Storm-time modeling of ionospheric electric currents and magnetic fields time-space variations

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Introduction

Modeling Earth's ionospheric electric currents and their associated magnetic fields is of fundamental importance for geomagnetism and for the study of ionosphere coupling with the neutral atmosphere and the magnetosphere. Modeling these fields and currents during geomagnetic storms is particularly challenging due to the limited data available combined with high time-space variations during such events. In this study, we propose an extension of the approach developed by Egbert et al. (2021) to build a new model of the storm-time ionospheric electric currents and magnetic fields. It relies on a joint utilization of magnetic data from ground and the Swarm satellites and of the physics-based Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM).

Overview of the methodology

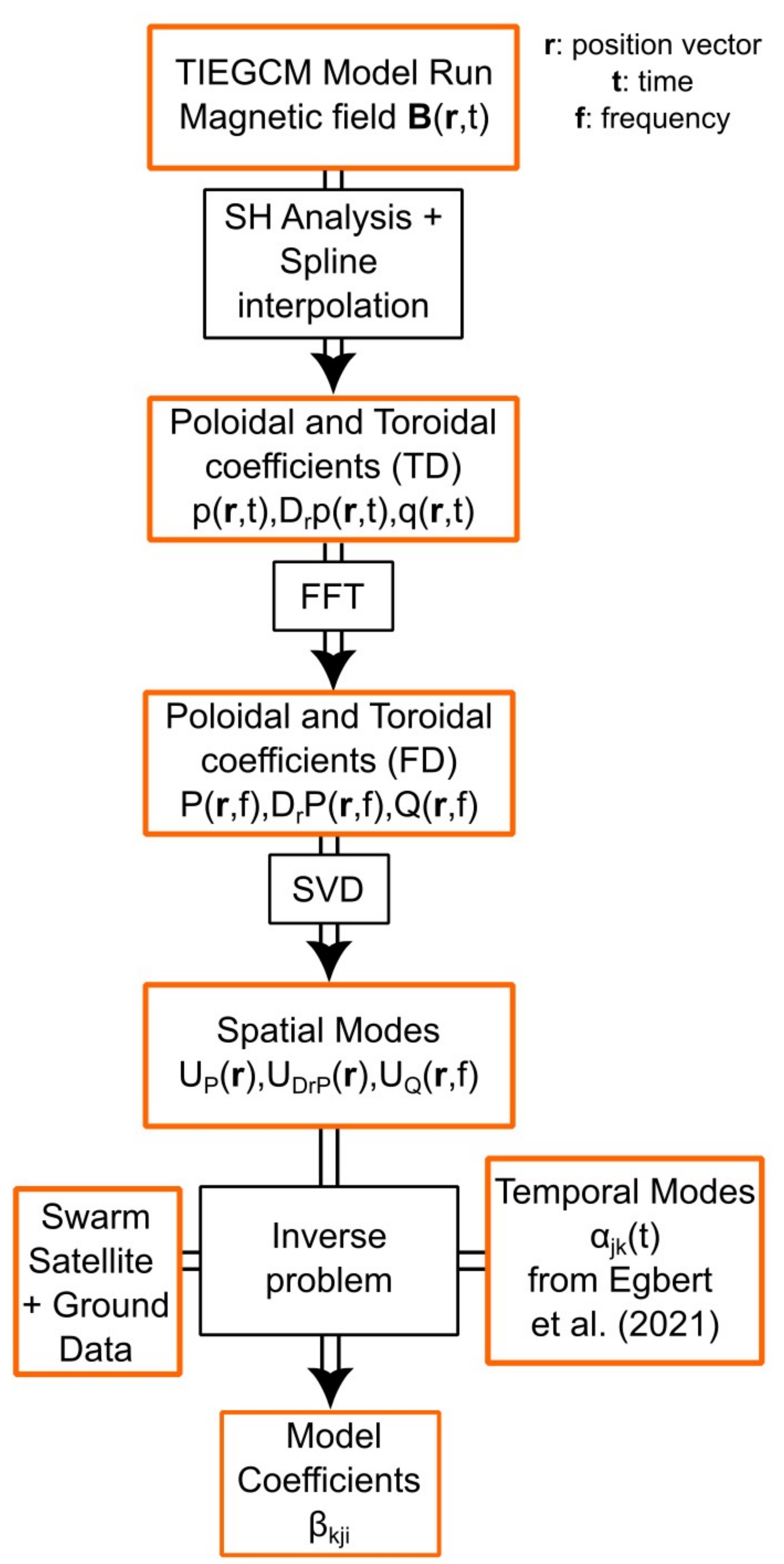

Figure 1: Diagram showing the main steps in computing the model coefficients.

