Bridging the gap between CHAMP and Swarm: Using Ørsted and ground observatory data

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Talk Outline

1. Observations: CHAMP, Ørsted & ground observatories
2. Modelling approach
3. Lithospheric field from low altitude, solar min, CHAMP data
4. Secular variation during the satellite era
5. External field: variations with solar cycle?
6. Perspective: Looking forward to Swarm

Monitoring the present geomagnetic field

- Ørsted satellite launched in 1999.
- Since then, continuous monitoring from ground and space.
- The CHAMP satellite provided low altitude vector data 2000 - 2010.
- Ground network has evolved, now with new stations in remote locations.
- Overall, a wealth of data: CHAOS model aims to capture this in terms of high resolution spherical harmonic field models.

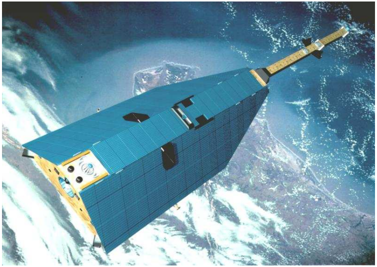

Fig: Examples of modern geomagnetic observation platforms: the CHAMP satellite 2000-2010 and Tristan da Cunha ground observatory, South Atlantic, since 2009.

The final days of CHAMP

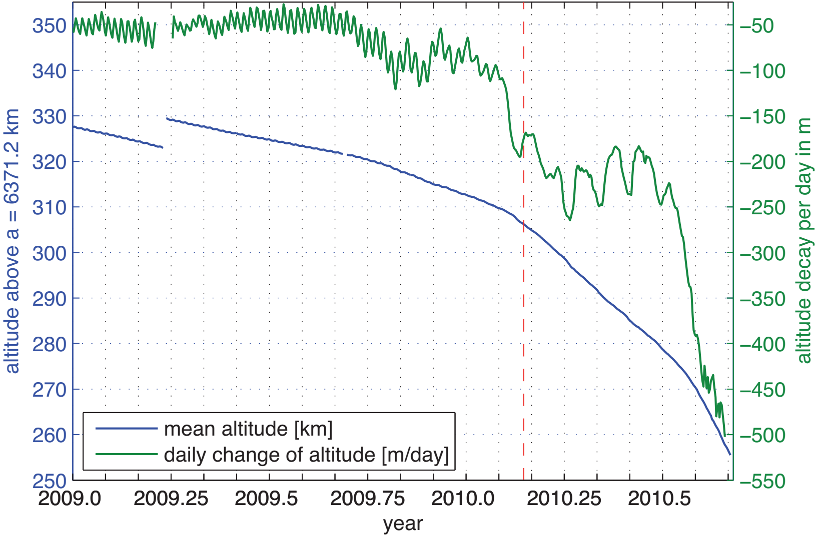

Fig: CHAMP altitude decrease post 2009.0.

Post-CHAMP era

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- No vector satellite observations available for about 3 years.
- What else do we have available?
- Thankfully Ørsted is still providing some scalar data!
- And we have the ground observatories (some now reporting quasi-definitive data)

The Ørsted satellite

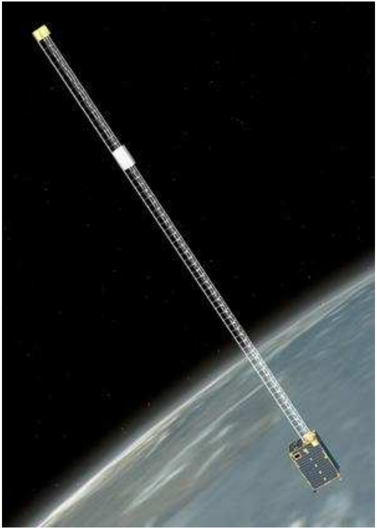

Fig: The Ørsted satellite.

