Swarm SCARF Comprehensive Inversion 2017 Production

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Introduction

The Swarm SCARF (**S**atellite **C**onstellation **A**pplication and **R**esearch **F**acility), a consortium of several research institutions, has been established with the goal of deriving Level-2 products by combination of data from the three satellites. Here we present the results of the Swarm SCARF team at DTU Space and NASA Goddard who conducts the Comprehensive Inversion (**CI**) magnetic field model processing chain; we present the results from using three years of Swarm data. The CI chain 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 oceans using single and dual satellite gradient information. Level-2 products containing the corresponding model parameter estimations will be generated regularly and distributed via ESA at ftp://swarm-diss.eo.esa.int/Level2longterm/ (see https://earth.esa.int/swarm on how to gain access).

Model Parametrization, Data, and Data Selection

The parametrization of the comprehensive model is given in the table below.

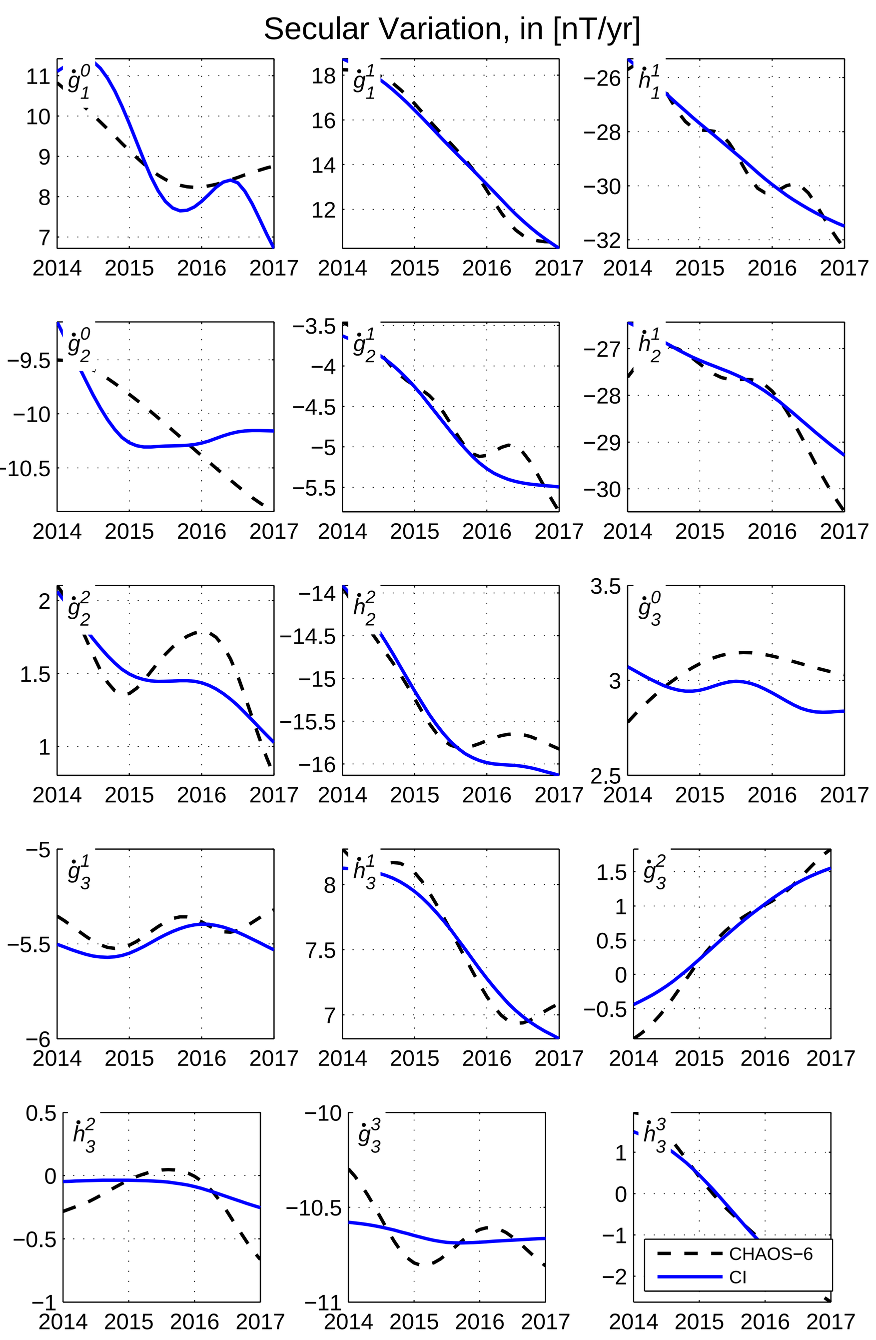
Table: Comprehensive Model Parametrization

