Geomagnetic Field Modeling Lessons learned from Ørsted and CHAMP and prospects for *Swarm*

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RAS Discussion Meeting on *Swarm*

October 9th 2009

DTU Space
National Space Institute

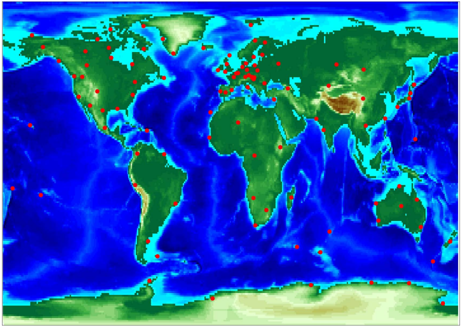
Outline of Talk

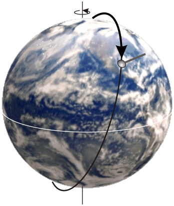
1. Exploring Earth's Magnetic Field from Space
2. Previous Missions: POGO and Magsat
3. Present Missions: Ørsted, CHAMP and SAC-C
4. Near Future: Swarm
5. Recent Core Field Changes

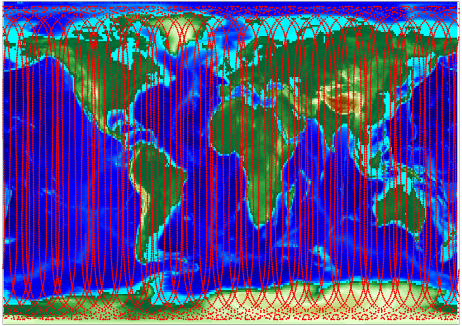
Outline of Talk

Why should we measure magnetic field from space?

Global coverage with ground observatories







... and with 3 days of satellite data

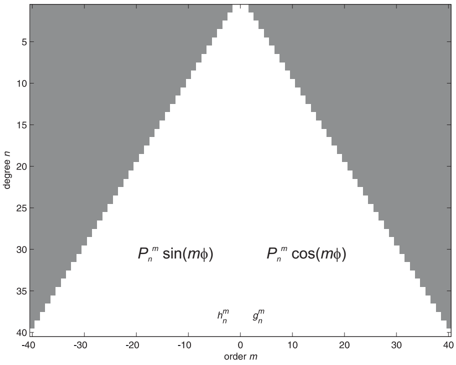
Magnetic Field Model From Satellite Data

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

r, θ, ϕ are spherical coordinates

a is Earth's radius
g_n^m and h_n^m are the spherical harmonic expansion coefficients of the internal magnetic field

Expansion Coefficients g_n^m, h_n^m of the Internal Field



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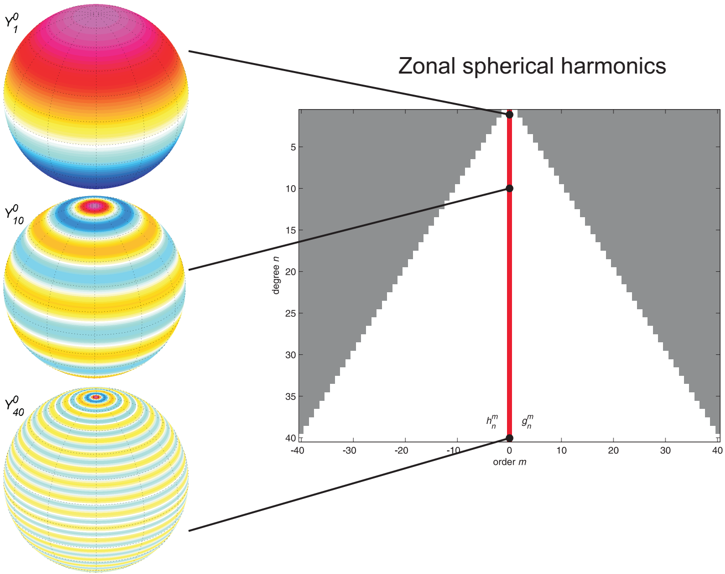

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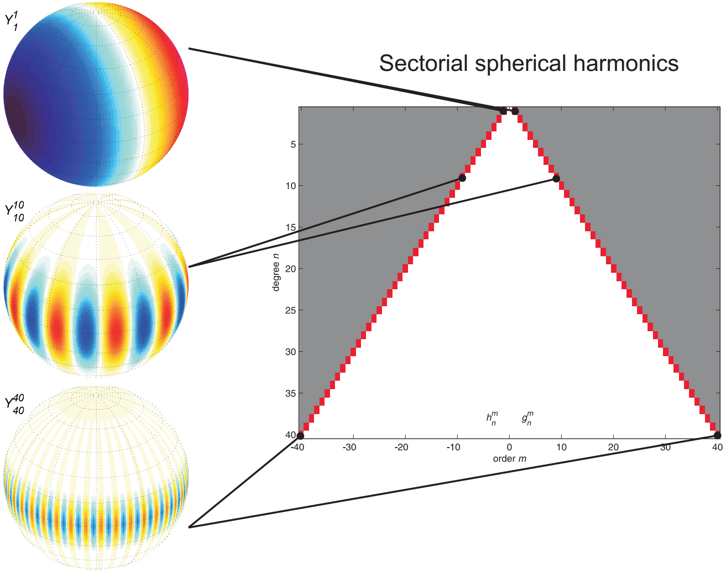

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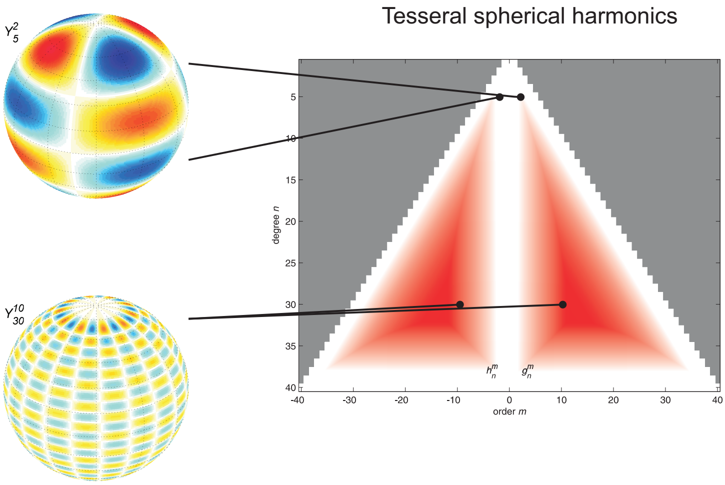