Ørsted scalar data availability since 2010.0

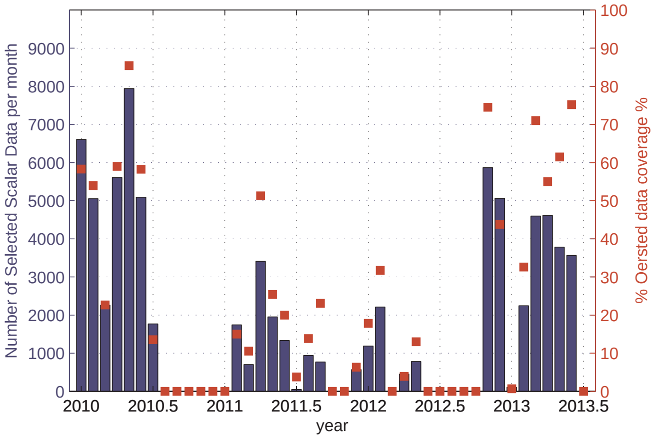

Fig: Ørsted scalar data per month: As a percentage of the total possible (red dots), and the number of data suitable for CHAOS-type field modelling (blue bars).

- Data available from: ftp://ftp.space.dtu.dk/data/magnetic-satellites/Oersted/mag-f/

Example: 1 month of selected Ørsted F data from 2013

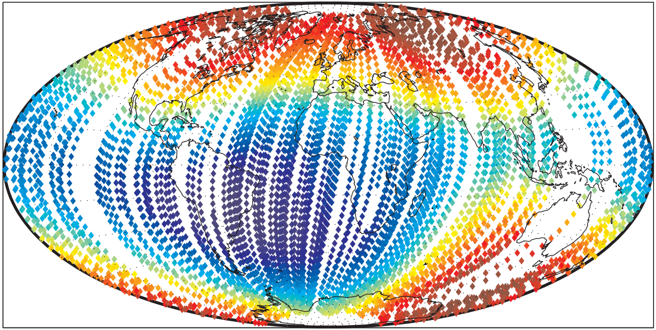

Fig: Selected Ørsted scalar field measurements, 15th March to 15th April 2013. Colour scale runs from 15,000nT to 45,000nT. The altitude varied from 630 to 850 km.

Location of ground observatories

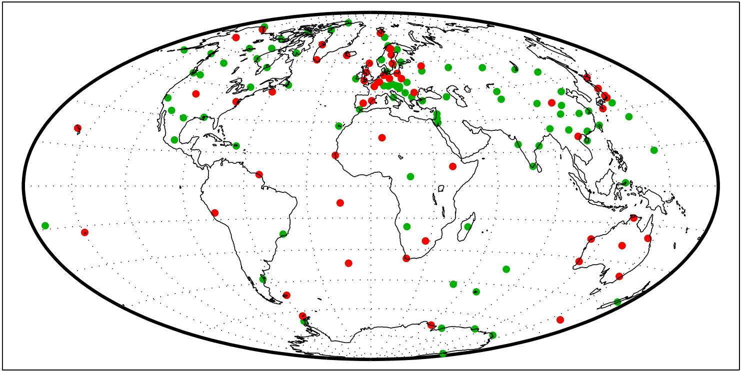

Fig: Observatories where annual differences of monthly means are available. Those reporting quasi-definitive (QD) data in 2013 shown in red.

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Forward modelling scheme: CHAOS

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- The internal field is parameterized as

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi \right) \left(\frac{a}{r} \right)^{n+1} P_n^m(\cos\theta)$$

- For $n \leq 20$, $g_n^m(t)$ and $h_n^m(t)$ expanded in order 6 splines with knot spacing 0.5 yrs.
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- The external field parameterization consists of:
  - In SM co-ords, co-estimate degree 1 (0.5 day bins) and degree 2 (5 day bins).
  - Rapid changes in SM degree 1 parameterized by new (hourly) RC index.
  - Also solve for static degree 1 and 2 in GSM co-ords.

$$\begin{aligned} V^{\text{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d \right) P_n^m(\cos\theta_d) \\ &+ a \sum_{m=0}^{1} \left(\hat{q}_1^m \cos T_d + \hat{s}_1^m \sin T_d \right) \cdot \left\{ RC_{\text{e}}(t) \left(\frac{r}{a} \right) + RC_{\text{i}}(t) \left(\frac{a}{r} \right)^2 \right\} P_1^m(\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\text{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

Inversion: data selection & model estimation

- **Data selection**
  - Quiet times: ($Kp \leq$ 2o, $|dD_{st}/dt| \leq$ 2nT.)
  - Night side: data from dark regions (sun 10 deg below horizon).
  - Vector CHAMP and Ørsted data below 55 deg geomag lat if available.
  - Otherwise scalar data from CHAMP, Ørsted and SAC-C.
  - Also annual differences of revised monthly means from ground stations.

