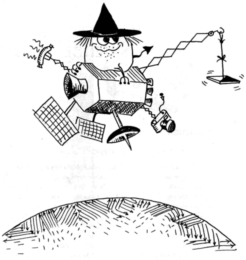
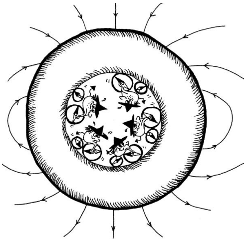
Exploring the Earth's Magnetic Field Using Satellites – From Ørsted to Swarm

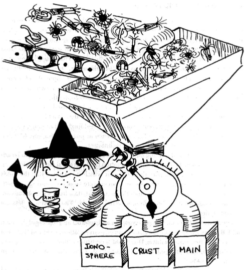
Nils Olsen

Leverhulme Visiting Professor
School of GeoSciences, Univ Edinburgh

on leave from DTU Space, Copenhagen







Outline of Talk

1. Introduction
   - Observations
   - Magnetic field sources
2. Tools to Separate the Various Sources
   - Magnetic field model
   - The Geomagnetic Spectrum
3. Exploring the Core and Crust
   - The Dynamics of the Core
   - Crustal Magnetization
4. The next years: *Swarm* Satellite Constellation

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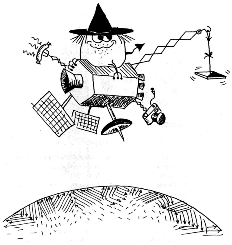
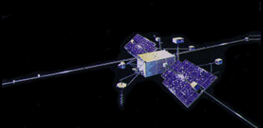


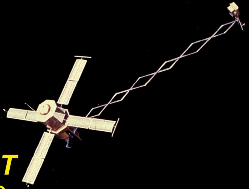
Satellites for Measuring Earth´s Magnetic Field

1965-70

Satellites for Measuring Earth´s Magnetic Field

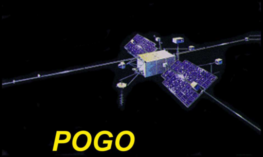


POGO
1965-70



MAGSAT
1979-80

Satellites for Measuring Earth´s Magnetic Field



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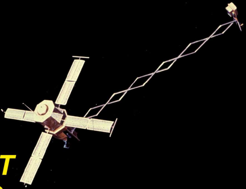
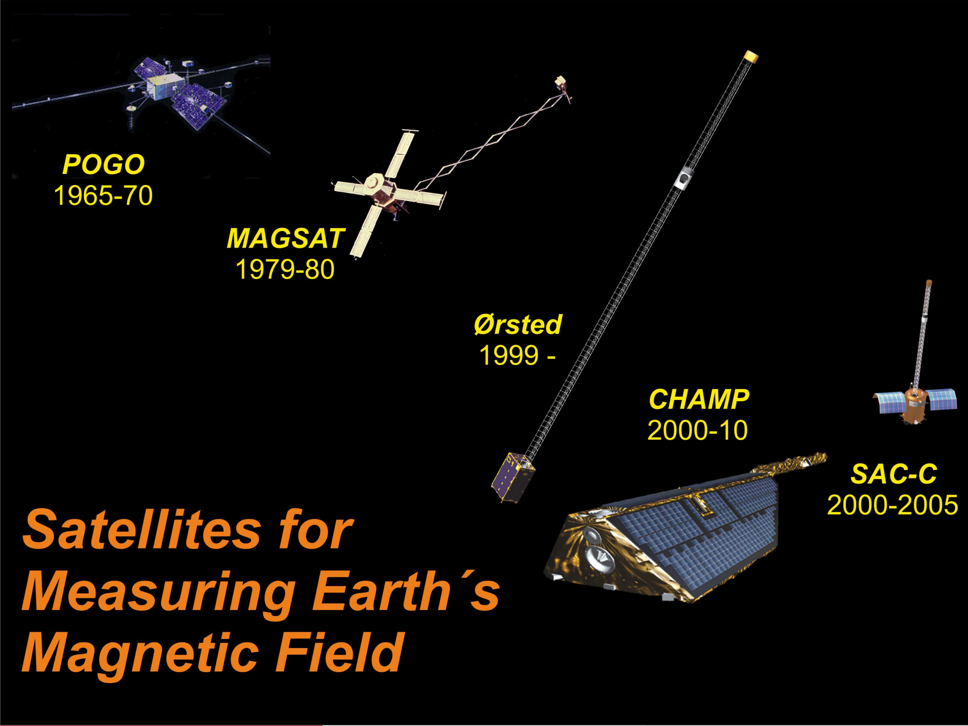