Model Resolution

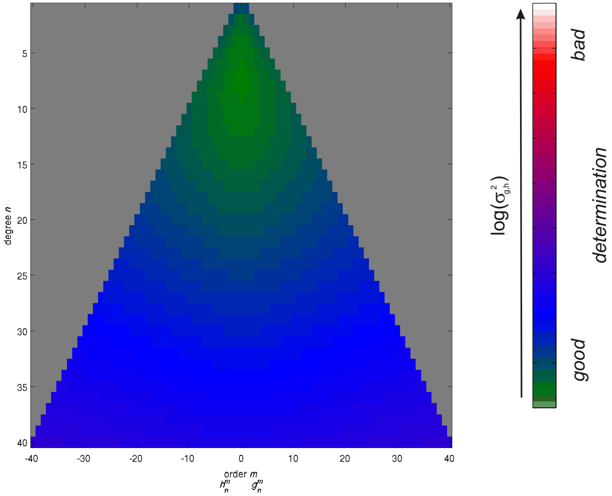
Vector data

10,000 observations
No external field
Static internal field

Perfectly polar orbit
(inclination = 90°)

Vector data at all
latitudes

Ideal case:
Perfect satellite,
perfect environment, ...



Outline of Talk

Satellite Missions: POGO

Model Resolution

Scalar data

10,000 observations
No external field
Static internal field

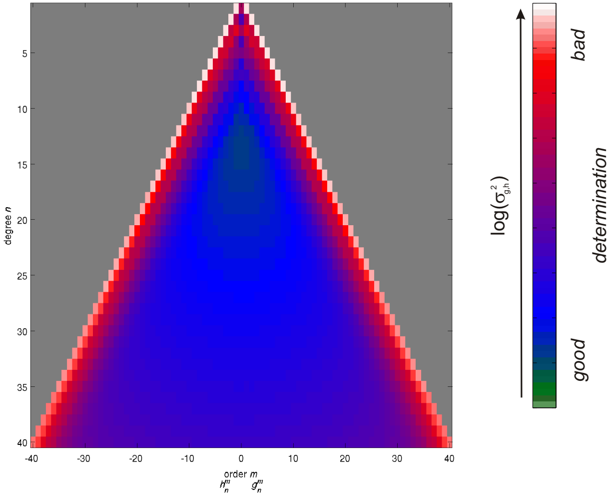
Perfectly polar orbit
(inclination $= 90^\circ$)

Only intensity data

strong Backus effect!

Sectorial coefficients
g_n^n, h_n^n are poorly
determined

Example: data from
POGO satellite series
(1965-72)



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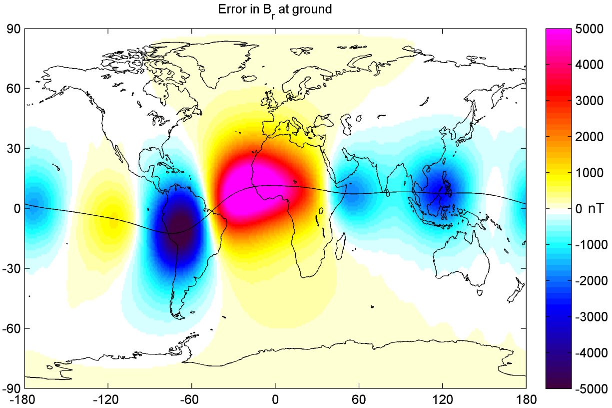


Model Resolution

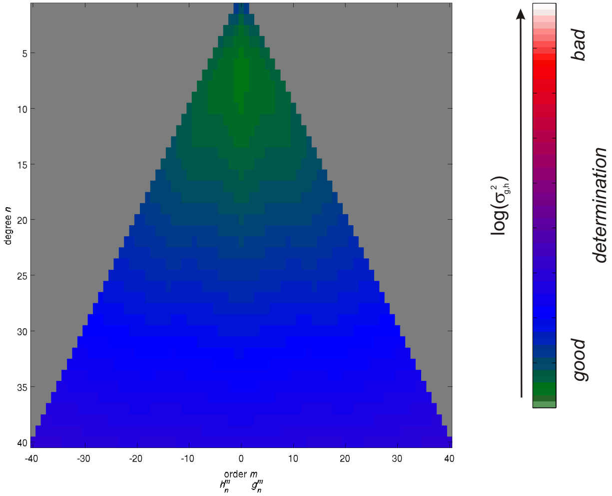
Vector and scalar data

10,000 observations
No external field
Static internal field

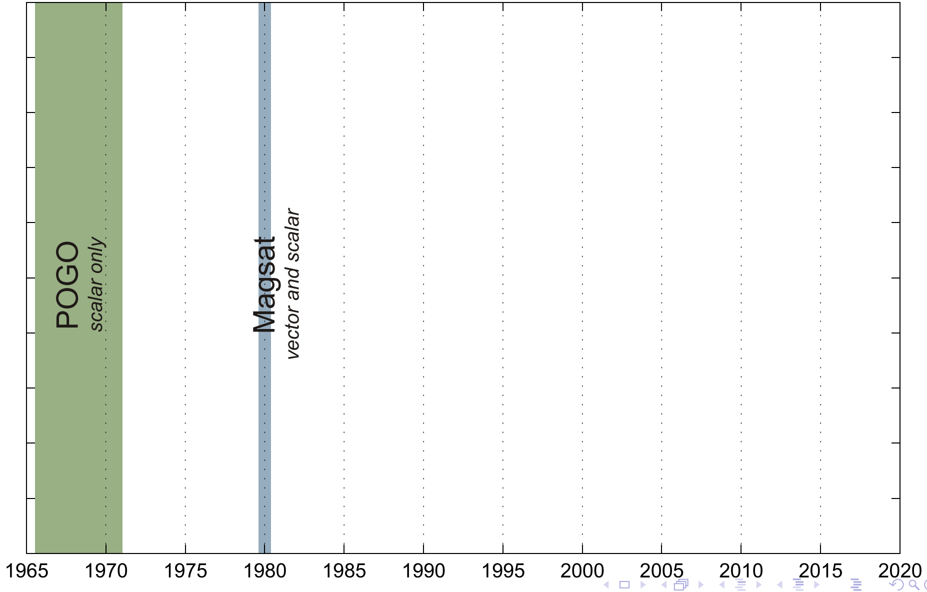
Perfectly polar orbit
(inclination = 90°)

