DTU Space
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Updating the CHAOS series of field models using Swarm data and resulting candidate models for IGRF-12

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SUMMARY

Ten months of magnetic field observations from ESA's Swarm mission, together with recent ground observatory monthly means, have been used to update the CHAOS series of field models. Our new model, called CHAOS-5, includes more than 15 years of satellite data. The internal field is time-dependent up to spherical harmonic degree 20, using 6th order splines with a 0.5 yr knot spacing. CHAOS-5 is able to consistently fit data from six independent low Earth orbit satellites: Ørsted, CHAMP, SAC-C and the three Swarm satellites. Furthermore, it provides a good description of the secular variation measured at ground observatories, capturing rapid field evolution events in 2006.2, 2009.2 and 2012.9. DTU candidate models for IGRF-12 (the main field in epochs 2010 and 2015, and the predicted linear secular variation for 2015 to 2020) were extracted from CHAOS-5.

Field Modelling Methodology

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\mathrm{int}} + V^{\mathrm{ext}}$.
- The internal part of the potential takes the form

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

- Internal coefficients are further expanded in time using order 6 B-splines with 0.5 yr spacing.
- The external part is defined in the SM and GSM co-ordinate systems, with θ_d and T_d being dipole co-latitude and dipole local time

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

- Degree-1 coefficients in *SM* coordinates also depend explicitly on $\epsilon(t)$ and $\iota(t)$, the external and induced parts of the RC index.
- The field in magnetometer frame is related to that in the North-East-Center (NEC) frame by

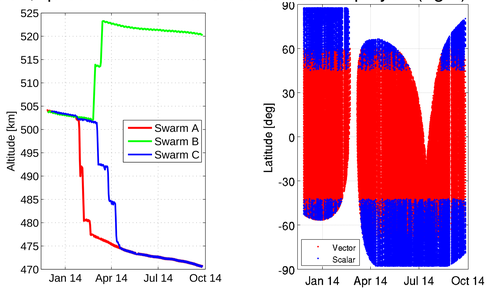
$$\mathbf{B}_{\mathrm{NEC}} = -\nabla V = \underline{\underline{\mathbf{R}}}_q \cdot \underline{\underline{\mathbf{R}}}_3 \cdot \mathbf{B}_{\mathrm{VFM}}$$

$\underline{\underline{\mathbf{R}}}_3$ rotates from the magnetometer *VFM* system to the Common Reference Frame (*CRF*) of the star tracker, while $\underline{\underline{\mathbf{R}}}_q$ rotates from the *CRF* to the NEC frame. $\underline{\underline{\mathbf{R}}}_3$ involves co-estimated Euler angles.

- Model estimation: regularized, Huber-weighted, NL least squares.

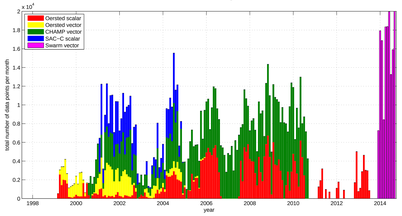
Swarm

Use of Level 1B Swarm VFM data (baseline 0301/0302), scaled to match ASM scalar field, until 25th Sept. 2014. Below is the evolution of mean altitude of the Swarm satellites (left) and the selection of night-side, quiet-time vector and scalar data employed (right).

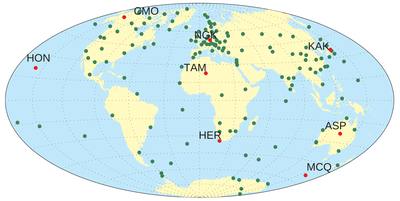


Satellites and Ground Observatories

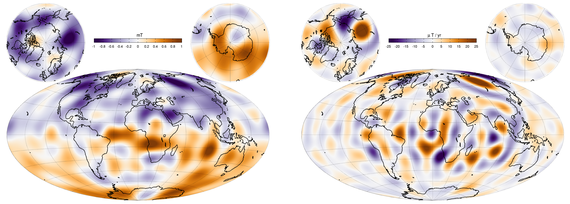
CHAMP, Ørsted and SAC-C satellite data, as previously used in the construction of CHAOS-4, were also employed. Below: Histogram of vector/scalar satellite data used at non-polar latitudes for each month.



