Comparisons of magnetic data from Swarm and previous missions using CHAOS-5

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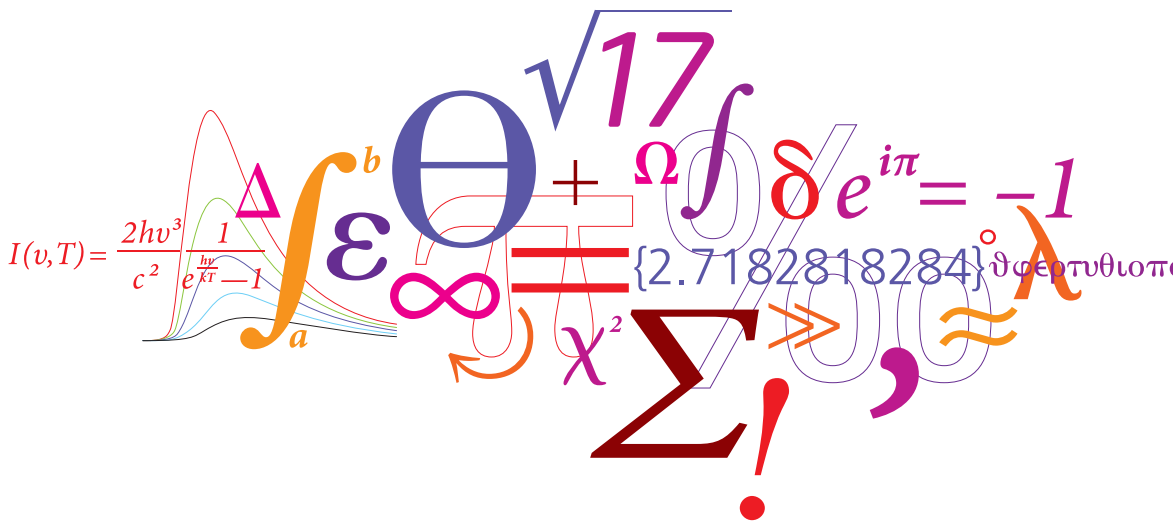

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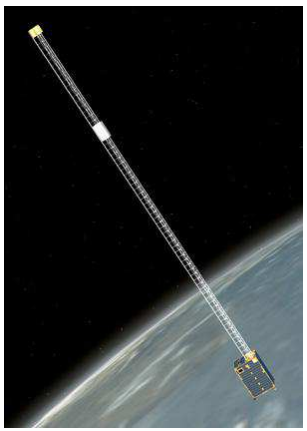
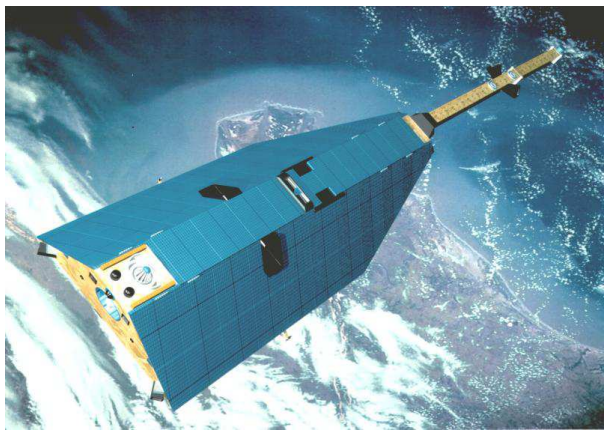
Talk Outline

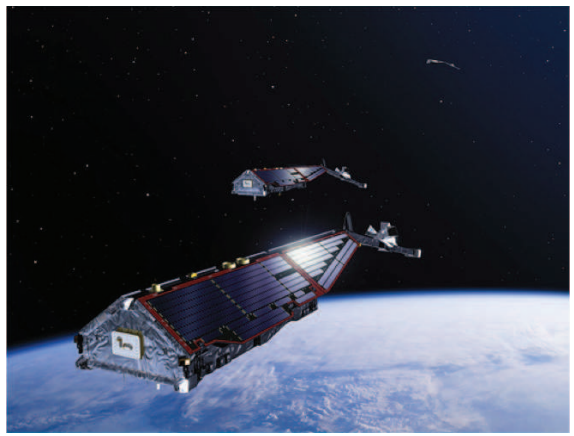
1. Introduction
2. Comparisons, CHAOS-5l: 1999-2015
3. Comparisons, CHAOS-5h: Sept 2008-2010 & Nov 2013-2014
4. Summary

The CHAOS series of field models

- Models of the near-Earth magnetic field (Olsen et al., 2006, 2009, 2010, 2014)
- Aims to describe the internal field with high spatial and temporal resolution
- Initially based on **CH**amp **O**ersted and **S**ac-c satellite data -> **CHAOS**
- Recent versions also include ground observatory secular variation data







- Latest update: CHAOS-5 using baseline 0302 *Swarm* L1b VFM and ASM data
- Given importance of *Swarm* for CHAO**S**-5, now better to interpret **S** = *Swarm* !

Model parameterization

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.

- The internal part of the potential takes the form

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

- Define external potential in SM and GSM co-ordinate systems, with θ_d and T_d being dipole co-lat. and dipole local time

$$\begin{aligned} V^{\text{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d\right) \left(\frac{r}{a}\right)^{n} P_n^m(\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\text{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

- Degree-1 coefficients in *SM* coordinates dependent on the the RC index

Model estimation

- Work with data in **magnetometer frame** co-estimating Euler angles

- **Robust non-linear least squares including regularization**, iteratively minimizing

$$[\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}}^{-1} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}$$

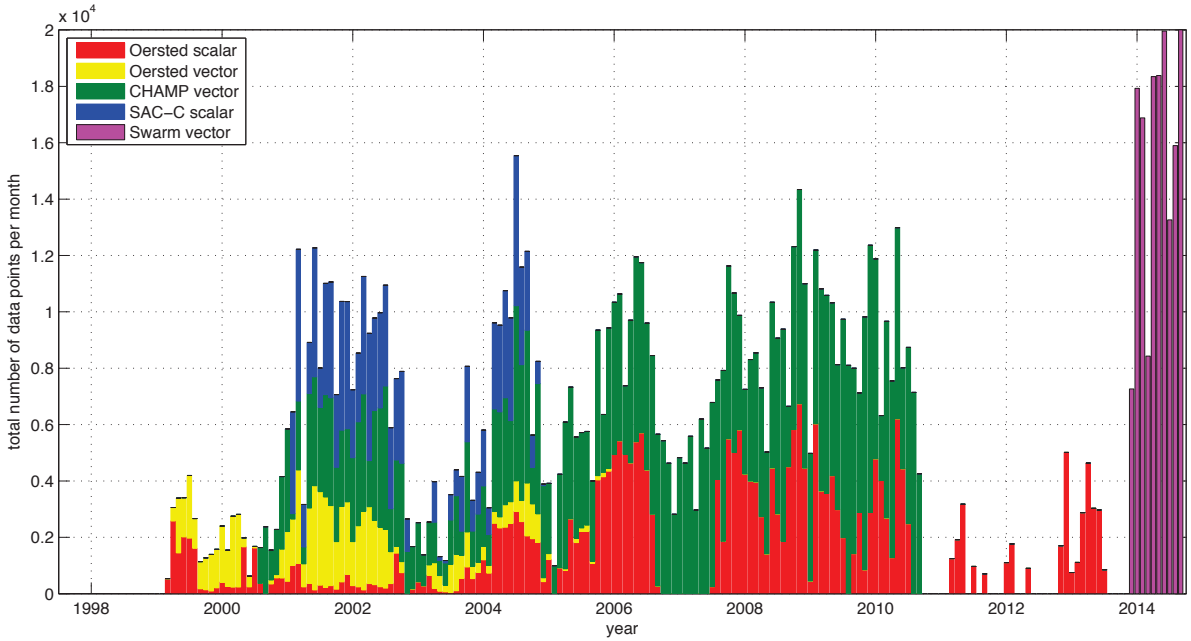
$\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are regularization matrices