Vector data at non-polar latitudes (below ±60°), else intensity data

Vector data only needed at low latitudes to avoid Backus effect



Satellite Missions: Magsat



Model Resolution

Vector and scalar data

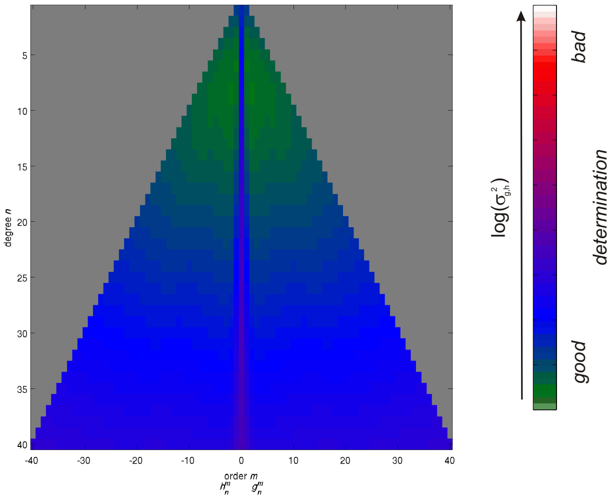
10,000 observations
No external field
Static internal field

Near polar orbit
(inclination = 97°)

Vector data at non-polar latitudes (below ±60°), else intensity data

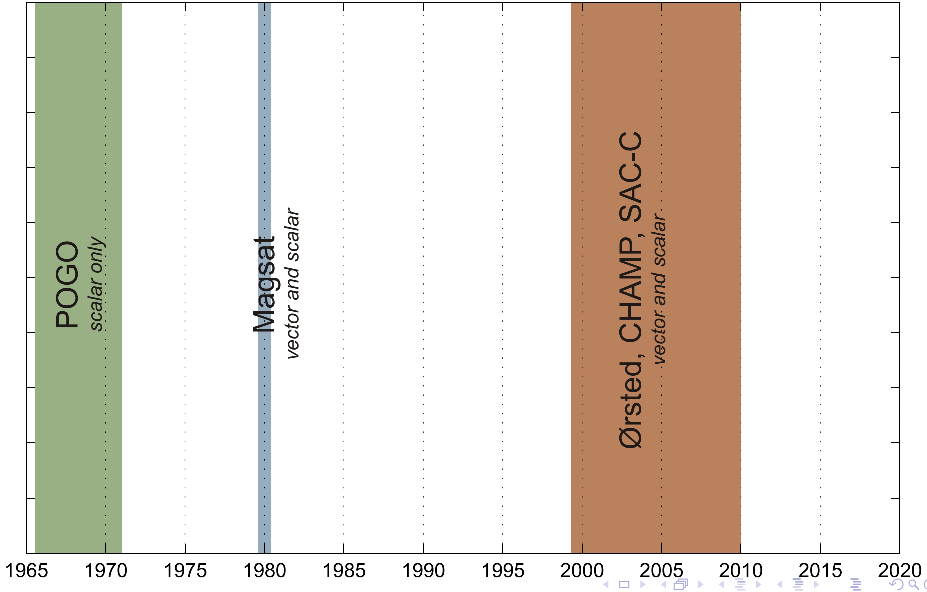
Zonal coefficients poorly determined due to polar gap

Example: data from Magsat satellite (1979-80)



Outline of Talk

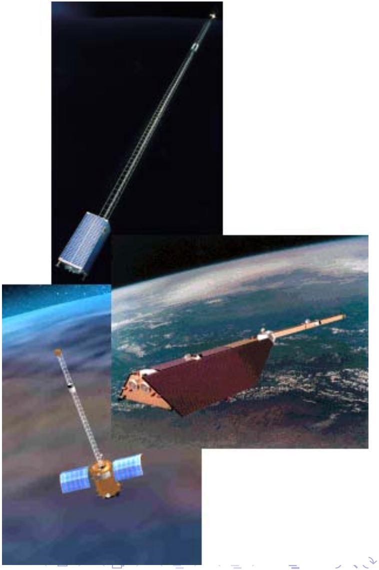
Satellite Missions: Ørsted, CHAMP and SAC-C



Present Satellites

Satellites of the International Decade of Geopotential Research

- Ørsted
  Launched on 23th February 1999
  Polar orbit, 650-850 km altitude
  all local times within 790 days (2.2 years)
- CHAMP
  Launched on 15th July 2000
  low altitude (350-450 km)
  all local times within 130 days
- SAC-C
  Copy of Ørsted experiment
  Launched on 21th November 2000
  700 km altitude, fixed local time 1030/2230
  (no high-precision vector data due to payload failure)



Single satellites: Space-Time Ambiguity

A low-Earth-orbiting satellite moves with 8 km/s.
It is difficult to distinguish whether an observed field change is due to a temporal field change or due to the movement of the satellite.

Multi-point observations in space can resolve this ambiguity

Satellite Constellation

N Single Satellites vs. Constellation of N Satellites

- Data treated as multiple single-satellite observations

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    $\rightarrow$ increase of number of data by N
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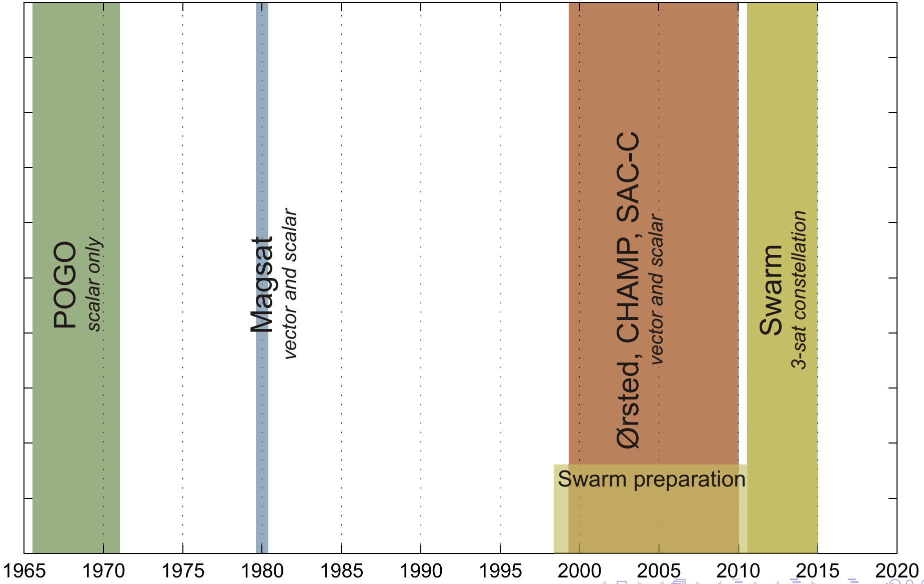
    $\rightarrow$ reduction of model error by $\sqrt{N}$
    (if data are independent)
  - improvement less than $\sqrt{N}$ if data are not independent
- Take advantage of constellation:
  potential of improvement better than $\sqrt{N}$

