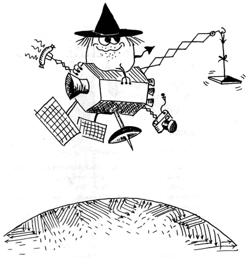
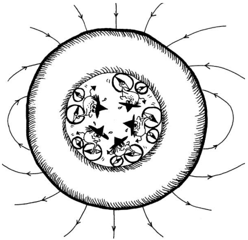
Exploring the Earth's Core From Space

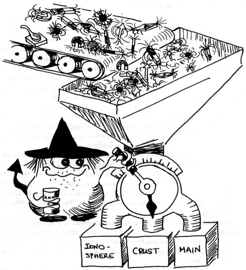
On the use of satellite magnetic data to explore core dynamics

Nils Olsen

DTU Space, Technical University of Denmark



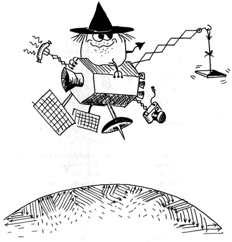




Outline of Talk

1. Magnetic Observations for Studying the Earth's Core
2. *Swarm* Satellite Constellation Mission
3. Extraction of core field signal: Separation of internal and external contributions
4. Dynamics of the Recent Core Field
5. Conclusions

Outline of Talk



1. Magnetic Observations for Studying the Earth's Core
2. *Swarm* Satellite Constellation Mission
3. Extraction of core field signal: Separation of internal and external contributions
4. Dynamics of the Recent Core Field
5. Conclusions

Magnetic Observations for Studying the Earth's Core

- Paleo- and Archeomagnetic Data
  - cover hundred thousands to billions of years
  - very few data, mainly in Northern Hemisphere

Magnetic Observations for Studying the Earth's Core

spatial resolution:

- Paleo- and Archeomagnetic Data — $n = 1$
  - cover hundred thousands to billions of years — (dipole)
  - very few data, mainly in Northern Hemisphere

Magnetic Observations for Studying the Earth's Core

spatial resolution:

- Paleo- and Archeomagnetic Data — $n = 1$ (dipole)
  - cover hundred thousands to billions of years
  - very few data, mainly in Northern Hemisphere
- Historic Data — $n \leq 8$
  - last 400 years
  - land observatory and ship navigation data
  - absolute intensity data since 1835 (C. F. Gauss)

Magnetic Observations for Studying the Earth's Core

spatial resolution:

- Paleo- and Archeomagnetic Data — $n = 1$ (dipole)
  - cover hundred thousands to billions of years
  - very few data, mainly in Northern Hemisphere
- Historic Data — $n \leq 8$
  - last 400 years
  - land observatory and ship navigation data
  - absolute intensity data since 1835 (C. F. Gauss)
- Satellite Data — $n \leq 100$
  - last 50+ years

Magnetic Observations for Studying the Earth's Core

- Paleo- and Archeomagnetic Data
  - cover hundred thousands to billions of years
  - very few data, mainly in Northern Hemisphere
- Historic Data
  - last 400 years
  - land observatory and ship navigation data
  - absolute intensity data since 1835 (C. F. Gauss)
- Satellite Data
  - last 50+ years

spatial resolution:

$n = 1$ (dipole)

$n \leq 8$

$n \leq 100$

Magnetic Observations for Studying the Earth's Core

- Paleo- and Archeomagnetic Data
  - cover hundred thousands to billions of years
  - very few data, mainly in Northern Hemisphere
- Historic Data
  - last 400 years
  - land observatory and ship navigation data
  - absolute intensity data since 1835 (C. F. Gauss)
- Satellite Data
  - last 50+ years
- ... and (quasi) continuous satellite data since 1999!

spatial resolution:

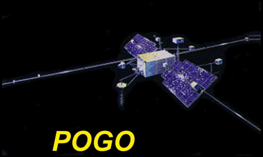
$n = 1$ (dipole)

