Comprehensive Magnetic Field Inversion from 10 Years of Swarm Data

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Introduction

The Swarm DISC (**D**ata, **I**nnovation, and **S**cience **C**luster) is a consortium of more than 30 research institutions funded by ESA with the goal of a.o. deriving scientific Level-2 products by combination of data from the three Swarm spacecraft together with observations from other sources such as ground based observatories and complementary space missions. Here, we present the results of the Swarm DISC team at DTU Space and NASA Goddard who conducts the Comprehensive Inversion (CI) magnetic field model processing chain which takes full advantage of the Swarm constellation by doing a comprehensive co-estimation of the magnetic fields from Earth's core, lithosphere, ionosphere, and magnetosphere together with induced fields from Earth's mantle and ocean tides using direct field measurements as well as single and dual satellite gradient information. This is complemented by data from 180 geomagnetic ground observatories around the world as well as calibrated *platform magnetometer* data from the CryoSat-2 mission. We present the results from using 10 years of Swarm data denoting our model CIY10. Level-2 products containing the corresponding model parameter estimations are distributed via ESA at ftp://swarm-diss.eo.esa.int/Level2longterm/ (see also https://earth.esa.int/swarm).

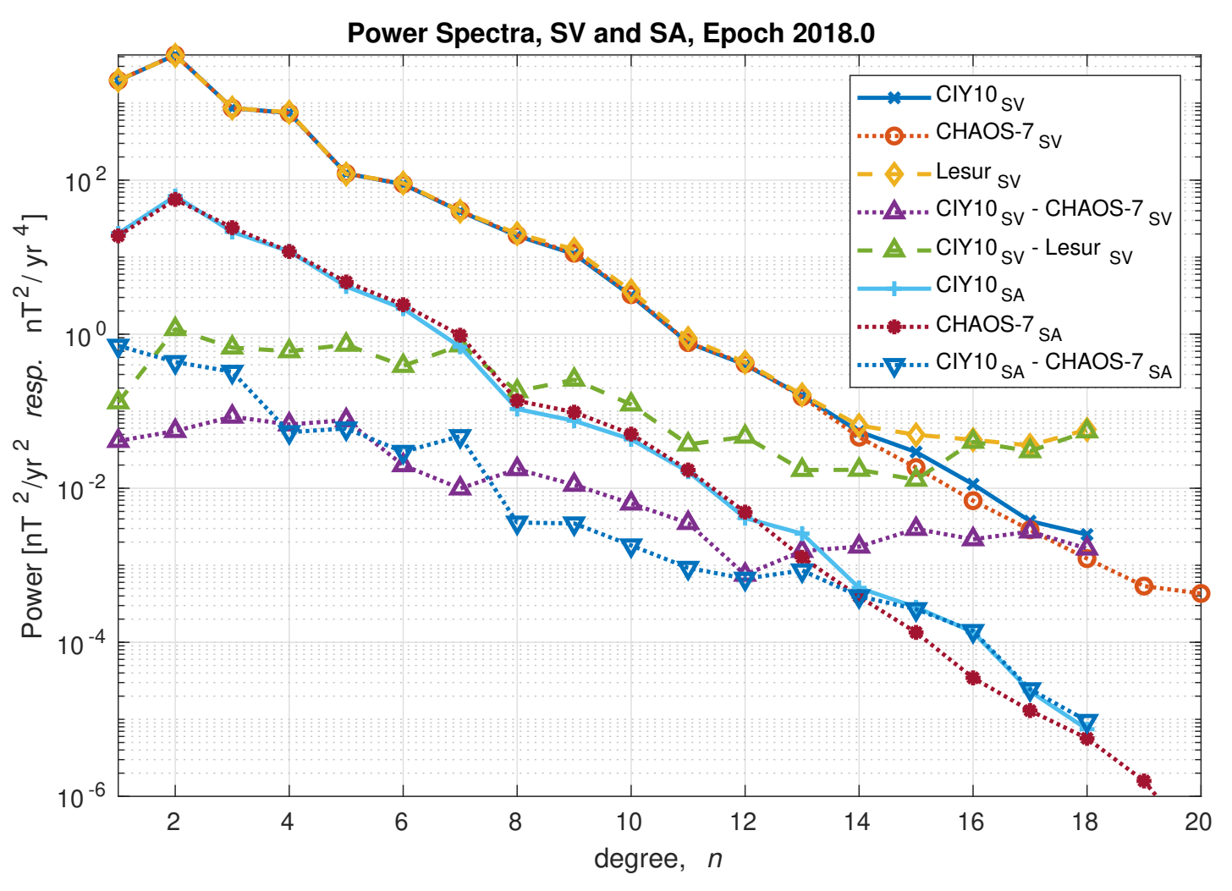
Model Parametrization, Data, and Data Selection