MAGSAT
1979-80

Ørsted
1999 -

Satellites for Measuring Earth´s Magnetic Field


POGO
1965-70
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CHAMP
2000-10
SAC-C
2000-2005
Satellites for
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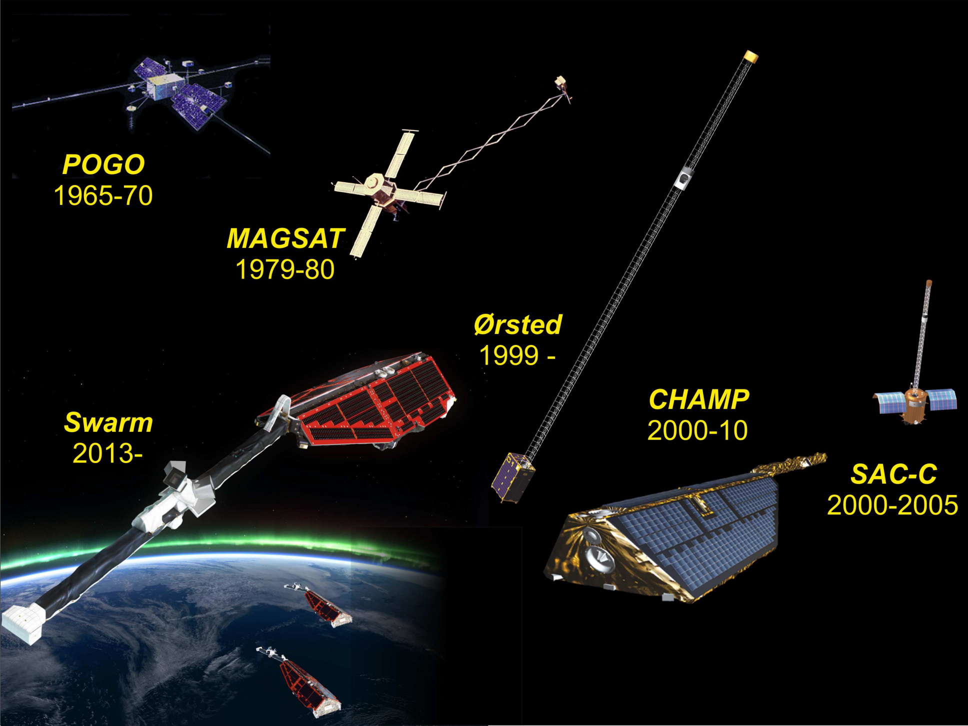
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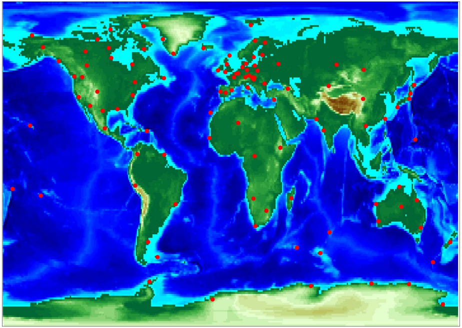
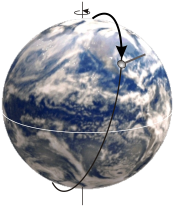
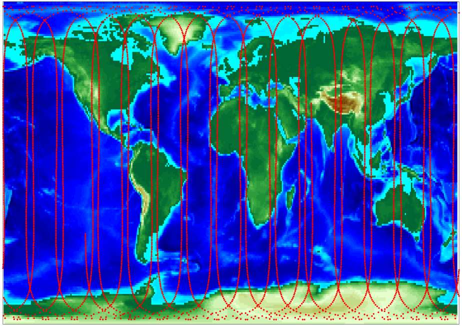
SAC-C
2000-2005
Swarm
2013-

Global coverage ...

... with ground observatories



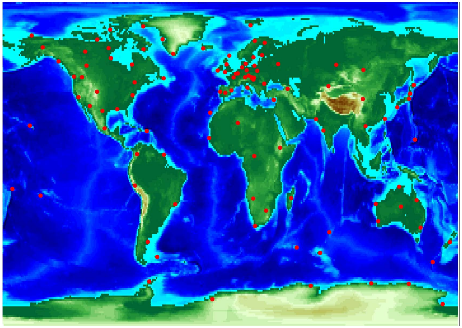


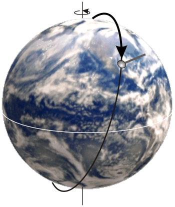


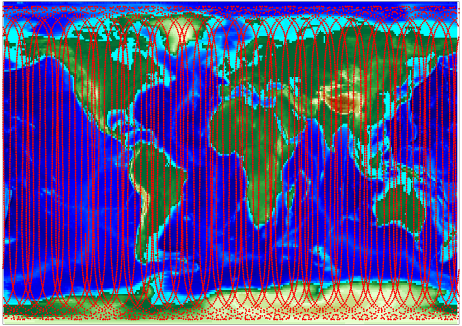
... and with 1 day of satellite data

Global coverage ...