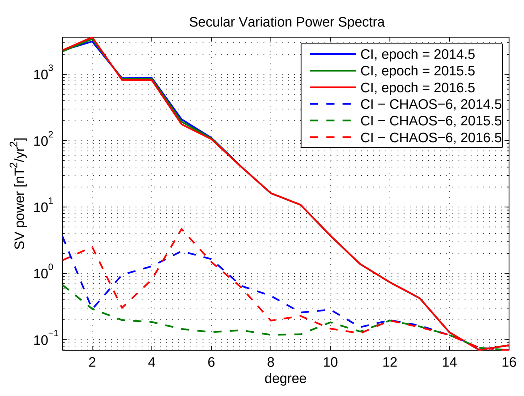
Field	Description	Number of coefficients
Core	Spherical harmonic expansion $n_{max} = 16$. Secular variation (SV) through order 5 B-splines with $\frac{1}{2}$ year knot spacing, damping of 2nd and 3rd derivative of B_r.	2,880
Lithosphere	Spherical harmonic expansion $n = 17 \dots 90$	7,992
Ionosphere	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 depth	5,520
Magnetosphere	Quiet times: Spherical harmonic expansion $n_{max} = 1$ external and internal (induced). Discretized in 1 hour bins. All data: $n_{max} = 2$, $m_{max} = 1$ external, $n_{max} = m_{max} = 3$ internal; dipole terms in $1\frac{1}{2}$ hour bins, other terms in 6 hour bins.	126,348 or 121,716
M_2 Tidal	Spherical harmonic expansion $n_{max} = 36$. Periodicity: 12.42060122 hr, phase fixed with respect to 00:00:00, 1999 January 1 GMT	2,736
Nuisance	Day-side core, lithosphere, and M_2 tidal, ground observatory biases, spacecraft alignment	15,483
Total		160,959