Table: Comprehensive Model Parametrization

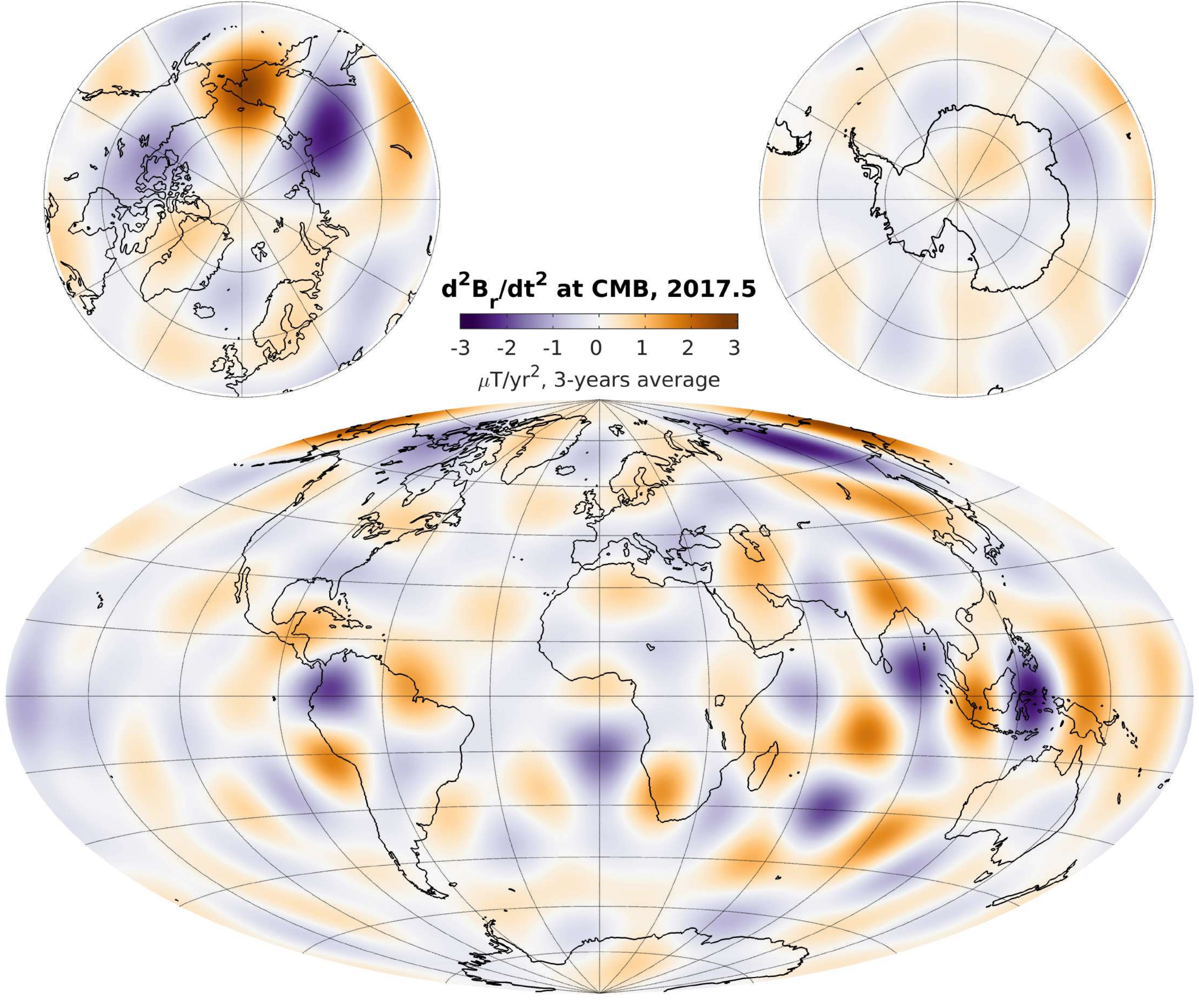
Field	Description	Number of coefficients
Core	Spherical harmonic expansion $n_{max} = 18$. Secular variation (SV) through order 5 B-splines with $\frac{1}{2}$ year knot spacing, regularisation of the 2^{nd} and 3^{rd} derivative of B_r.	9,720
Lithosphere	Spherical harmonic expansion $n = 19 \ldots 120$. Regularisation of high degree terms.	14,280
Ionosphere	Spherical harmonic expansion in quasi-dipole (QD) frame, underlying dipole SH $n_{max} = 60$, $m_{max} = 12$. Temporal: annual, semi-annual, 24-, 12-, 8- and 6-hr periodicities with F10.7 scaling plus induction via a-priori 3-D conductivity model ("1-D+oceans") and infinite conductor at core-mantle boundary (CMB). Regularisation of nightside currents between MLT 21h through 05h peaking at 02h.	5,520
Magnetosphere	Quiet times: Spherical harmonic expansion $n_{max} = 1$ external and internal (induced). Discretized in 1 hour bins. All data: $n_{max} = 3$, $m_{max} = 2$ internal and external; dipole terms in $1\frac{1}{2}$ hour bins, other terms in 6 hour bins.	186,711or 468,224
M_2 Tidal	Spherical harmonic expansion $n_{max} = 18$. Periodicity: 12.42060122 hr, phase fixed with respect to 00:00:00 GMT, 1 January 1999. Regularisation to damp spectral power.	740
Nuisance	Day-side core, lithosphere, and M_2 tidal, ground observatory biases, spacecraft alignment	30,012
Total		528,476