... with ground observatories





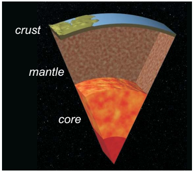


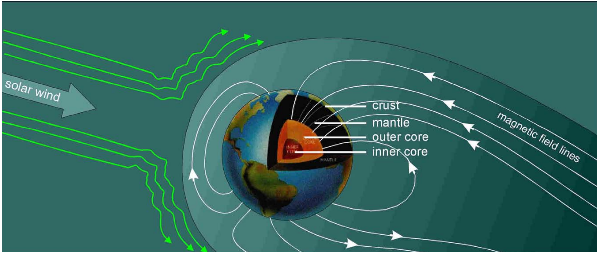
... and with 3 days of satellite data

Sources of the Near-Earth Magnetic Field

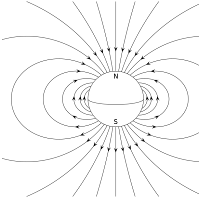
Sources of the Near-Earth Magnetic Field

- Internal sources
  - fluid outer core: 94%
    electrical currents created by motion of a conducting fluid
  - crust: 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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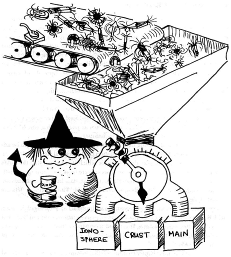

External-Internal Field Separation

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

CHAOS-4
A Geomagnetic Model Determined from 14 Years of Data

Goal: Describe magnetic field with

- high spatial resolution
  - determine small scale structure of core and crustal field
- high temporal resolution
  - determine rapid core field changes

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Method:

- 14 years of data from CHAMP, Ørsted and SAC-C satellites and from 150 ground observatories
- Model parameterization:
  - static field (core and crust) up to $n \leq 100$
  - time variation of core field ($n \leq 20$) described by splines with 6 month knot spacing between 1997.0 and 2013.5
  - Co-estimation of external field and instrument calibration

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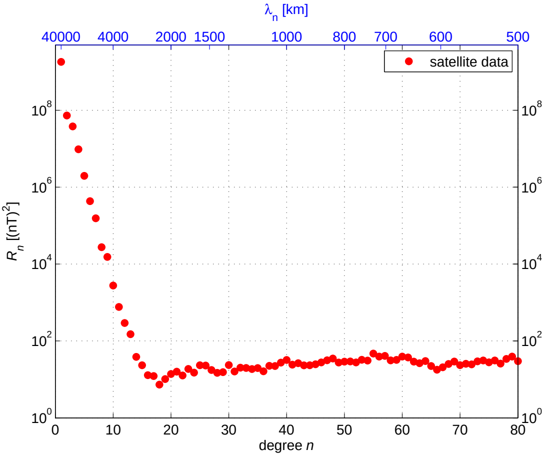
  - Co-estimation of external field and instrument calibration
- About 25.000 model parameters estimated from 1.5 mio. observations

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 Earths surface ($r = a$) due to contributions with horizontal wavelength $\lambda_n = \frac{2\pi a}{n}$



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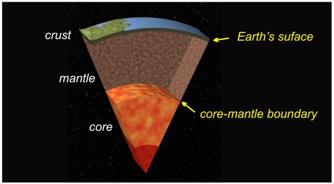
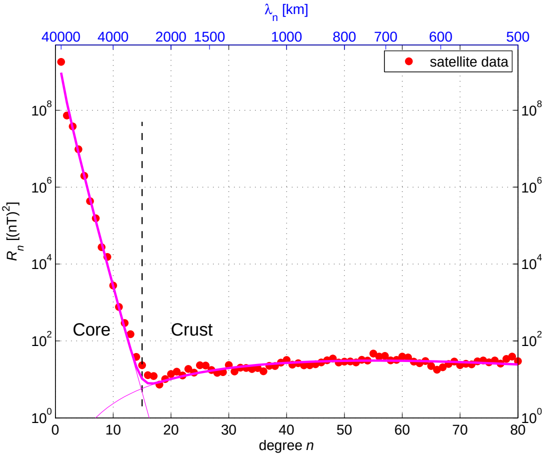
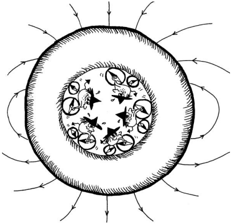


