Characterize the magnetic signal generated in the magnetosphere from geomagnetic observations

Yael SH1, Vincent LESUR1, Erwan THEBAULT2

1Université Paris Cité, Institut de physique du globe de Paris, CNRS F-75005 Paris, France
2Université Clermont-Auvergne, Laboratoire Magnas et Volcans, CNRS F-63170 Aubière, France

Introduction

The main contribution to the geomagnetic field is from the core, but fields generated from the magnetosphere during geomagnetic storms play an important role. They may have geomagnetic contributions up to hundreds of nT over hours during magnetic storms. To study the geomagnetic field, contributions from different sources need to be separated and modeled. In current models of the geomagnetic field derived from satellite data, the magnetospheric components are poorly described because of the limitation of satellite data spatiotemporal resolution. The poorly described magnetospheric component limits the resolution of other geomagnetic contributing sources, especially the contributions from the Moon (Thebault et al. (2013)) and the solar wind (Leur et al. (2011)). It is therefore important and necessary to design and describe model precisely the magnetospheric components. We describe here an approach for their modeling based on Kalman filter approach and magnetic observatory data. These provide a data set with a temporal resolution particularly well suited to characterize rapidly varying magnetospheric signals.

Objective:
- Study the magnetospheric field up to spherical harmonic (SH) degree 6 (L=6) through normal distributions ( \( \mathbf{M}_0 = m, \sigma^2 = \sigma^2 \) ) with a time resolution of an hour, based on a Kalman filter and correlation-based modeling.

Test models with synthetic data

Synthetic data at each observatory include only magnetospheric field signal and its response in the mantle: 1. generation of a random hourly sequence during the whole 2021 year for each Gauss coefficient \( \sigma^2 \) up to degree L=6; 2. removal of the principal trend by PCA and normalization of the random distribution of \( \sigma^2 \) by the variance trends from the IGRF-13 field power spectrum; 3. generation of \( \sigma^2 \) by multiplying the normalized \( \sigma^2 \) with a 10 electrical conductivity model (Verhoeven, Thebault, Labitron, Houliez, and Langhans 2021).

INTERMAGNET observatory data

1. The main magnetic field contribution is removed from the hourly mean INTERMAGNET observatory data for full year 2021 using the spherical harmonic model \( \mathbf{M}_0 \) (Rapp et Leur (2020)).
2. Observatory data are selected between 23:00 - 05:00 LT and during geomagnetically quiet time (Dst between -30 nT and 30 nT) to minimize the contributions of ionospheric perturbations.

Figure 1: Distribution of the hundred or so used geomagnetic observatory positions

Parameters

- Prior information: mean prior model \( \mathbf{M}_0 \), prior covariance matrix \( \mathbf{C}_0 \)
- Analysis step: adjustment of models at the \( k \)-th hour by fitting INTERMAGNET observatory data, based on the Least Square method
- Prediction step: prediction of the next hour’s model (at the \( (k+1) \)-th hour) based on the previous adjusted hourly model (at the \( k \)-th hour)
- Smoothing step: a posteriori smoothing of the calculated, series, based on conditioning rules of Gaussian distribution

Approach – Kalman Filter

Results applied to real data

Future works

- The hourly model needs to be extended to cover 1999 to 2024
- Improvement of hourly model: observatory data including day side should be used. The ionospheric contribution distribution of each component at each observatory should be co-estimated, and a correlation of ionospheric contributions among observatories should be added as a priori information
- Statistics from theoretical or semi-empirical models to separate the different contributions in the magnetosphere could be used, in order to develop a better understanding of the evolution of magnetospheric sources during solar cycles

References


The distribution of residuals over year 2021 for each component at each observatory is calculated. Most of observatories have an annual average residual nearby 0 nT and an annual residual standard deviation smaller than 10 nT, except some observatories located at high latitudes shown in figure 6 where the residual standard deviation can reach 90 nT

Figure 6: Distribution of the 23 geomagnetic observatory positions with annual residual standard deviations greater than 10 nT (red) versus between observatory data and modeling signal

Figure 4: Example of the comparison between \( \Delta \) (in blue) and modeling \( \Delta \) (orange, green) for 20 days

Figure 5: Example of the comparison between \( \Delta \) (Chernobyl) and \( \Delta \) (Chernobyl) observatory data (in blue) and smoothed modeling signal (in orange) for a component over 20 days, the dotted grey line represents the annual average residual between observatory data and modeling signal

Figure 3: Top: A view of a comparison between the first 20 days between synthetic Gauss coefficient (blue) and the estimated Gauss coefficient (orange, green) by fitting only synthetic data at night (23:00 – 05:00) with error bar 3e (waver). Bottom: the number of used data at each hour

Figure 2: The left: results by fitting only night synthetic data. The right: results by fitting full-year synthetic data. Top: The diagonal elements of the model covariance matrix. Bottom: Power spectrum of SH Gauss coefficient as a function of SH degree.

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