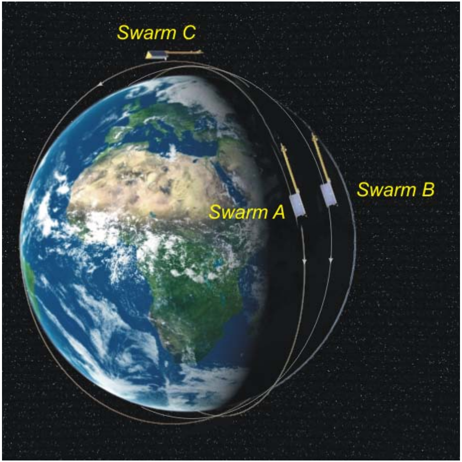
Outline of Talk

After Ørsted and CHAMP: Swarm



The *Swarm* Concept

- ESA mission, to be launched in 2010
- 3 satellites:
  2 side-by-side in low orbit
  1 in higher orbit
- Three orbital planes with two different near-polar inclinations
- Science objectives
  - Monitoring of core field changes after Ørsted and CHAMP
  - Improved determination of the small-scale crustal field
  - 3D mantle conductivity
  - Magnetospheric and ionospheric current systems
  - Magnetic forcing of the upper atmosphere



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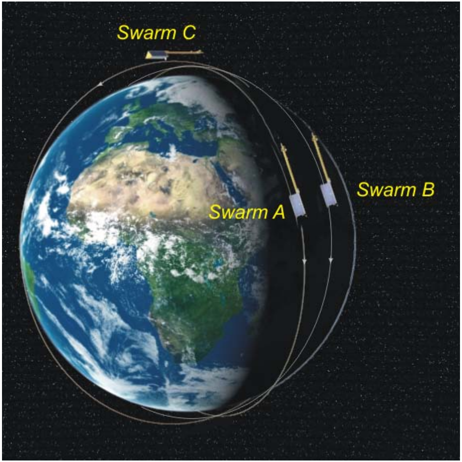
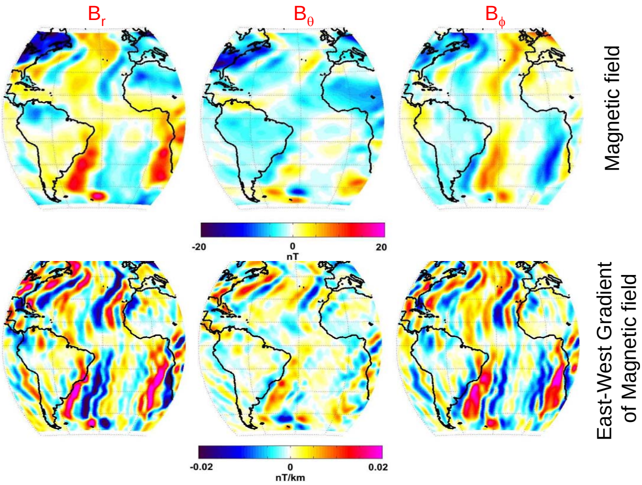


Lower Pair of *Swarm* Satellites Measures Magnetic Field Gradient

Swarm allows to measure the East-West Gradient, which is more sensitive to the small-scale lithospheric field



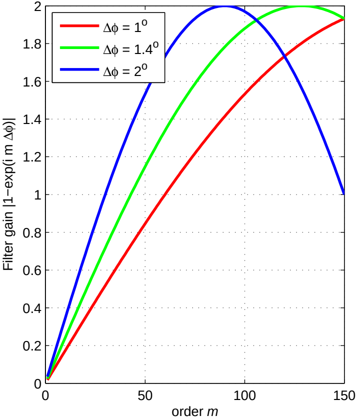
Advantage of two satellites flying side-by-side

Quasi-complex representation of crustal field:

$$\begin{aligned} \mathbf{B} &= -\mathrm{Re}\{\mathrm{grad}\ V\} \\ V &= a \sum_{n,m} \left(\frac{a}{r}\right)^{n+1} \gamma_n^m P_n^m e^{im\phi} \\ \gamma_n^m &= g_n^m - i h_n^m \end{aligned}$$

Difference of **B** at two satellites separated by $\Delta\phi$ in longitude:

$$\begin{aligned} \Delta\mathbf{B} &= \mathbf{B}(r,\theta,\phi) - \mathbf{B}(r,\theta,\phi+\Delta\phi) \\ &= -\mathrm{Re}\{\mathrm{grad}\ \Delta V\} \\ \Delta\gamma_n^m &= \gamma_n^m \left(1 - e^{im\Delta\phi}\right) \end{aligned}$$



$$|1 - e^{im\Delta\phi}| \approx m\Delta\phi$$

Sensitive to higher order *m*

Model Resolution

East-West gradient data

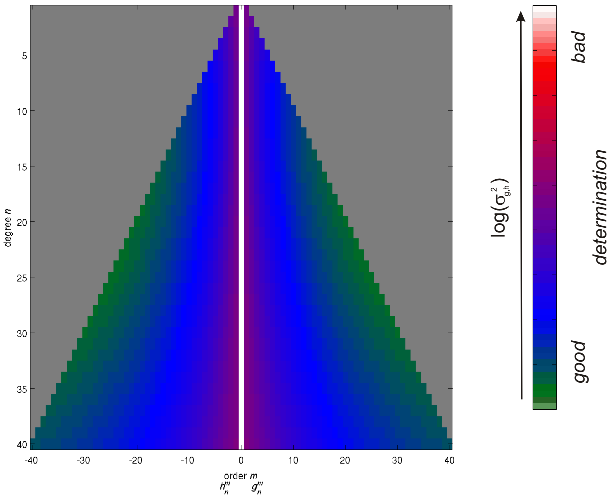
10,000 observations
No external field
Static internal field