Model of core and crustal spectrum



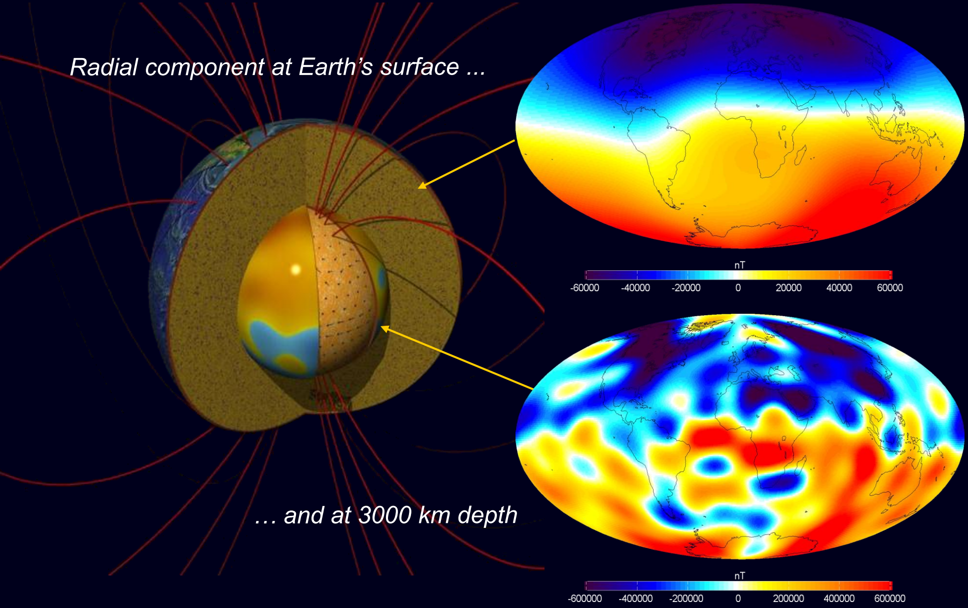
Outline of Talk



Magnetic Field Acceleration

Radial component, $\partial^2 B_r/\partial t^2$, at Earth's surface

Radial component B_r



Fluid Flow at Top of Core

Induction equation at top of core:

$$\dot{\mathbf{B}} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{\text{advection}} \quad + \quad \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{dissipation}}$$

$$\text{advection} \gg \text{dissipation}$$

B is the magnetic field vector
v is the velocity vector (flow)
$\eta = 1/(\mu_0 \sigma) \approx 1.6$ m^2/s is the magnetic diffusivity of the core
$\sigma \approx 5 \cdot 10^5$ S/m is electrical conductivity

Fluid Flow at Top of Core

Induction equation at top of core:

$$\dot{\mathbf{B}} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Induction equation in "frozen flux approximation"

B is the magnetic field vector
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Fluid Flow at Top of Core

Induction equation at top of core:

$$\dot{\mathbf{B}} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

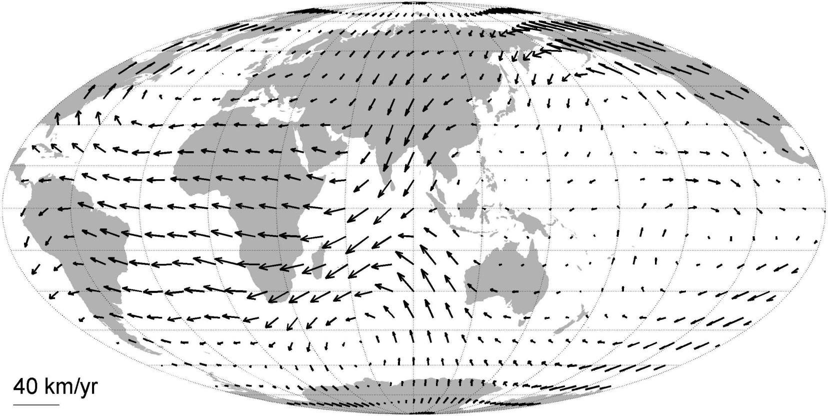
Induction equation in “frozen flux approximation”

$\mathbf{B}$ is the magnetic field vector
$\mathbf{v}$ is the velocity vector (flow)

Determination of $\mathbf{v}$ from known $\mathbf{B}$ and $\dot{\mathbf{B}}$

Fluid Flow at Top of Core

Mean horizontal velocity for 1999-2010

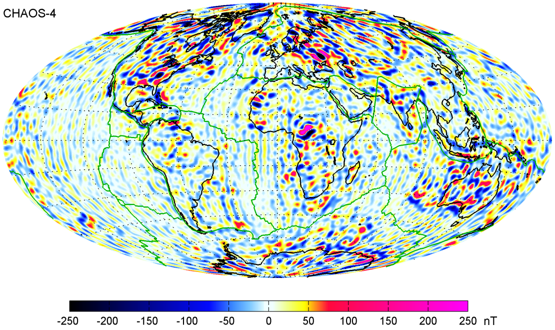


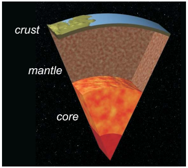
Assumption: tangentially geostrophic flow (balance between pressure gradient, Coriolis and buoyancy forces)

Magnetic Field due to Magnetized Rocks

Crustal field is caused by magnetized rocks in Earth's crust at depths below Curie temperature.