Swarm satellite data for this work consist of magnetic field measurements version 0602/03 for the period 25 November 2013 through November 2023 with gross outliers removed and decimated to 45 second sampling rate. Along-track differences ("gradients") are formed by taking single satellite differences separated by 15 seconds, whereas cross-track differences are formed from the lower Swarm pair, Alpha and Charlie, taking measurements at equal geographic latitude temporally separated by typically 4 to 15 seconds. The optimum satellite constellation for the cross-track differences was obtained and maintained since mid April 2014 except for May-June 2022 and April-May 2023 where the altitudes of Alpha and Charlie were raised causing larger separation between the two spacecraft. To avoid the essential doubling of the number of data along the tracks of Alpha and Charlie, the 45 second samples are taken intermittent between Alpha and Charlie. Magnetic data from the calibrated *platform vector magnetometer* (FGM1) of the CryoSat-2 spacecraft (Olsen, 2020) for the period 26 November 2013 through March 2022, as well as available hourly mean values from 180 ground based magnetic observatories for the period 25 November 2013 through September 2023 have been included in the modelling. Magnetically quiet periods were selected for the modelling (except for the modelling of the continuous magnetospheric field) based on *Kp* and *Dst* such that $Kp \leq 2^-$ for direct measurements and $Kp \leq 3^0$ for differences, and commonly $\left|\frac{dDst}{dt}\right| \leq 3$ nT/hr. Direct measurements from satellite are restricted to night-side (dark) only, i.e. with Sun at least 10° below the horizon, and direct satellite vector measurements are further restricted to QD-latitude within ±45°. For the continuous magnetospheric field model only direct vector field measurements were used subject to a smooth weighting scheme of the satellite vector data damping low ($|lat_{QD}| < 10°$) and high ($|lat_{QD}| > 45°$) latitude data (see to the right).