$n \leq 8$

$n \leq 100$

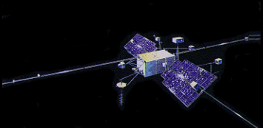
$n \leq 16$ for $\dot{\mathbf{B}}$

Satellites for Measuring Earth´s Magnetic Field

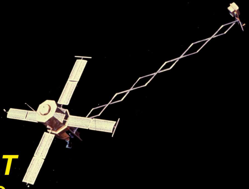


POGO
1965-70

Satellites for Measuring Earth´s Magnetic Field

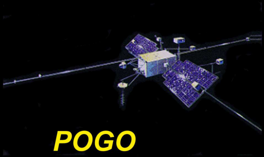


POGO
1965-70

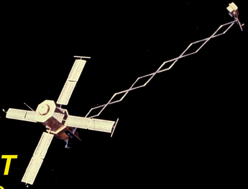


MAGSAT
1979-80

Satellites for Measuring Earth´s Magnetic Field



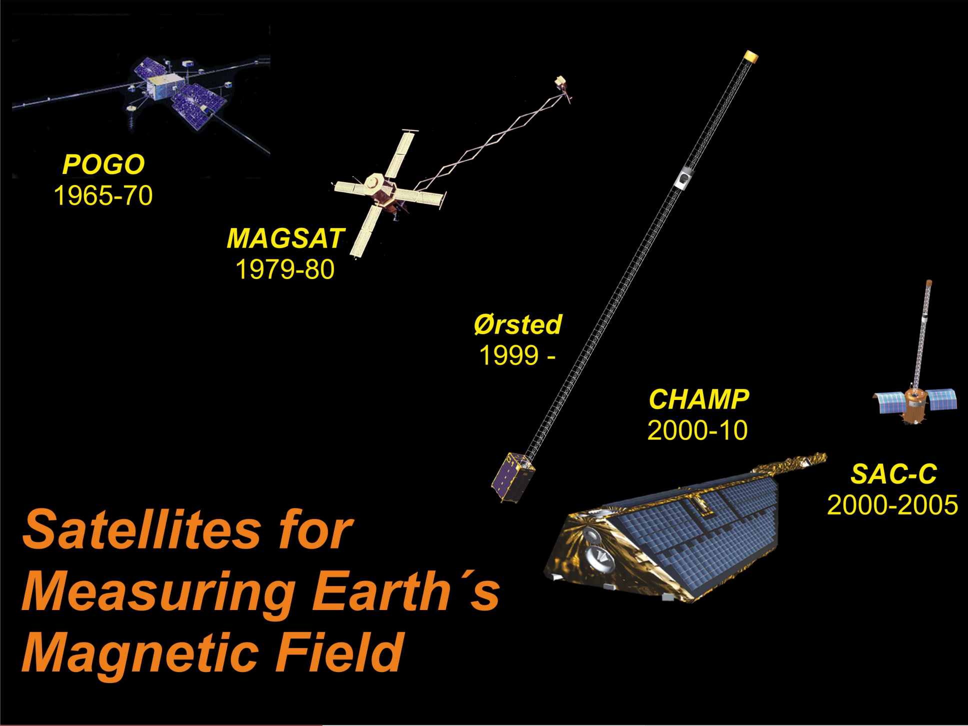
POGO
1965-70

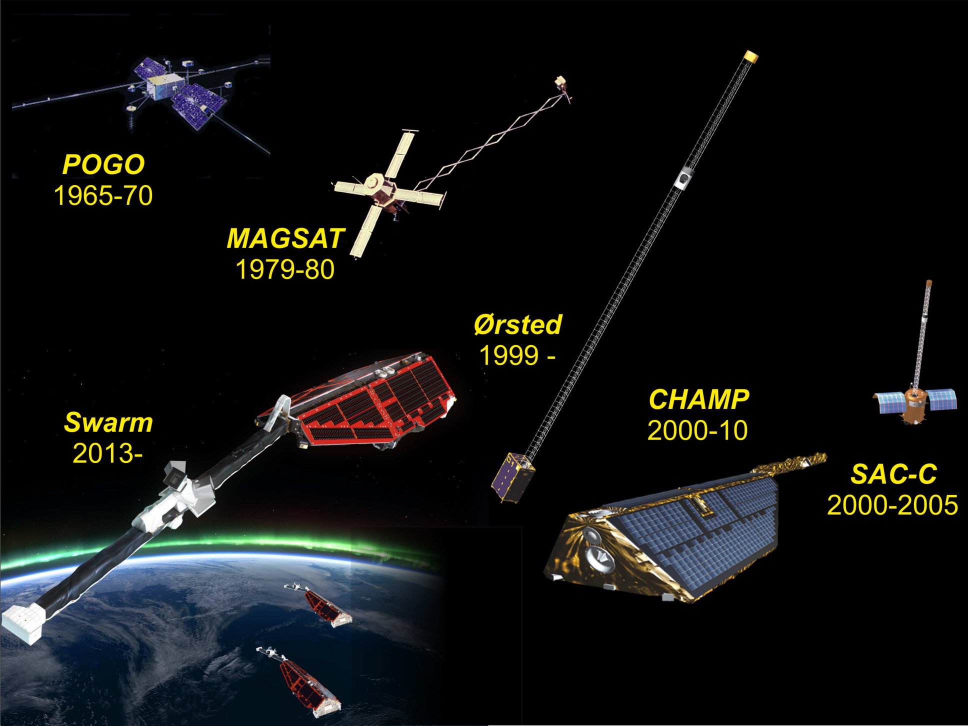


MAGSAT
1979-80

Ørsted
1999 -

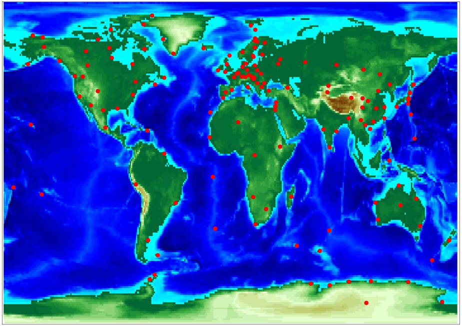
Satellites for Measuring Earth´s Magnetic Field

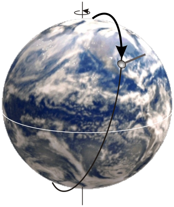

POGO
1965-70
MAGSAT
1979-80
Ørsted
1999 -
CHAMP
2000-10
SAC-C
2000-2005
Satellites for
Measuring Earth´s
Magnetic Field

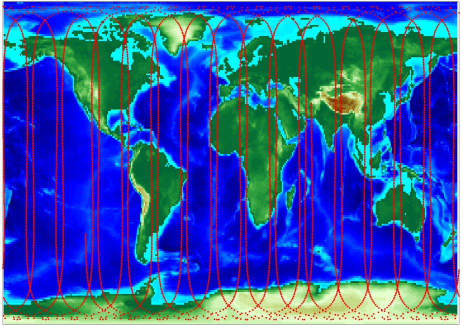

POGO
1965-70
MAGSAT
1979-80
Ørsted
1999 -
CHAMP
2000-10
SAC-C
2000-2005
Swarm
2013-

Global coverage ...

... with ground observatories



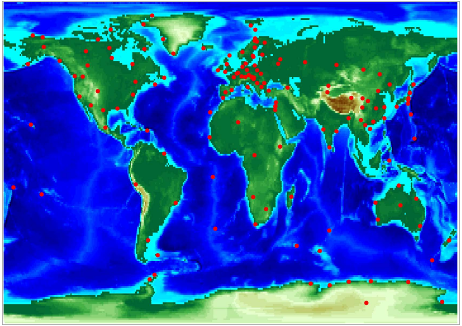


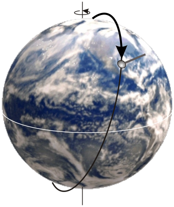


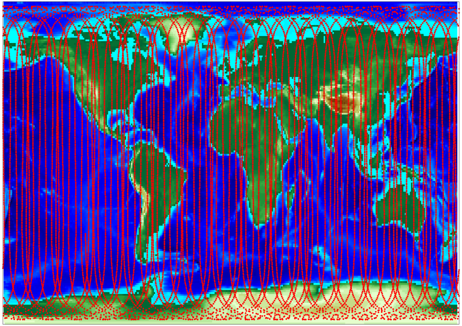
... and with 1 day of satellite data

Global coverage ...

... with ground observatories



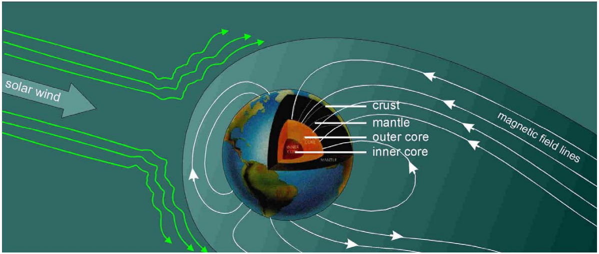




... and with 3 days of satellite data

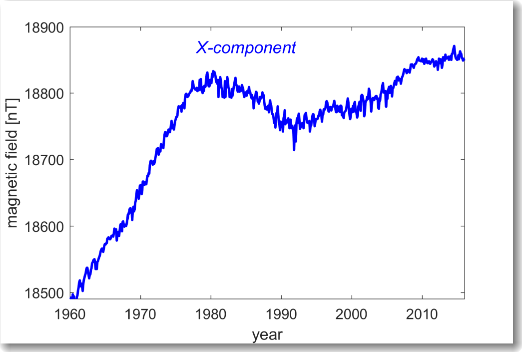
Sources of the Near-Earth Magnetic Field

- 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



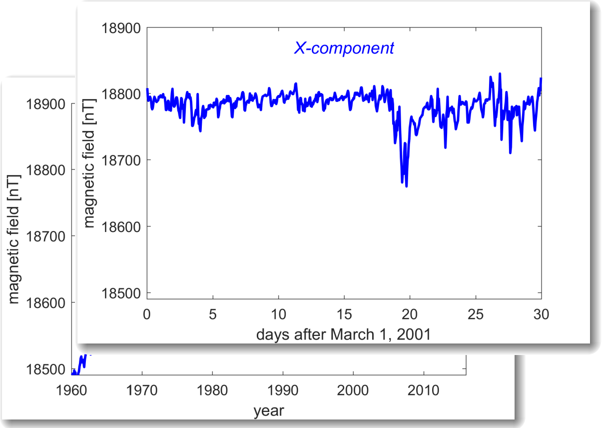
Time Change of the Magnetic Field at Niemegk/Germany

Minutes to Years



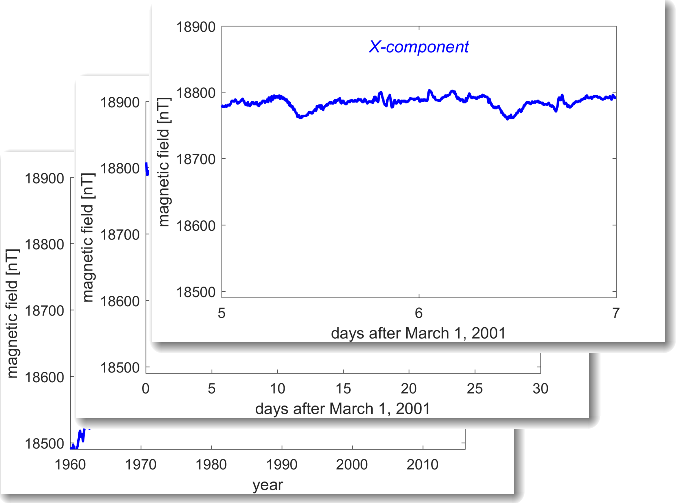
Time Change of the Magnetic Field at Niemegk/Germany