Much stronger crustal field over continents, due to thicker crust



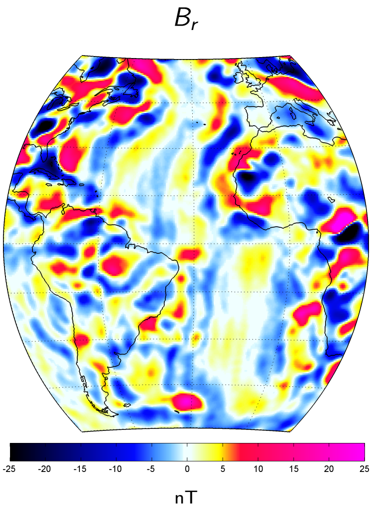


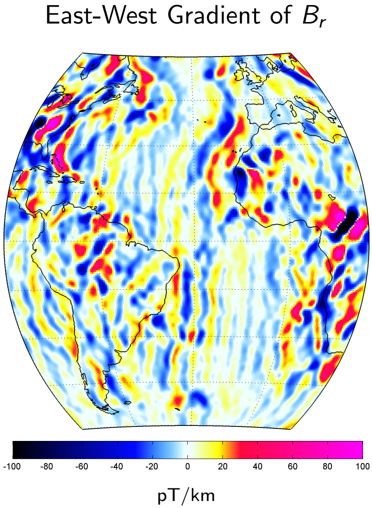
Outline of Talk

The *Swarm* Concept

- 2002: proposed to ESA
- 2004: selected by ESA
- 2013: launched on 22 Nov
- Constellation of 3 satellites
  - two side-by-side at low altitude
  - third at higher altitude
- Each *Swarm* satellite measures
  - magnetic field vector **B** ($<$ 1 ppm absolute accuracy)
  - electric field **E** and plasma parameters
  - acceleration (neutral wind, neutral density)

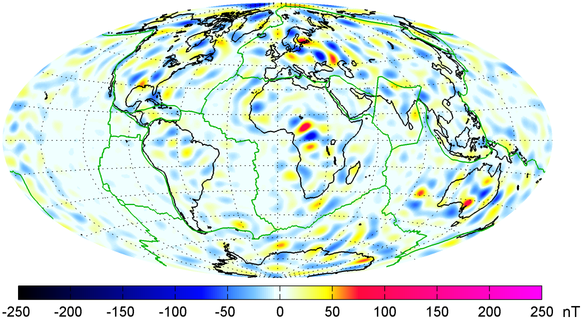
Pair of *Swarm* Satellites Measures Magnetic Field Gradient





East-West Gradient is more sensitive to small-scale lithospheric field

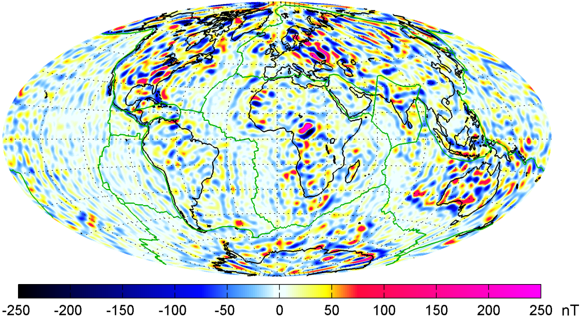
Improvement of Crustal Field Model



- POGO and Magsat ...
  $n \leq 40$, resolution: 1000 km

B_r at ground

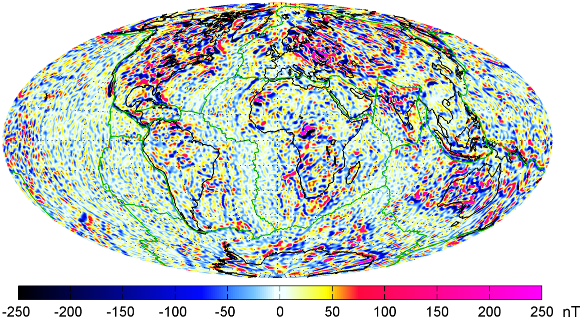
Improvement of Crustal Field Model



- POGO and Magsat ...
  $n \leq 40$, resolution: 1000 km
- ... with present satellites Ørsted and CHAMP ...
  $n \leq 80$, resolution: 500 km

B_r at ground

Improvement of Crustal Field Model

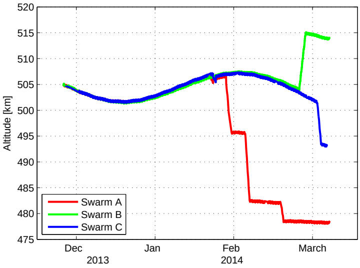


- POGO and Magsat ...
  $n \leq 40$, resolution: 1000 km
- ... with present satellites Ørsted and CHAMP ...
  $n \leq 80$, resolution: 500 km
- ... and with *Swarm*
  $n \leq 150$, resolution: 270 km

