Enhanced Swarm-Based Climatological Models of the Non-Polar Geomagnetic Daily Variations

Arnaud Chulliat\textsuperscript{1}, Louis Chauvet\textsuperscript{2}, Gauthier Hulot\textsuperscript{2}, Robin Duchêne\textsuperscript{2}, Martin Fillion\textsuperscript{1}

\textsuperscript{1} CIRES, University of Colorado Boulder & NOAA NCEI, \textsuperscript{2} Université Paris Cité, Institut de Physique du Globe de Paris
Background & Motivation (1)

• Non-polar geomagnetic daily variations are present in all geomagnetic field recordings, on ground and in low-Earth orbit (LEO).

• They are caused by electric currents in the ionospheric E-region on the day side (ionospheric wind dynamo), and by induced electric currents in the Earth’s mantle.

• The amplitudes and phases of the diurnal variation and its harmonics vary as a function of location, season, solar cycle and geomagnetic activity.

• They are also affected by the day-to-day variability of thermospheric winds and tides.

BOU (red), HON (yellow), KAK (blue), TUC (green), VIC (cyan). Figure from Chulliat et al. (2005)
Background & Motivation (2)

- Physics-based models often focus on investigating the dynamics of the ionosphere-thermosphere rather than accurately predicting geomagnetic variations for practical applications.

- Empirical equivalent current models based on ground-based data generally lack truly global coverage (in longitude) and do not separate primary and induced magnetic fields.

Figure from Yamazaki & Maute (2017)
Global Modeling of the Sq (and EEJ) Fields

- An empirical modeling approach incorporating LEO satellite data was pioneered as part of the Comprehensive Model 20+ years ago (Sabaka et al., 2003).
  - CM3 used a limited number of satellite data with insufficient LT coverage.

- It was decided during the Swarm mission preparation to develop two independent processing chains for non-polar geomagnetic daily variations: the CM and the Dedicated Ionospheric Field Inversion (DIFI).

- ”Dedicated” modeling allows for more frequent updates and a wider variety of data correction methods, and provides an independent validation.

- DIFI models provide global representations of the quiet-time, climatological, non-polar daily variations at ground and in LEO during the Swarm mission. They separate primary and induced fields.

- Seven DIFI models have been released so far; DIFI-8 to be released later this year.
DIFI Methodology

- Swarm Alpha & Bravo vector data and observatory hourly mean values (from the “SW_OPER_AUX_OBS” product developed by BGS)
  - Extended DIFI (“xDIFI”): adding CHAMP data
- Quiet-time data only: Kp < 2, |Dst| < 20 nT, |IMF By| < 8 nT, -2 nT < IMF Bz < 6 nT
- Data corrections using the latest CHAOS (core and magnetospheric field) and MF7 (crustal)
- Additional track-by-track corrections and filtering to remove unmodelled magnetospheric field variations and high-latitude ionospheric fields in satellite data
- Inversion in Quasi-Dipole (QD) coordinates until degree 45 and order 5 (11,875 coefficients),
- Model released in dipole coordinates (degree 60 and order 12)
- Regularization minimizing the horizontal gradient of the current density at all local times
Toroidal Fields Corrections

• Climatological model of non-polar F-region ionospheric currents developed by Fillion et al. (2023)

• Model predicts toroidal magnetic fields \((B_\theta, B_\varphi)\) at Swarm Alpha and B altitudes

• See Martin Fillion’s talk in this session
## Data

<table>
<thead>
<tr>
<th>Data</th>
<th>Baseline</th>
<th>Start Date</th>
<th>End Date</th>
<th># of Data</th>
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<tbody>
<tr>
<td>Swarm A &amp; B</td>
<td>0602/0603</td>
<td>Jan 1, 2014</td>
<td>Dec 31, 2023</td>
<td>~ 2.5 M</td>
</tr>
<tr>
<td>Observatories</td>
<td>Definitive and QD</td>
<td>Jan 1, 2014</td>
<td>Dec 31, 2023</td>
<td>~ 2.5 M</td>
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</tbody>
</table>

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# Data Residuals

<table>
<thead>
<tr>
<th>Satellite data (area of validity)</th>
<th>Observatory data (area of validity)</th>
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<tbody>
<tr>
<td></td>
<td>No TF correction</td>
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<tr>
<td>Mean $B_r$ (nT)</td>
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<tr>
<td>Std $B_r$ (nT)</td>
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<tr>
<td>Mean $B_{\theta}$ (nT)</td>
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<td>Mean $B_{\phi}$ (nT)</td>
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<td></td>
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<td>Std $B_{\phi}$ (nT)</td>
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</table>
Equivalent Current Function

Jan 1

Apr 1

Jun 1

Sep 1
Total Current Intensity

![Graph showing total current intensity over time](image-url)
Model Predictions at Ground (1)
Model Predictions at Ground (2)
Conclusions & Perspectives

• DIFI models can be used to correct for external field variations for various applications.
  • Satellite data processing and geomagnetic field modeling
  • Marine and aeromagnetic survey data processing
  • Magnetic field based navigation

• DIFI models provide information on the geometry and climatology of ionospheric Sq and EEJ currents.

• Extension backward in time (“xDIFI”) using time-varying QD basis functions is ongoing.