Core Field and Secular Variation

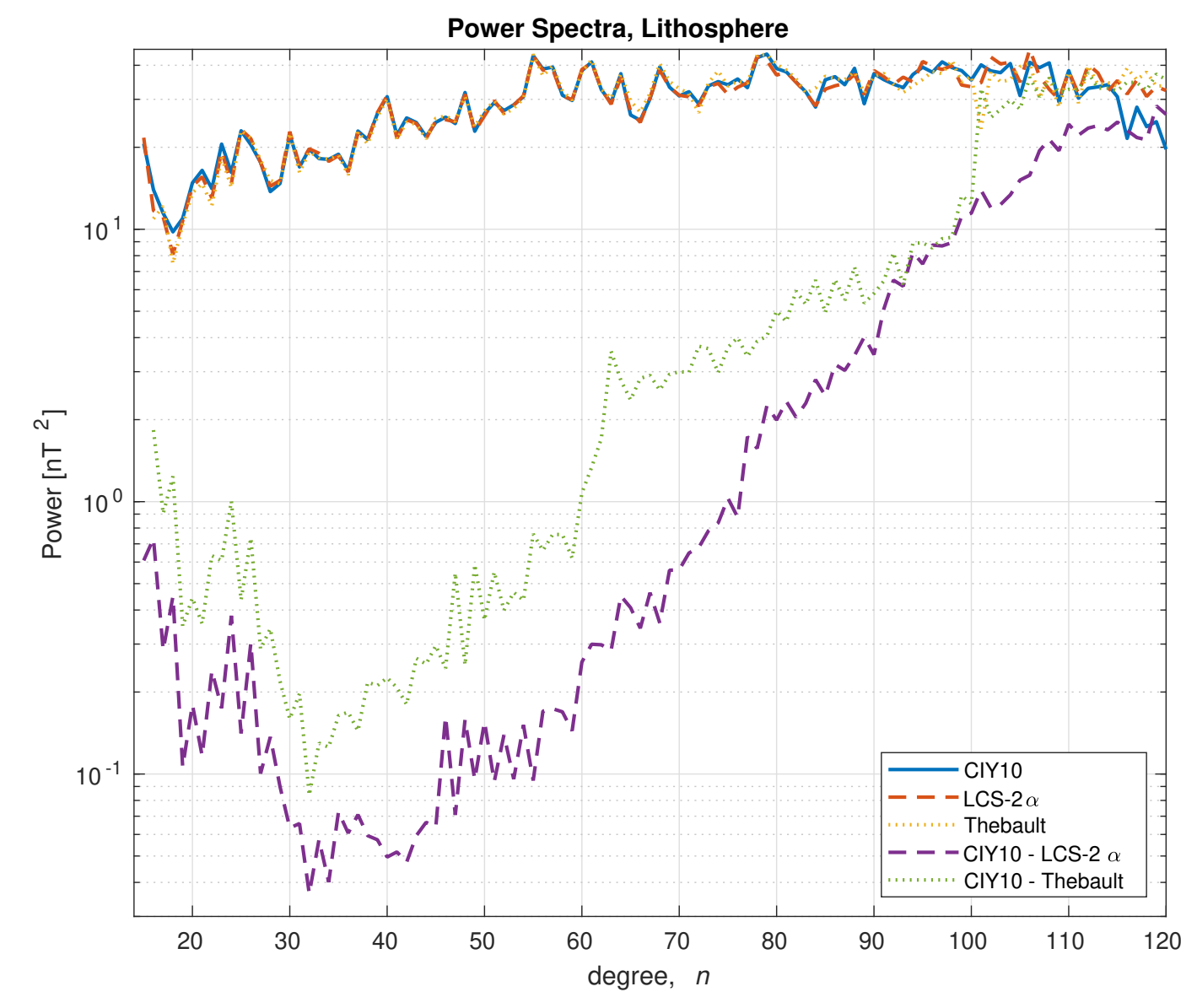


To the right, plots of the power spectra of the secular variation (SV) respectively secular acceleration (SA) of CIY10, *CHAOS-7* (Finlay, 2020) version x17, and the Swarm DISC model of IPGP (MCO_SHA_2Y, "Lesur", only SV) are shown. The core fields agree well up to degree 13 above which the CIY10 model has slightly higher power than the CHAOS-7 model, but less power than the Lesur model. Below, a map of the acceleration of the radial field component (d^2B_r/dt^2) at the core-mantle boundary (CMB) is shown averaged over the years 2017 through 2019. The map shows similar elements as a map based on *CHAOS-7* with significant features near the North pole and around Equator in Asia, West of Africa, and in the Western part of South America. Though, for CIY10 we see weak, checkered patterns which are believed to stem from the spherical harmonic functions which do not represent the actual physical patch flows at the core-mantle boundary.