B_r at ground

Swarm Status

- Commissioning phase ended this week
- First data provided to the Cal-Val Team
- *Swarm* session at EGU, Vienna, April 2014
- 3rd International *Swarm* Science Meeting, 19-20 June in Copenhagen



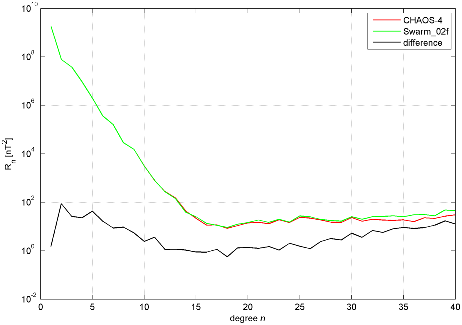
Altitude evolution of *Swarm* showing various orbital manoeuvres

First Results: Field Model from *Swarm* data

Combined analysis of 3 months of data from all 3 *Swarm* satellites
Field model ($n \leq 40$) for epoch 2014.0, co-estimation of instrument parameters

Comparison with CHAOS-4 extrapolated in time to epoch 2014.0

Spectrum: Good agreement (difference smaller than signal)



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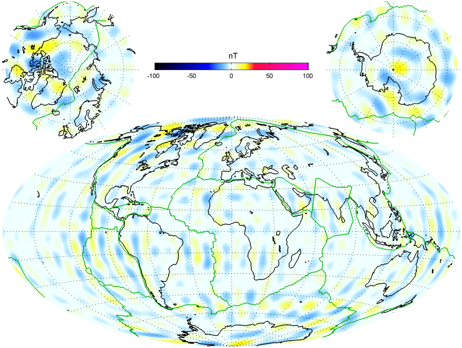
Crustal field difference B_r ($n = 15 - 40$): Good agreement



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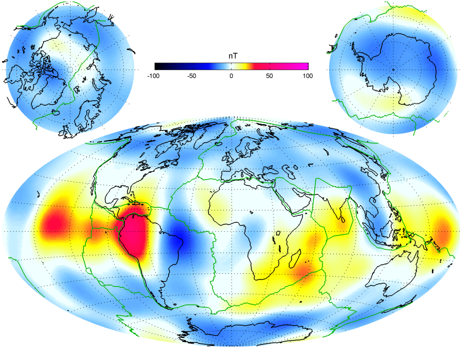
Comparison with CHAOS-4 extrapolated in time to epoch 2014.0

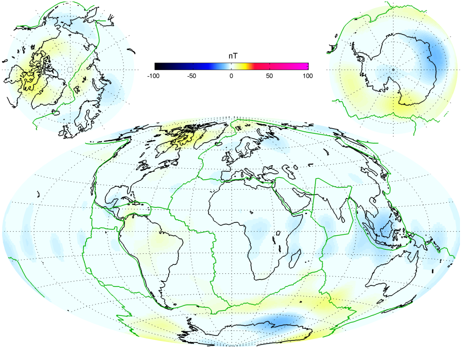
Core field difference ($n \leq 14$) in 2014.0: CHAOS-4 extrapolation error