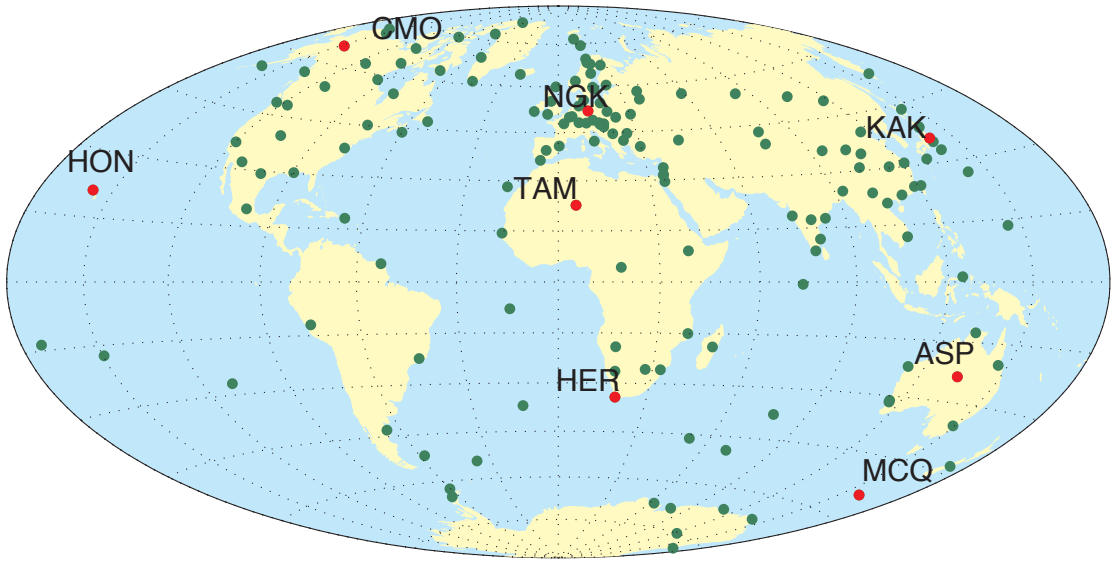
CHAOS-5I: Model setup

- Night side: data from dark regions, sun 10 deg below horizon
- Quiet times: ($Kp \leq$ 2o, $|dD_{st}/dt| \leq$ 2nT/hr)
- Vector data below 55 deg quasi-dipole latitude
- Only use polar data if E_m averaged over preceding 2hrs ≤ 0.8mV/m
- Scale $|\mathbf{B_{VFM}}|$ to be consistent with F_{ASM} (not correct: interim approach!)

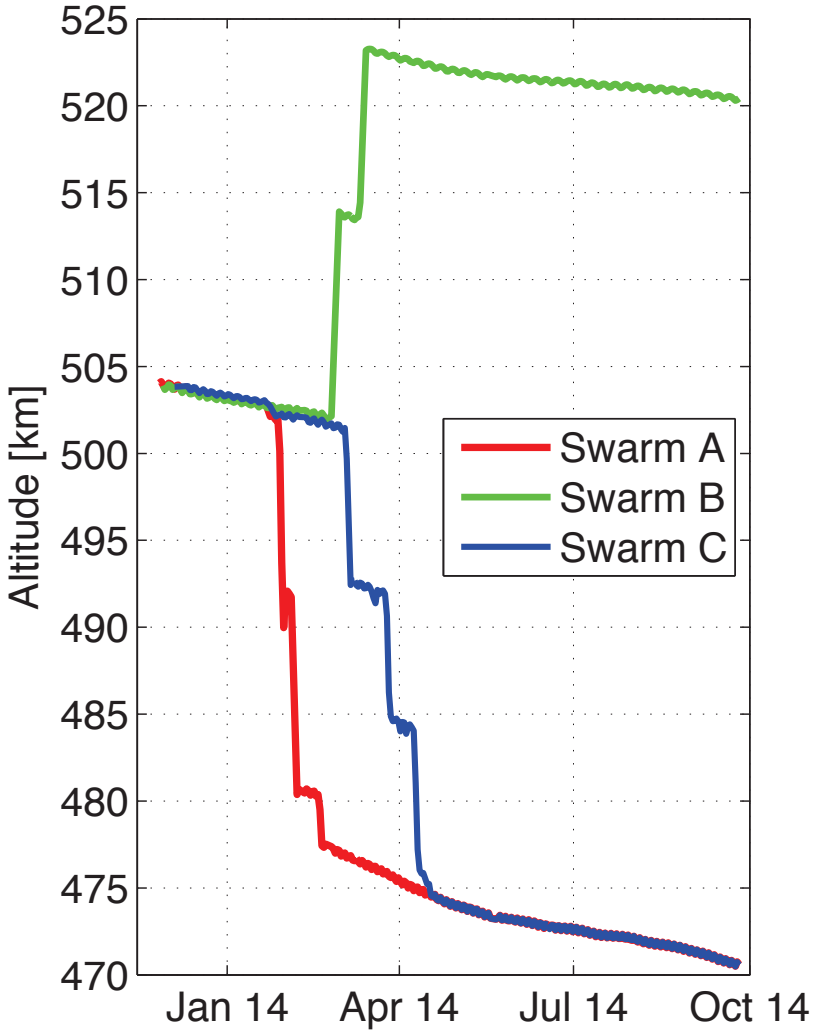
- Model time span: 1999-2015.
- Internal field: degrees 1-20, time-dependent (6th order splines, 0.5 yr spacing)
- Internal field: degrees 20-85, static
- External field, SM part: 5 day bins for q_1^0, 30 day bins for q_1^1, s_1^1
- Euler angles: co-estimated in 10 day bins for CHAMP, *Swarm*