Near polar orbit
(inclination = 97°)

East-West gradient data

Zonal coefficients undetermined

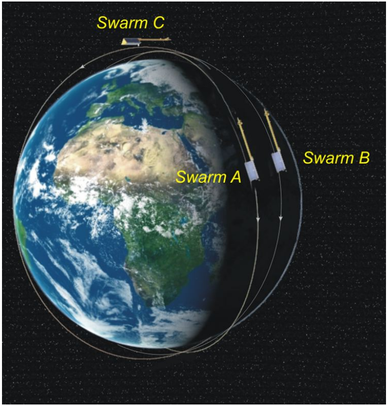
Enhanced resolution of sectorial coefficients

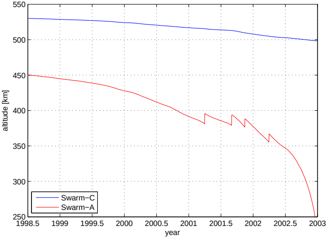


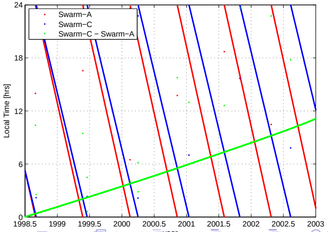
End-To-End Mission Simulation

Generation of synthetic orbits

- simulation starts on July 1, 1998 (one solar cycle before anticipated launch)
- simulation length of 4.5 years



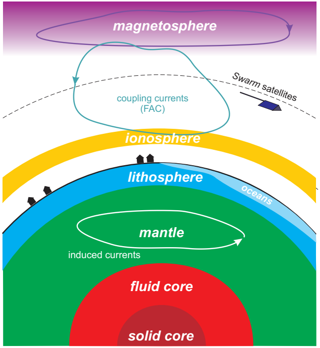




End-To-End Mission Simulation

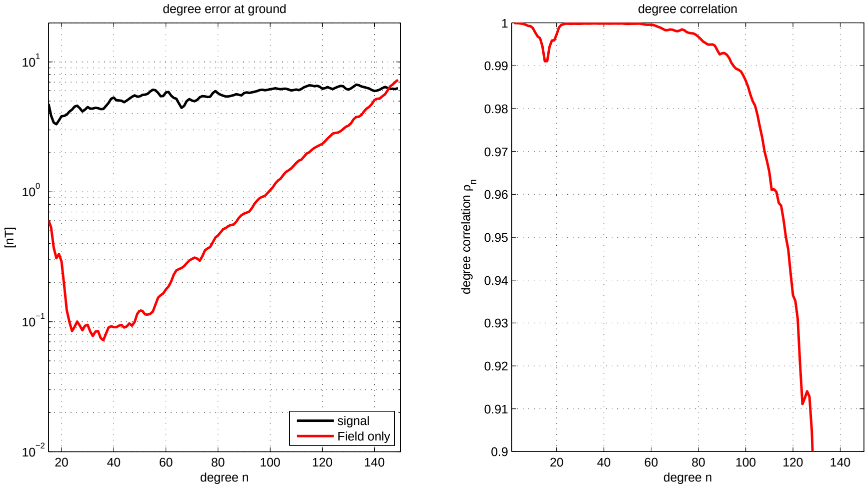
Magnetic Field Generation

- Core field time changes up to $n = 19$
- Crustal field (static) up to $n = 250$
- Ionospheric field, daily + seasonal periodicity
  Amplitude modulated by daily values of F10.7
  Induced field by means of 1D conductivity model
- Magnetospheric field
  Time dependence of external coefficients up to $n = 3, m = 0, 1$ given by observatory data (hourly mean values)
- Induced field (up to $n = 45$) calculated using 3D mantle conductivity, including oceans
- Toroidal (non-potential) field
  daily + seasonal periodicity
- Instrument noise



