The Swarm Initial Field Model - a model of the Earth's magnetic field for 2014 determined from one year of Swarm satellite constellation data

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Introduction

Data from the first year of ESA's *Swarm* constellation mission are used to derive the *Swarm Initial Field Model* (SIFM), a new model of the Earth's magnetic field and its time variation. In addition to the conventional magnetic field observations provided by each of the three *Swarm* satellites, explicit advantage is taken of the constellation aspect by including East-West magnetic intensity gradient information from the lower satellite pair. Along-track differences in magnetic intensity provide further information concerning the North-South gradient. The SIFM static field shows excellent agreement (up to at least degree 60) with recent field models derived from CHAMP data, providing an initial validation of the quality of the *Swarm* magnetic measurements. Use of gradient data improves the determination of both the static field and its secular variation, with the mean misfit for East-West intensity differences between the lower satellite pair being only 0.12 nT.

Data selection

One year (26 Nov. 2013 – 17 Nov. 2014) data, 30 secs sampling rate, similar selection criteria as for CHAOS-4 model.

Vector and scalar data:

- nightside data (sun at least 10° below horizon)
- $|dRC/dt| < 2$ nT/hr
- vector data at non-polar regions ($< \pm 55°$ QD latitude) if $Kp < 2$
- scalar intensity data at polar regions ($> \pm 55°$ QD latitude) if merging electric field at magnetopause $E_m < 0.8$ mV/m

"Gradient" (horizontal difference) data:

- only scalar (no vector) gradient data
- inclusion of periods of higher geomagnetic activity ($Kp < 3^0$, $|dRC/dt| < 3$ nT/hr), and of dayside non-equatorial ($> \pm 10°$ QD latitude) data
- E-W gradient: $\delta F_{\rm EW} = [F_A(t_A, r_A, \theta_A, \phi_A) - F_C(t_C, r_C, \theta_C, \phi_C)]$, measured by the two satellites SW-A and SW-C. Data from same latitude ($\theta_A \approx \theta_C$) within $|\delta t| = |t_A - t_C| < 50$ secs
- N-S gradient data from along-track first differences: $\delta F_{\rm NS} = [F_k(t_k, r_k, \theta_k, \phi_k) - F_k(t_k + 15{\rm secs}, r_k + \delta r, \theta_k + \delta\theta, \phi_k + \delta\phi)]$ of subsequent scalar data measured by the same satellite ($k = 1, 2$ or 3) 15 secs later (corresponding to a distance of $\approx$ 115 km)

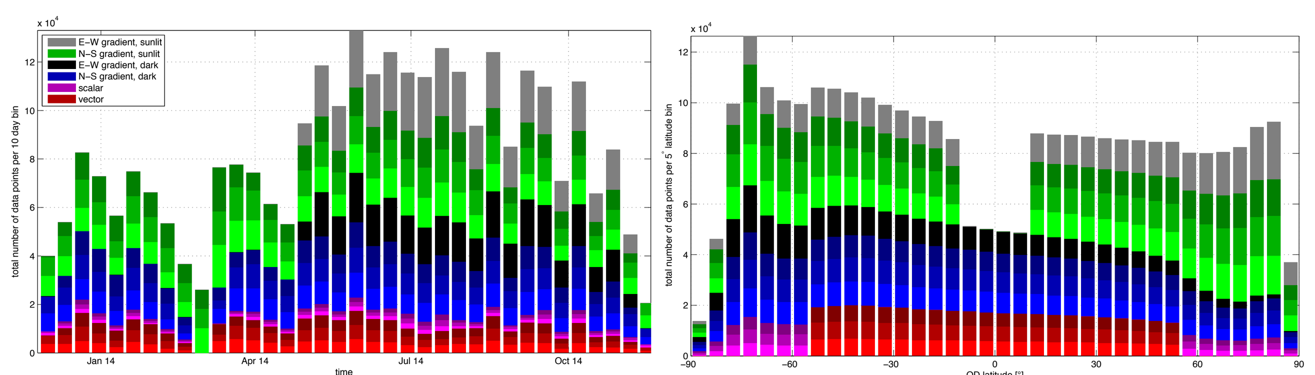

Figure : Total number of *Swarm* satellite data (stacked histogram) as a function of time (left), respectively latitude (right). For vector (red), scalar (purple) and N-S gradient (blue and green) data the dark/normal/light colour represents SW-A/SW-B/SW-C. E-W gradient data are shown in black and grey.