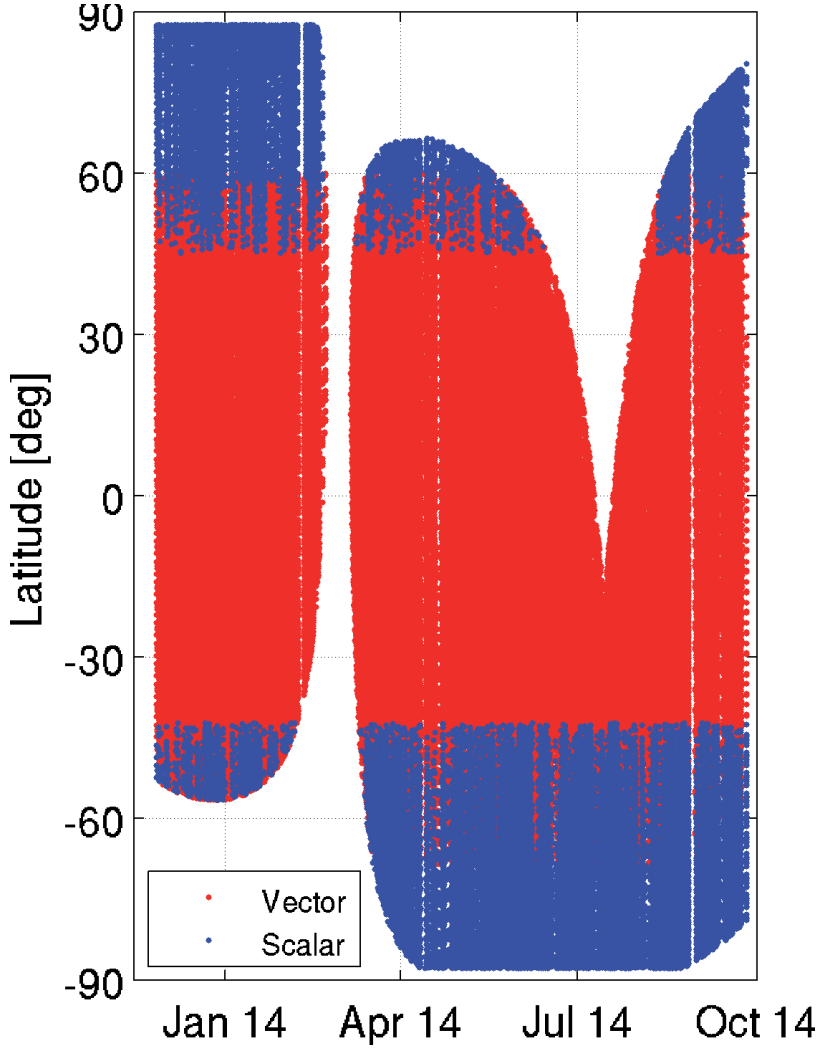
CHAOS-5I: Observations





Selected *Swarm* data: altitude and latitude coverage

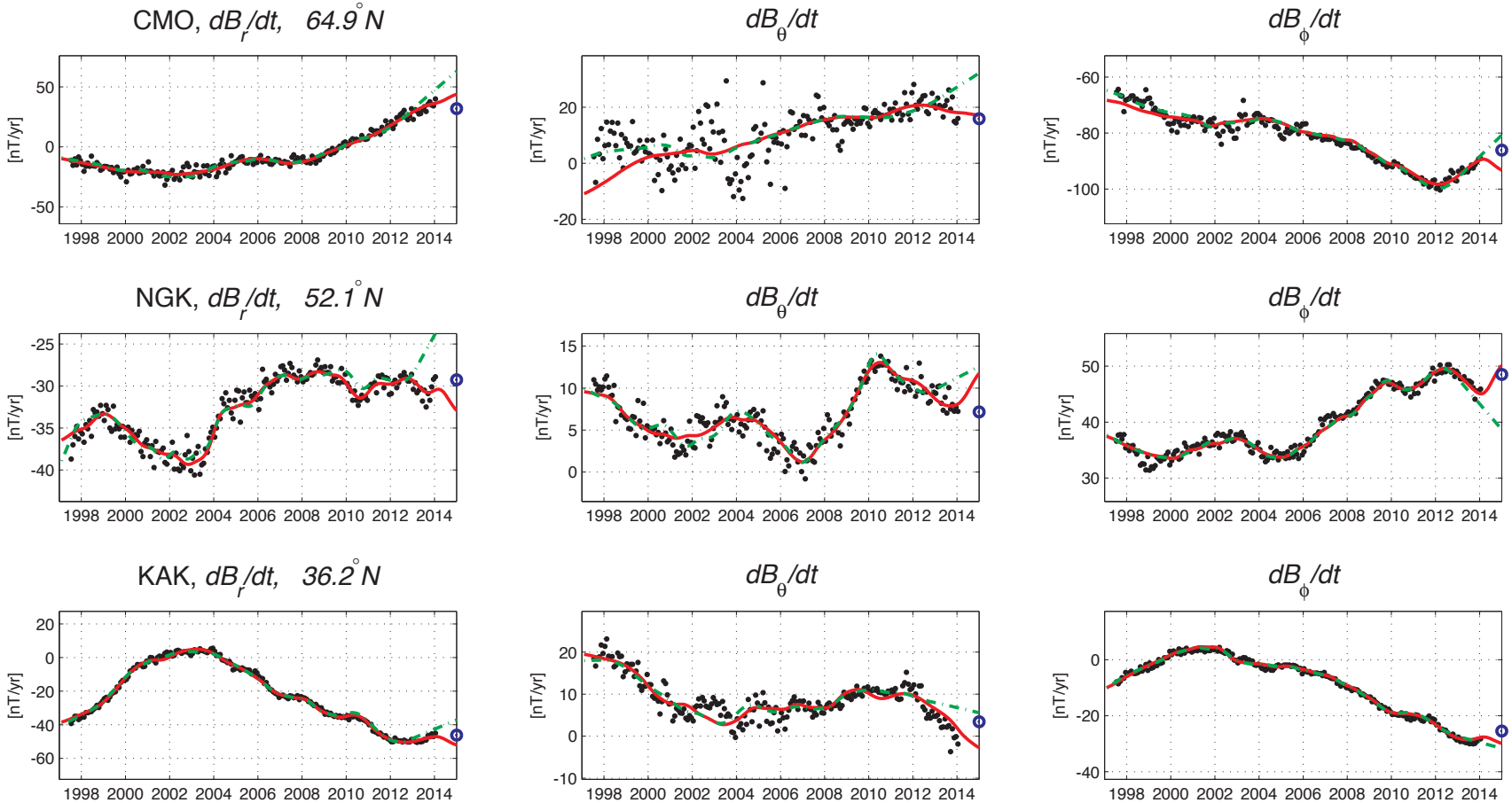




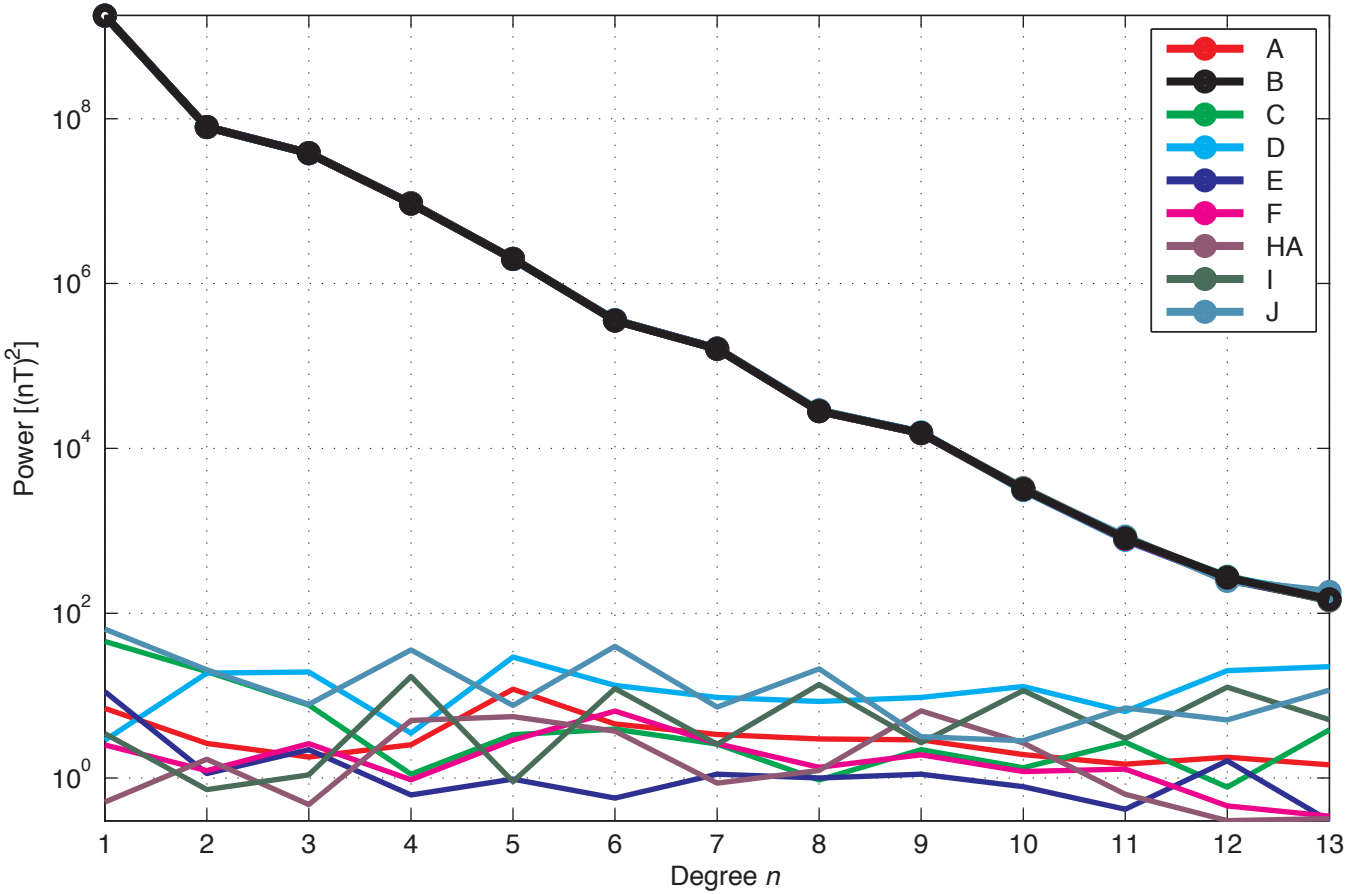
Comparison of misfit statistics for CHAOS-5I