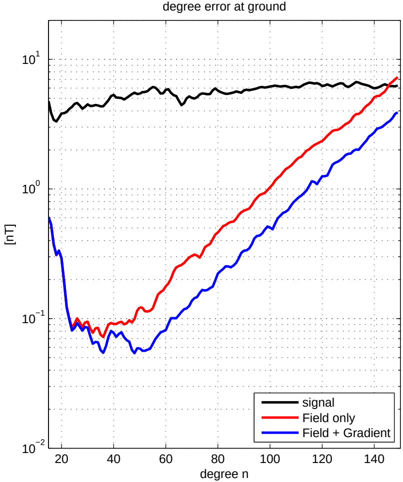
Crustal Field Recovery from **B** alone

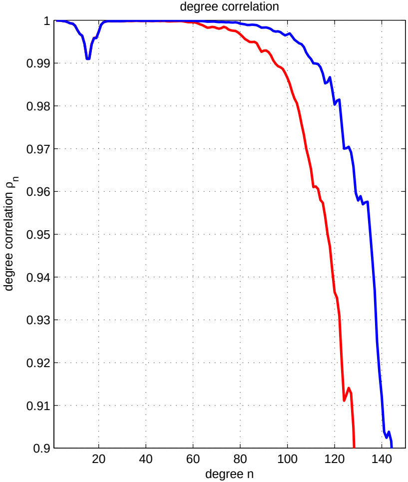
Single satellite approach



Crustal Field Recovery from $\mathbf{B}$ and $[\nabla\mathbf{B}]_{\mathrm{EW}}$

Constellation approach

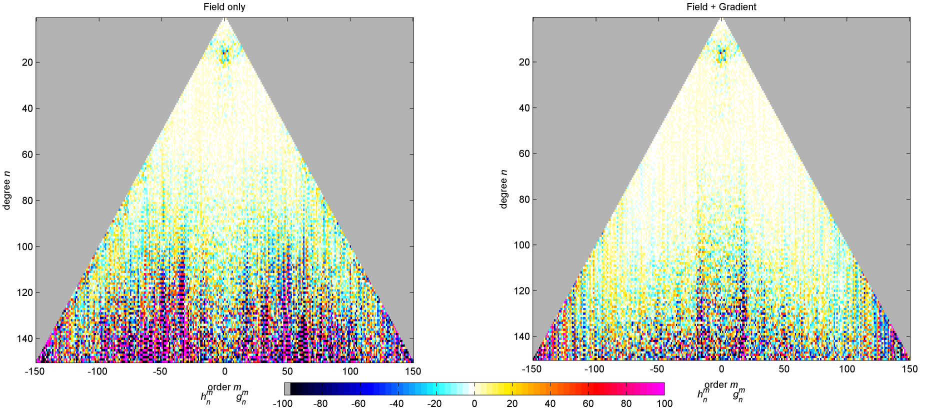




Same observations in both cases, but different arrangement of data subsets

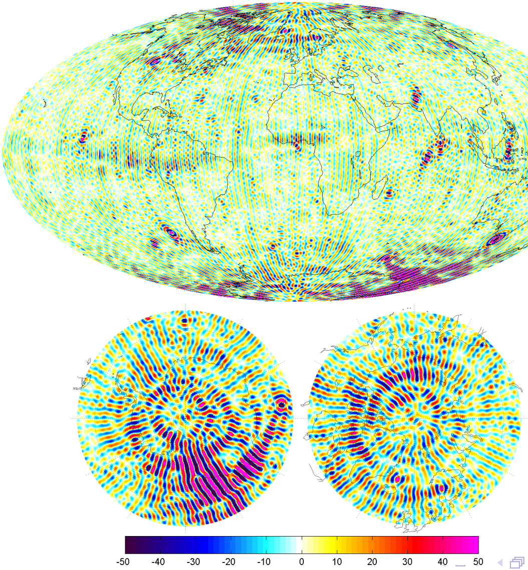
Crustal Field Recovery

Sensitivity matrix: relative error in %, normalized by mean power at that degree n



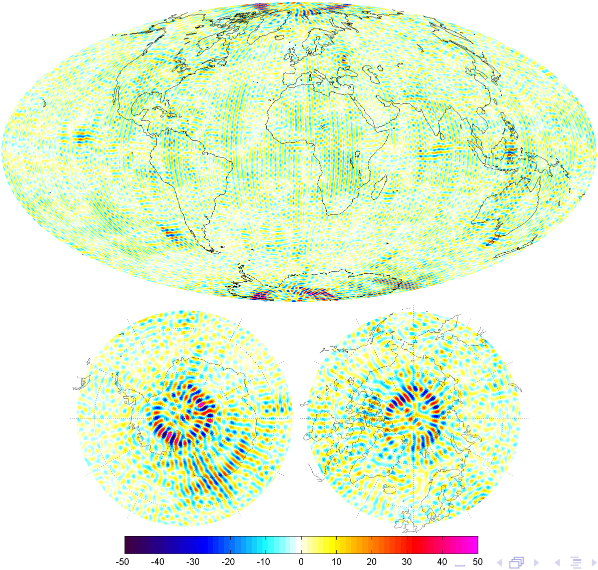
Map of Crustal Field Difference using **B** only

ΔB_r at surface, in nT

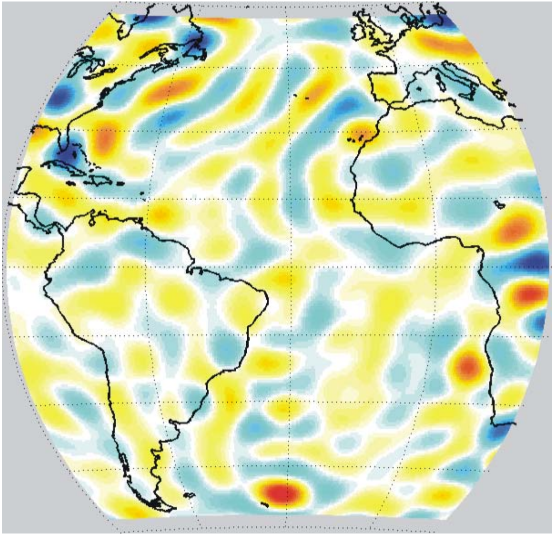


Map of Crustal Field Difference using B and $[\nabla \mathbf{B}]_{\mathrm{EW}}$

ΔB_r at surface, in nT



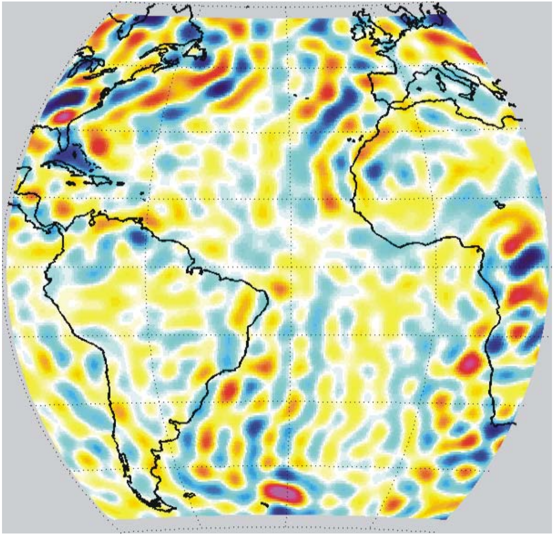
Improvement of Lithospheric Field Model



- POGO and Magsat ...
  $n \leq 30$, resolution: 1330 km

Magnetic field of Earths crust
radial component at 10 km altitude

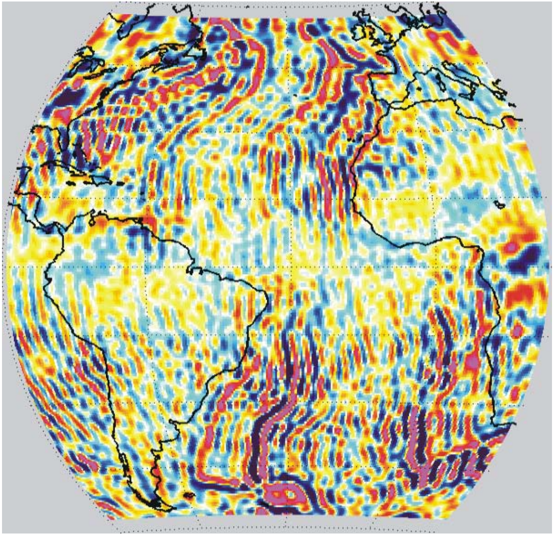
Improvement of Lithospheric Field Model



- POGO and Magsat ...
  $n \leq 30$, resolution: 1330 km
- ... with present satellites Ørsted and CHAMP ...
  $n \leq 60$, resolution: 670 km