Minutes to Years



Time Change of the Magnetic Field at Niemegk/Germany

Minutes to Years

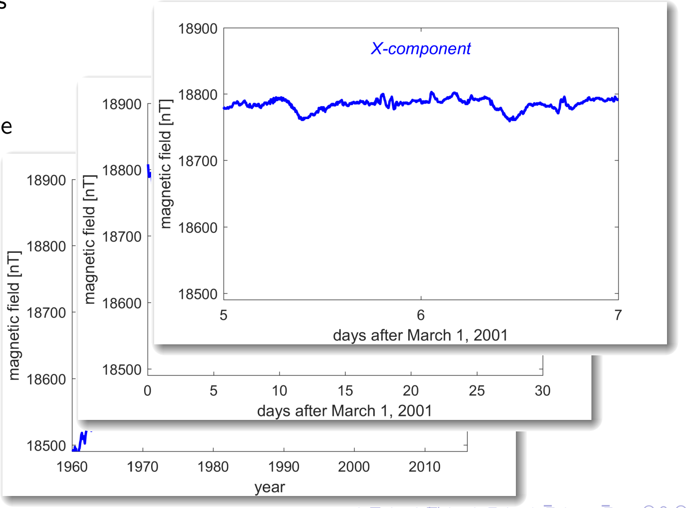


Time Change of the Magnetic Field at Niemegk/Germany

Minutes to Years

- seasonal variations
- daily variations
- hourly variations

of 10-100 nT amplitude



Ground Observatory vs. Satellite Magnetic Data

- Ground stations monitor time changes of Earth's magnetic field at fixed locations
- Attempt to minimize external field contributions by temporal averaging (Monthly or annual mean values) and/or by data selection (geomagnetic quiet times, dark conditions)

Ground Observatory vs. Satellite Magnetic Data

- Ground stations monitor time changes of Earth's magnetic field at fixed locations
- Attempt to minimize external field contributions by temporal averaging (Monthly or annual mean values) and/or by data selection (geomagnetic quiet times, dark conditions)

- 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
- Attempt to minimize external field signatures by data selection

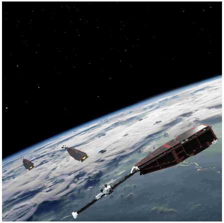
Outline of Talk

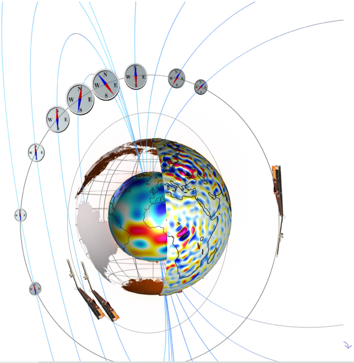
1. Magnetic Observations for Studying the Earth's Core
2. *Swarm* Satellite Constellation Mission
3. Extraction of core field signal: Separation of internal and external contributions
4. Dynamics of the Recent Core Field
5. Conclusions

The *Swarm* Satellite Constellation Mission

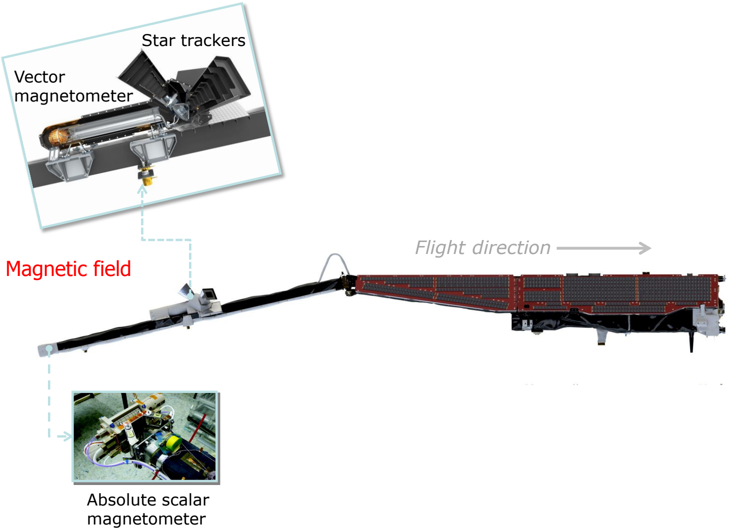
Constellation of 3 satellites to explore Earth's magnetic field and its environment

- launched on 22 Nov 2013
  10+ years lifetime
- two satellites side-by-side ($<$ 150 km separation) at 450 km altitude, measuring East-West magnetic gradient
- third satellite at 530 km altitude
- drifting Local Time orbits for better separation of external fields
- See http://earth.esa.int/swarm

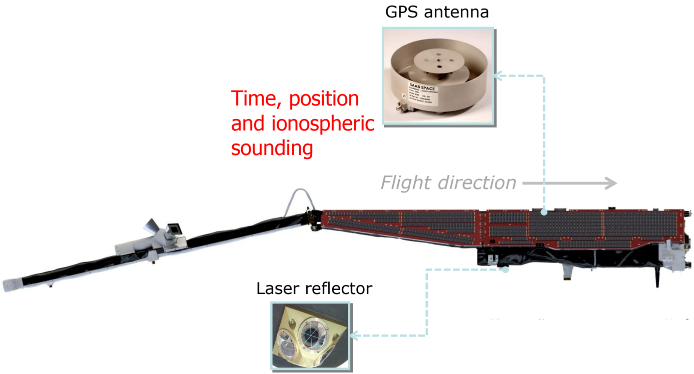




Swarm satellite payload



Swarm satellite payload



Swarm satellite payload

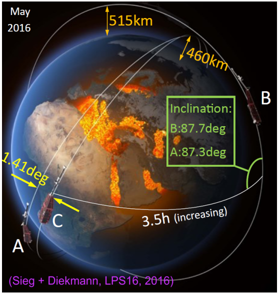
Thermospheric density
and winds

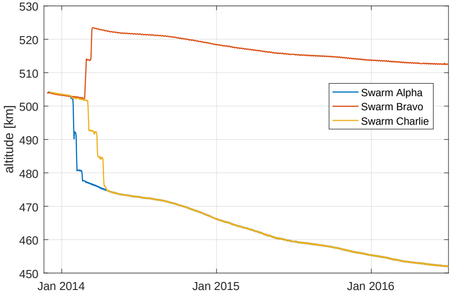
3D-accelerometer

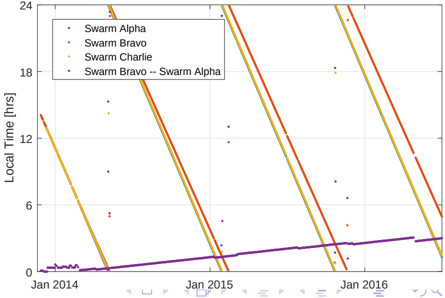
Swarm satellite payload

Evolution of the *Swarm* constellation

- all LT sampled in 9 months
- 3 hrs LT difference in 2016
- decaying altitude:
  re-entry of lower pair in 2023?
- discussion on future satellite constellation scenario:
  long mission (core field) vs. low-altitude data during solar minimum in 2020 (crustal field) ?