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- **Model Estimation**
  - Nonlinear problem: solve with iterative descent (quasi-Newton) algorithm.
  - Iteratively re-weighted least squares (Huber weights) for robust data misfit.
  - Regularize $n \leq 20$ by miniminzing $(d^3 B_r / dt^3)^2$ at CMB.
  - Regularize $n \geq 85$ by miniminzing B_r^2 at Earth's surface.

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- **CHAOS-4 strategy: 2 independent models**
  - Model 1: Full span 1997-2013.5, to degree 80. Focus on SV.
  - Model 2: Only low altitude/solar min CHAMP data post 2009.0. Focus on crustal field up to $n = 85$.
  - Final model by merging at degree 25 where high correlation btw models 1, 2.

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CHAOS-4h Lithospheric field at Earth's surface

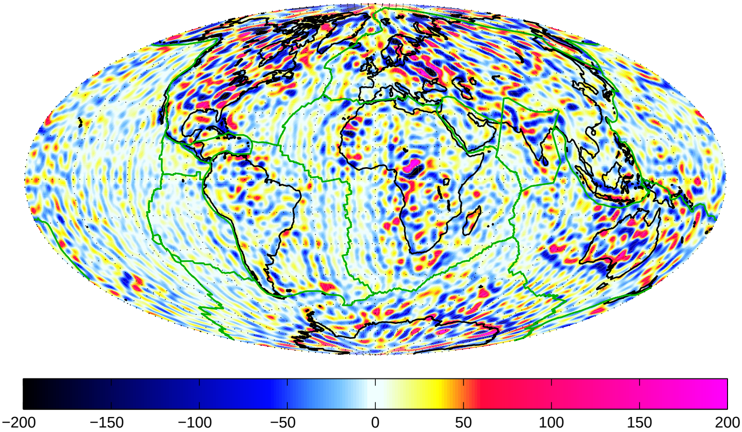

Fig: Radial field at Earth's spherical reference radius to $n = 85$. Units: nT.

CHAOS-4h - MF7

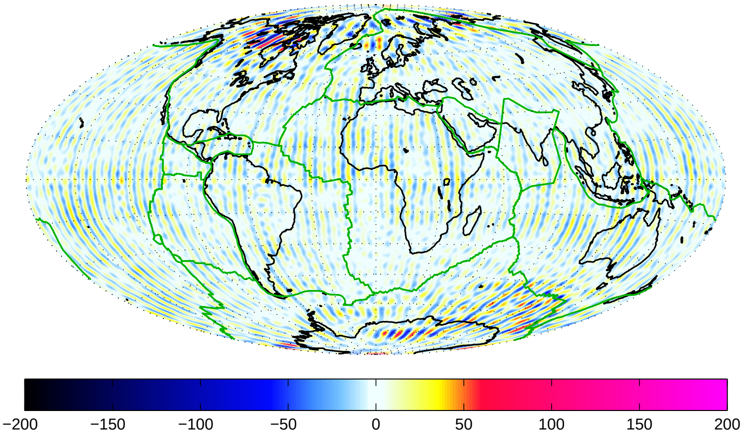

Fig: CHAOS-4h - MF7 (Maus et al., 2010), radial field to $n = 85$. Units: nT.