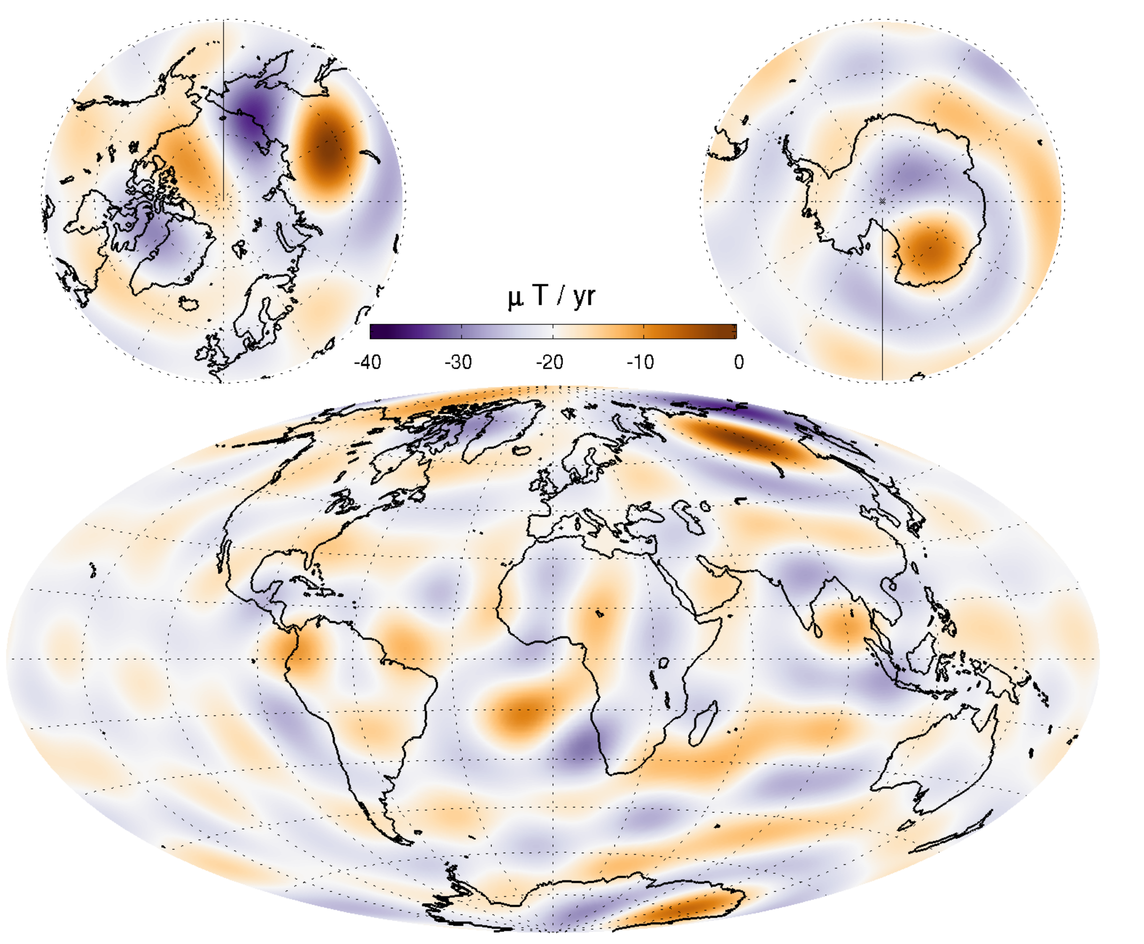
Swarm satellite data for this work consist of magnetic field vector measurements version 0501 from the period December 2013 through 2016 with gross outliers removed and decimated to 15 second sampling rate. Available hourly mean values from 142 ground based magnetic observatories for the period December 2013 through 2016 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 $Kp \leq 2^+$ and $\left|\frac{dDst}{dt}\right| \leq 3nT/hr$. Core and tidal fields are determined from night-side data only, i.e. with Sun at least 10° below the horizon.

Core Field and Secular Variation: Level 2 Product MCO_SHA_2C

The core field estimated by the Comprehensive Inversion corresponds well with the *CHAOS-6* model (Finlay, 2016) as can be seen from the plots of the first time derivatives of the Gauss coefficients ("Secular Variation") below on the left. In the middle, the power spectral densities of the secular variation confirms the good agreement. To the lower right, the first time derivative of B_r at the core-mantle boundary is shown. These maps shows some quite strong patch flows in the fluid core in particular in the northern hemisphere recently discussed in (Livermore, 2017). The patch flows also show weaker, circular features centered around the magnetic poles which are probably due to leakage from external magnetic fields.

