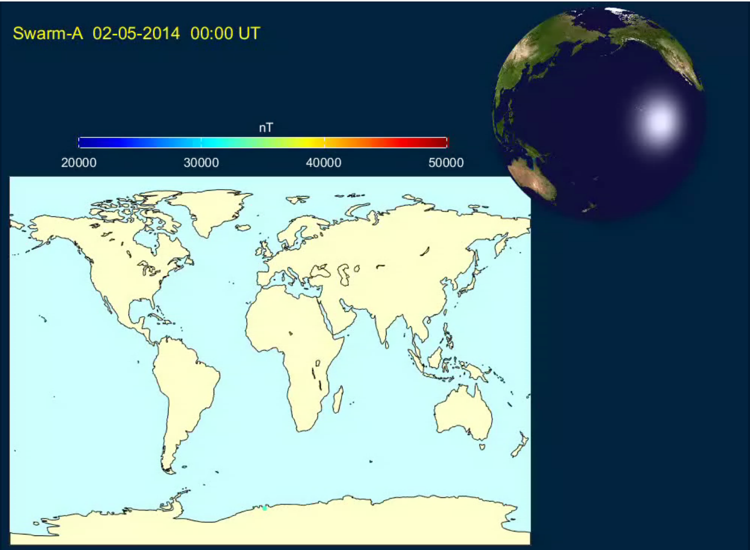

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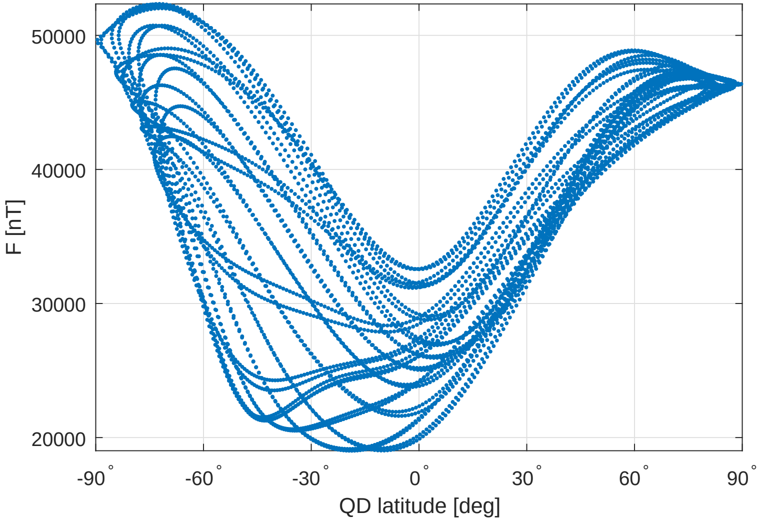

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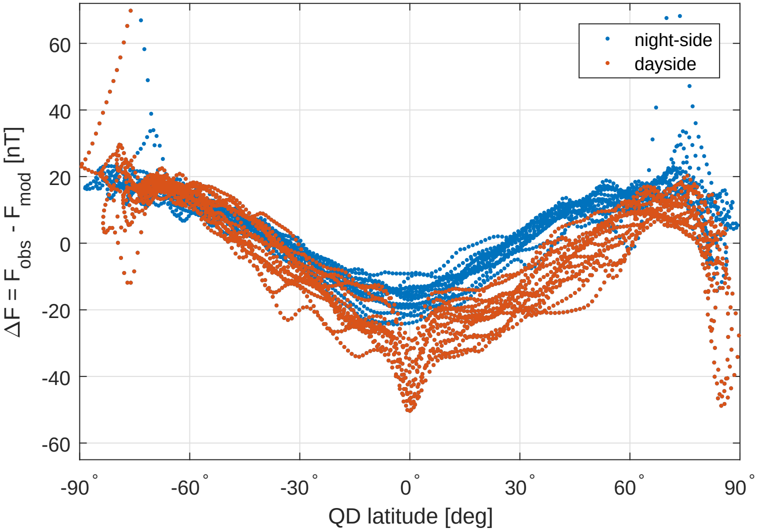

CHAOS-6 model removed for core ...

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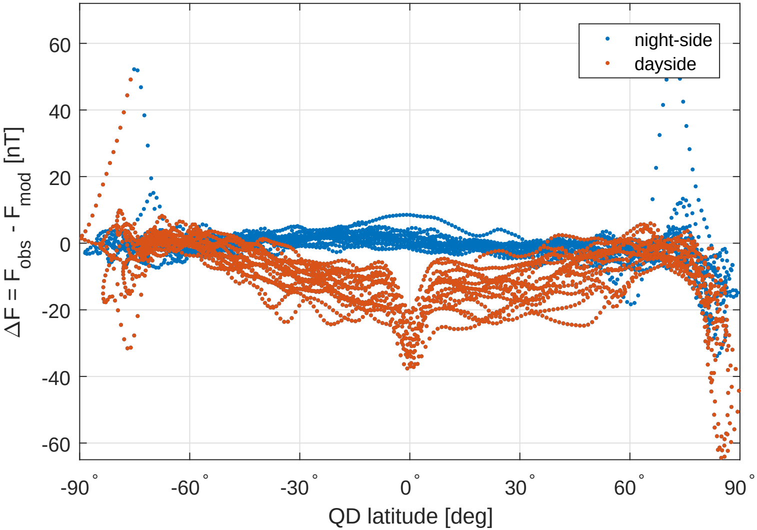

CHAOS-6 model removed for core + magnetosphere ...

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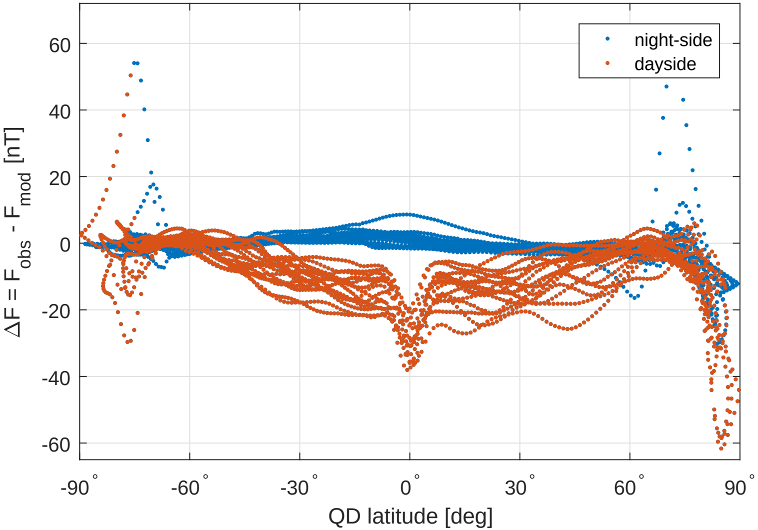

CHAOS-6 model removed for core + magnetosphere + lithosphere

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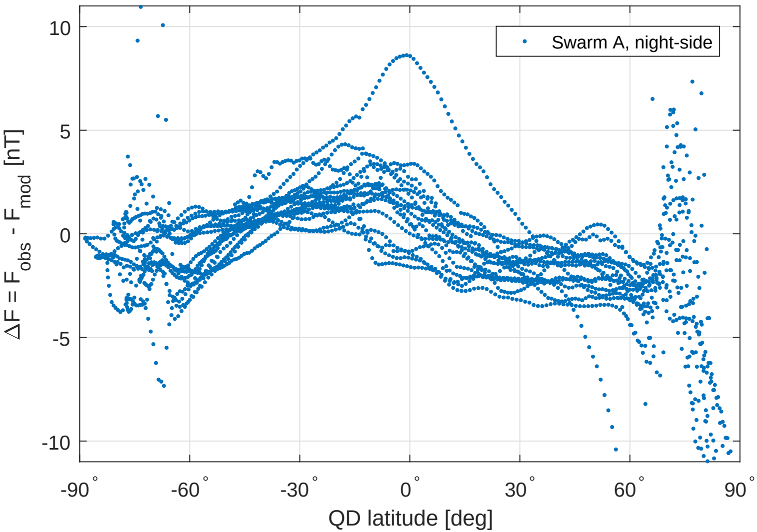
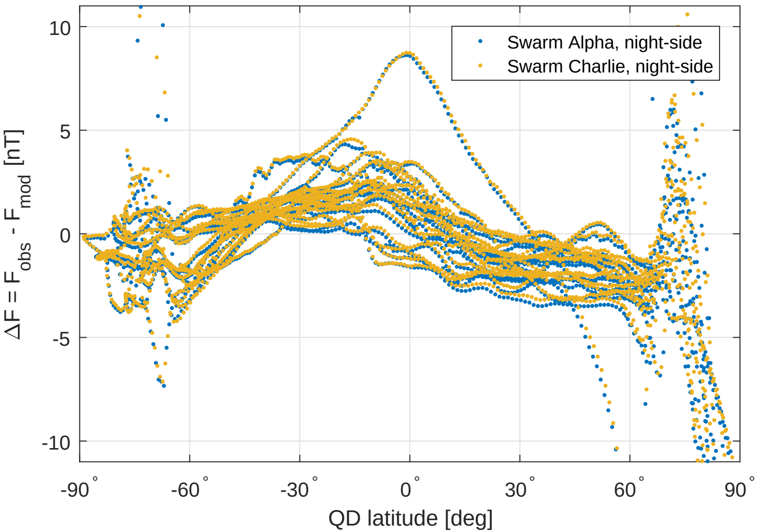