CHAOS-4h - GRIMM_L120

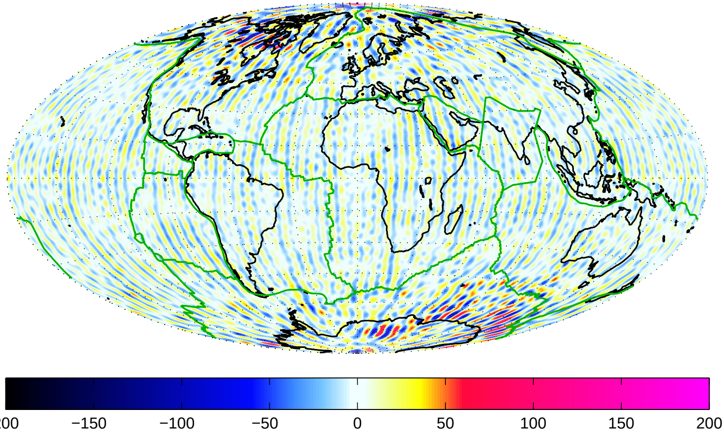

Fig: CHAOS-4h - GRIMM_L120 (Lesur et al., 2013), radial field to $n = 85$. Units: nT.

MF7 - GRIMM_ L120

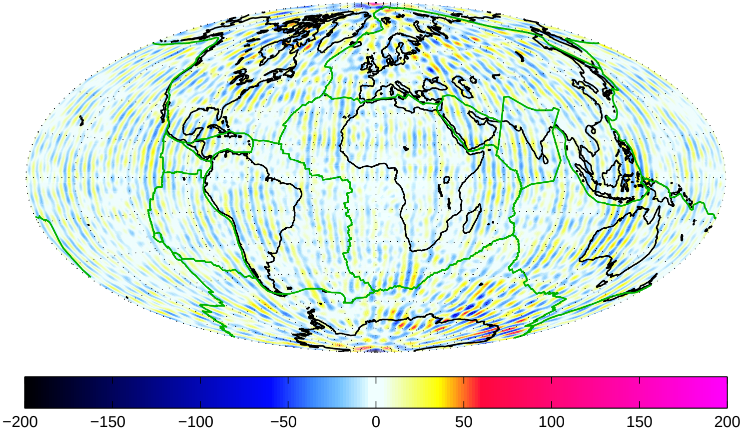

Fig: MF7 - GRIMM_ L120, radial field to $n = 85$. Units: nT.

Comparison of power spectra

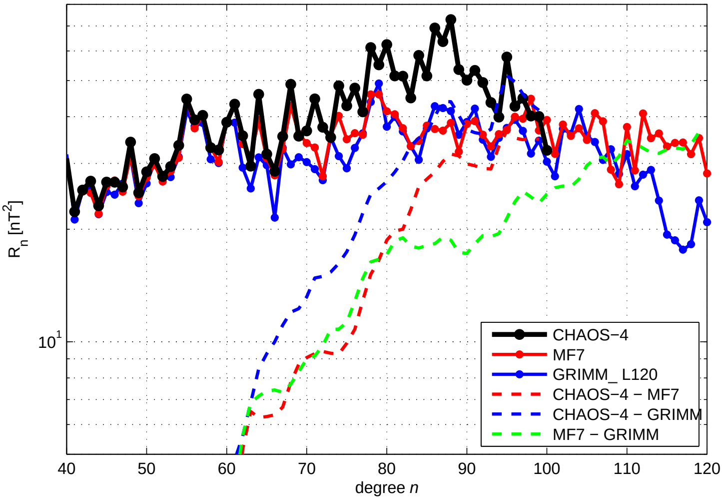

Fig: Comparison of power spectra of models and differences above degree 40.

Degree correlation

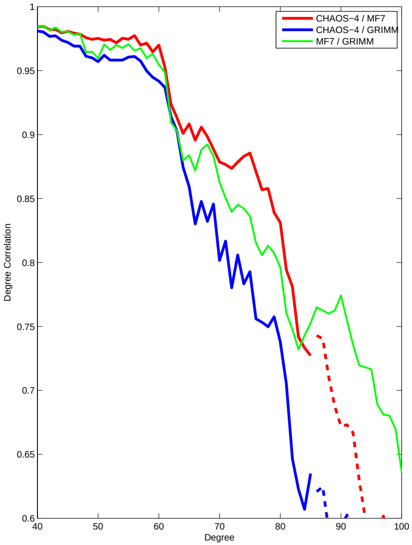

Fig: Degree correlation between models.