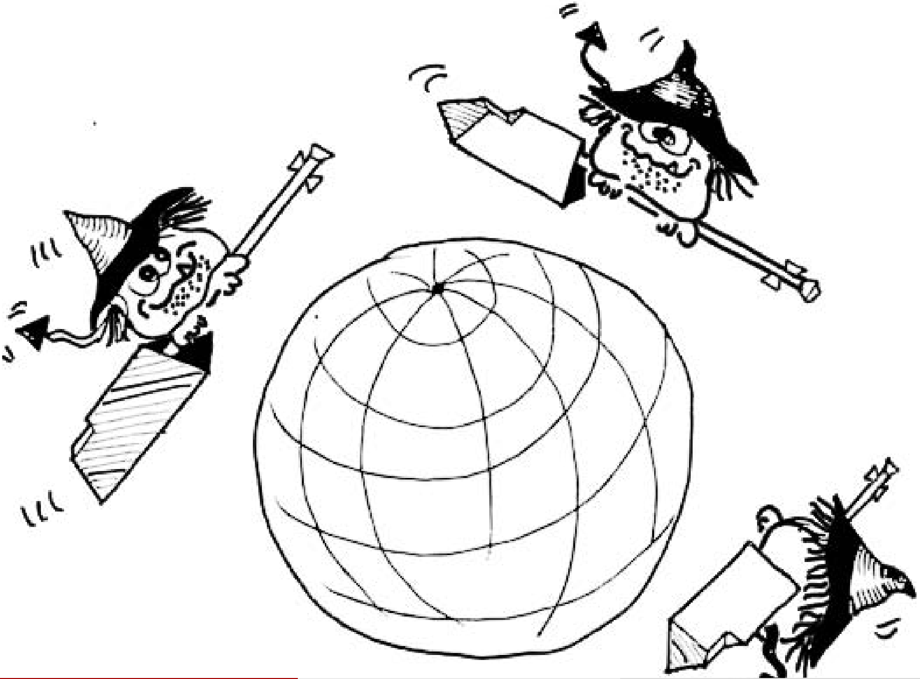


First Results: Field Model from *Swarm* data

Combined analysis of 3 months of data from all 3 *Swarm* satellites
Field model ($n \leq 40$) for epoch 2014.0, co-estimation of instrument parameters

Core field difference ($n \leq 14$) wrt a combined Ørsted, CHAMP and *Swarm* model (CHAOS-4+)

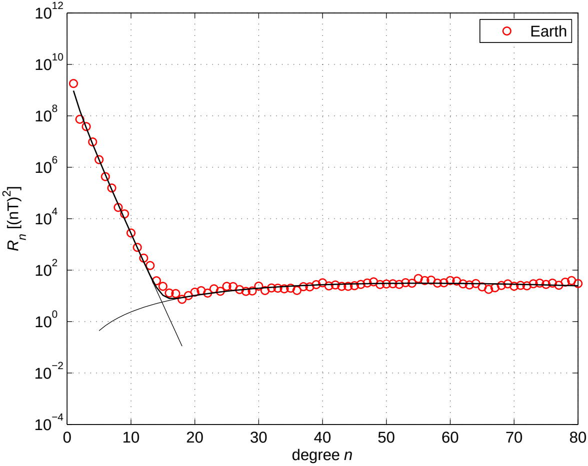




The Spatial Power Spectrum

Earth and other planets

- Earth
  - core and crustal field



after Olsen *et al* (2008), Maus *et al* (2008), Cain *et al* (2003), Purucker *et al* (2008), Connerney (2007)

The Spatial Power Spectrum

Earth and other planets

- Earth
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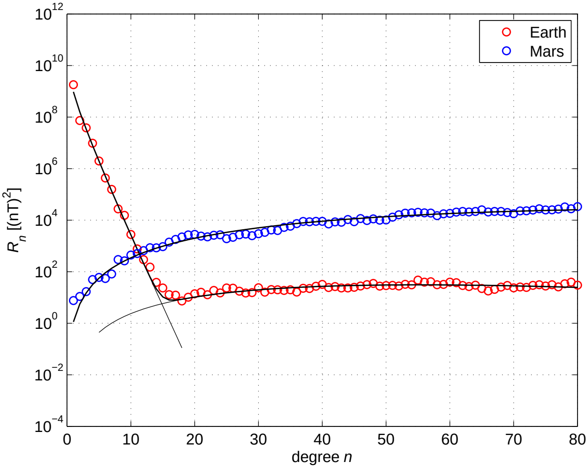
- Mars and Moon
  - presently only crustal field



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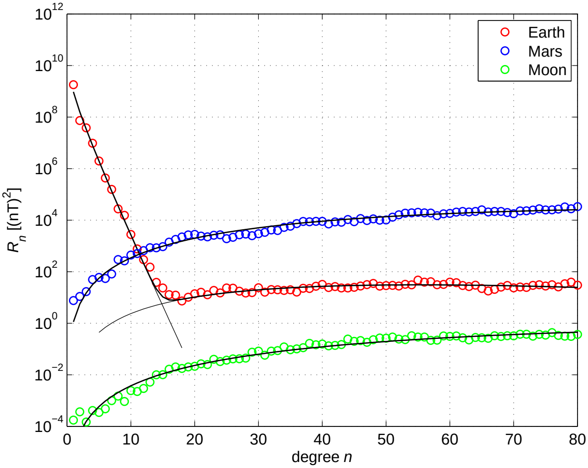

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The Spatial Power Spectrum

Earth and other planets

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  - core and crustal field
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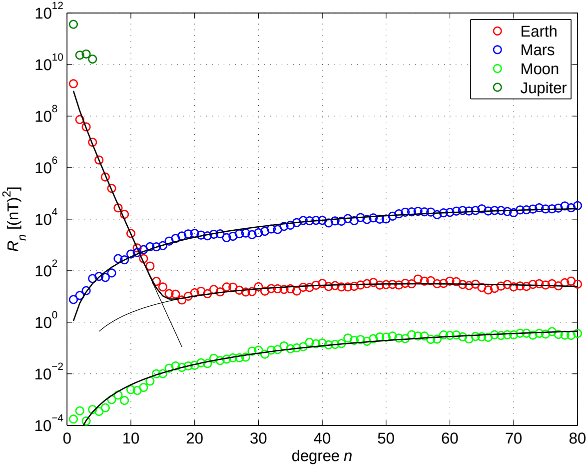
  - presently only crustal field
- Jupiter and Mercury
  - only core field