TIEGCM runs for Geomagnetic storms

We use the electrodynamo solver[2,3] developed to compute the 3D ionospheric current density and associated magnetic fields using outputs from the TIEGCM model which was adapted to simulate the thermosphere-ionosphere system during 4 geomagnetic storm periods: **March 2013**, **March 2015**, **May 2017**, and **September 2017**.

We obtain the magnetic field vector on a 1°X1° grid and 55 altitudes every 5 minutes for each storm run.

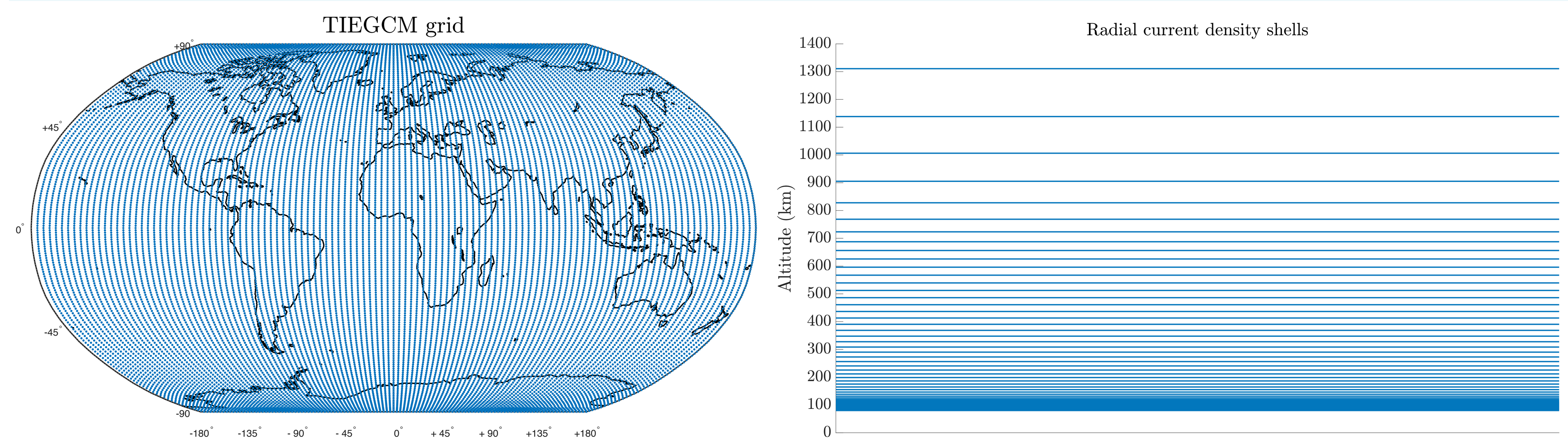

Figure 2: TIEGCM 1°X1° grid (left) and radial shells (right).

Analysis of the TIEGCM grids

- The magnetic field grids are decomposed into their poloidal and toroidal components and analyzed with spherical harmonics (SH) using the SHTns library[4].
- SH coefficients are next interpolated with splines to describe their variations with altitude.
- The set of interpolated SH coefficients forms a compact and continuous representation of the magnetic fields and currents in the ionosphere.