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Fit to annual differences of observatory monthly means

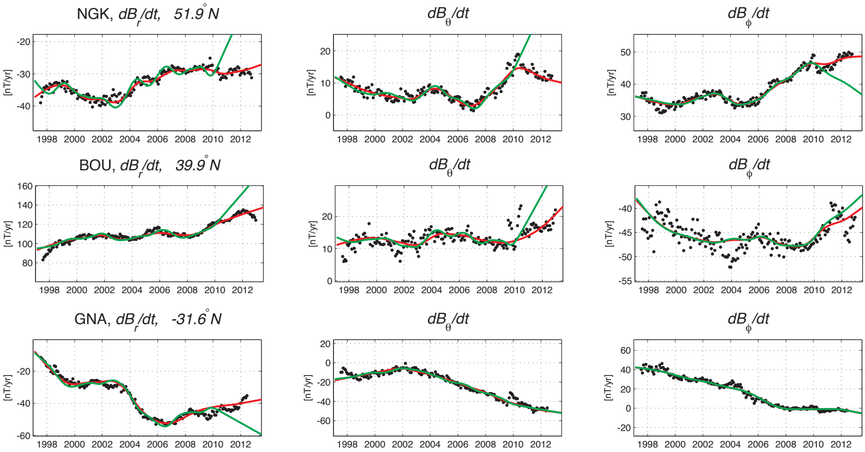

Fig: Fit of time-dep models CHAOS-4α (Olsen et al., 2010) (green) and the updated CHAOS-4 (red) to revised observatory monthly means. Components are plotted in dipole co-ordinates.

Time-dependence of secular variation coefficients

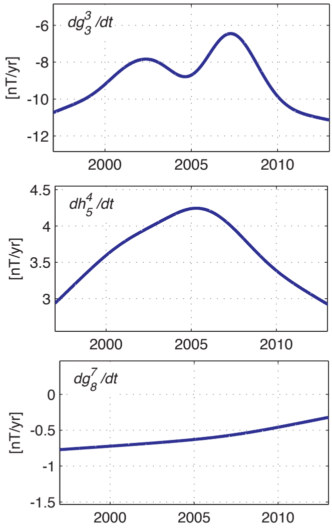

Fig: SV for a selection of Gauss coefficients. Units : nT/yr.

North magnetic dip pole and geomagnetic pole

Fig: Tracks of magnetic dip pole (red) and the geomagnetic pole (black), 1999 - 2013.5.

Core surface radial field in 1999.5

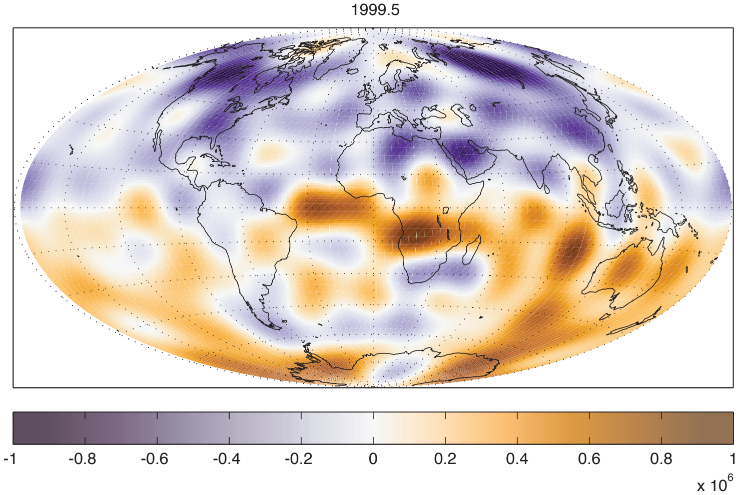

Fig: Radial field at core surface in 1999.5 to $n = 14$. Units : nT.

