DTU Space
National Space Institute

Tools for sharing and evaluating the CHAOS geomagnetic field model and the shc-file format for time-dependent spherical harmonic models

Clemens Kloss

Together with: Chris Finlay and Nils Olsen

DTU Space, National Space Institute, Technical University of Denmark

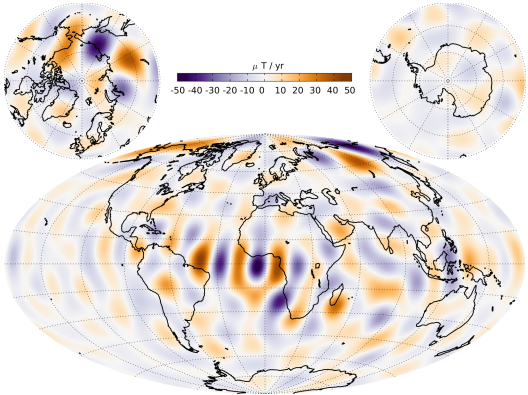
May 24, 2022

Introduction

- Geomagnetic field models are essential in the study of physical processes that contribute to Earth's magnetic field.
- Several groups build models: differences in magnetic data and mathematical methods used during model estimation (e.g. need not be spherical harmonic models).
- Choice between models depends on geophysical signals of interest.
- Currently no single platform for collecting models in standardised form.
- Here: details about the CHAOS geomagnetic field model and its distribution to users.

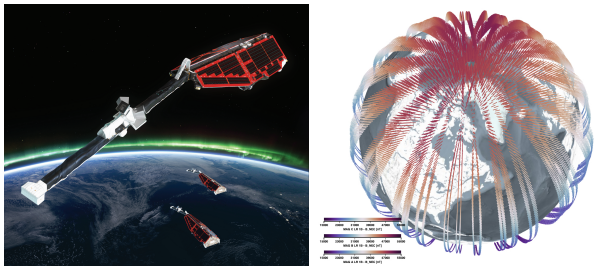
CHAOS - A Geomagnetic field Model

- Derived approx. every 4 months by the Division of Geomagnetism and Geospace at DTU Space using the latest ground and satellite data.
- Provides estimates of the recent internal field (generated in the Earth's core and crust) and the quiet-time external field (generated in the radiation belts, magnetotail and at the magnetopause).
- Current version covers the period between 1997 and 2022 (CHAOS-7.10).



Rate of change of the radial magnetic field in 2021 for $n \leq 16$ at the core-mantle boundary as given by CHAOS-7.9.

Magnetic Observations Used for Deriving CHAOS



Left: Artistic view of the three *Swarm* satellites in orbit. Right: Field intensity (color scale) of magnetic field measurements collected by the *Swarm* satellites over 18th October 2018 (images: ESA and VirES).

- Satellite magnetic survey missions are crucial by providing global observations of high temporal and spatial resolution.
- ESA's *Swarm* constellation consists of three identical satellites presently collecting high quality magnetic data.
- Also satellite data from previous survey missions (Ørsted, CHAMP, SAC-C) and platform magnetometer data (Cryosat-2).
- And monthly-means from a network of approximately 200 ground stations

Overview of Tools for Sharing and Evaluating CHAOS

Main repository of files and software is the CHAOS website.

Model Coefficient Files

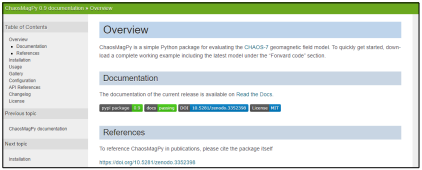
- Model coefficients stored in MATLAB's mat-format.
- Static internal field as shc-file (see following slides).
- Time-dependent internal field model in spline-coefficients format and as shc-file.

Computer Software for Evaluating CHAOS

- MATLAB code package (entire model).
- Python code package: ChaosMagPy (entire model, see next slide).
- Fortran-77 code for producing time series of Gauss coefficients and derivatives (int. field).

ChaosMagPy

- Open-source Python package for evaluating CHAOS and many other time-dep. spherical harmonic models
- Code can be viewed and downloaded on github.com.
- Extensive documentation available on readthedocs.org.



ChaosMagPy homepage.

```
1  chaos = load_CHAOS_matfile('CHAOS-7.10.mat')  # load latest CHAOS model from mat-file
2
3  dgnm = chaos.synth_coeffs_tdep(time, nmax=16, deriv=1)  # SV coefficients for n <= 16
4  B = chaos.synth_values_tdep(time, radius, theta, phi)  # time-dep. internal field
5
6  cals7k = load_CALS7K_txtfile('CALS7K.2')  # load CALS7K model file, usage like CHAOS
```

Python example code.