CHAOS-6 model removed for
core + magnetosphere + lithosphere
only nightside data

Swarm Alpha + Charlie, 2 May 2014, Quiet day (Kp $\leq$ 0+)



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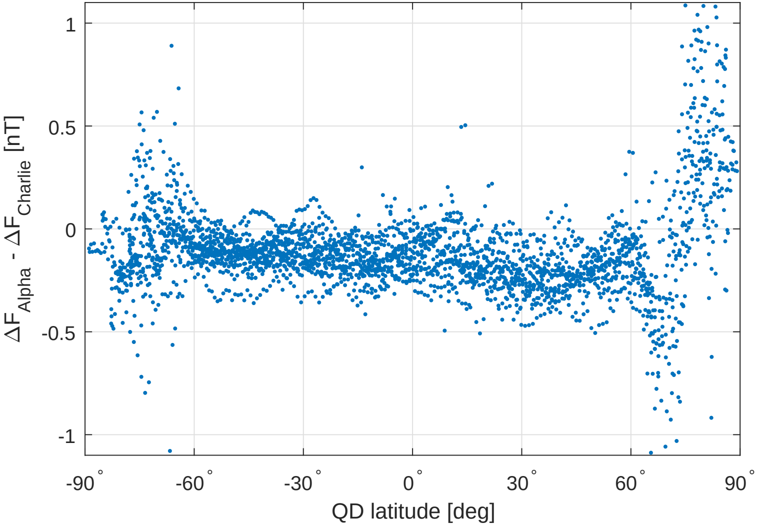

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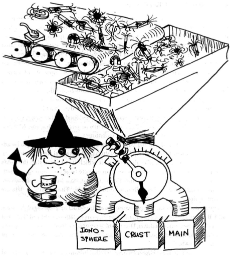

Credit: C. Barton

Magnetic Field Model

Assumption: no local electric currents ($\nabla \times \mathbf{B} = 0$):
$\mathbf{B}$ is a potential field

$$\begin{aligned} \mathbf{B} &= -\nabla\, V \\ V &= a \sum_{n=1}^{N} \sum_{m=0}^{n} \left[g_n^m \cos m\phi + h_n^m \sin m\phi \right] \left(\frac{a}{r}\right)^{n+1} P_n^m(\cos\theta) \\ &+ a \sum_{n=1}^{N} \sum_{m=0}^{n} \left[q_n^m \cos m\phi + s_n^m \sin m\phi \right] \left(\frac{r}{a}\right)^{n} P_n^m(\cos\theta) \end{aligned}$$

r, θ, ϕ are spherical coordinates
g_n^m, h_n^m and q_n^m, s_n^m describe internal, resp. external, magnetic field contributions
Time dependence of low-degree ($n \leq 20$) coefficients $g_n^m(t), h_n^m(t)$ described by splines

CHAOS-6: Model Determined from 17 Years of Satellite Data

Goal: To describe magnetic field with high temporal resolution (determine rapid core field changes) and high spatial resolution (lithospheric field)

(Finlay et al., 2016; Olsen et al., 2014)

CHAOS-6: Model Determined from 17 Years of Satellite Data

Goal: To describe magnetic field with high temporal resolution (determine rapid core field changes) and high spatial resolution (lithospheric field)

- 17 years of data from Ørsted, CHAMP, SAC-C and *Swarm* satellites and monthly mean values from 160 magnetic ground observatories

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- 17 years of data from Ørsted, CHAMP, SAC-C and *Swarm* satellites and monthly mean values from 160 magnetic ground observatories
- Data selection for magnetic field data ($\mathbf{B}, F$):
  - geomagnetic activity index $Kp \leq$ 2o, $|dD_{st}/dt| \leq 2$nT/hr
  - only data from dark regions, Sun at least 10° below horizon
  - Polar regions ($> \pm 55^\circ$ magnetic latitude): only F, selected based on Interplanetary Magnetic Field

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  - Polar regions ($> \pm 55^\circ$ magnetic latitude): only F, selected based on Interplanetary Magnetic Field
- Data selection for magnetic "gradient" data ($\Delta\mathbf{B}, \Delta F$):
  - N-S gradient approximated by alongtrack first differences (15 s sampling)
    E-W gradient approximated by difference *Swarm Alpha* - *Swarm Charlie*
  - allow for higher activity: $Kp \leq 3o$, $|dD_{st}/dt| \leq 3\text{nT/hr}$
  - only scalar data in polar regions

(Finlay et al., 2016; Olsen et al., 2014)

CHAOS-6: Model Determined from 17 Years of Satellite Data

- Model parameterization:
  - static field (core and lithosphere) up to $n \leq 120$
  - time variation of core field ($n \leq 20$) described by splines with 6 month knot spacing between 1997.1 and 2016.6
  - co-estimation of external field and instrument calibration

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  - co-estimation of external field and instrument calibration
- *Iteratively Reweighted Least Squares* to account for non-Gaussian data errors
- Regularisation of mean temporal complexity of $|d^3 B_r / dt^3|^2$ at CMB
  $10\times$ more heavy regularisation of zonal coefficients g_n^0
  ... and regularisation of temporal complexity of $\ddot{B}_r$ at model endpoints
- Regularisation of $||B_r||^2$ at surface for $n > 75$

CHAOS-6: Model Determined from 17 Years of Satellite Data

- Model parameterization:
  - static field (core and lithosphere) up to $n \leq 120$
  - time variation of core field ($n \leq 20$) described by splines with 6 month knot spacing between 1997.1 and 2016.6
  - co-estimation of external field and instrument calibration
- *Iteratively Reweighted Least Squares* to account for non-Gaussian data errors
- Regularisation of mean temporal complexity of $|d^3 B_r/dt^3|^2$ at CMB
  $10\times$ more heavy regularisation of zonal coefficients g_n^0
  ... and regularisation of temporal complexity of $\ddot{B}_r$ at model endpoints
- Regularisation of $||B_r||^2$ at surface for $n > 75$
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CHAOS-6: Model Determined from 17 Years of Satellite Data

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Alternative models include GRIMM (Lesur et al., 2008, 2010), POMMME (Maus et al., 2005, 2006), Comprehensive Model (CM) (Sabaka et al., 2002, 2004, 2015), ...