Satellite	Component	N	mean [nT]	rms [nT]
Ørsted	$F_{\text{non polar}}$	367,713	0.16	2.37
	B_r	87,672	0.13	**4.47**
	B_θ		0.23	**5.36**
	B_ϕ		0.00	**5.03**
CHAMP	$F_{\text{non polar}}$	497,394	-0.09	2.07
	B_r		0.02	**2.77**
	B_θ		0.10	**3.56**
	B_ϕ		- 0.01	**2.71**
Swarm A	$F_{\text{non polar}}$	53,137	-0.01	2.09
	B_r		-0.01	**1.83**
	B_θ		0.18	**2.95**
	B_ϕ		-0.16	**2.69**
Swarm B	$F_{\text{non polar}}$	53,253	0.06	2.07
	B_r		-0.02	**1.99**
	B_θ		0.22	**3.00**
	B_ϕ		-0.13	**2.71**
Swarm C	$F_{\text{non polar}}$	49,984	0.05	2.09
	B_r		0.02	**1.93**
	B_θ		0.11	**3.00**
	B_ϕ		-0.15	**2.71**

Model fit to ground observatory SV data



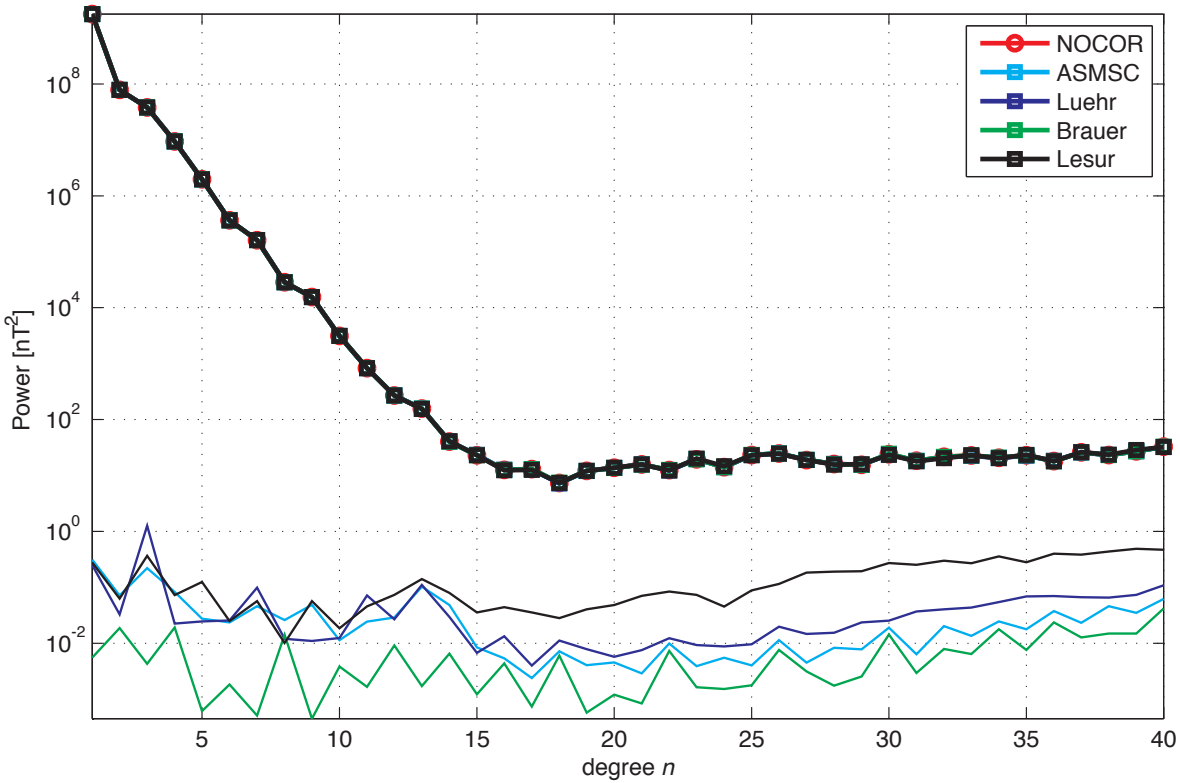
CHAOS-5I power spectra compared to IGRF-2015 candidates



- Mean RMS vector field diff across all candidate models: 8.73 nT
- RMS diff DTU and GFZ candidate with disturb. characterization applied: 5.09 nT
- RMS diff DTU and IPGP candidate from vector ASM data: 5.43 nT

Aside: Impact of ASM-VFM residual on field modelling

- **What is the possible impact on IGRF-12 candidates?**
- Input: ASM-VFM task force TDS2 (const. calib) & 3 proposed disturbance models
- RMS ($F - |\mathbf{B}|$), night, quiet time. Before: 0.48 nT, After corr: 0.13, 0.25, 0.45nT
- Method: CHAOS-type MF+linear SV models with each dataset
- MF: RMS diff to deg 13 with corr. 0.3, 1.2, 1.4 nT (c.f 7.3 nT, IGRF-11)
- SV: RMS diff to deg 8 with corr. 0.7, 3.0, 4.7 nT/yr (c.f 9.3 nT/yr, IGRF-11)