Model paremeterisation

- Static (crustal) field up to degree $n = 70$
- Linear time dependence (secular variation) for $n = 1 - 13$
- Large-scale magnetospheric field parameterised as in CHAOS-4 (SM and GSM coordinates, time dependence parameterized by *RC* index)
- Euler angles describing instrument alignmnet in bins of 10 days
- 5666 model parameters estimated from $\approx 3.75 \times 10^6$ observations (118,273 scalar data, $3 \times 376,994 = 1{,}130{,}982$ vector data, and 2,500,335 estimates of gradients)
- Dayside gradient data contribute to crustal field but not to core field
- *Iteratively Reweighted Least Squares* with Huber weights
- No model regularisation

Results: Power spectra and degree variances

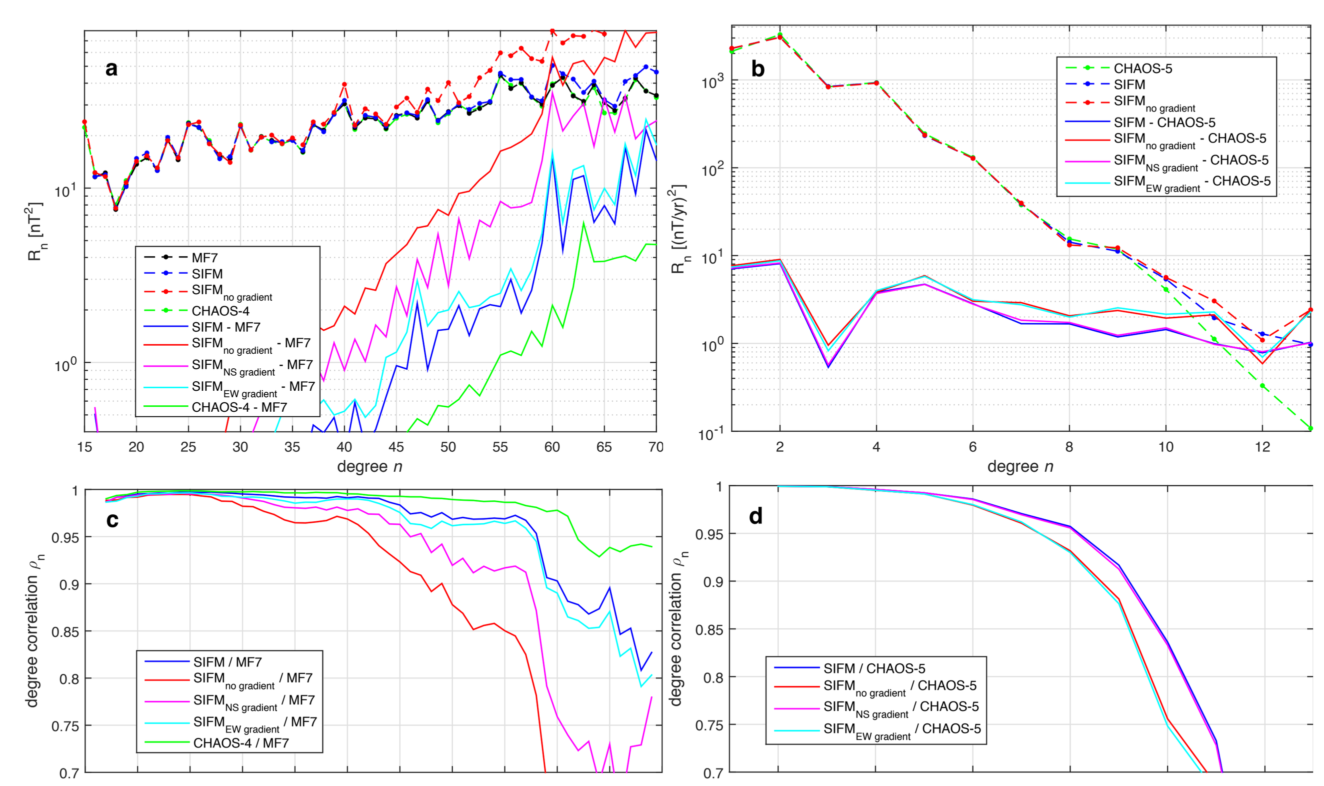

Figure : Top: Lowes-Mauersberger power spectra of the static field ($n = 15 - 70$, left) and of the linear SV ($n = 1 - 13$, right) from the SIFM together with various reference and data-subset model at the Earth's surface. Spectra of models are shown in dotted lines, spectra of differences between models in solid lines. Bottom: Degree correlations of the SIFM and other models with respect to model MF7 (*Maus et al.* 2010) for the static field (left), and with respect to CHAOS-5 for the SV (right)

Inclusion of East-West gradient data (from difference of the lower *Swarm* pair) improves deteremination of the crustal field, while inclusion of North-South gradient data (from alongtrack first differences of each of the three *Swarm* satellites) improves determination of secular variation.