Magnetic field of Earths crust radial component at 10 km altitude

Improvement of Lithospheric Field Model



- POGO and Magsat ...
  $n \leq 30$, resolution: 1330 km
- ... with present satellites Ørsted and CHAMP ...
  $n \leq 60$, resolution: 670 km
- ... and with *Swarm*
  $n \leq 130$, resolution: 300 km

Magnetic field of Earths crust radial component at 10 km altitude

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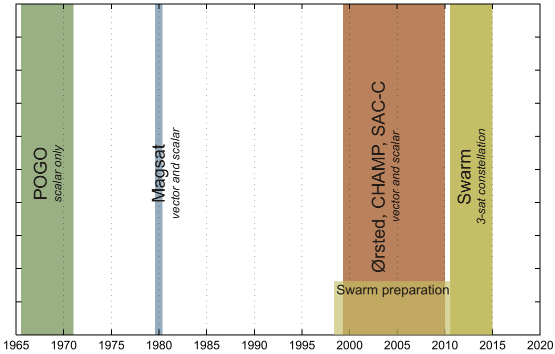
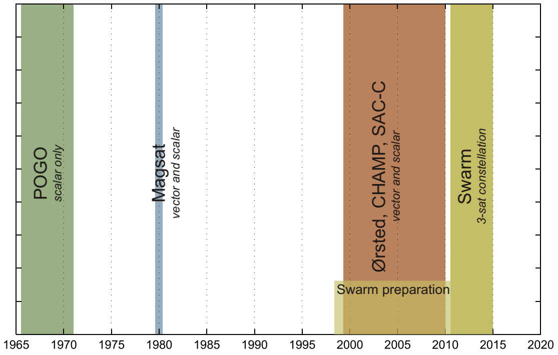
Core field changes



Core field changes



Ground observatory data monitor field change in time at a fixed location in space

The role of observatory data:

- help in separating spatial and temporal variations when analyzing satellite data
- help in bridging the gap between satellite missions

Observatory monthly means

- monitor field change at fixed locations
- but: contain internal and external field contribution
- challenge: extraction of core field signal

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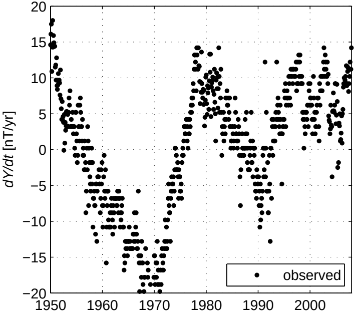
dY/dt at Niemegk/Germany



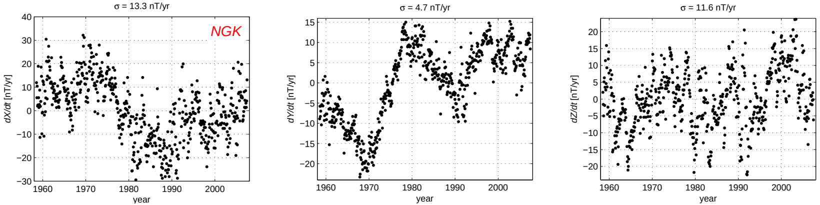
annual differences of monthly means

Scatter (partly) due to magnetospheric ring-current contributions

Revised monthly means

50 years (1958-2007) of hourly mean values from Niemegk

Traditional way: arithmetic mean (all days, all local times)



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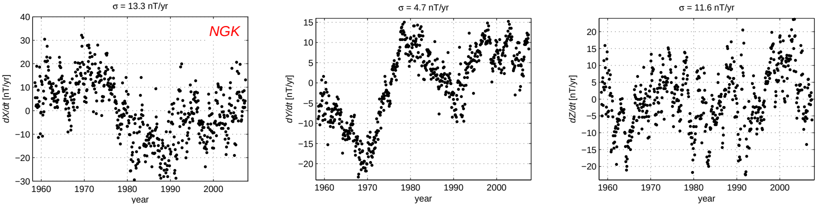
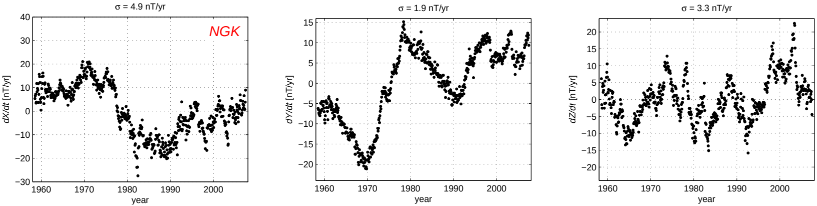


New: robust (Huber) average of data
after correction for ionospheric and magnetospheric contributions



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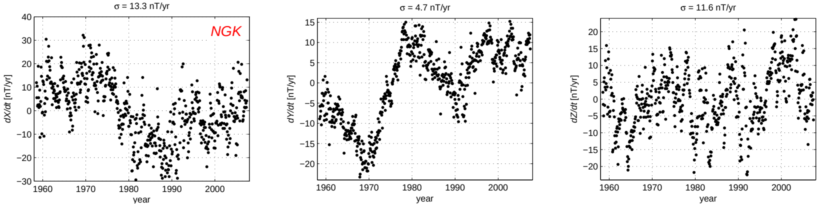

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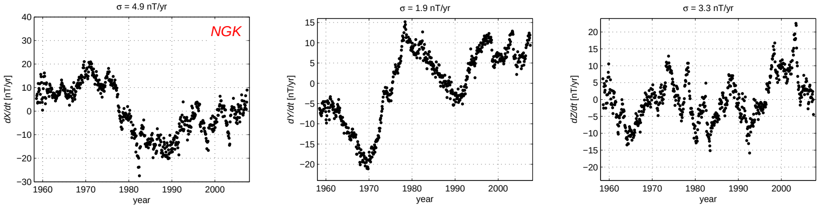