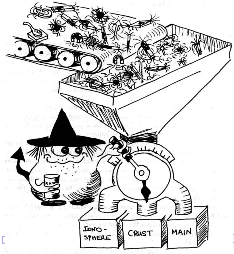






Outline of Talk

1. Magnetic Observations for Studying the Earth's Core
2. *Swarm* Satellite Constellation Mission
3. Extraction of core field signal: Separation of internal and external contributions
4. Dynamics of the Recent Core Field
5. Conclusions



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
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 spatial resolution (lithospheric field) and high temporal resolution (determine rapid core field changes)

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

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

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

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

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

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

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

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

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

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

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

- 17 years of data from Ørsted, CHAMP, SAC-C and *Swarm* satellites and monthly mean values from 160 magnetic ground observatories
- Data selection - magnetic field data:
  - geomagnetic activity index $Kp \leq 2o$, $|dD_{st}/dt| \leq 2\text{nT/hr}$
  - Only data from dark regions, Sun at least 10° below horizon
  - only scalar intensity data in polar regions ($> \pm 55^\circ$ magnetic latitude)
  - Polar regions: selection based on Interplanetary Magnetic Field
- Data selection - magnetic "gradient" data:
  - N-S gradient approximated by alongtrack first differences
    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 intensity data in polar regions

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

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

- Model parameterization:
  - static field (core and crust) up to $n \leq 110$
  - 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

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

- Model parameterization:
  - static field (core and crust) up to $n \leq 110$
  - 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
- ... plus regularisation of temporal complexity of $\ddot{B}_r$ at model endpoints

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

- Model parameterization:
  - static field (core and crust) up to $n \leq 110$
  - 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
- ... plus regularisation of temporal complexity of $\ddot{B}_r$ at model endpoints
- About 28.000 model parameters estimated from 7.4 mio. observations

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

- Model parameterization:
  - static field (core and crust) up to $n \leq 110$
  - 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
- ... plus regularisation of temporal complexity of $\ddot{B}_r$ at model endpoints
- About 28.000 model parameters estimated from 7.4 mio. observations

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

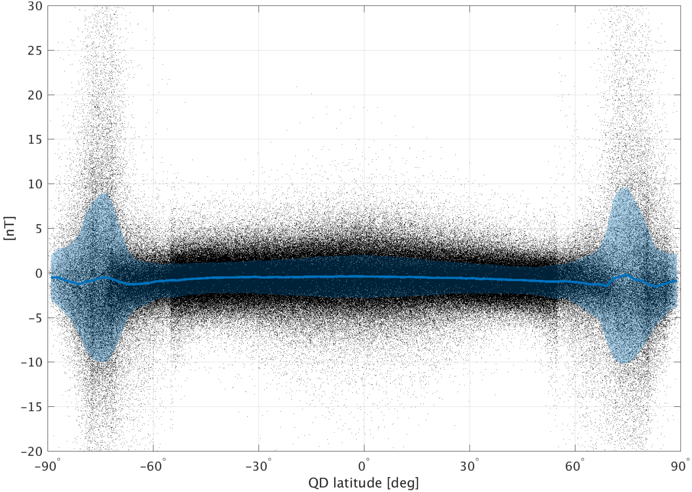
CHAMP Scalar Residuals

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

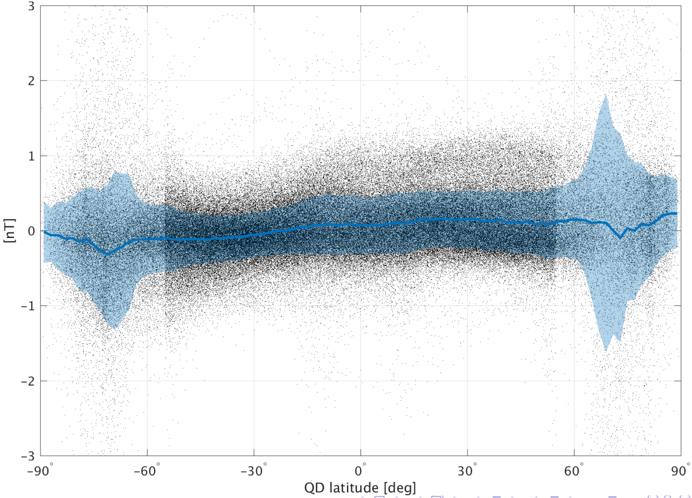
mean $\pm 1\sigma$ in 2° bins

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 $> \pm 55^\circ$magnetic latitudes



Extracting the core signal

- Regularisation of core field models, e.g. by minimizing the time-space average of $|d^3 B_r / dt^3|^2$, results in a latitude-independent damping
- Data errors (mainly due to unmodeled external sources) are hardly known, but are certainly much larger at polar latitudes
- Therefore rapid core field changes better resolvable at non-polar latitudes
- How to account for this?
    - Data errors are non-Gaussian, and not independent
      Data covariance matrix $\mathbf{C_e}$ is hardly known, not even its diagonal elements
      Time-correlation of minutes to hours?
    - Instead: ad-hoc solution by adjustment of regularisation
      For CHAOS-6: zonal coefficients g_n^0 are more heavily regularized

Monthly Means at Virtual Observatories

An alternative way of extracting the core signal:
Satellite-derived monthly mean values from "Virtual Observatories in space"

(Mandea & Olsen, 2006; Olsen & Mandea, 2007; Beggan et al., 2009)
see also posters by Diana Saturnino et al., and by Magnus Hammer & Chris Finlay

Monthly Means at Virtual Observatories

An alternative way of extracting the core signal:
Satellite-derived monthly mean values from "Virtual Observatories in space"

Example: CHAMP-based monthly means at regular $5^\circ \times 5^\circ$ grid in space

- Take CHAMP vector data of each month that are located within 400 km from "target point" (which is the grid point at 400 km height)
- Date are interpolated (or extrapolated) to common altitude (400 km) assuming that observed $\mathbf{B}$ is a (local) potential field
- Monthly means on the regular grid for each of the 113 months of the years 2001.0 – 2010.75

(Mandea & Olsen, 2006; Olsen & Mandea, 2007; Beggan et al., 2009)
see also posters by Diana Saturnino et al., and by Magnus Hammer & Chris Finlay

Monthly Means at Virtual Observatories

An alternative way of extracting the core signal:
Satellite-derived monthly mean values from "Virtual Observatories in space"

Example: CHAMP-based monthly means at regular $5^\circ \times 5^\circ$ grid in space

- Take CHAMP vector data of each month that are located within 400 km from "target point" (which is the grid point at 400 km height)
- Date are interpolated (or extrapolated) to common altitude (400 km) assuming that observed $\mathbf{B}$ is a (local) potential field
- Monthly means on the regular grid for each of the 113 months of the years 2001.0 – 2010.75

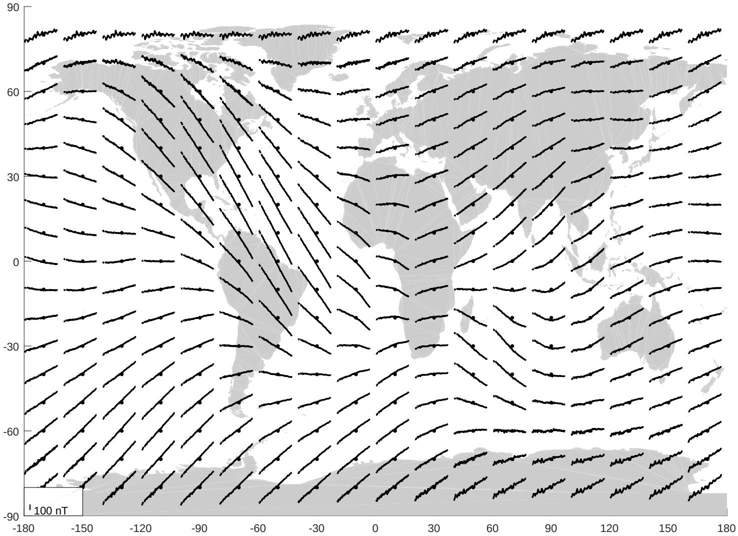
(Mandea & Olsen, 2006; Olsen & Mandea, 2007; Beggan et al., 2009)
see also posters by Diana Saturnino et al., and by Magnus Hammer & Chris Finlay

Similar approach possible for *Swarm*, including magnetic gradient information for improved removal external fields