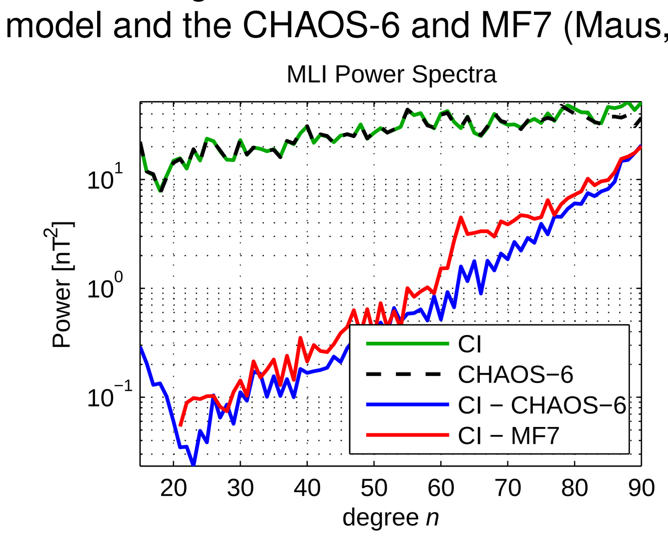


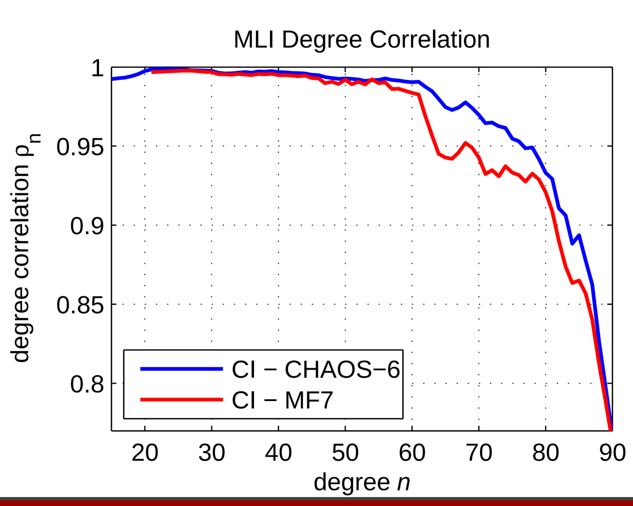


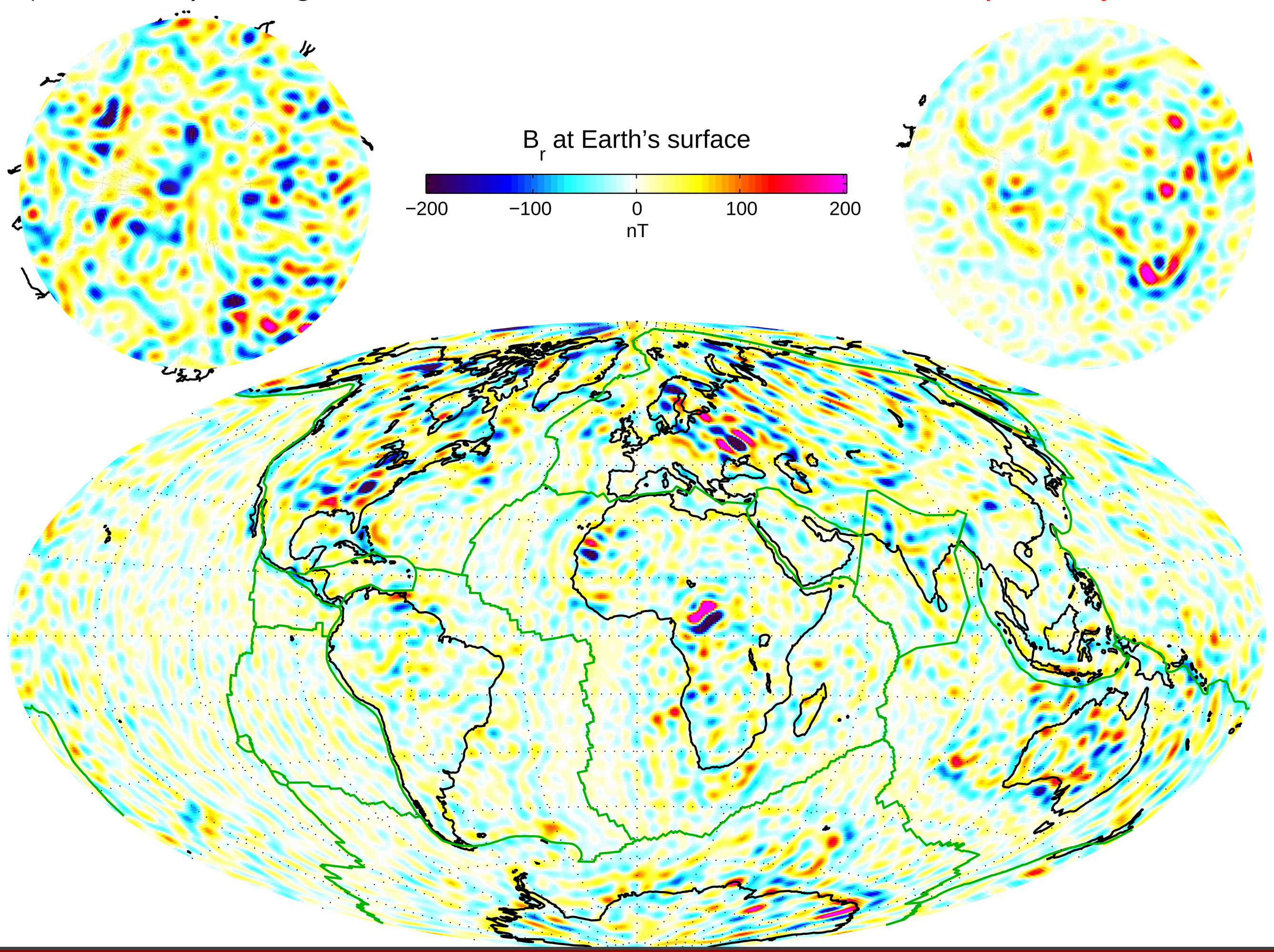


Lithospheric Field: Level 2 Product MLI_SHA_2C

The part of the lithospheric field of degree $n \geq 17$ is determined solely from along-track (*North-South*) and cross-track (*East-West*) gradient information. Vector gradient information is used at low latitudes (QD-latitude below 55°) whereas scalar gradients are used at all latitudes. Both day- and night-side gradient information is used. Along-track gradients are formed by taking single satellite differences separated by 15 seconds, whereas cross-track gradients are formed by taking differences between the lower Swarm pair, Alpha and Charlie, at equal latitude temporally separated by typically 4 to 15 seconds. The optimum satellite constellation for the cross-track gradient information was obtained and maintained since mid April 2014. We obtain excellent agreement between our model and the CHAOS-6 and MF7 (Maus, 2010) models up to degree $\simeq 90$ with rms-differences of 13.3 nT respectively 15.1 nT.