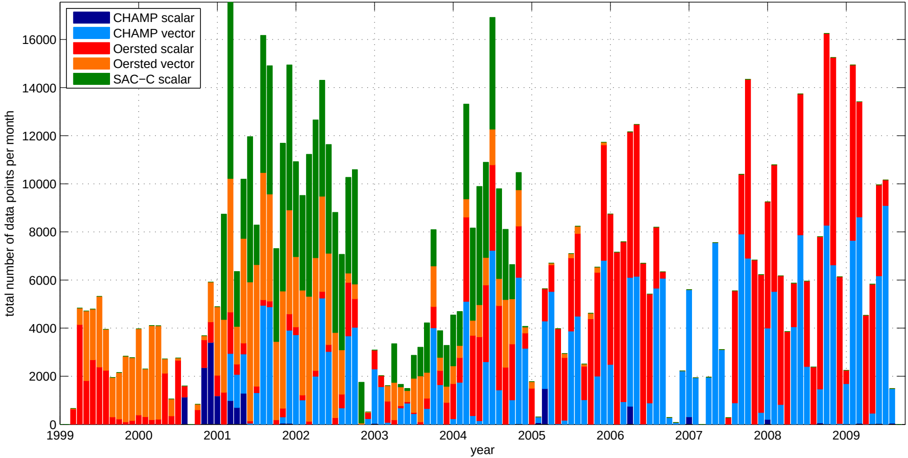
Standard deviation σ (wrt a GCV spline fit) is reduced by a factor of 3

The CHAOS Field Model Series

- CHAOS
  - 6.5 years of satellite data (March 1999 and December 2005)
  - Order 4 splines up to spherical harmonic degree $n = 14$, static up to $n = 50$
  - Regularization of $< |\ddot{\mathbf{B}}|^2 >$ at Earth's surface
- CHAOS-2
  - 10 years of satellite data (March 1999 and March 2009)
  - Observatory monthly means (1997-2006)
  - Order 6 splines up to $n = 20$, static for $n = 21 - 60$
  - Regularization of $< |\ddot{\mathbf{B}}|^2 >$ at Core-Mantle Boundary (CMB)
- CHAOS-3
  - 10.5 years of satellite data (March 1999 and August 2009)
  - Revised observatory monthly means (1997-2009)
  - Order 6 splines up to $n = 20$, static for $n = 21 - 60$
  - Regularization of $< |d^3\mathbf{B}/dt^3|^2 >$ at CMB

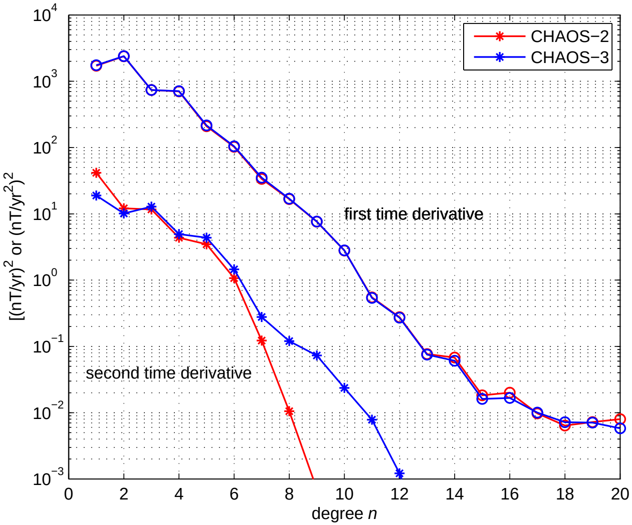
CHAOS-3 Data Selection

Distribution of non-polar data



stacked histogram

Spectrum of first and second time derivative at $t = 2005.0$



CHAOS-3 shows less secular acceleration power at $n = 1$, more power at $n > 6$

Fit to observatory data

component	CHAOS-2 mean	CHAOS-2 rms	CHAOS-3 mean	CHAOS-3 rms
$\dot{X}$ [nT/yr]	-2.74	13.42	0.02	7.35
$\dot{Y}$ [nT/yr]	0.17	11.41	-0.02	5.02
$\dot{Z}$ [nT/yr]	0.92	9.91	-0.10	7.02

CHAOS-3 rms misfit reduced by factor 2 for X and Y, and by 30% for Z
The non-zero mean values of CHAOS-2 are not present in CHAOS-3

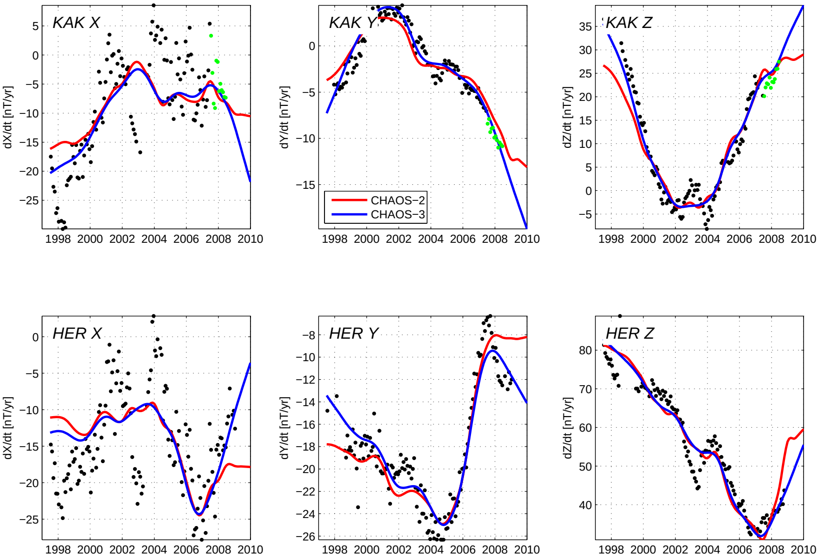
Fit to observatory data

component	CHAOS-2 mean	CHAOS-2 rms	CHAOS-3 mean	CHAOS-3 rms
$\dot{X}$ [nT/yr]	-2.74	13.42	0.02	7.35
$\dot{Y}$ [nT/yr]	0.17	11.41	-0.02	5.02
$\dot{Z}$ [nT/yr]	0.92	9.91	-0.10	7.02

CHAOS-3 rms misfit reduced by factor 2 for X and Y, and by 30% for Z
The non-zero mean values of CHAOS-2 are not present in CHAOS-3

Also satellite rms misfit data is slightly lower for CHAOS-3 compared to CHAOS-2

Fit to observatory data



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