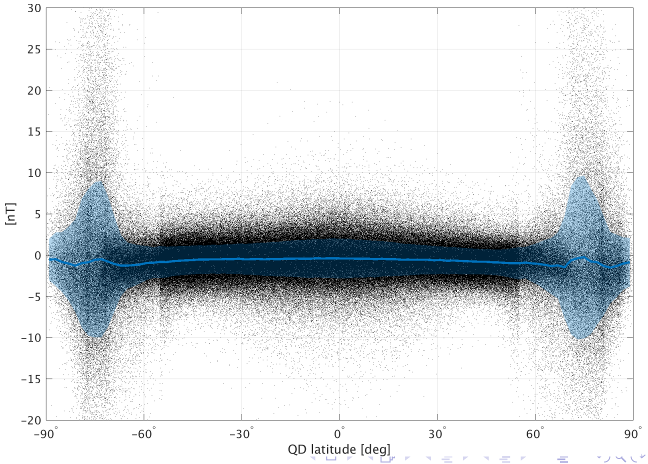
CHAMP Scalar Residuals

Aug 2000 to Sept 2010

mean $\pm 1\sigma$ in 2° bins

non-polar latitudes:
1.95 nT rms

$\approx 5\times$ larger residuals at polar latitudes due to unmodeled external contributions



Swarm East-West Scalar Difference Residuals

Apr 2014 to Mar 2016

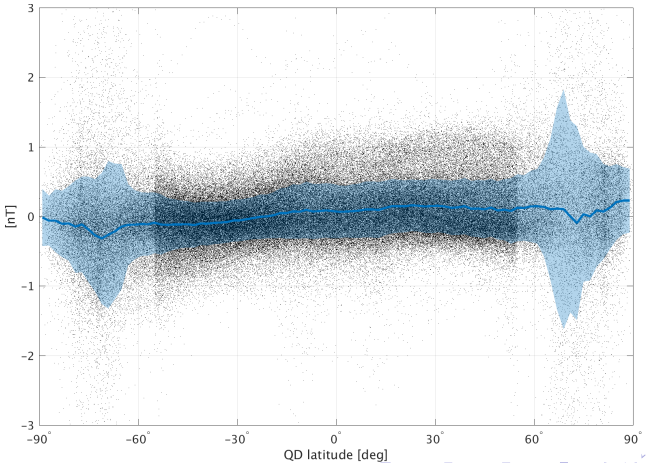
mean $\pm 1\sigma$ in 2° bins

non-polar latitudes:
0.38 nT rms

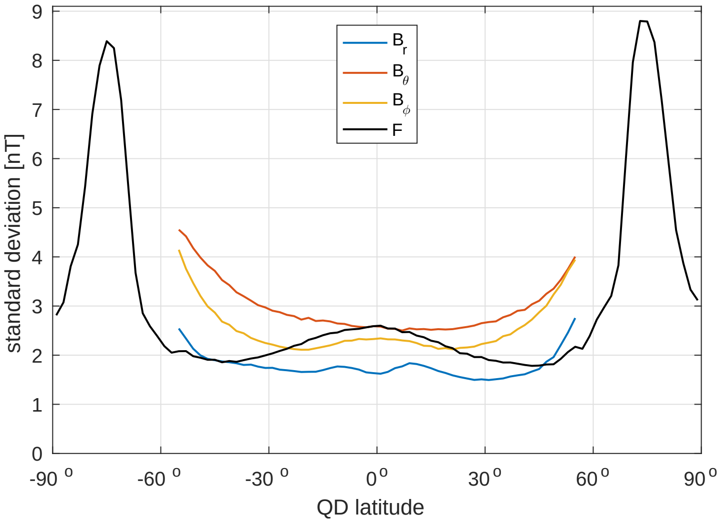
$\approx 3\times$ larger residuals at polar latitudes

Difference of instantaneous measurements between the two satellites *Swarm Alpha* and *Swarm Charlie*

Note different data selection criteria for $> \pm 55°$ magnetic latitudes



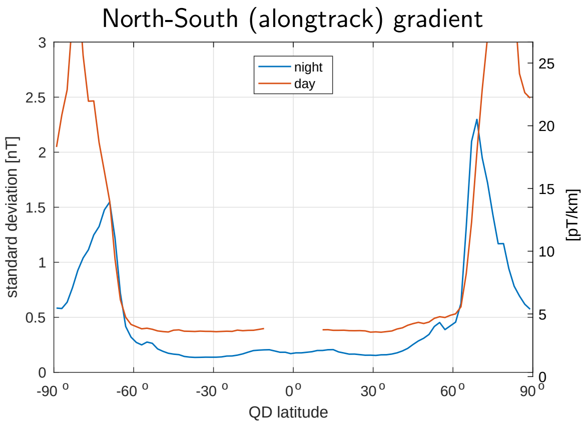
Residual scatter vs. latitude: Field Data

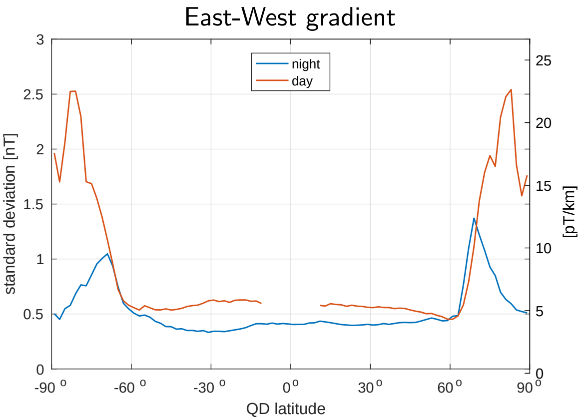


- Enhanced scatter in auroral region
- B_r is least disturbed (in non-polar regions)
- Smallest scatter in F at $\pm 35°$ where magnetospheric ring-current field is $\perp$ to internal dipole field

Residual scatter vs. latitude: Gradient Data

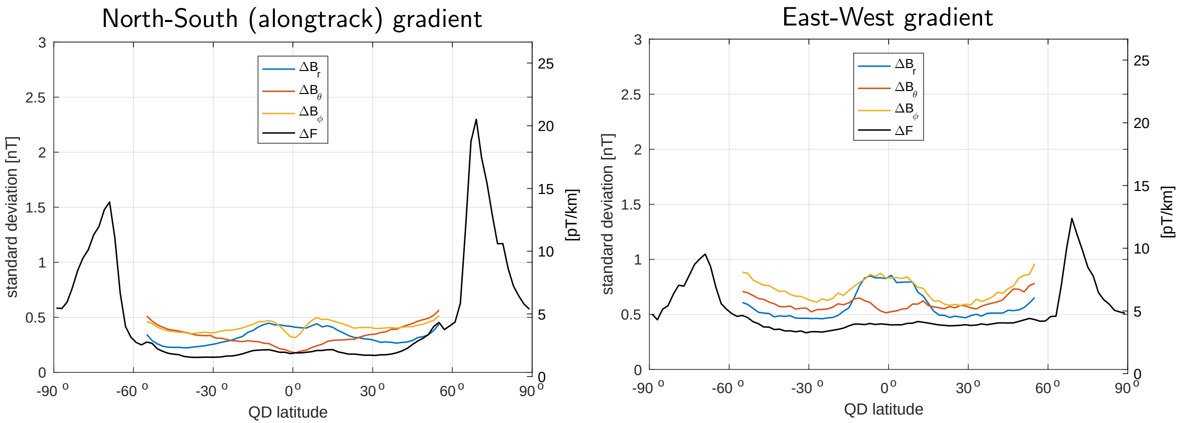
scalar gradients, day and night





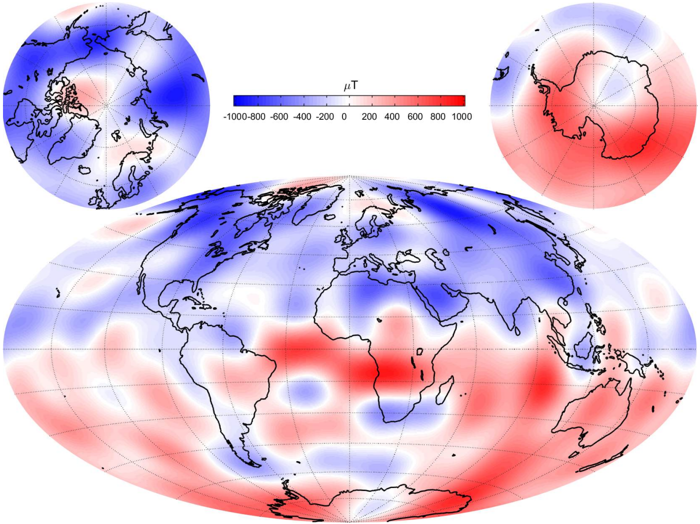
Residual scatter vs. latitude: Gradient Data

scalar and vector gradients, only nightside



Core Field Dynamics during the last 15 years

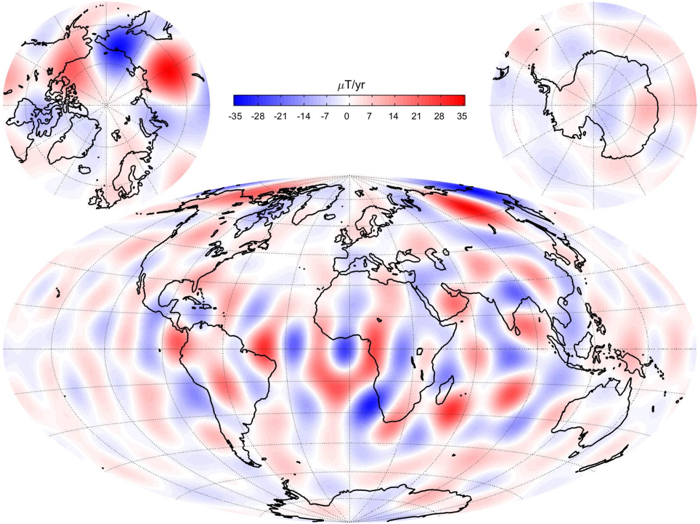
B_r at CMB in 2015, $n = 1 - 13$



(Finlay et al., 2016)