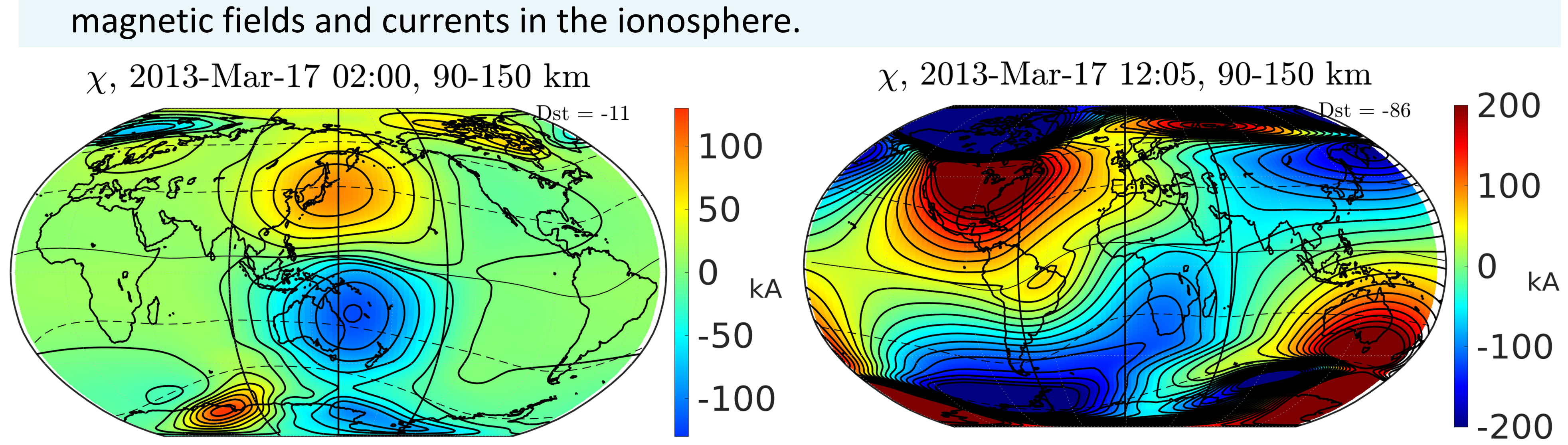

Figure 3: Height-integrated current density stream function in the ionosphere E region (90-150 km) before the geomagnetic storm of March 2013 (left) and during the main phase (right) computed using SH coefficients.

Comparison with Swarm data

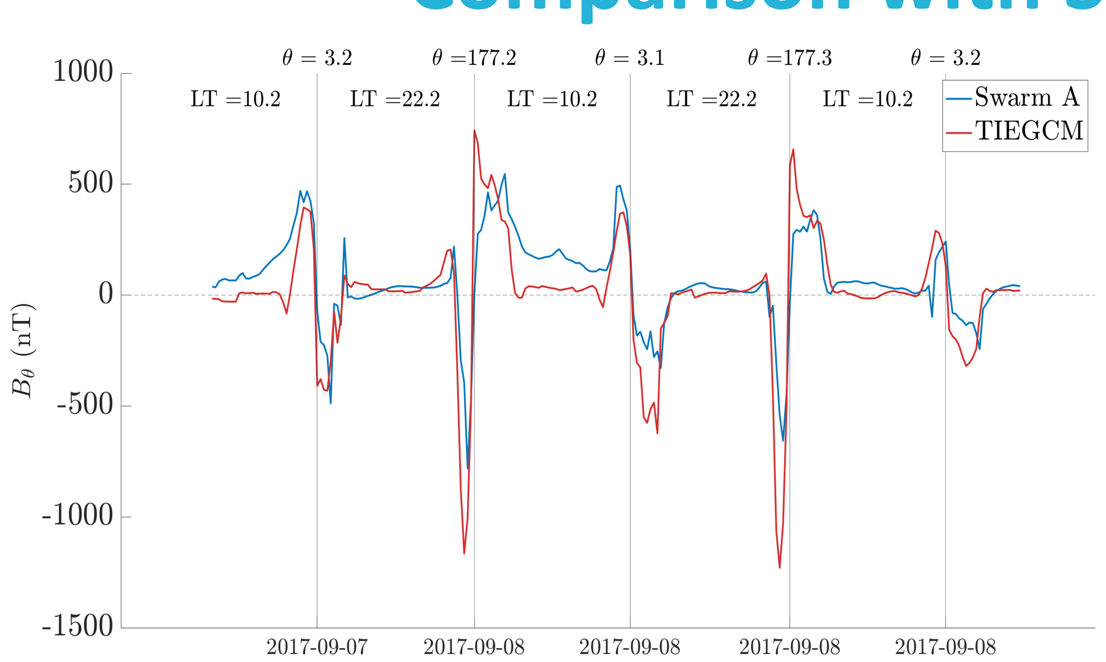

Figure 4: Comparison between the South component of the TIEGCM model prediction and data from the Swarm satellite Alpha.

We compare the TIEGCM model prediction computed using the SH representation with data from the Swarm satellites corrected from non-ionospheric sources using the CHAOS-7 model[7].