CHAOS-5h: Model setup

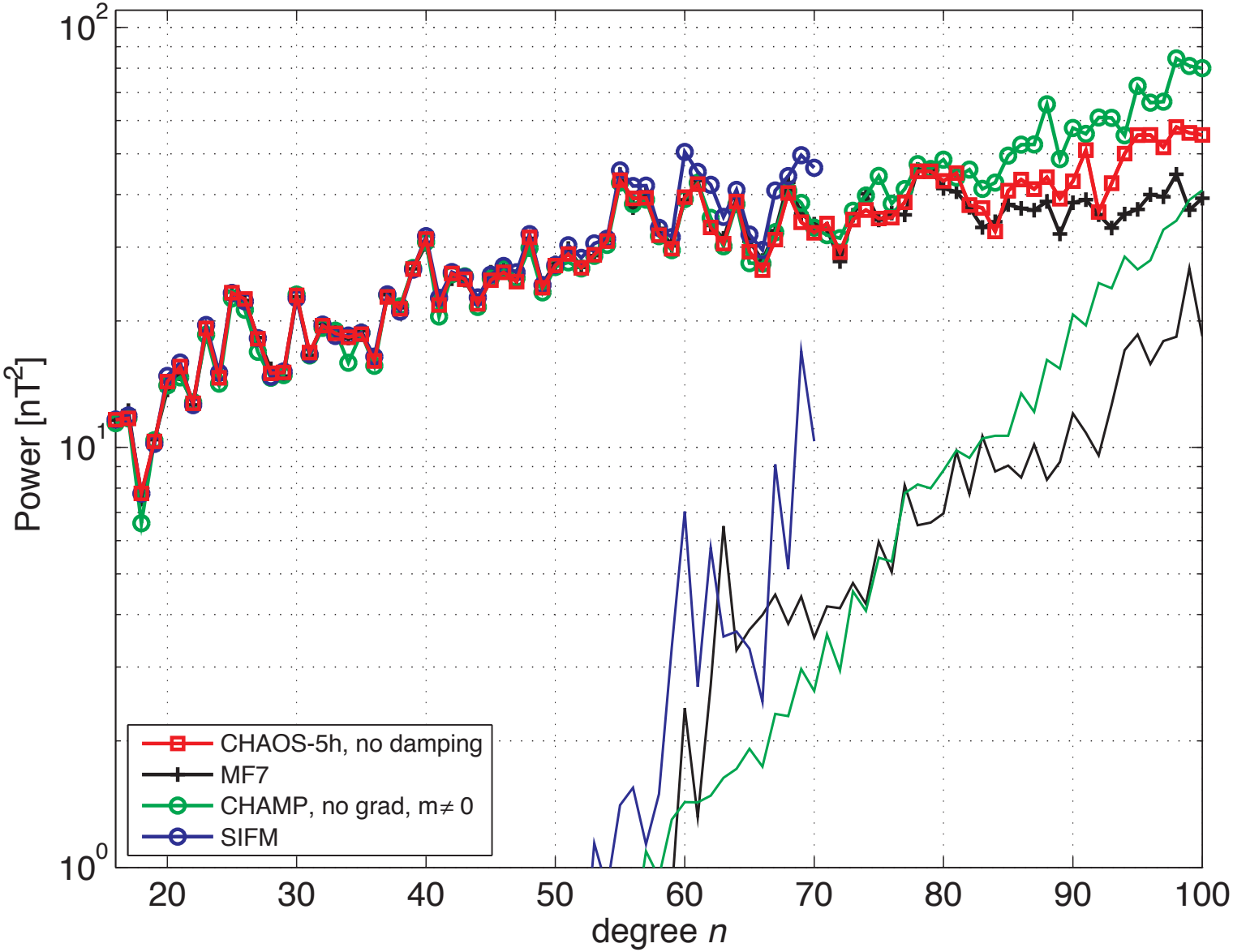
- Vector and scalar selection criteria as for CHAOS-5l
- Except only select CHAMP vector data when both star cameras operating
- Scalar NS, EW gradient data as for SIFM (using day-side and higher activity levels)

- Model time span Sept 2008-Sept 2010 & Nov. 2013-Nov 2014
- Internal field: degrees 1-14, time-dependent (2nd order splines, 1 yr spacing)
- Internal field: degrees 15-120, static
- External field, SM part: 0.5 day bins for q_1^0, 5 day bins for q_1^1, s_1^1
- Euler angles: co-estimated in 10 day bins for CHAMP, *Swarm*

Comparison of misfit statistics for CHAOS-5h

Satellite	Component	N	mean [nT]	rms [nT]
CHAMP	$F_{\text{non polar}}$	296,808	-0.02	1.75
	$dF_{\text{non polar}}$	299,796	0.01	**0.27**
	B_r	296,808	-0.04	**1.85**
	B_θ		-0.05	**2.53**
	B_ϕ		- 0.07	2.13
Swarm A	$F_{\text{non polar}}$	257,256	0.00	2.26
	$dF_{\text{non polar}}$	352,127	0.01	**0.27**
	B_r	257,256	-0.01	**1.89**
	B_θ		-0.05	**2.91**
	B_ϕ		-0.05	2.49
Swarm B	$F_{\text{non polar}}$	256,924	0.00	2.22
	$dF_{\text{non polar}}$	346,293	0.01	**0.25**
	B_r	256,924	0.01	**1.95**
	B_θ		-0.09	**2.97**
	B_ϕ		-0.08	2.51
Swarm C	$F_{\text{non polar}}$	239,608	0.06	2.28
	$dF_{\text{non polar}}$	329,914	0.01	**0.27**
	B_r	239,608	0.02	**1.90**
	B_θ		-0.15	**2.98**
	B_ϕ		-0.05	2.49