Results: Crustal field coefficient differences

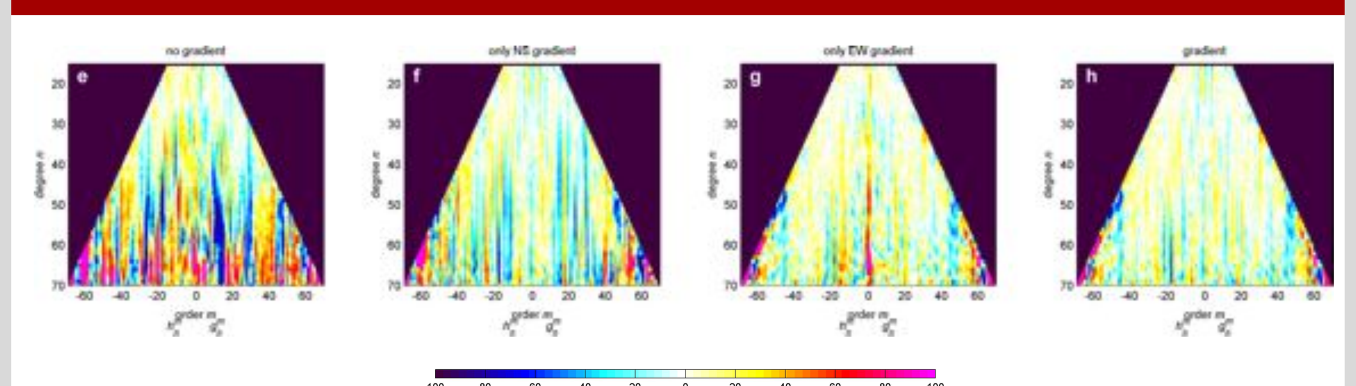

Figure : Normalized crustal field coefficient differences (in %) w.r.t. MF7, for SIFM$_{\rm no\ gradient}$ (left), SIFM (right) and SIFM$_{\rm NS\ gradient}$, resp. SIFM$_{\rm EW\ gradient}$ (middle).