Monthly Means at Virtual Observatories

Z at 400 km altitude, 2001-2010

CHAMP-based monthly means at regular $10^\circ \times 20^\circ$ grid in space



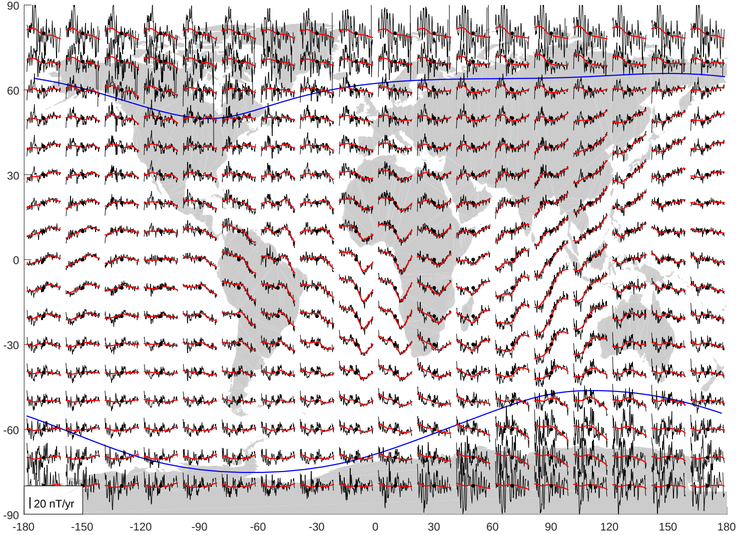
Monthly Means at Virtual Observatories

dZ/dt at 400 km altitude, 2001-2010

CHAMP-based monthly means at regular $10^\circ \times 20^\circ$ grid in space

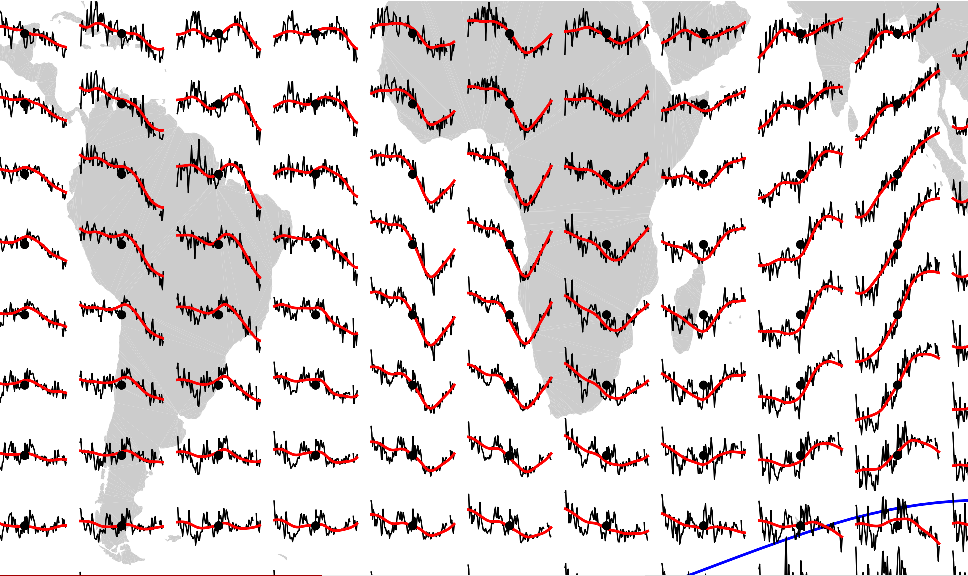
CHAOS-6

$\pm 60^\circ$ magnetic latitude



Monthly Means at Virtual Observatories

dZ/dt at 400 km altitude, 2001-2010



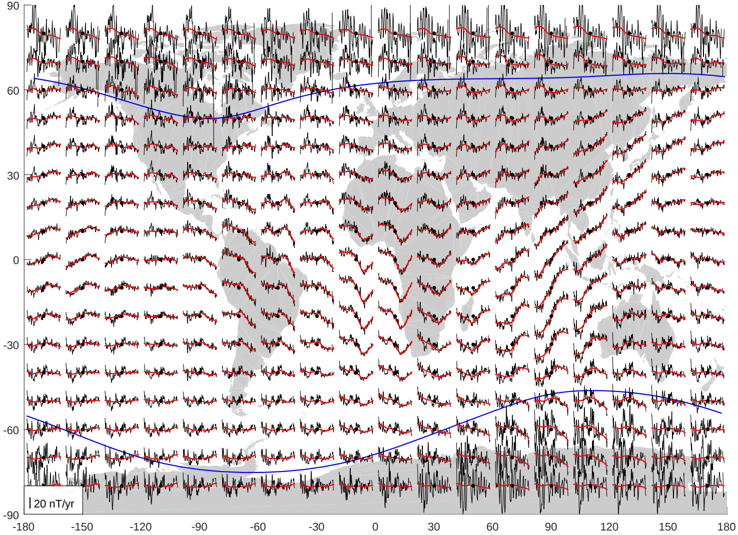
Monthly Means at Virtual Observatories

dZ/dt at 400 km altitude, 2001-2010

CHAMP-based monthly means at regular 10° × 20° grid in space

CHAOS-6

±60° magnetic latitude

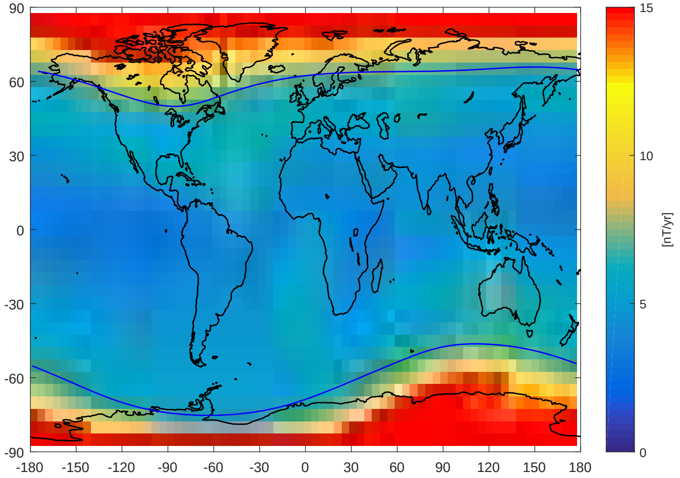


Monthly Means at Virtual Observatories

Scatter (standard deviation σ) of dZ/dt at 400 km altitude, 2001-2010

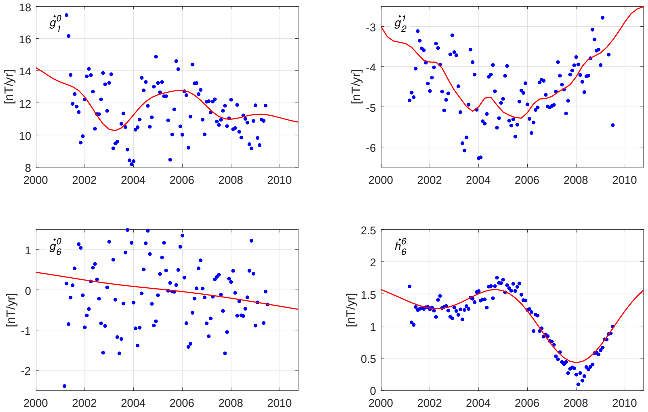
CHAMP-based monthly means at regular $10^\circ \times 20^\circ$ grid in space

$\pm 60^\circ$ magnetic latitude



Secular variation terms $\dot{g}_n^m, \dot{h}_n^m$

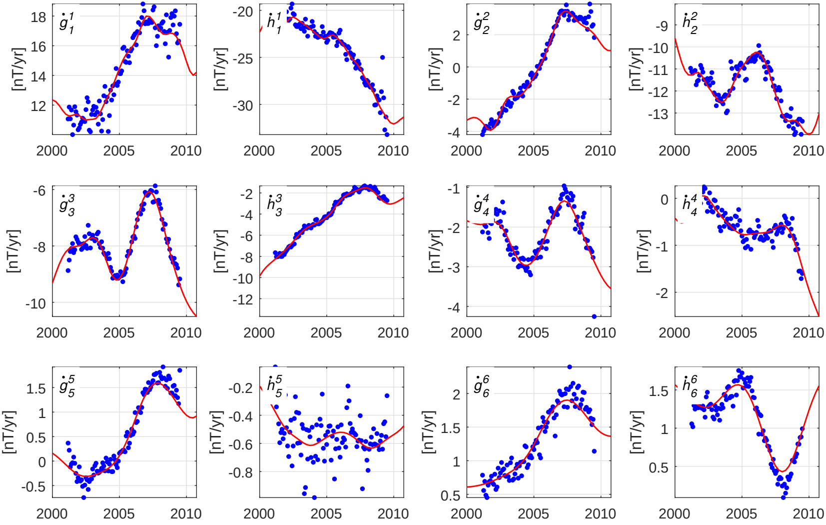
From annual differences at virtual observatories, resp. from CHAOS-6