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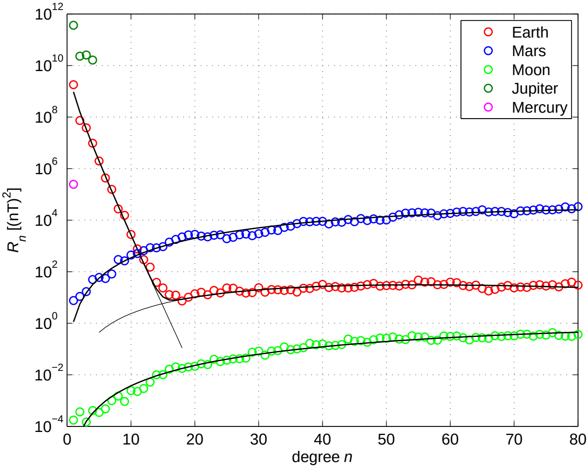

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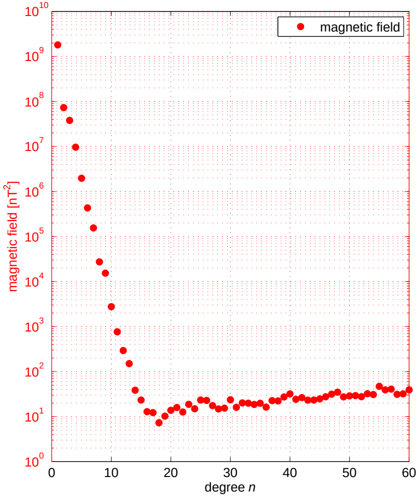
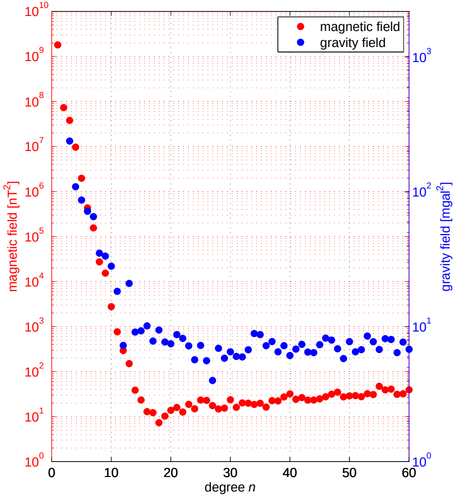
The Spatial Power Spectrum

Earth's magnetic vs. gravity field



The Spatial Power Spectrum

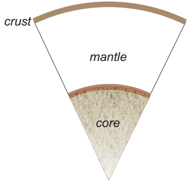
Earth's magnetic vs. gravity field

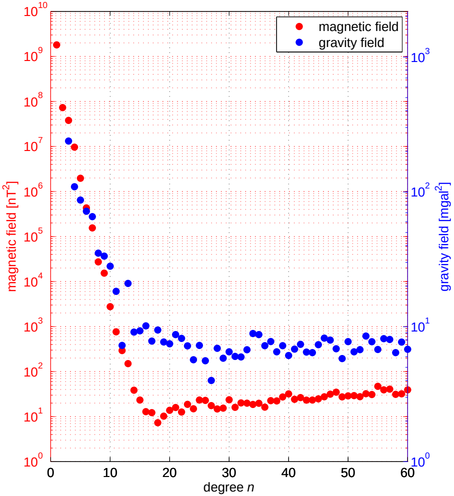


The Spatial Power Spectrum

Earth's magnetic vs. gravity field

Sources of the magnetic field

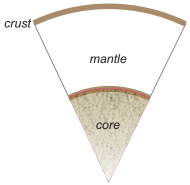


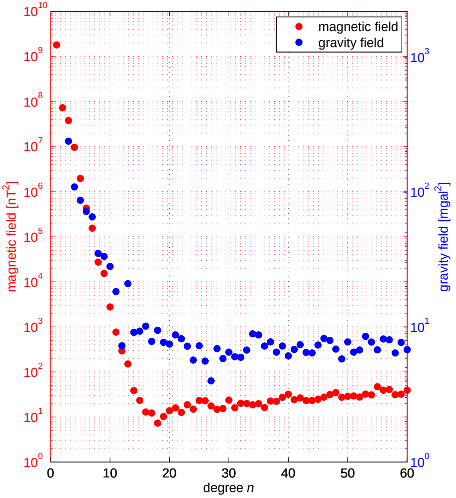


The Spatial Power Spectrum

Earth's magnetic vs. gravity field

Sources of the magnetic field





Sources of the gravity field