Map of crustal field at ground

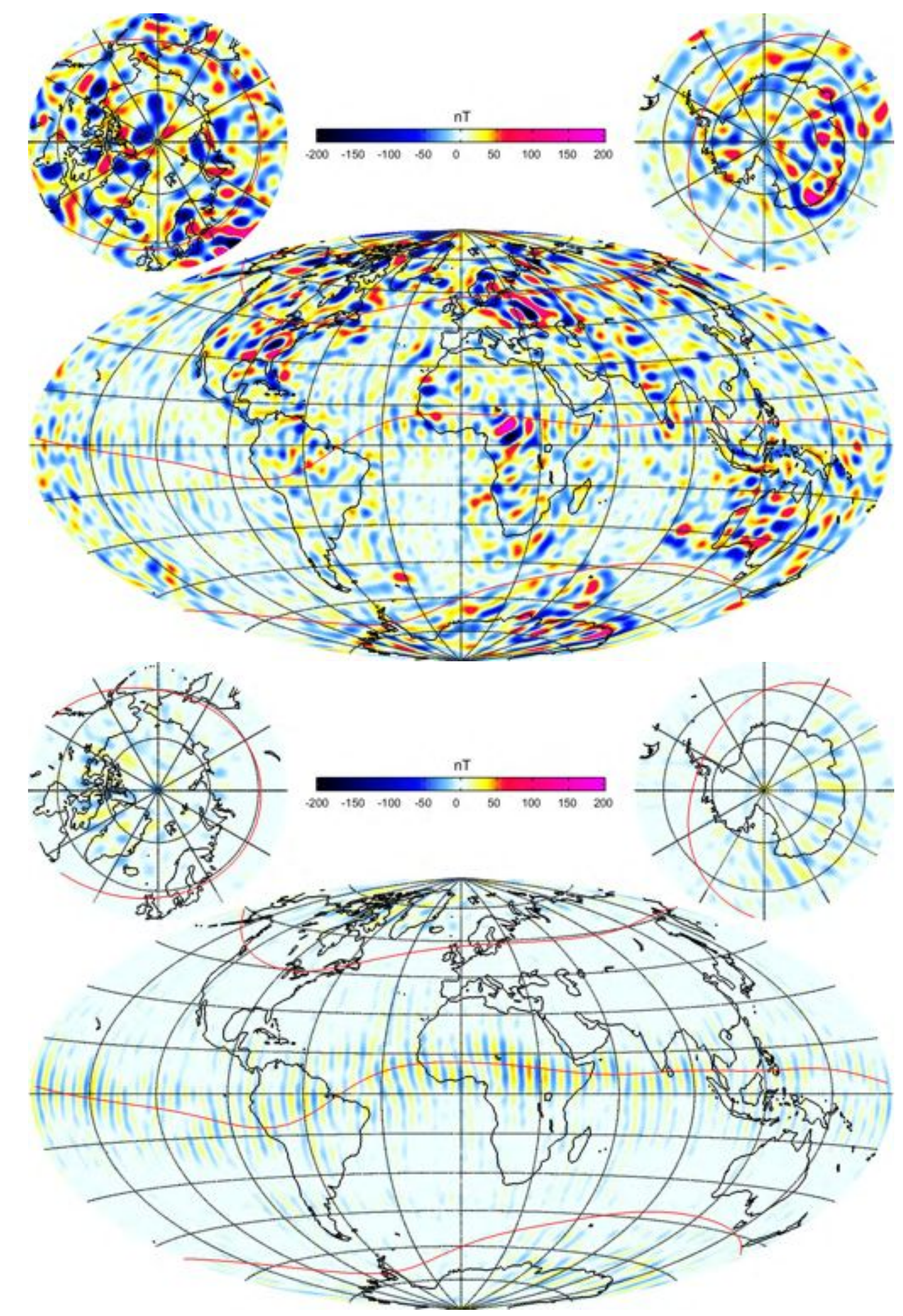

Figure : Top: B_r at Earth's surface, for degrees $n = 16 - 65$. Red lines locate the dip-equator (0° QD latitude) and $\pm 55°$ iso-QD latitudes. Bottom: Difference of B_r between SIFM and MF7, for degrees $n = 16 - 65$. The signature of sectorial terms along the magnetic equator may indicate a Backus effect at the highest degrees, where only scalar gradients data constrains the model.