Scatter ("error") of coefficients depends on degree n and order m
Some coefficients (like h_6^6) are much better determined than others (like g_1^0 or g_6^0)

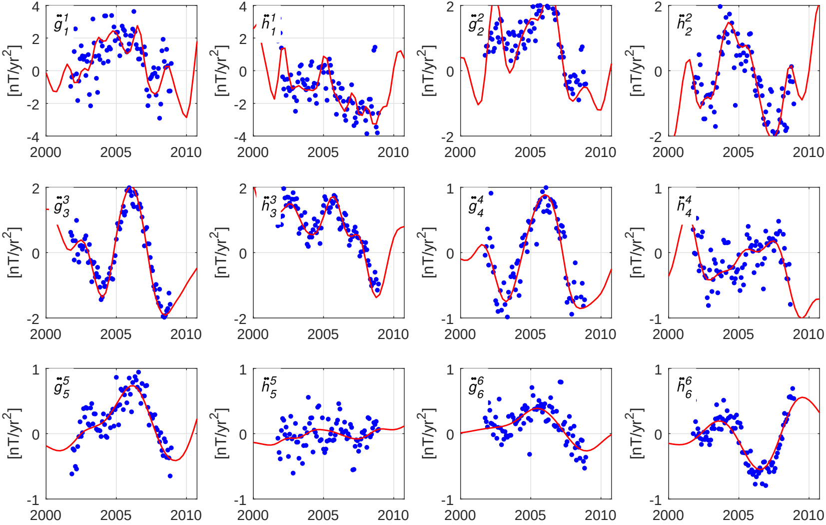
Secular Variation: sectorial terms $\dot{g}_n^n, \dot{h}_n^n$

From virtual observatories, resp. from CHAOS-6



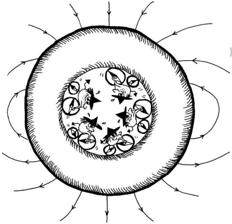
Secular Acceleration: sectorial terms $\ddot{g}_n^n, \ddot{h}_n^n$

From virtual observatories, resp. from CHAOS-6



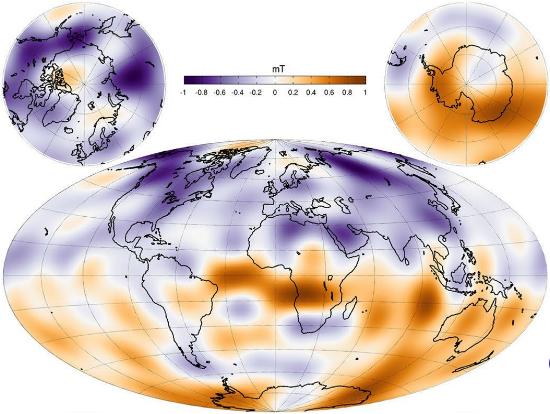
Outline of Talk

1. Magnetic Observations for Studying the Earth's Core
2. *Swarm* Satellite Constellation Mission
3. Extraction of core field signal: Separation of internal … utions
4. **Dynamics of the Recent Core Field**
5. Conclusions



Core Field Dynamics during the last 15 years

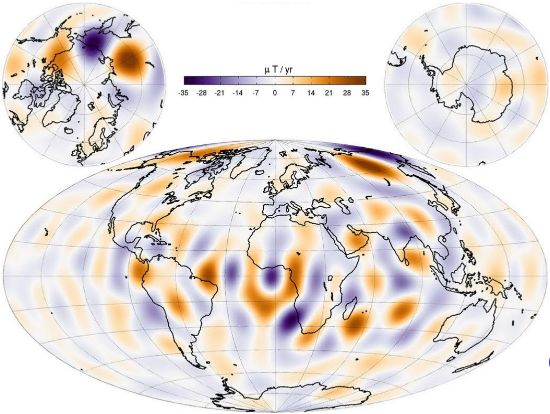
B_r at CMB in 2015, $n = 1 - 13$



(Finlay et al., 2016)

Core Field Dynamics during the last 15 years

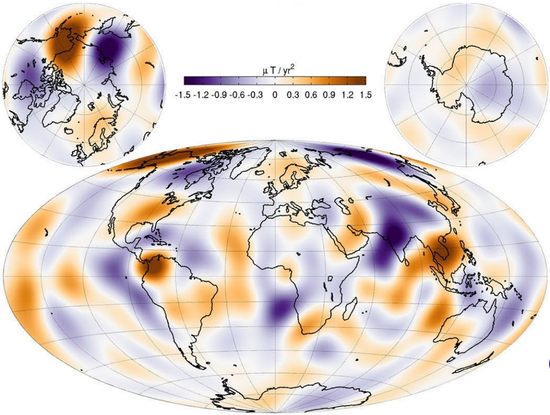
$\dot{B}_r$ at CMB in 2015, $n = 1 - 16$



(Finlay et al., 2016)

Core Field Dynamics during the last 15 years

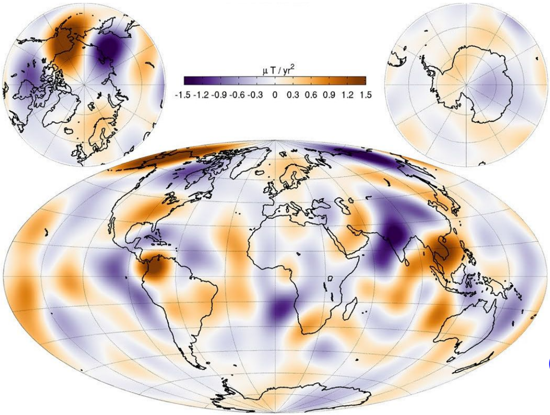
$\ddot{B}_r$ at CMB in 2015, $n = 1 - 16$



(Finlay et al., 2016)

Core Field Dynamics during the last 15 years

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



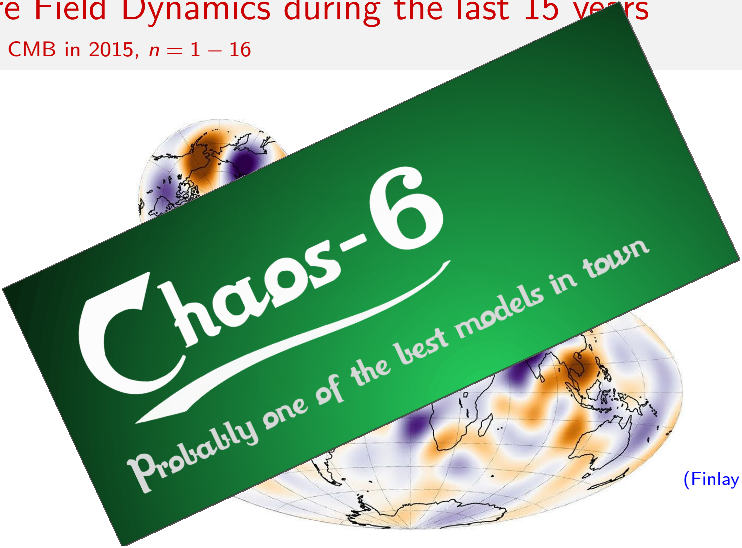
(Finlay et al., 2016)

Consistent picture of

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

Core Field Dynamics during the last 15 years

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



(Finlay et al., 2016)