Core Field Dynamics during the last 15 years

$\dot{B}_r$ at CMB in 2015, $n = 1 - 16$



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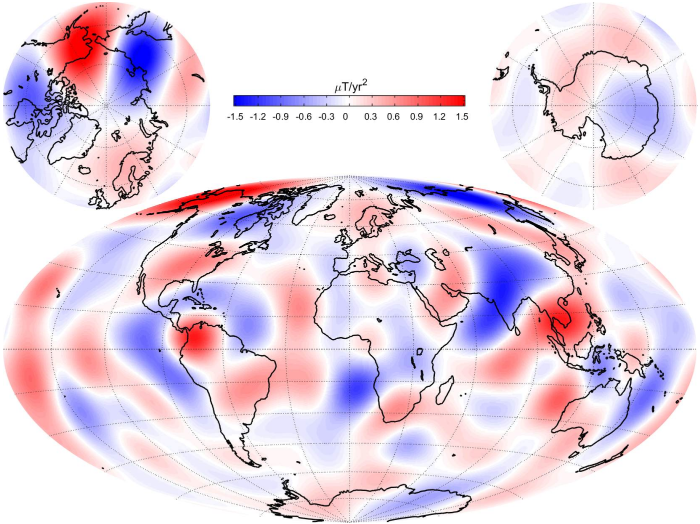

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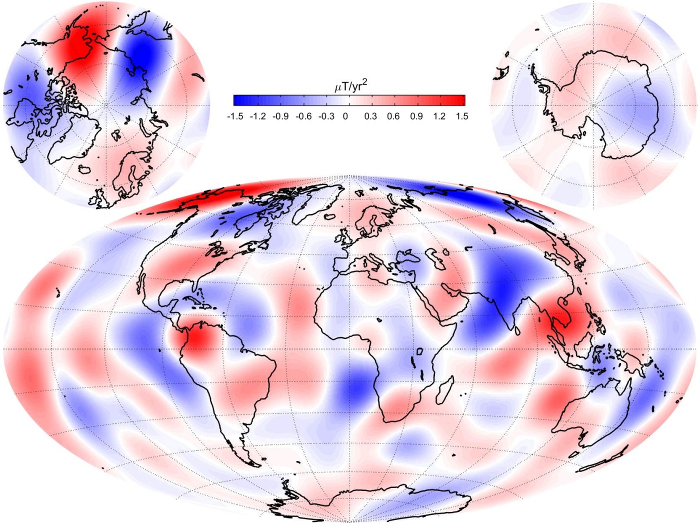


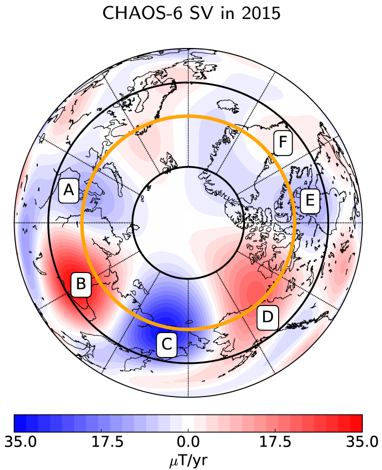
Consistent picture of

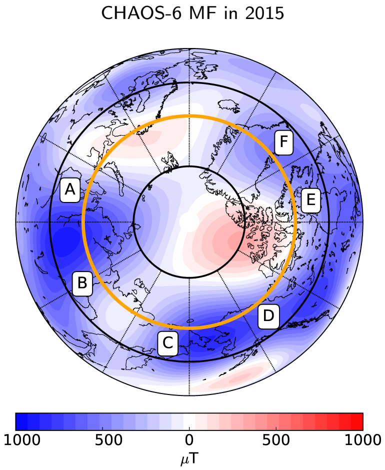
- spatial structure of (time-averaged) secular variation
- secular acceleration at large length scales ($n < 9$)

(Finlay et al., 2016)

An accelerating high-latitude Jet in Earth's Core

Livermore, Finlay, Hollerbach (2016)





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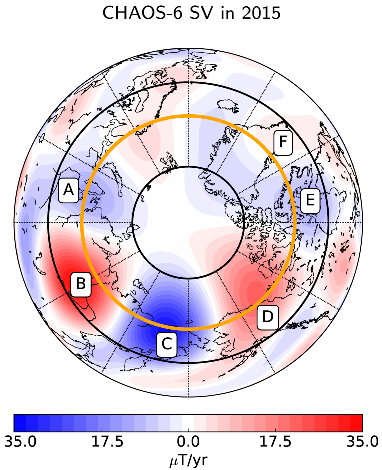

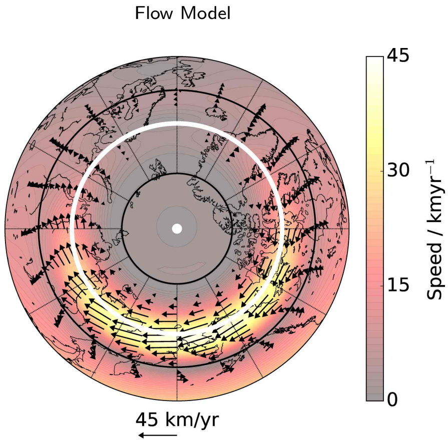

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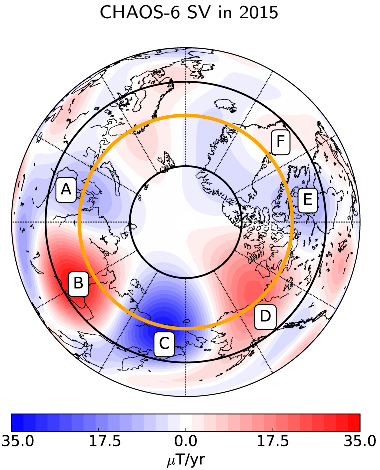
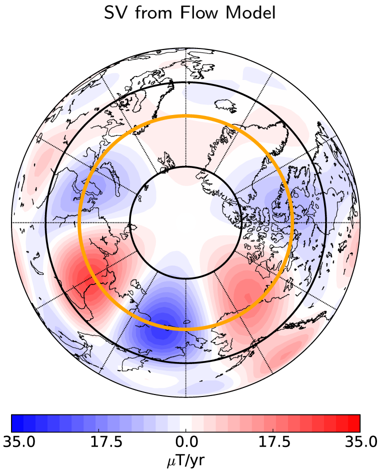




Outline of Talk

1. Satellites for Measuring Earth's Magnetic Field
2. *Swarm* Satellite Trio
3. The Recent Geomagnetic Field and Core Field Dynamics
4. The Lithospheric Field
5. Conclusions and Outlook

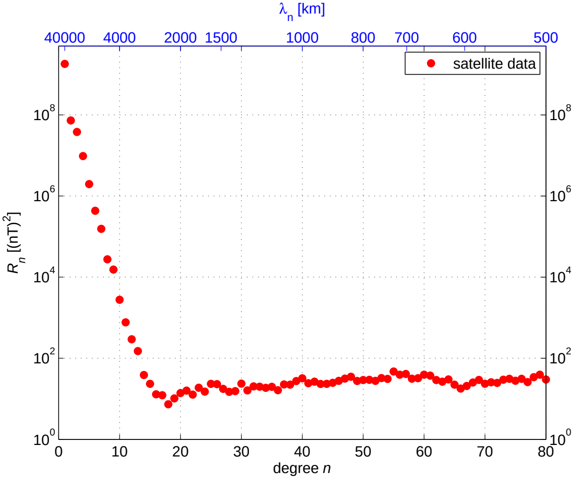
Credit: C. Barton

The Geomagnetic Spectrum

$$R_n = \langle \mathbf{B}_n \cdot \mathbf{B}_n \rangle = (n+1) \sum_{m=0}^{n} \left[(g_n^m)^2 + (h_n^m)^2 \right]$$

mean square magnetic field at Earth's surface ($r = a$) due to contributions with horizontal wavelength $\lambda_n = \frac{2\pi a}{n}$