Core surface radial field in 2013.5

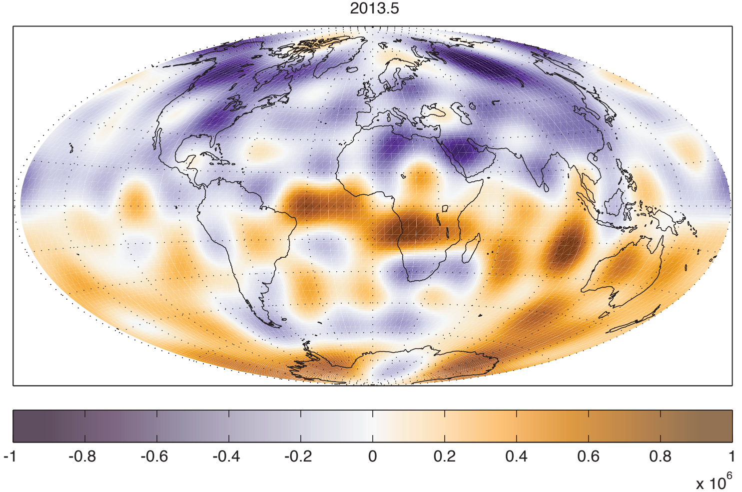

Fig: Radial field at core surface in 2013.5 to $n = 14$. Units : nT.

Core surface SV in 2013.5

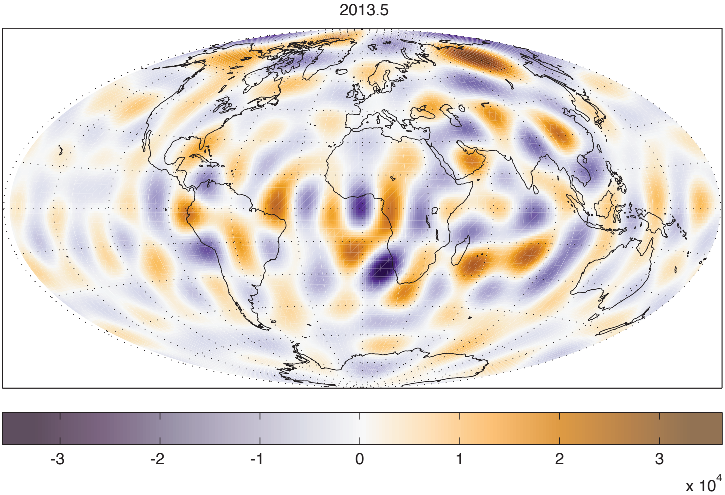

Fig: SV of radial field at core surface in 2013.5 to $n = 16$. Units : nT/yr.

SV and SA spectra at core surface

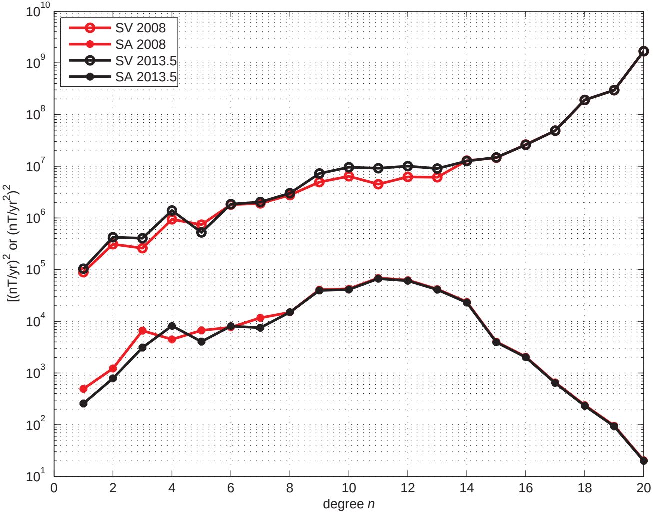

Fig:SV and SA spectrum for 2008.0 and 2013.5 at core surface.