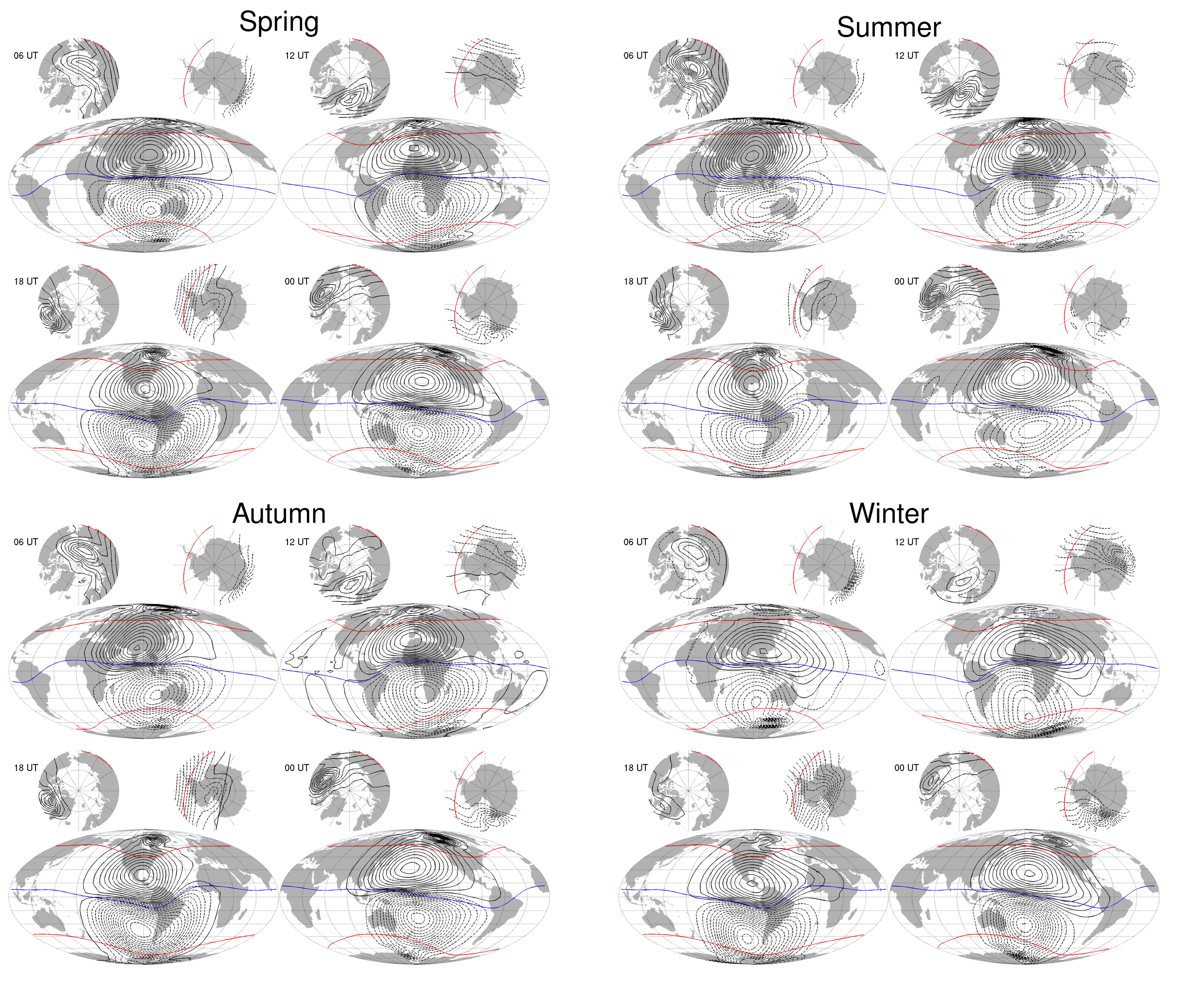






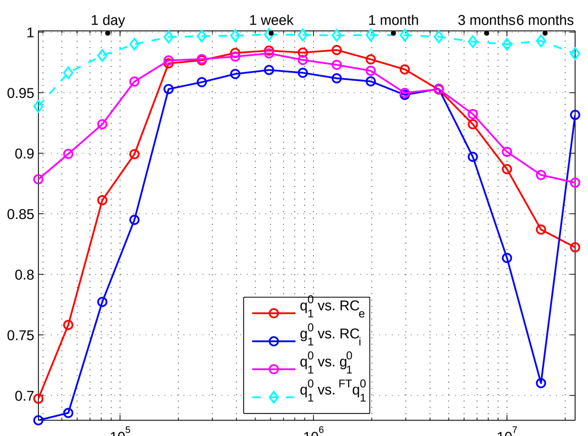
Ionospheric Field: Level 2 Product MIO_SHA_2C

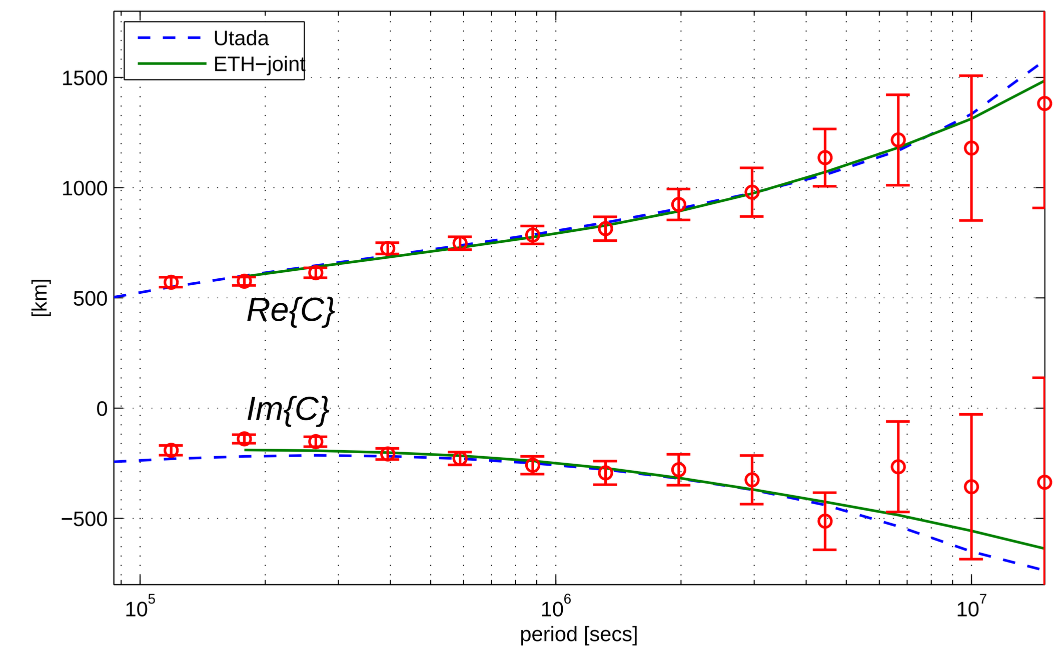
The figures below show the equivalent current function of the primary ionospheric currents for four different epochs (equinoxes and solstices) and four different local times (morning, noon, afternoon, and midnight). The dip equator is shown in blue, and the ±55° quasi dipole latitudes are shown in red. These maps are in good agreement with other models although the "secondary" vortices near the magnetic poles may be some form of contamination.