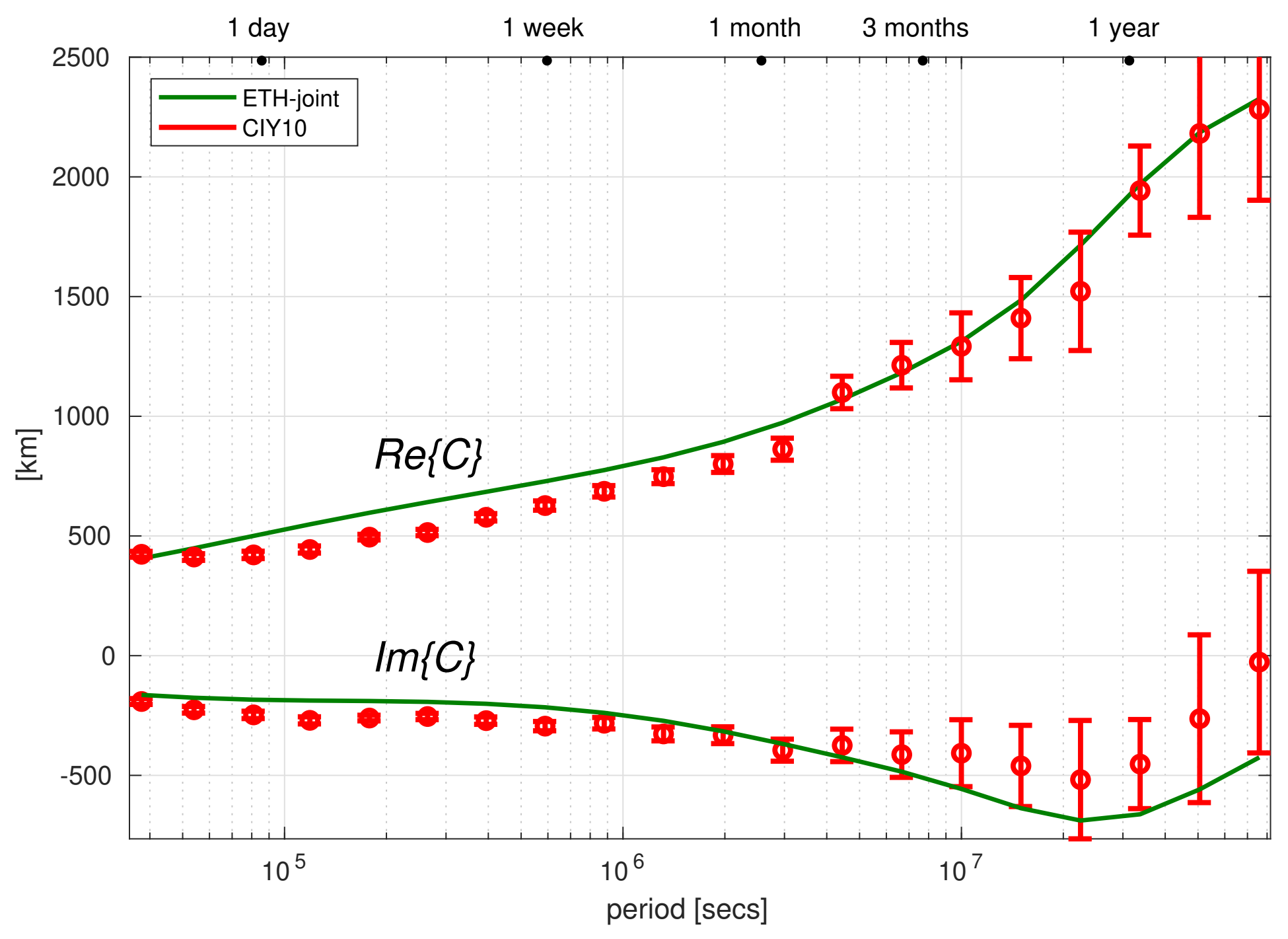


Lithospheric Field

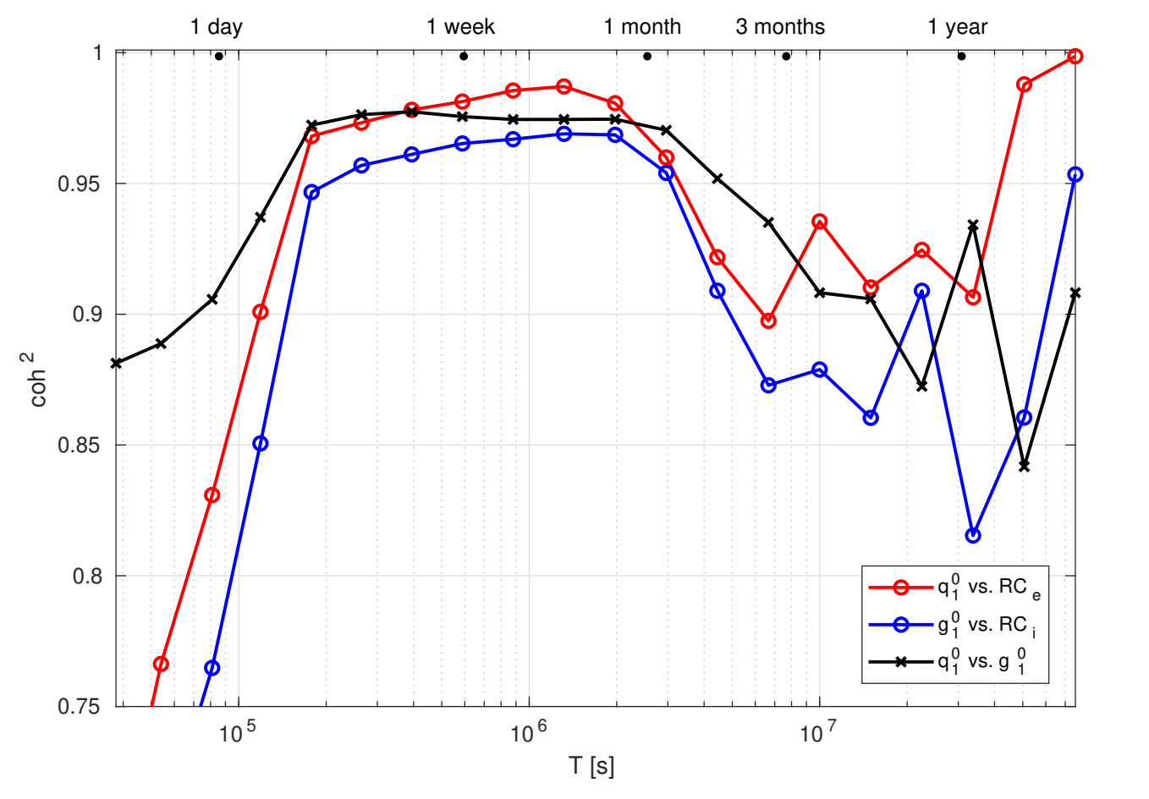
The part of the lithospheric field of degree $n \geq 19$ is determined from nightside scalar and vector data as well as from along- track (*North-South*) and cross-track (*East-West*) differences from all local times. Vector differences are used at low latitudes (QD-latitude below 45°) whereas scalar differences are used at all latitudes. We obtain excellent agreement between our model and the LCS-2α (extension of Olsen, 2016) up to degree at least 105, and very good agreement with the Swarm DISC model of University of Nantes (MLI_SHA_2E, "Thebault" (2021)) up to degree 100 above which the Thebault/Nantes model shows a sudden jump in comparison possibly due to a transition of their model from a global to a regional, non-satellite based surveys, basis.