Recent rapid SV in the South Atlantic

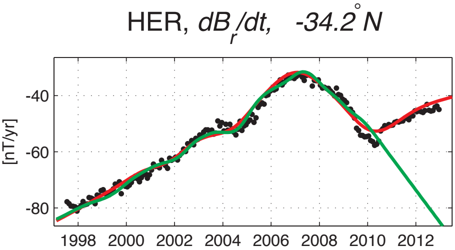

Fig: dB_r/dt at HER, South Africa. CHAOS-4: red, earlier CHAOS-4α: green.

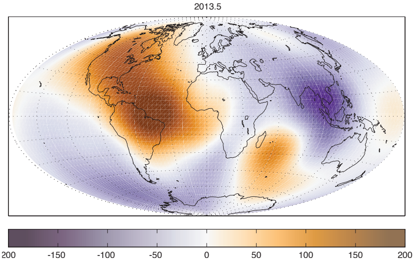

Fig: Map of dB_r/dt at surface in 2013.5. Units: nT/yr.

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RC index

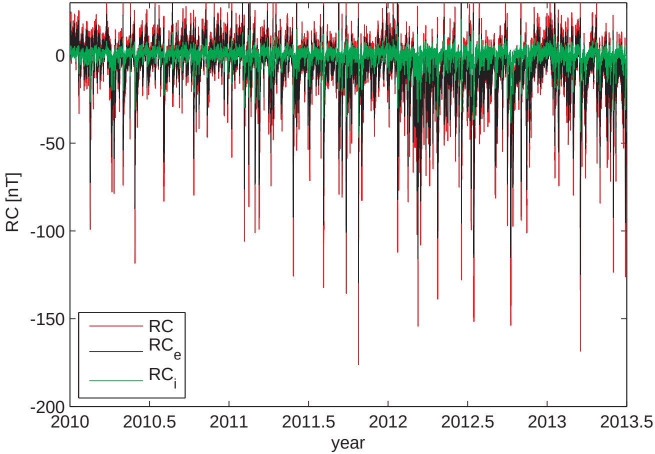

Fig : RC index since 2010, with decomposition into internal and external parts.

- Derived from hourly spherical harmonic analysis of mid/low latitude ground observatories, after correction for core field, static external field and observatory bias.

RC index: zoom in to storm, July 2012

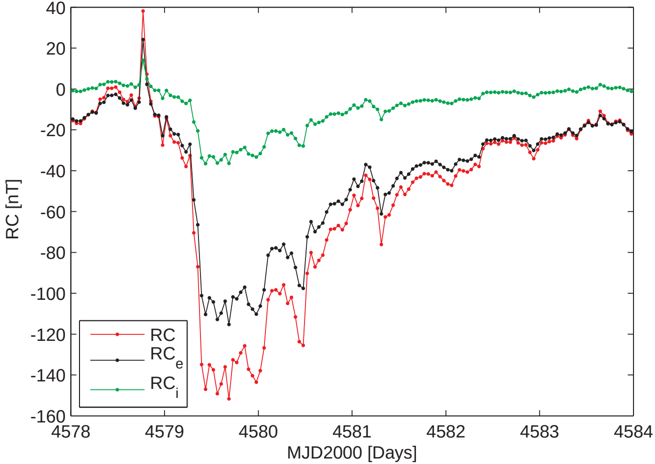

Fig : Zoom in to show RC index tracking of a storm during July 2012.

External dipole from satellites: solar cycle dependence?

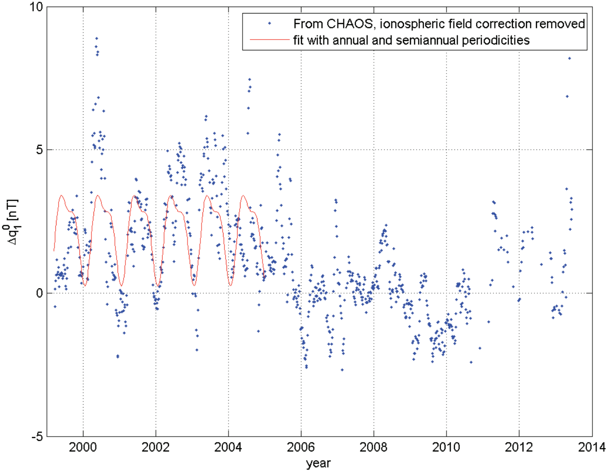

Fig : $\Delta q_1^0(t)$ in SM co-ords estimated from satellite data, this is the correction to RC_e derived from ground data.