Map of secular variation at CMB

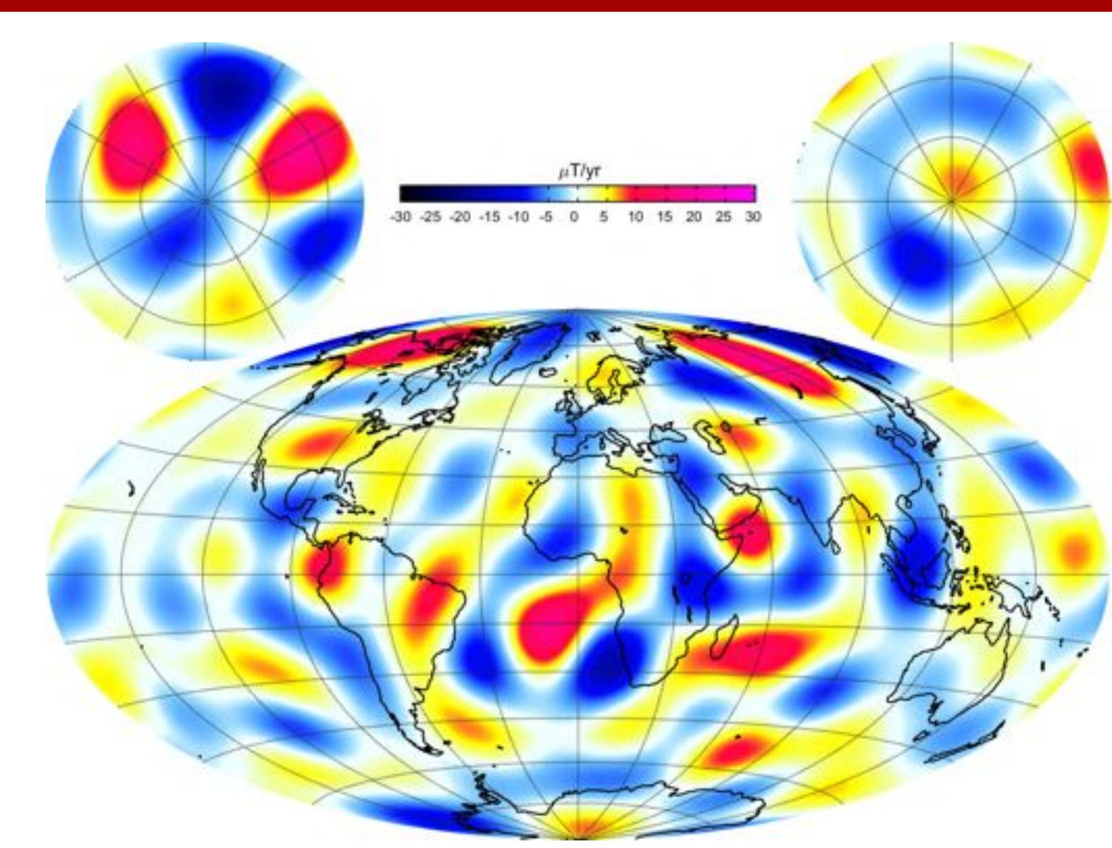

Figure : November 2013 to November 2014 rate of change of B_r at the CMB from SIFM for degrees $n = 1 - 11$.

Model Residuals vs. latitude

Figure : Residuals of the scalar (green) and scalar gradient (blue for N-S, red for E-W) data vs. QD latitude for dark regions and magnetically quiet conditions. Note the non-linear y-axis ($\propto \arctan(y/5{\rm nT})$), which emphasizes near-zero values. Solid curves show the (Huber-weighted) mean value of the residuals in bins of 2° in latitude; dashed curves represent the mean $\pm$ one standard deviation.

Model Statistics

Table : Number N of data points, (Huber-weighted) mean, and rms misfit (in nT) of scalar (F), vector (B_r, B_θ, B_ϕ), N-S gradient ($\delta F_{\rm NS}$) and E-W gradient ($\delta F_{\rm EW}$) data, at polar ($> \pm 55°$) and non-polar ($< \pm 55°$) QD latitudes.

	SW-A			SW-B			SW-C			SW-A – SW-C		
	N	mean	rms	N	mean	rms	N	mean	rms	N	mean	rms
$F_{\rm polar}$	40037	-0.21	3.80	41011	-0.08	3.77	37225	-0.11	3.78			
$F_{\rm non-polar}$	128689	0.02	2.49	128473	-0.00	2.44	119832	0.08	2.52			
B_r	128689	0.02	1.95	128473	0.01	2.00	119832	0.06	1.97			
B_θ	128689	-0.16	3.37	128473	-0.16	3.43	119832	-0.24	3.44			
B_ϕ	128689	-0.03	2.56	128473	-0.06	2.58	119832	-0.03	2.55			
$\delta F_{\rm NS,polar}$	250559	-0.01	1.06	252495	-0.01	1.00	234361	-0.01	1.06			
$\delta F_{\rm NS,non-polar,dark}$	177982	0.00	0.18	179773	0.00	0.17	166201	0.01	0.18			
$\delta F_{\rm NS,non-polar,sunlit}$	187262	0.01	0.34	187910	0.01	0.32	175093	0.01	0.34			
$\delta F_{\rm EW,polar}$										279777	-0.12	0.54
$\delta F_{\rm EW,non-polar,dark}$										197769	-0.12	0.28
$\delta F_{\rm EW,non-polar,sunlit}$										211152	-0.03	0.44

rms misfit of B_r at non-polar latitudes is ≤ 2 nT. Mean value of scalar field difference δF_{EW} between the two side-by-side flying satellites SW-A and SW-C is 0.12 nT, with an rms misfit of 0.28 nT. The rms misfit of the NS gradient, obtained with the same satellite, is ≤ 0.18 nT, demonstrating the high accuracy of the *Swarm* magnetic measurements.

References

Model coefficients and used data sets available at `www.spacecenter.dk/files/magnetic-models/SIFM/`.

Maus, S. (2010), Magnetic field model MF7, www.geomag.us/models/MF7.html.

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

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