CHAOS-5h: Comparison of power spectra



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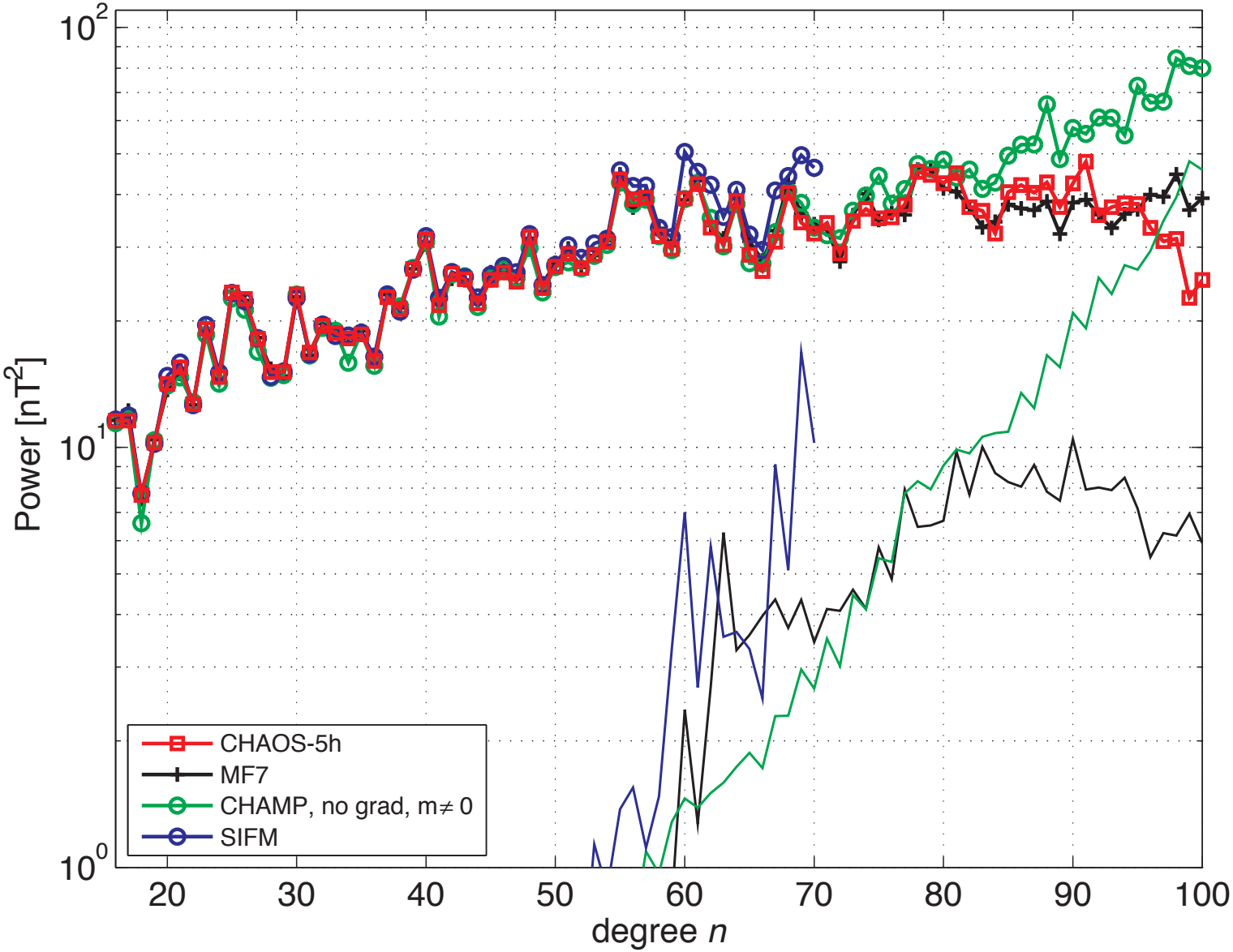
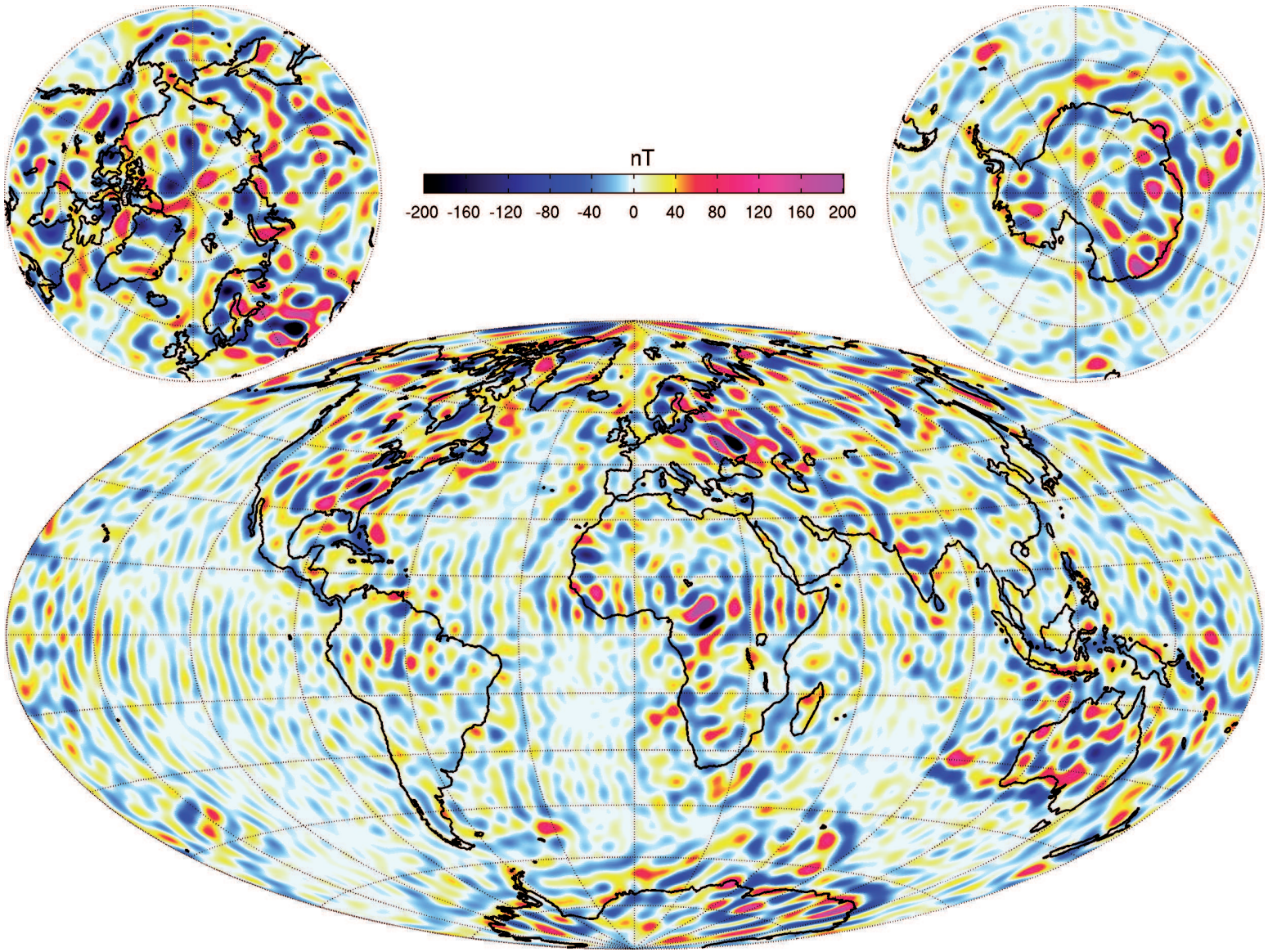
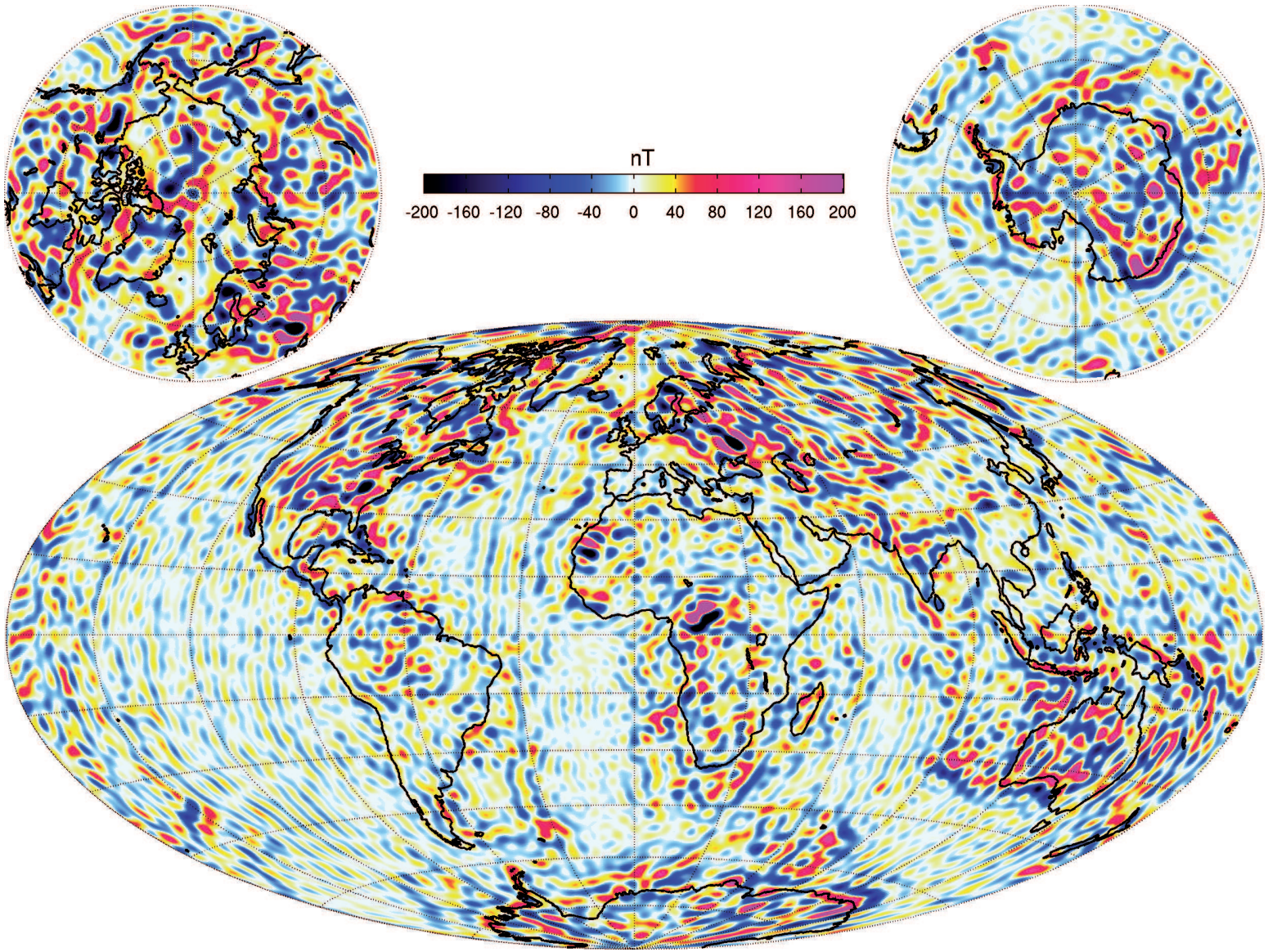