(Lowes, 1966; Mauersberger, 1956)



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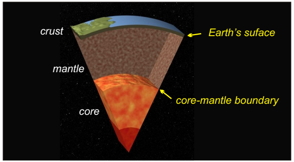
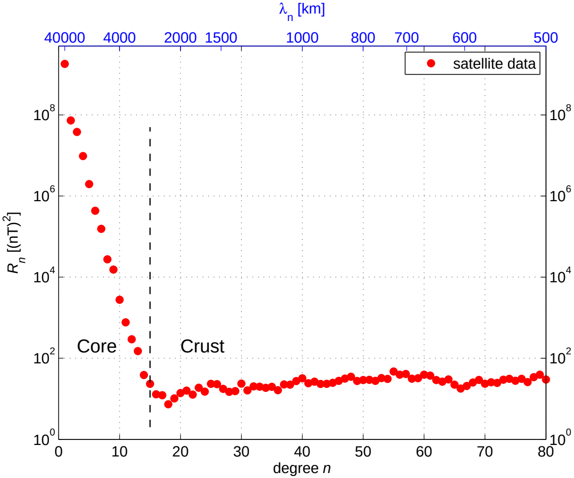
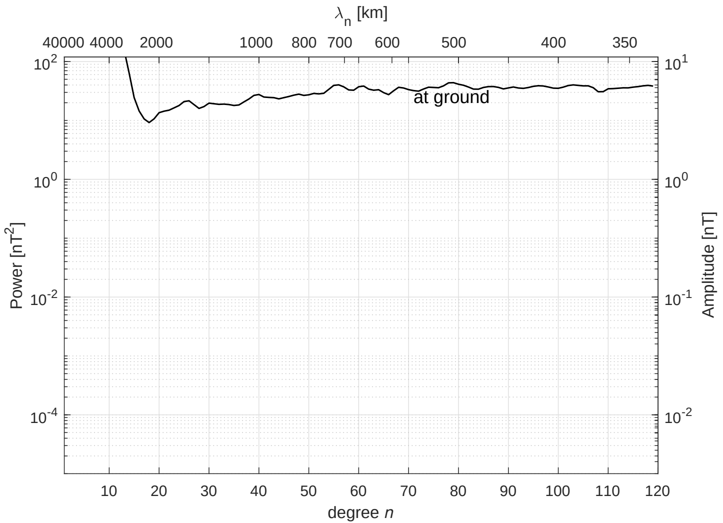




Lithospheric signature at various altitudes



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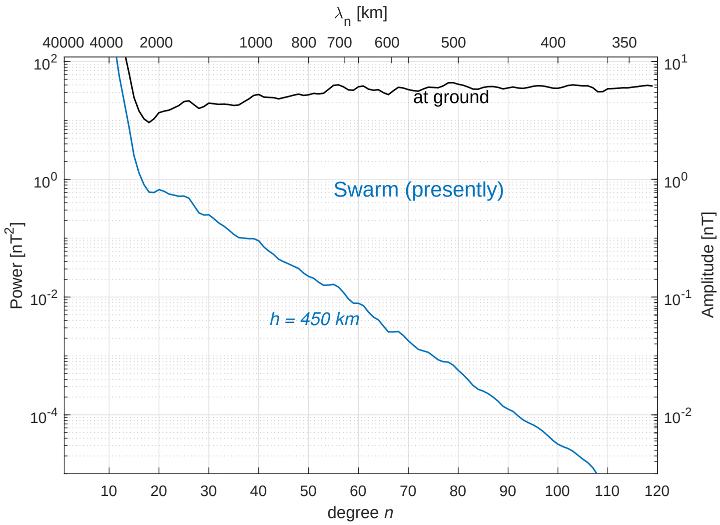

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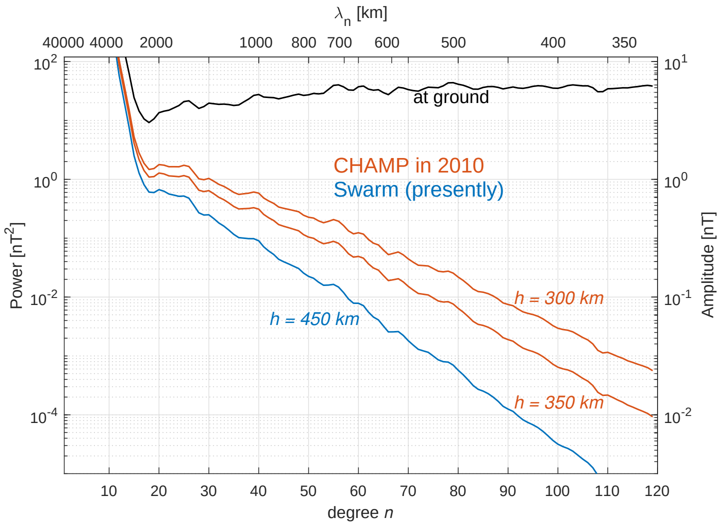

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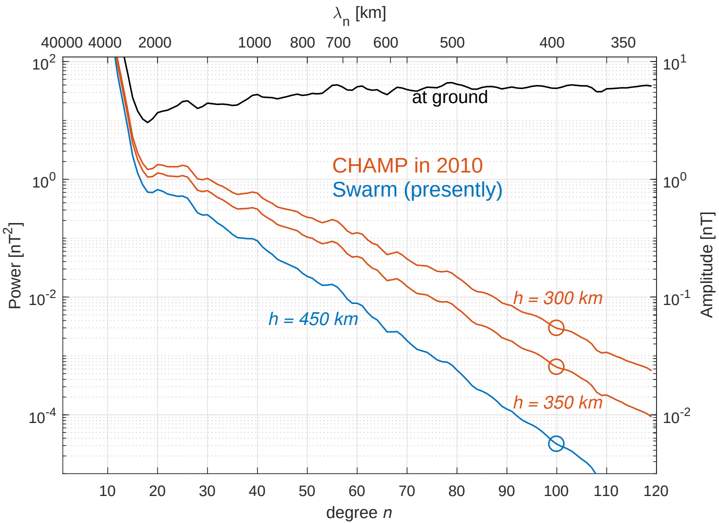

Lithospheric signal
for $n = 100$ ($\lambda = 400$ km):

54 pT @ 300 km altitude
25 pT @ 350 km altitude
5.6 pT @ 450 km altitude

SIFM+: The Swarm Initial Field Model, including vector gradient data Proof-of-concept of field modelling using satellite constellation data

- 20 months of Swarm data, selection as for CHAOS-6:
  scalar and vector field data $(F, \mathbf{B})$
  N-S scalar and vector gradient data: alongtrack first differences
  E-W scalar and vector gradient data: Alpha – Charlie

(Olsen et al., 2015, 2016)

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- ... and compare with the CHAMP-derived model MF7 (Maus, 2010)

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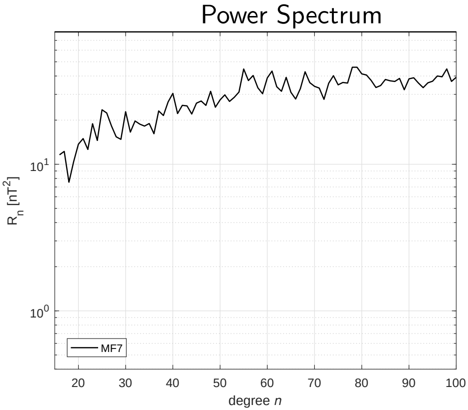

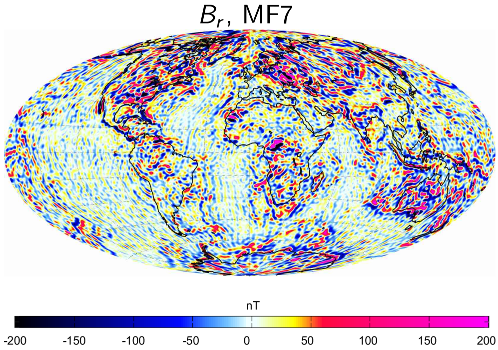

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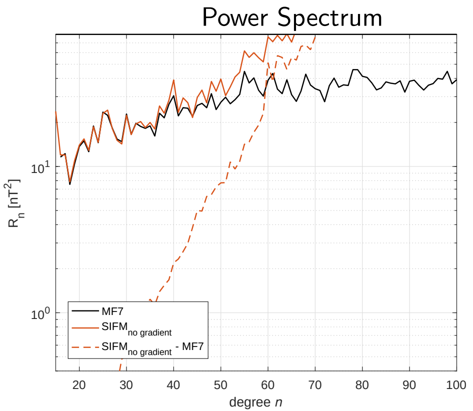