Magnetospheric Field



The magnetospheric field is estimated in two steps: First, data from magnetically quiet conditions (see "Data Selection" to the left) are used to estimate the comprehensive collection of models including a preliminary magnetospheric model (the "Quiet times" model). Second, all data are used to estimate the "All data" model which is the official magnetospheric model of the CI chain. Below, the squared coherences between q_1^0 and RC_e, g_1^0 and RC_i, and q_1^0 and g_1^0 are shown. These show nice coherencies for shorter periods but for periods longer than a few months, the coherencies start to fluctuate, though, generally the coherencies stay above 0.85. A possible explanation for the fluctuations could be the quite different geomagnetic conditions throughout the Swarm mission so far. Above, the C-response estimates based on q_1^0 and g_1^0 are shown in red with error bars. The green curves shows theoretical values based on the joint conductivity models of ETH (Grayver 2018), which demonstrates quite good agreement though with some lack in amplitude at short to medium length periods and a tendency to deviation in phase at longer periods, though still within the error bars.



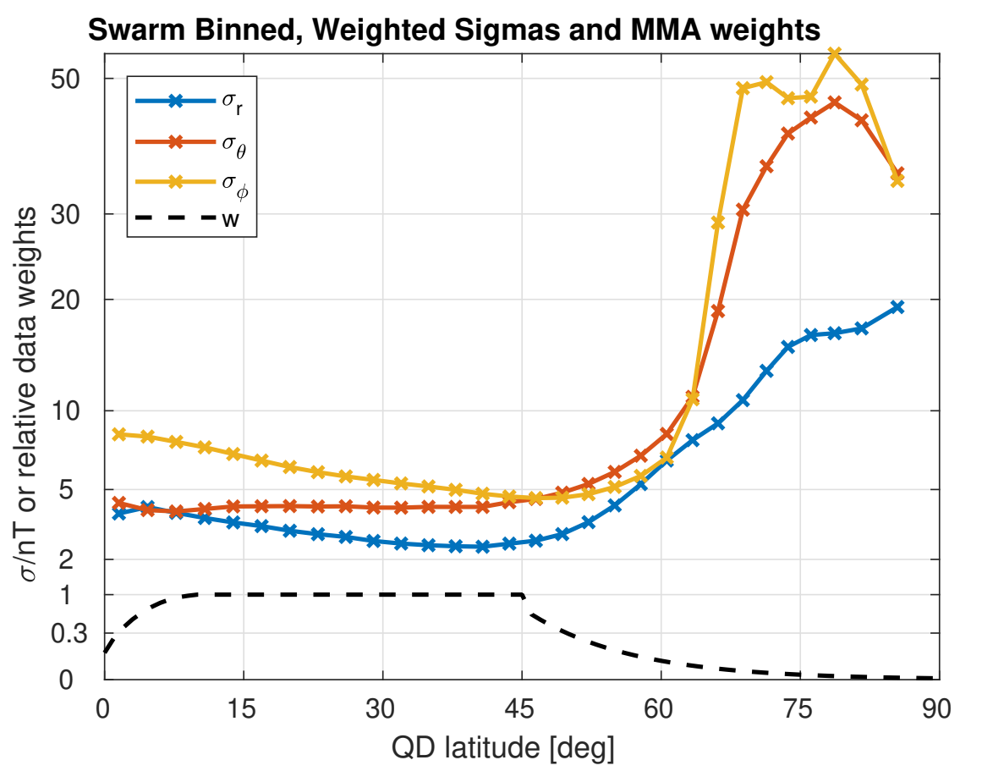
Data Residual Statistics and Weights

The residual statistics of the quiet time data vs. the comprehensive model (with "Quiet time" magnetospheric model) are listed in the table below. Grey cells indicate data from night-side (dark), white cells indicate data from day-side (sunlit) periods. "Field" indicate the pure vector and scalar measurements, whereas "NS diff" and "EW diff" indicate the North-South (along-track) and East-West differences respectively. The standard deviations are very impressive, partly due to the quite strict selection criteria of the quiet time "Field" data ($Kp \leq 2^-$), and partly due to the assigned uncertainties for these measurements. The Table of statistics also show the almost perfect identity of the side-by-side flying pair Alpha and Charlie and of the North-South differences for all Swarm spacecraft. Swarm Bravo shows slightly higher residuals in most "Field" elements at low and mid latitudes though lower at high latitudes. Finally, the statistics for the calibrated platform magnetometer of Cryosat is also pretty remarkably given this is not a magnetic mission.