Introducing the SHC-file Format

- Developed for storing time-dependent spherical harmonic models.
- Adopted by the European Space Agency (ESA) for *Swarm* Level 2 and auxiliary product files (i.e. spherical harmonic field models that may be time-dependent).

Advantages

- ASCII file readable without installation of special software.
- Model snapshots in terms of Gauss coefficients can be directly read and used (no B-spline reconstruction).
- Provides enough information to properly reconstruct the continuous time-dependence of spline models.

Disadvantages

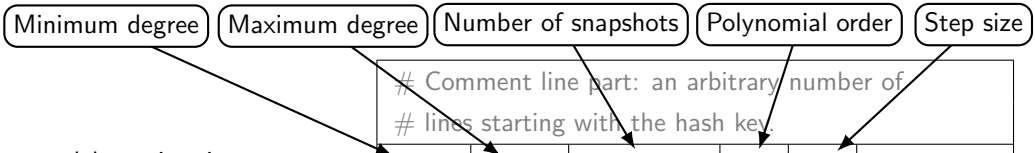
- Fixed time sampling unless full reconstruction is performed.
- Sensitive to the precision of the used floating-point format (since not specified in the shc-file definition).
- Lack of official reader/writer software.

SHC-file Layout Description

- Snapshot models at time instants t_i (decimal years) stored column-wise.
- Gauss coefficients stored row-wise in natural order (g_1^0, g_1^1, h_1^1, g_2^0, ...).
- Step size S indicates extra snapshots needed for reconstructing the polynomial pieces and, hence, the continuous time-dependence.

# Comment line part: an arbitrary number of # lines starting with the hash key.					
$n_{\min}$	$n_{\max}$	N	K	S	
		t_1	...	...	t_N
$n_{\min}$	0	$g^0_{n_{\min}}(t_1)$	...	...	$g^0_{n_{\min}}(t_N)$
$n_{\min}$	1	$g^1_{n_{\min}}(t_1)$	...	...	$g^1_{n_{\min}}(t_N)$
$n_{\min}$	-1	$h^1_{n_{\min}}(t_1)$	...	...	$h^1_{n_{\min}}(t_N)$
...	...	...	...	...	...
n	m	$g^m_n(t_1)$	...	...	$g^m_n(t_N)$
...	...	...	...	...	...
$n_{\max}$	-$n_{\max}$	$h^{-n_{\max}}_{n_{\max}}(t_1)$	...	...	$h^{-n_{\max}}_{n_{\max}}(t_N)$

SHC-file Layout Description



- Snapshot models at time instants t_i (decimal years) stored column-wise.
- Gauss coefficients stored row-wise in natural order (g_1^0, g_1^1, h_1^1, g_2^0, ...).
- Step size S indicates extra snapshots needed for reconstructing the polynomial pieces and, hence, the continuous time-dependence.

Comment line part: an arbitrary number of
lines starting with the hash key.

$n_{\min}$	$n_{\max}$	N	K	S	
		t_1	...	...	t_N
$n_{\min}$	0	$g^0_{n_{\min}}(t_1)$	...	...	$g^0_{n_{\min}}(t_N)$
$n_{\min}$	1	$g^1_{n_{\min}}(t_1)$	...	...	$g^1_{n_{\min}}(t_N)$
$n_{\min}$	-1	$h^1_{n_{\min}}(t_1)$	...	...	$h^1_{n_{\min}}(t_N)$
...	...	...	...	...	...
n	m	$g^m_n(t_1)$	...	...	$g^m_n(t_N)$
...	...	...	...	...	...
$n_{\max}$	$-n_{\max}$	$h^{-n_{\max}}_{n_{\max}}(t_1)$	...	...	$h^{-n_{\max}}_{n_{\max}}(t_N)$

Summary and Conclusions

- SHC-file format developed for exchanging time-dependent field models of various types in the context of the *Swarm* mission.
- ChaosMagPy package developed primarily for the CHAOS geomagnetic field model.
- Nonetheless, both are usable more broadly for time-dependent spherical harmonic field models.
- Recommendation for strengthening cross-disciplinary sharing of models:
  1. Provide open-source software for reading/writing model files of any format and for evaluating models (field values, Gauss coefficients, etc.).
  2. Provide simple online tools for producing time series of Gauss coefficients and derivatives (downloadable, e.g., as csv-file).

Summary and Conclusions

- SHC-file format developed for exchanging time-dependent field models of various types in the context of the *Swarm* mission.
- ChaosMagPy package developed primarily for the CHAOS geomagnetic field model.
- Nonetheless, both are usable more broadly for time-dependent spherical harmonic field models.
- Recommendation for strengthening cross-disciplinary sharing of models:
  1. Provide open-source software for reading/writing model files of any format and for evaluating models (field values, Gauss coefficients, etc.).
  2. Provide simple online tools for producing time series of Gauss coefficients and derivatives (downloadable, e.g., as csv-file).

Thank you for your attention