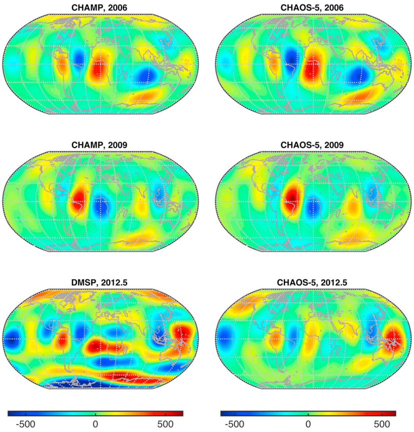
Consistent picture of

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

Low latitude secular acceleration pulses

Chulliat et al. (2015), Fast equatorial waves propagating at the top of the Earths core, GRL

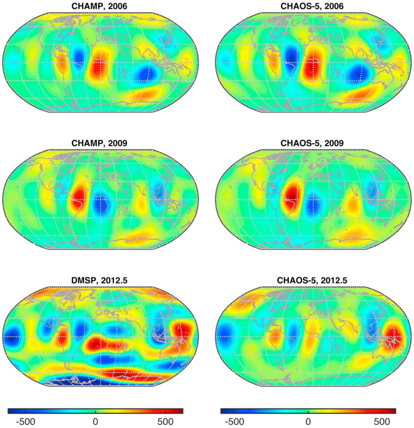
$\ddot{B}_r$ (in nT/yr^2) at CMB at three different epochs (2006, 2009, and 2012.5), when equatorial SA patches in the Atlantic sector are of maximum amplitude



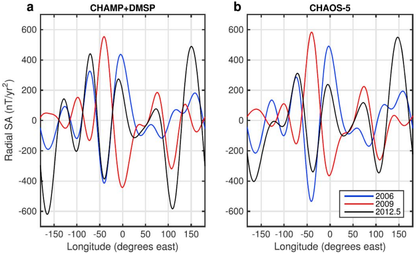
Low latitude secular acceleration pulses

Chulliat et al. (2015), Fast equatorial waves propagating at the top of the Earths core, GRL

$\ddot{B}_r$ (in nT/yr^2) at CMB at three different epochs (2006, 2009, and 2012.5), when equatorial SA patches in the Atlantic sector are of maximum amplitude



Variation along the geographic equator

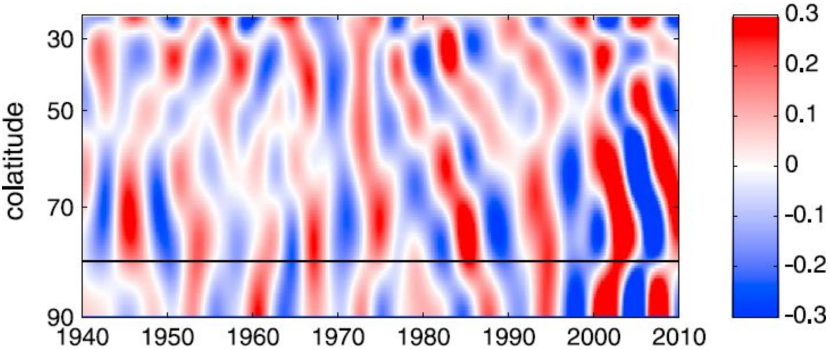


Secular acceleration pulses of alternating sign in 2006, 2009, and 2012.5

Quasi-geostrophic equator-symmetric flow

Gillet et al. (2015), Planetary gyre, time-dependent eddies, torsional waves, and equatorial jets at the Earths core surface, JGR

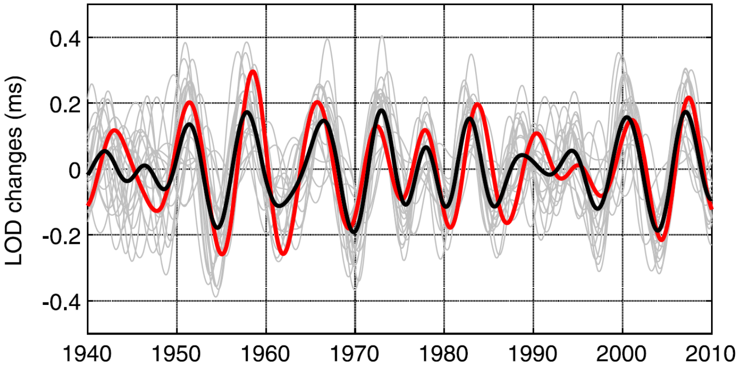
Ensemble mean of the geostrophic flow (in km/yr), band-pass filtered between 4 and 9.5 years



Quasi-geostrophic equator-symmetric flow

Gillet et al. (2015), Planetary gyre, time-dependent eddies, torsional waves, and equatorial jets at the Earths core surface, JGR

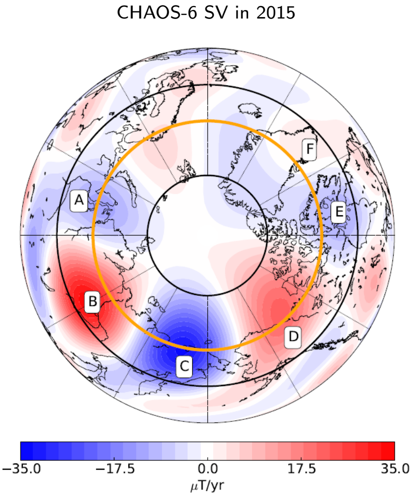
LOD predictions (grey and black) and observed LOD changes (red), band-pass filtered between 4 and 9.5 years

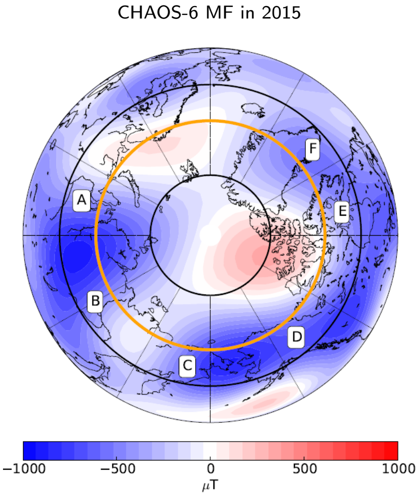


Quasi-geostrophic flow can explain the observed time-varying SV, if one accounts for time-correlated errors in unknown small scale fields and allows rapid flow changes on small length scales.

An accelerating high-latitude Jet in Earth's Core

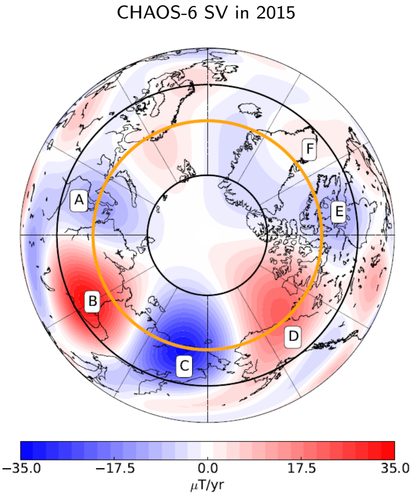
Phil Livermore et al: Poster # 81

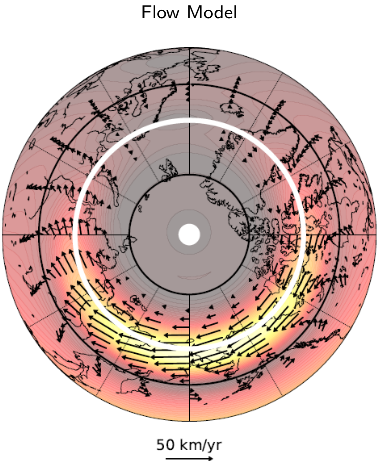




An accelerating high-latitude Jet in Earth's Core

Phil Livermore et al: Poster # 81

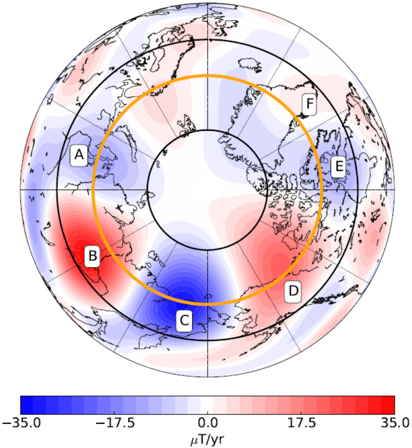




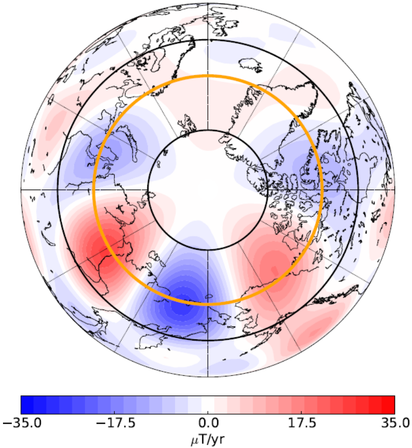
An accelerating high-latitude Jet in Earth's Core