Table: Comprehensive Model Data Statistics

		Geomagnetic Quasi Dipole (QD) Latitude, λ								
		Low $\lvert\lambda\rvert \leq 10°$				Mid $\lvert\lambda\rvert \in]10° \ldots 45°]$				High $\lvert\lambda\rvert > 45°$
		Weighted Standard Deviation in *nT*								
Sat		$\sigma(B_r)$	$\sigma(B_\theta)$	$\sigma(B_\phi)$	$\sigma(F)$	$\sigma(B_r)$	$\sigma(B_\theta)$	$\sigma(B_\phi)$	$\sigma(F)$	$\sigma(F)$
A	Field	0.91	0.97	1.09	0.94	0.77	1.14	1.35	0.87	7.75
	NS	0.28	0.15	0.32	0.12	0.22	0.26	0.36	0.14	1.85
	diff	1.17	0.88	1.16	0.75	0.57	0.68	1.19	0.35	2.40
B	Field	0.91	1.50	1.23	1.49	0.82	1.65	1.49	1.13	7.00
	NS	0.27	0.13	0.30	0.14	0.22	0.27	0.36	0.14	1.56
	diff	1.01	0.72	1.02	0.61	0.54	0.64	1.11	0.33	2.06
C	Field	0.94	0.96	1.10	0.95	0.76	1.15	1.35	0.88	7.69
	NS	0.29	0.15	0.32	0.12	0.23	0.28	0.37	0.14	1.84
	diff	1.18	0.88	1.15	0.75	0.58	0.69	1.20	0.35	2.39
A-C	EW	0.63	0.50	0.58	0.42	0.42	0.55	0.56	0.39	0.62
	diff	1.80	0.76	2.15	0.57	0.88	0.98	1.42	0.51	0.70
Cryosat		4.45	4.99	4.11	3.82	4.35	5.62	4.36	3.13	6.79

The figure to the right shows the weighted sigmas for Swarm data binned according to QD latitude. These sigma values form the basis for the data weights applied in the full time magnetospheric model estimation shown as black, dashed line.



Conclusion

The results from the Comprehensive Inversion chain of the Swarm DISC consortium applied to 10 years of Swarm and Cryosat data are very satisfactory. Using Swarm and Cryosat data together with magnetic observatories at ground we are able to estimate models of the internal and external magnetic fields of the Earth separated into models of the core, lithospheric, ionospheric, magnetospheric, and oceanic tides induced fields. These models agree very well with other magnetic field models estimated from Swarm and/or other data. We will continue our work to provide updated and refined models of the Comprehensive Inversion as Swarm continues to deliver high quality magnetic field data.

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