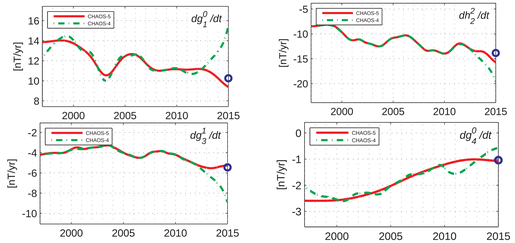
Below: Map showing locations of ground observatories used.



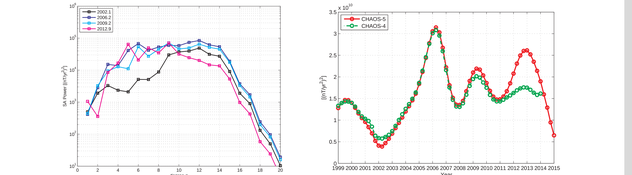
Core Field Variations 1999-2015



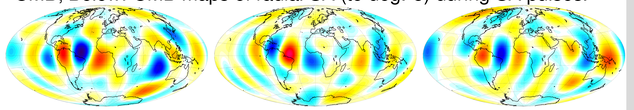
Radial field (left) and its time rate of change or **secular variation (SV)** (right), to deg. 14 and 15, at the CMB in 2014.5.



Time evolution of the secular variation (at Earth's surface) for selected spherical harmonic coefficients of the internal potential. Blue circles are the DTU IGRF-12 candidate SV model for 2015 to 2020.

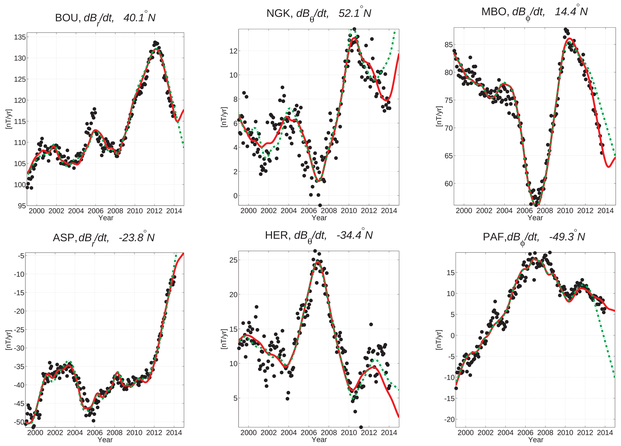


Secular acceleration (SA): Above left: SH spectra of SA at CMB; Above right: Norm (squared, integrated value to deg. 8) of SA at the CMB; Below: CMB maps of radial SA (to deg. 8) during SA pulses.



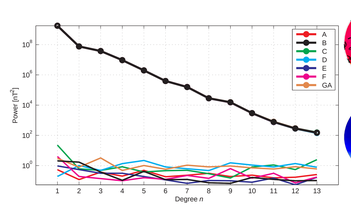
2006.2 2009.2 2012.9

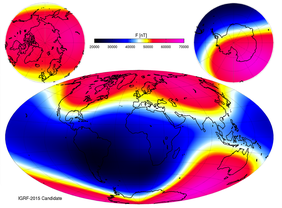
Fit to Ground Observatories



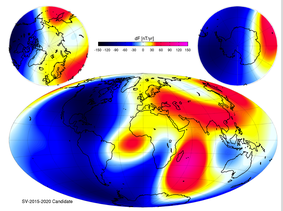
Annual differences of revised observatory monthly means **(black dots)** compared to the SV from CHAOS-5 (red curve) and also for comparison the pre-Swarm model CHAOS-4 (green dashes).

IGRF-12: DTU Candidate Models





Above: DGRF-2010 spectra with DTU candidate based on CHAOS-5 in black, differences to other candidates, coloured lines.



Right: Intensity maps: IGRF-2015 candidate (top) and candidate for predicted intensity change per year 2015-2020 (bottom).