Note: The TIEGCM based curve only corresponds to the primary ionospheric field whereas the Swarm curve includes contributions from the induced ionospheric field and the asymmetric primary and induced magnetospheric fields.

Derivation of the spatial modes

- SH coefficients time series are first transformed to the frequency domain (FD) using FFT.
- Complex FD SH coefficients for all frequencies (roughly from one tenth of cpd to the Nydquist frequency) are next combined in a matrix.
- We compute the Singular Value Decomposition (SVD) of this matrix.
- Spatial modes can be recovered from the left singular vectors.

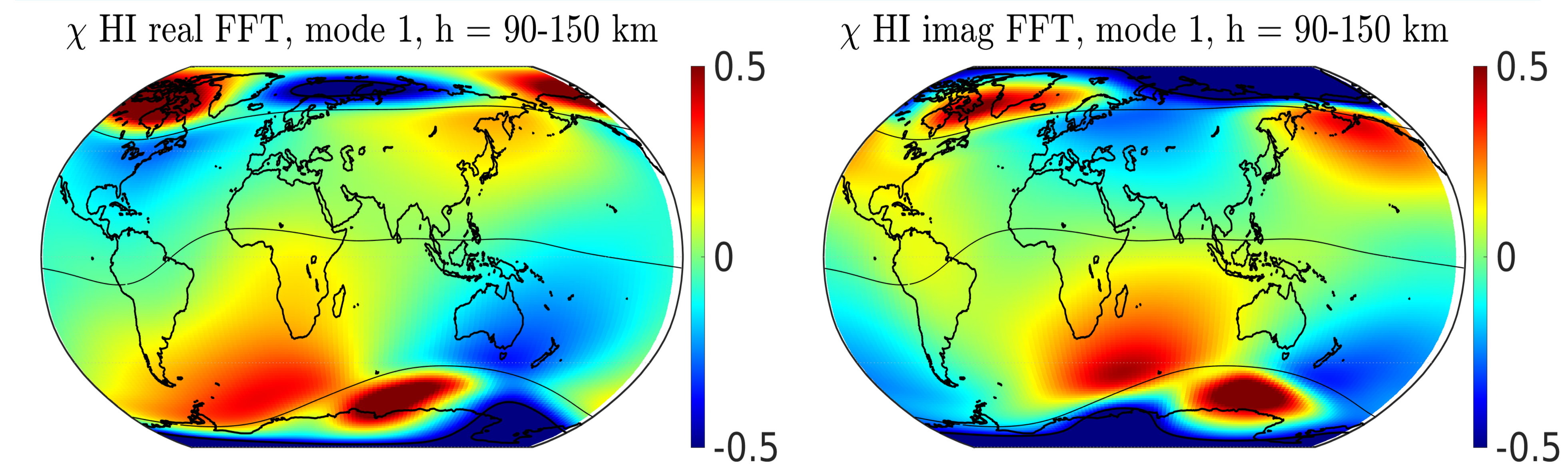

Figure 5: Real (right) and imaginary (left) parts of the height-integrated current density stream function in the ionosphere E region (90-150 km) computed with coefficients of the first mode derived with the March 2013 run.

Note: The first modes obtained with the SVD represent the spatial patterns averaged over all frequencies that explain the most variability in the TIEGCM storm runs.

Model parametrization and inversion

Example of a model equation that combines the spatial modes (in blue) and the temporal modes (in red) to represent the 3D magnetic field in the ionosphere. The model coefficients are the constant coefficients β (in green). The model coefficients can be estimated by solving an inverse problem.

$$\mathbf{B}(\mathbf{r},t) = \Re\left\{\sum_{j=1}^{J}\sum_{k=1}^{K_j}\alpha_{kj}(t)\sum_{i=1}^{I}\beta_{jki}\Phi^i(\mathbf{r})\right\}$$

Note: This model does not take into account the induced ionospheric field yet.

Conclusions

We successfully derived some global spatial modes that can be combined with temporal modes of Egbert et al. (2021) to build models of the Storm time ionospheric magnetic fields and electric currents.

In the future:

- The spatial mode will be improved by analyzing more storms.
- Spatial modes could be optimized to better represent specific regions of the globe (for instance, the high latitudes in the northern hemisphere).
- The model equation will be modified to take into account induced fields.
- The model coefficients β will estimated using Swarm data for several storm period and by solving an inverse problem.

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