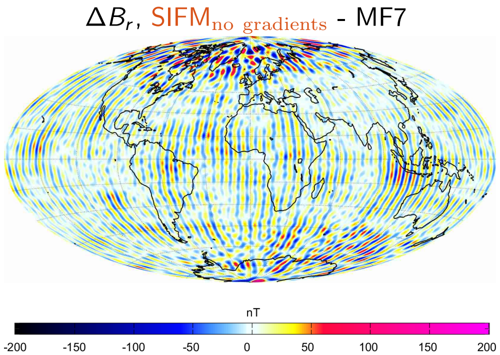

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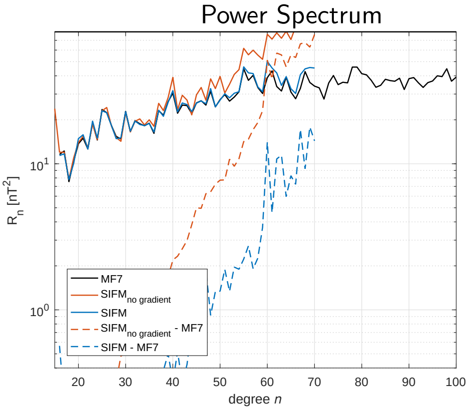
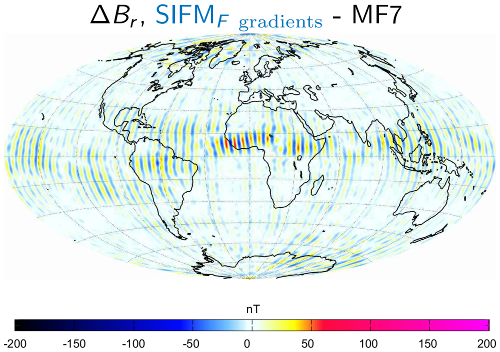
SIFM$_{\text{no gradients}}$: no gradient data

SIFM: The Swarm Initial Field Model





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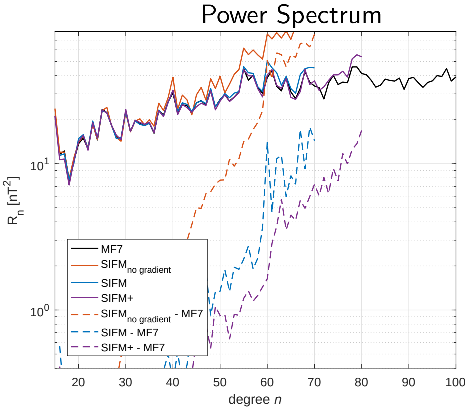

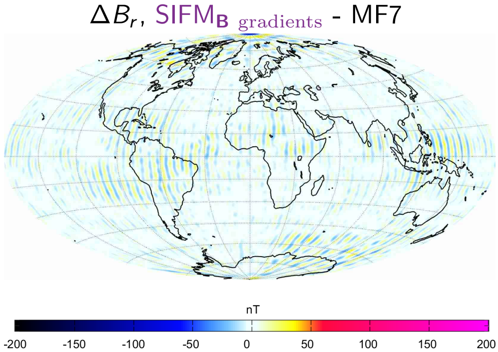

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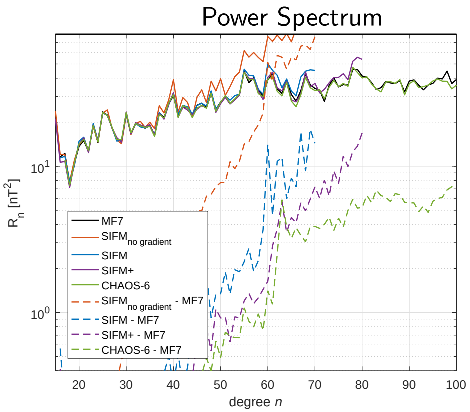

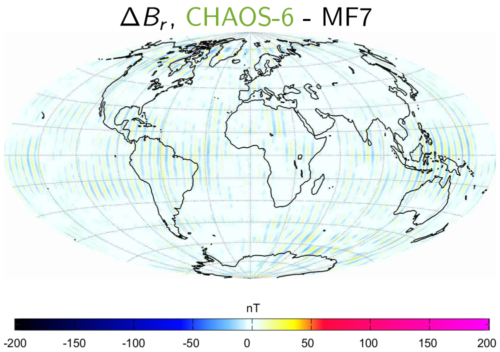

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CHAOS-6: Model from 2 years of CHAMP data at 320 km altitude (10 x higher crustal field signal at $n = 100$)

On The Art of Lithospheric Field Modeling

- What part of the model is defined (constrained) by the observations?
- Small-scale structure of *all* global lithospheric field models are regularized
    - CHAOS-6 (Finlay et al., 2016) and MF7 (Maus, 2010): only part $n \leq 75$ is purely determined by observations, part $n = 76 - 133$ is constrained by "additional information"

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A new Lithospheric Field Model

- Same CHAMP data as for CHAOS-6 (but only 2009 – 2010 when altitude < 350 km)
  15 sec sampling, geomagnetic quiet conditions
  scalar and vector fields $(\mathbf{B}, F)$; scalar and vector alongtrack gradients $(\Delta\mathbf{B}, \Delta F)$
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Work in progress with Tiku Ravat and Chris Finlay

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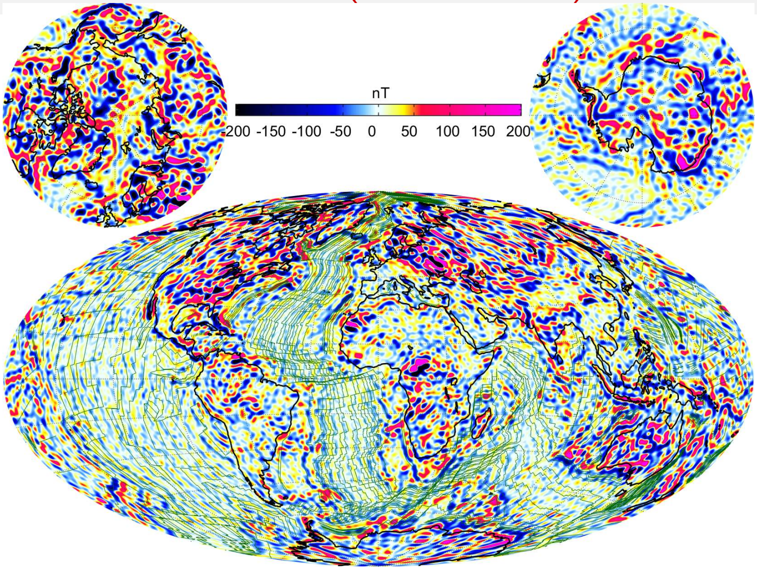
- Final step: Representation by spherical harmonics up to $n = 185$ ensuring $\nabla \cdot \mathbf{B} = 0$

Work in progress with Tiku Ravat and Chris Finlay

B_r at Earth's surface ($n = 16 - 133$)



MF7 Lithospheric Model

(Maus, 2010)