Magnetospheric Field: Level 2 Product MMA_SHA_2C

The magnetospheric field is estimated in two steps: First, data from magnetically quiet periods are used to estimate the models described above together with 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. To the right, the squared coherences between q_1^0 and RC_e, g_1^0 and RC_i, q_1^0 and g_1^0, and q_1^0 and ${}^{FT}q_1^0$ (of the *Fast-Track* magnetospheric processing chain) are shown. The latter shows a very high coherence, despite of the fact that they are derived in quite distinct ways. To the left, the C-response estimates based on q_1^0 and g_1^0 are shown in red with error bars. The blue and green curves shows theoretical values based on the conductivity models of Utada et al. and ETH (Püthe and Grayver), which demonstrates very good agreement.





Data Residual Statistics

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, white cells indicate data from day-side (sunlit) periods. "Field" indicate the pure vector and scalar measurements, whereas "NS grad" and "EW grad" indicate the North-South (along-track) and East-West gradient respectively. The standard deviations are quite impressive, and also show the expected similarity between Swarm A and C (side-by-side flying pair) and in the North-South gradients for all three satellites. Swarm B shows slightly higher residuals in the "Field" components at low and mid latitudes though lower at high latitudes.

Table: Comprehensive Model Data Statistics

Sat		Geomagnetic Quasi Dipole (QD) Latitude, λ								
		Low, $\lvert\lambda\rvert \leq 10°$				Mid, $\lvert\lambda\rvert \in]10° \dots 55°]$				High, $\lvert\lambda\rvert > 55°$
		Weighted Standard Deviation in nT								
		$\sigma(B_r)$	$\sigma(B_\theta)$	$\sigma(B_\phi)$	$\sigma(F)$	$\sigma(B_r)$	$\sigma(B_\theta)$	$\sigma(B_\phi)$	$\sigma(F)$	$\sigma(F)$
A	Field	1.77	3.30	1.98	3.21	2.73	3.62	2.86	2.06	5.97
	NS	0.38	0.18	0.37	0.19	0.26	0.33	0.39	0.20	1.84
	grad	1.30	0.98	1.20	0.85	0.61	0.72	1.27	0.33	2.59
B	Field	1.95	4.07	2.84	4.00	3.14	4.48	3.77	2.73	5.78
	NS	0.39	0.18	0.36	0.19	0.26	0.34	0.40	0.22	1.61
	grad	1.10	0.79	1.06	0.66	0.58	0.68	1.21	0.31	2.28
C	Field	1.78	3.33	2.02	3.27	2.79	3.66	2.83	2.11	5.98
	NS	0.40	0.19	0.38	0.19	0.28	0.35	0.41	0.21	1.85
	grad	1.30	0.98	1.21	0.89	0.63	0.74	1.29	0.33	2.59
A-C	EW	0.83	0.36	0.99	0.29	0.43	0.49	0.94	0.28	0.62
	grad	2.10	0.78	2.52	0.55	0.96	1.10	1.64	0.44	0.75

Conclusion

The results from the Comprehensive Inversion chain of the Swarm SCARF consortium applied to three years of Swarm data are very satisfactory. Using data from the first 37 full months of the mission 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, and magnetospheric fields. These models agree very well with other magnetic field models estimated from Swarm and/or previous data.

References

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