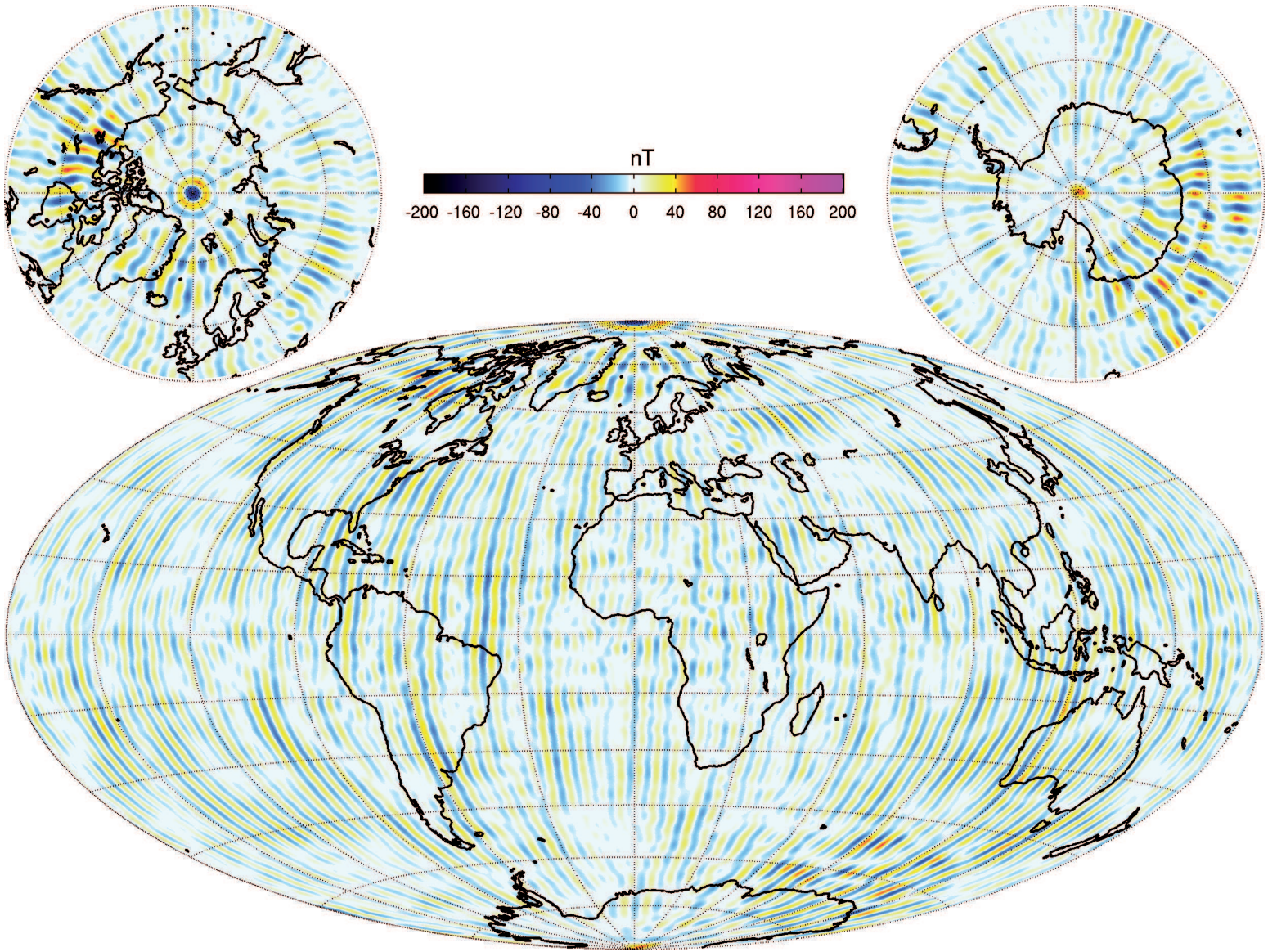
SIFM



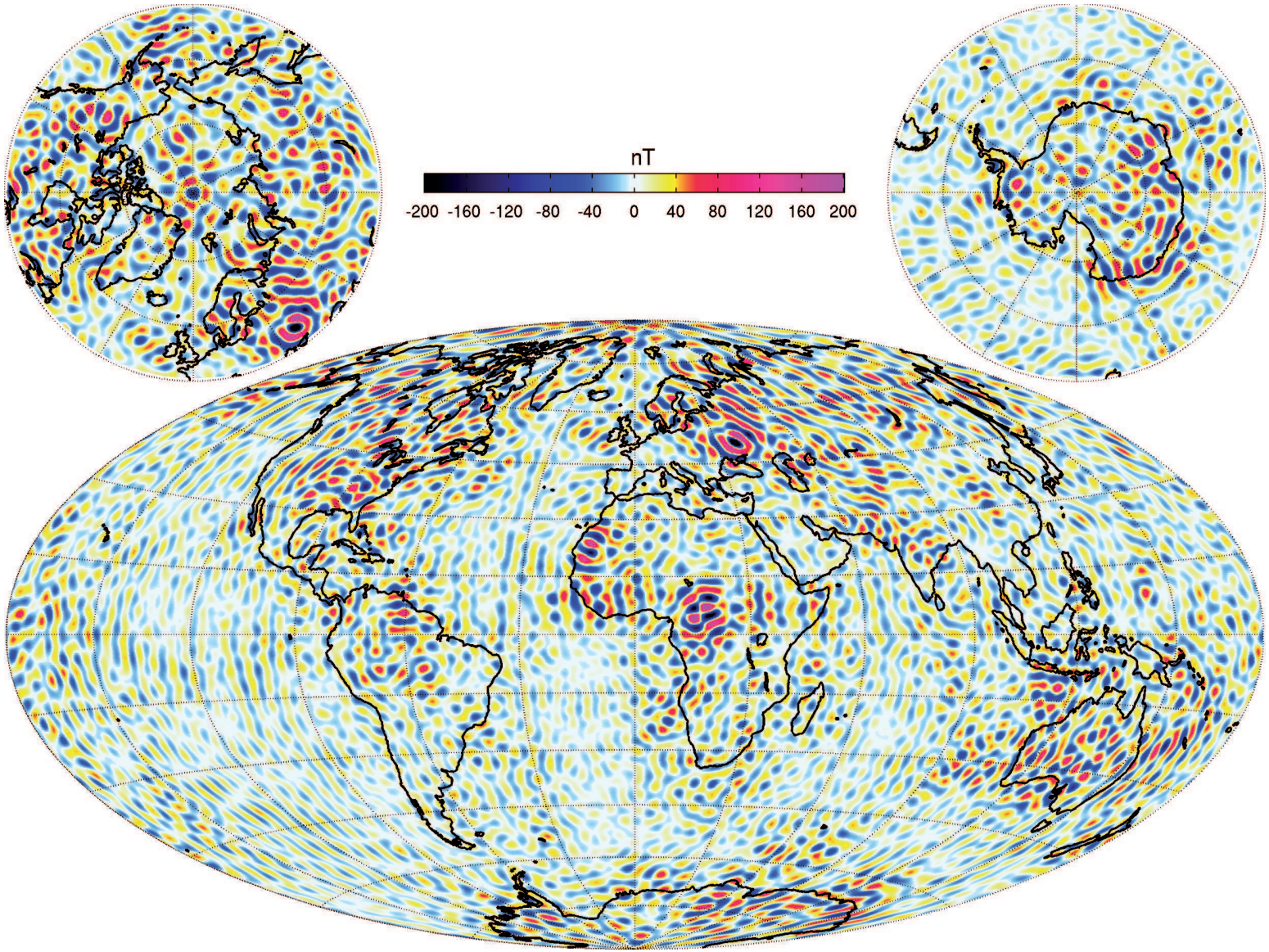
CHAOS-5h



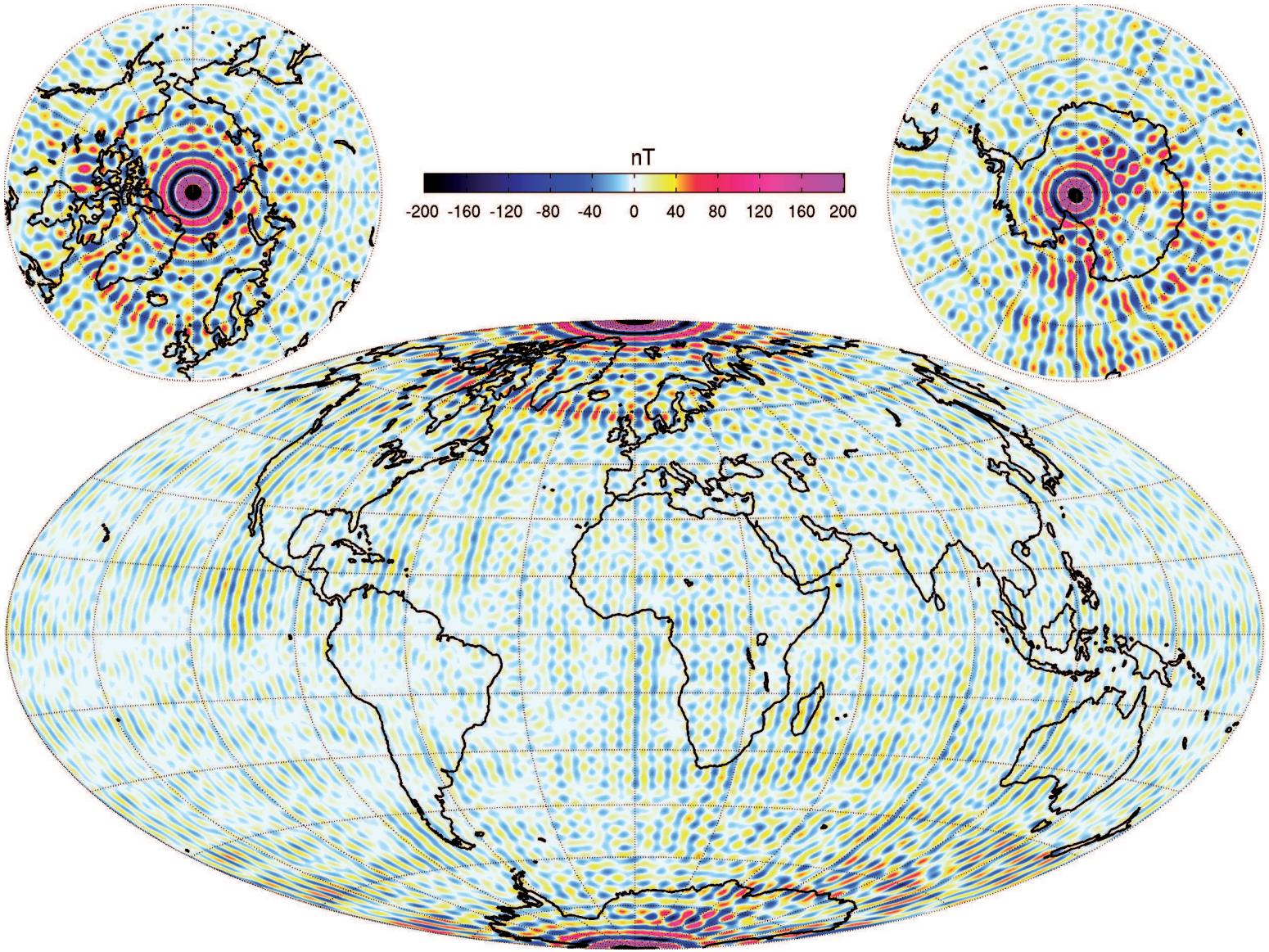
Difference CHAOS-5h to MF7



Difference CHAOS-5h and SIFM



Difference CHAOS-5h to CHAMP, no gradients model



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- CHAOS-5l model fits 15 yrs of magnetic data from Ørsted, CHAMP and the 3 *Swarm* satellites as well as ground observatory data.

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- Including CHAMP vector and along-track scalar gradient estimates allow us to improve on the SIFM.

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- The RMS misfit of CHAMP and Swarm along-track scalar field gradients is very similar ~ 0.25 nT.
- Including CHAMP vector and along-track scalar gradient estimates allow us to improve on the SIFM.
- Use of Swarm and CHAMP gradients enables stable models to higher degree and helps resolve the polar gap problem (see also Kotsiaros et al., - in press, GJI).

Olsen, N., Lühr, H., Sabaka, T. J., Mandea, M., Rother, M., Tø ffner 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.

Olsen, N., Mandea, M., Sabaka, T. J., & Tøffner-Clausen, L., 2009. CHAOS-2 – A Geomagnetic Field Model Derived from one Decade of Continuous Satellite Data, *Geophys. J. Int.*, **179**(3), 1477–1487.

Olsen, N., Mandea, M., Sabaka, T. J., & Tøffner-Clausen, L., 2010. The CHAOS-3 Geomagnetic Field Model and Candidates for the 11th Generation of IGRF, *Earth Planets Space*, **62**, 719–727.

Olsen, N., Luehr, H., Finlay, C. C., Sabaka, T. J., & Tø ffner Clausen, L., 2014. The CHAOS-4 geomagnetic field model, *Geophys. J. Int.*, **197**(2), 815–827.