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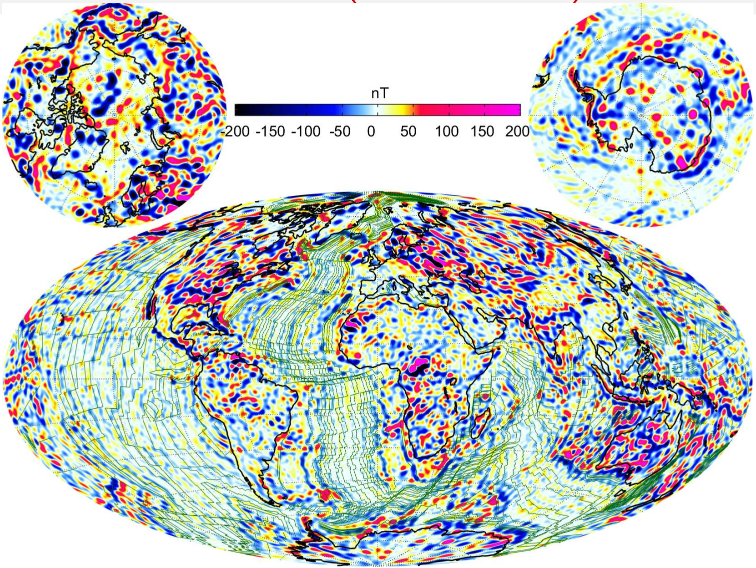
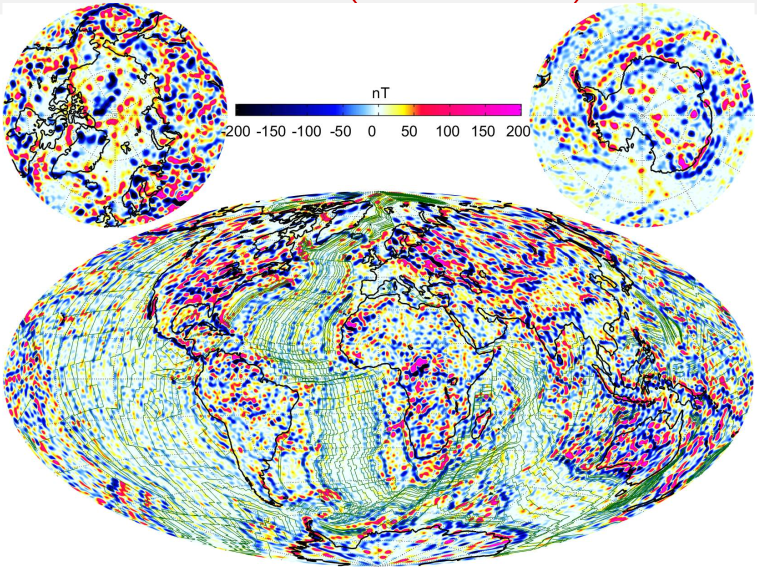


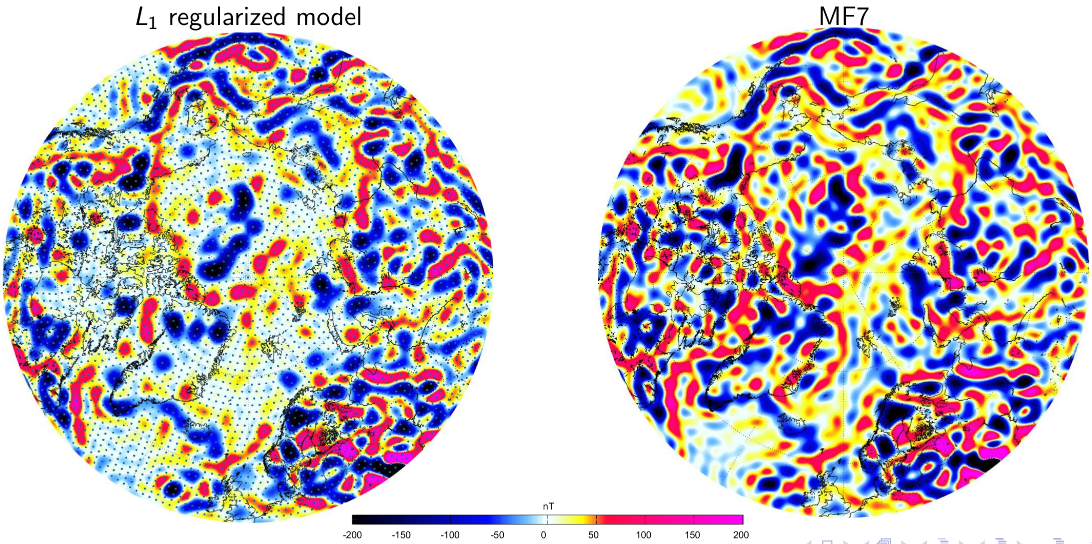
L_1 regularized model

B_r at Earth's surface ($n = 16 - 185$)

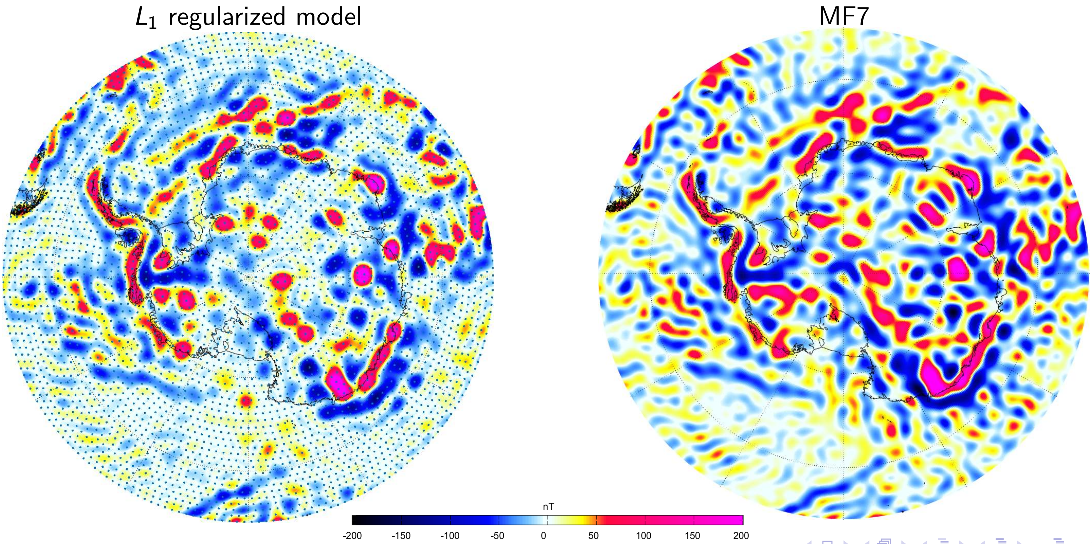


L_1 regularized model

B_r at Earth's surface: Arctic

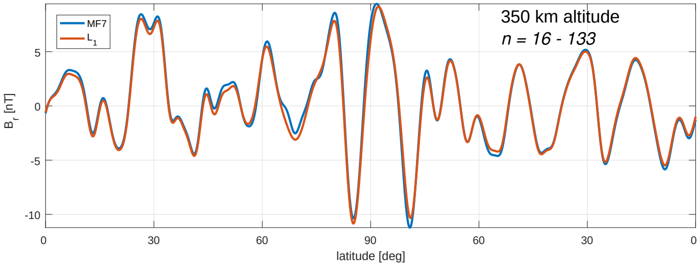


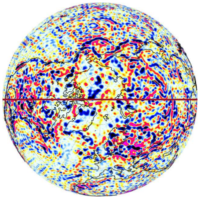
B_r at Earth's surface: Antarctic



A latitudinal profile over the North-Pole

$n = 16 - 133$





Good agreement at satellite altitude

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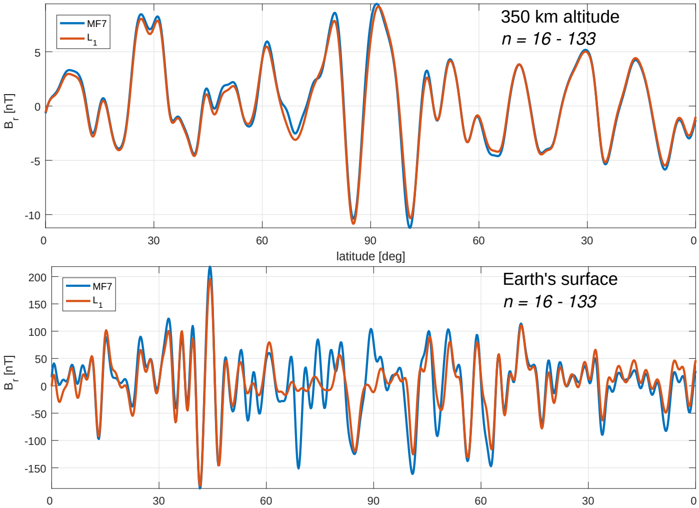
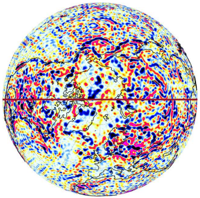
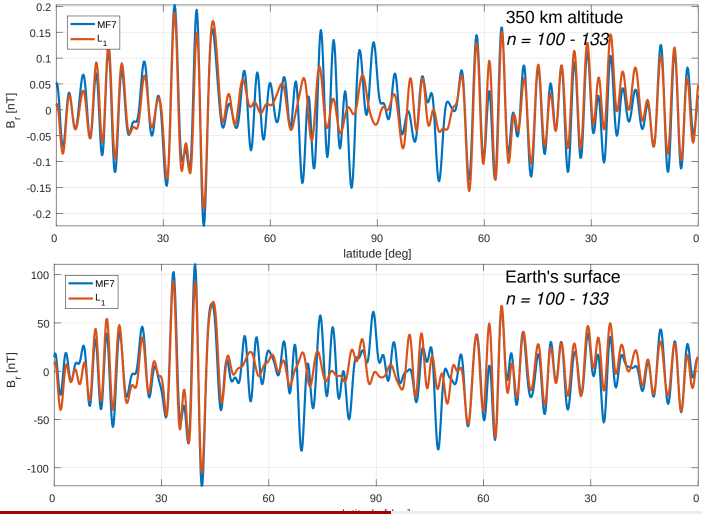