Phil Livermore et al: Poster # 81

CHAOS-6 SV in 2015



SV from Flow Model



Outline of Talk

Conclusions

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
- Rapid core field variations are better resolved in non-polar ($< \pm 60^\circ$) regions
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years

Conclusions and Challenges

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
- Rapid core field variations are better resolved in non-polar ($< \pm 60^\circ$) regions
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years

Conclusions and Challenges

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
  . . . what are proper data error covariances?
- Rapid core field variations are better resolved in non-polar ($< \pm 60^\circ$) regions
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years

Conclusions and Challenges

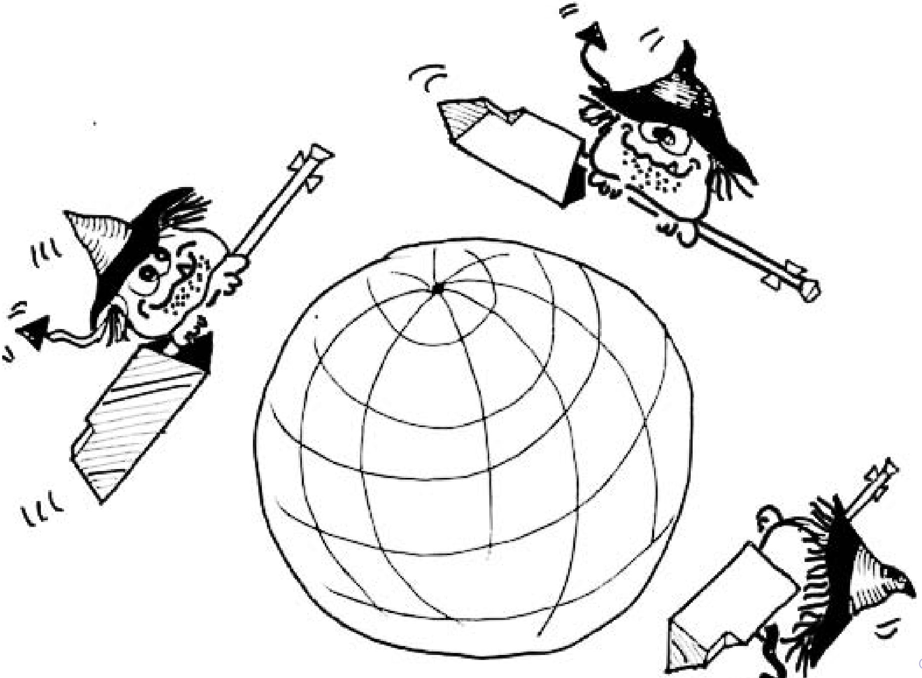
- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
  ... what are proper data error covariances?
- Rapid core field variations are better resolved in non-polar ($< \pm 60°$) regions
  ... should we give op the "global model" idea?
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years

Conclusions and Challenges

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
  …what are proper data error covariances?
- Rapid core field variations are better resolved in non-polar ($< \pm 60°$) regions
  …should we give op the "global model" idea?
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years
  …but presently no consolidated follow-on satellite

Conclusions and Challenges

- Thanks to the satellites Ørsted, CHAMP and now *Swarm*, there is a consistent picture of
  - secular variation up to spherical harmonic degree $n = 16$
  - time change of SV at large length scales ($n < 9$)
- Consideration of external (ionospheric and magnetospheric) magnetic field signatures is one of the biggest challenges for extracting core field signal
  . . . what are proper data error covariances?
- Rapid core field variations are better resolved in non-polar ($< \pm 60^\circ$) regions
  . . . should we give op the "global model" idea?
- Magnetic gradients from the *Swarm* constellation help to reduce (but do not remove!) external field contamination
  – improved crustal *and* core field models
- Bright future: *Swarm* will likely continue for 10+ years
  . . . but presently no consolidated follow-on satellite
- **Physics-based core field modeling (e.g. through data assimilation)**



References I

Beggan, C. D., Whaler, K. A., & Macmillan, S., 2009. Biased residuals of core flow models from satellite-derived 'virtual observatories', *Geophys. J. Int.*, **177**(2), 463–475.

Chulliat, A., Alken, P., & Maus, S., 2015. Fast equatorial waves propagating at the top of the Earth's core, *Geophys. Res. Lett.*, **42**(9), 3321–3329.

Finlay, C. C., Olsen, N., Kotsiaros, S., Gillet, N., & Tøffner-Clausen, L., 2016. Recent geomagnetic secular variation from Swarm and ground observatories in the CHAOS-6 geomagnetic field model, *Earth Planets Space*, **68**, 112.

Gillet, N., Jault, D., & Finlay, C. C., 2015. Planetary gyre, time-dependent eddies, torsional waves and equatorial jets at the earths core surface, *J. Geophys. Res.*.

Lesur, V., Wardinski, I., Rother, M., & Mandea, M., 2008. GRIMM: the GFZ Reference Internal Magnetic Model based on vector satellite and observatory data, *Geophys. J. Int.*, **173**, 382–294.

Lesur, V., Wardinski, I., Hamoudi, M., & Rother, M., 2010. The second generation of the GFZ reference internal magnetic model: GRIMM-2, *Earth Planets Space*, **62**, 765–773.

Mandea, M. & Olsen, N., 2006. A new approach to directly determine the secular variation from magnetic satellite observations, *Geophys. Res. Lett.*, **33**.

Maus, S., Lühr, H., Balasis, G., Rother, M., & Mandea, M., 2005. Introducing POMME, the POtsdam Magnetic Model of the Earth, in *Earth Observation with CHAMP, Results from Three Years in Orbit*, edited by C. Reigber, H. Lühr, P. Schwintzer, & J. Wickert, pp. 293–298, Springer Verlag, Berlin.

Maus, S., Rother, M., Stolle, C., Mai, W., Choi, S., Lühr, H., Cooke, D., & Roth, C., 2006. Third generation of the Potsdam Magnetic Model of the Earth (POMME), *Geochem. Geophys. Geosyst.*, **7**(7), Q07008.

Olsen, N. & Mandea, M., 2007. Investigation of a secular variation impulse using satellite data: The 2003 geomagnetic jerk, *Earth Planet. Sci. Lett.*, **255**, 94–105.

References II

Olsen, N., Lühr, H., Finlay, C. C., Sabaka, T. J., Michaelis, I., Rauberg, J., & Tøffner-Clausen, L., 2014. The CHAOS-4 Geomagnetic Field Model, *Geophys. J. Int.*, **197**, 815 – 827.

Sabaka, T. J., Olsen, N., & Langel, R. A., 2002. A comprehensive model of the quiet-time near-Earth magnetic field: Phase 3, *Geophys. J. Int.*, **151**, 32–68.

Sabaka, T. J., Olsen, N., & Purucker, M. E., 2004. Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data, *Geophys. J. Int.*, **159**, 521–547.

Sabaka, T. J., Olsen, N., Tyler, R. H., & Kuvshinov, A., 2015. CM5, a pre-*Swarm* comprehensive magnetic field model derived from over 12 years of CHAMP, Ørsted, SAC-C and observatory data, *Geophys. J. Int.*, **200**, 1596–1626.

Spatial Spectrum of Secular Variation at CMB