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Methodological challenges

- Residuals show correlated structures in both space and time: how best to handle?
- Can low altitude/solar min CHAMP data be used to better constrain lithospheric field? And can we develop more appropriate filtering and regularization schemes? e.g. Lesur et al. (2013)
- Core MHD suggests that the small length scale field should change more rapidly. Can we develop field models that are consistent with this prior information? e.g. Gillet et al. (2013)

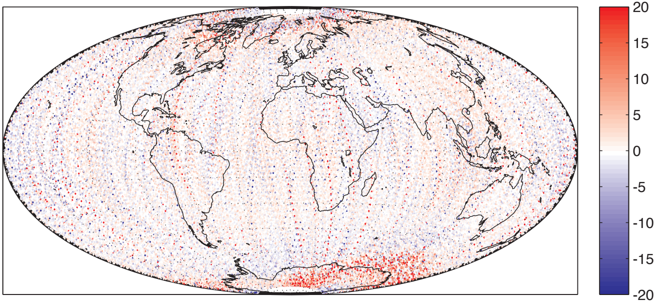

Fig: Ørsted scalar residuals since 2010.0. Units: nT, scale is saturated.

Looking forward to ESA's Swarm mission

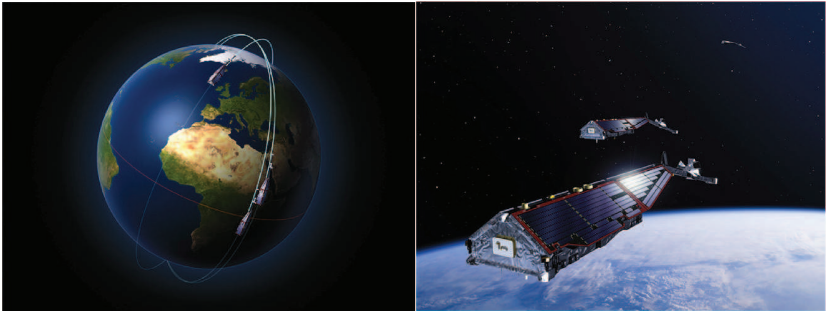

Fig: Artist's visualization of Swarm satellites due for launch in late 2013. Credit: ESA

- Improved local time coverage to help unravel puzzling structure of external fields.
- E-W low altitude pair to give definitive answers on $n > 80$ lithospheric field.
- In combination with better physics-based core field modelling schemes, should provide improved constraints on the core motions underlying rapid SV.

Summary

- Presented an updated CHAOS-4 model valid until 2013.5.
- Using only low altitude, solar min CHAMP data for the high degree field.
- Encouraging agreement between CHAOS-4, MF7 and GRIMM_ L120 to degree 75.
- Post-CHAMP, rely on Ørsted scalar data and ground station monthly means.
- Further rapid field changes in past 7 yrs in the South Atlantic region.
- (And of course) we are all looking forward to Swarm!

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Lesur, V., Rother, M., Vervelidou, F.AND Hamoudi, M., & Thébault, E., 2013. Post-processing scheme for modelling the lithospheric magnetic field., *Solid Earth*, **4**, 105–118.

Maus, S., Lühr, H., amd Rother, M., Hemant, K., Balasis, G., Ritter, P., & Stolle, C., 2010. Magnetic field model MF7, *http://www.geomag.us/models/MF7.html*.

Olsen, N., Lühr, H., Sabaka, T. J., Mandea, M., Rother, M., Tøffner-Clausen, L., & Choi, S., 2006. CHAOS— A model of Earth's Magnetic Field derived from CHAMP, Ørsted and SAC-C magnetic satellite data, *Geophys. J. Int.*, **166**, 67–75.

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