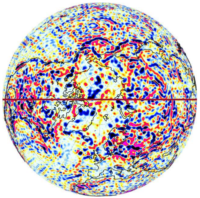


Good agreement at satellite altitude and at surface in non-polar regions

A latitudinal profile over the North-Pole

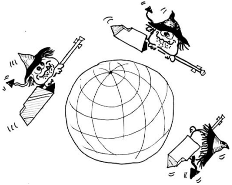
$n = 100 - 133$





Good agreement at $n \geq 100$ in non-polar regions, confirming robustness of lithospheric models up to (at least) $n = 100$, though not in polar regions

Outline of Talk



Credit: C. Barton

Conclusions

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - lithospheric field (at least up to $n = 100$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core and lithospheric field signal
- Rapid core field variations and lithospheric field are better resolved in non-polar ($< \pm 60°$) regions
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved lithosphere *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years

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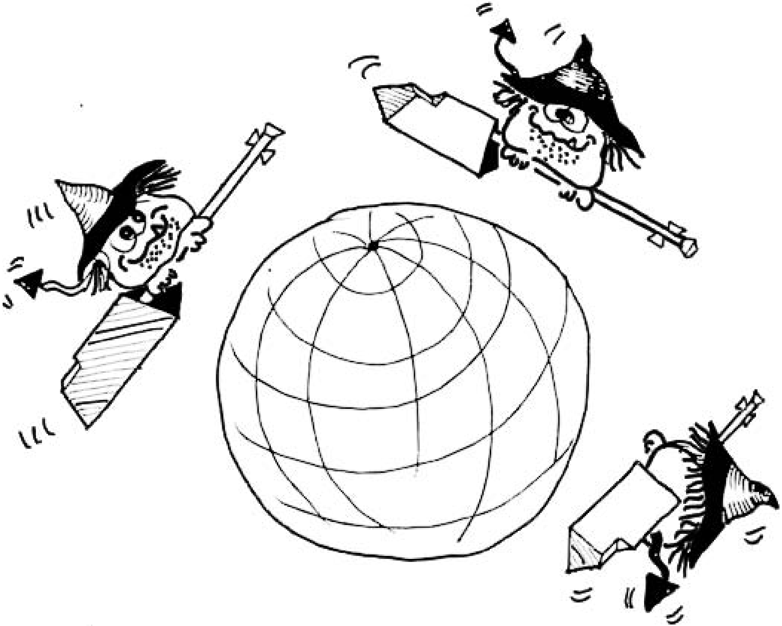
- **Physics-based field modeling (e.g. through data assimilation)**



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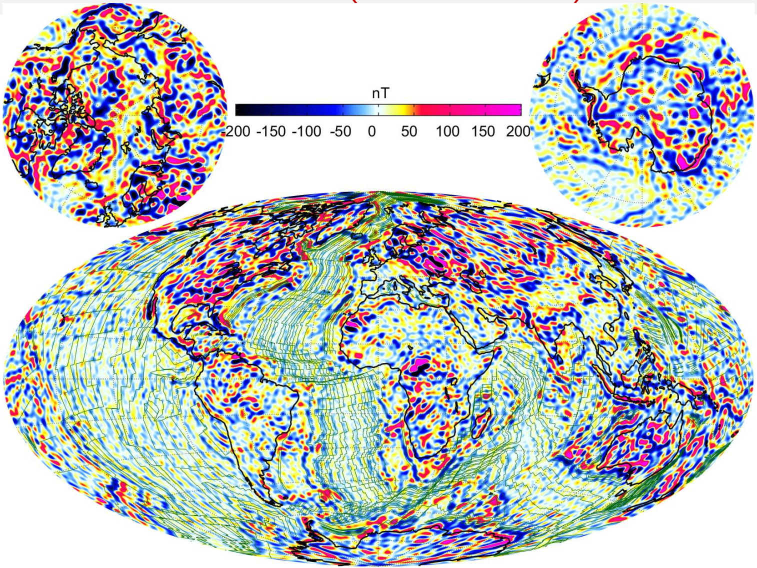
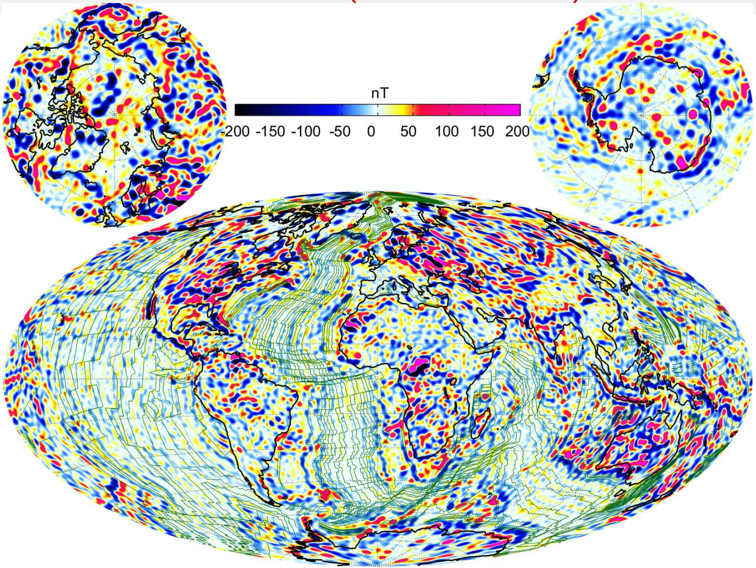
B_r at Earth's surface ($n = 16 - 133$)



MF7 Lithospheric Model

(Maus, 2010)

B_r at Earth's surface ($n = 16 - 133$)



L_1 regularized model

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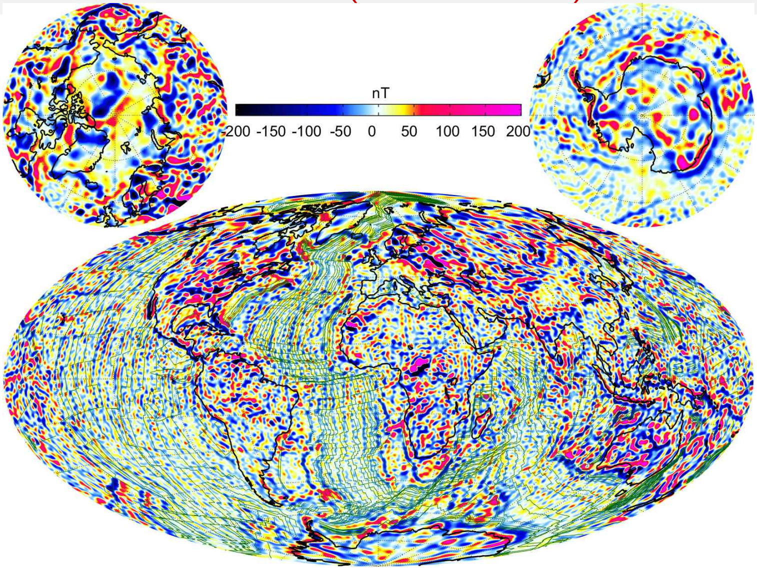

L_2 regularized model

Geomagnetic Spectra at Earth's surface