Kuslits Lukács Benedek

Reconstruction of the source process of Earth's magnetic field based on machine learning

Thesis Booklet

Supervisor:

Viktor Wesztergom, Dr.

Director, Institute of Earth Physics and Space Science, ELRN

Eötvös University

Faculty of Science

Doctoral School of Environmental Sciences

Environmental Physics Program

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1. Introduction

Research into the Earth's internal magnetic field, in particular the geodynamo process in the liquid outer shell of the planetary core, which is largely responsible for the magnetic field, is still problematic due to many uncertainties. A significant part of these uncertainties is obviously caused by the indirect nature of the measurements (only surface observatories and satellites orbiting around the planet provide direct data on the magnetic field on a regular basis). However, the likely extreme complexity of the geodynamo process and the estimation of the physical parameters that determine it (e.g. electrical conductivity, viscosity of the outer core material) and their uncertainties are also responsible for the problematic nature of the research.

The need to reduce this uncertainty is emphasised by the increasingly important societal expectation to better understand the structural characteristics and the time evolution of the geodynamo. The main reasons behind this expectation are as follows. Firstly, the historical record of observatory measurements shows that the strength of the Earth's magnetic field has been decreasing over the last centuries. In addition, a region of weak magnetic intensity, the so-called South Atlantic geomagnetic anomaly, is emerging over the South Atlantic Ocean, with increasing spatial extent and amplitude. The magnetic field around our planet is known to provide protection against the effects of solar activity and cosmic radiation. These phenomena therefore continue to affect the operation of satellite systems, especially in the region of the abovementioned anomaly. The consequences of a direct interaction between the results of a major solar activity and Earth's weakening magnetic field might have incalculable consequences for global telecommunications, information technology systems and electrical grids.

In my doctoral thesis, I present a phenomenological approach that attempts to complement the existing efforts to map the geodynamo process, which have shown serious and promising results, with an alternative model and method of investigation.

2. Background, research objectives

Today, three main research directions aim to map the geodynamo process.

One such trend is to study the time evolution and structure of the turbulent magnetohydrodynamic process that generates and maintains the magnetic field in the outer core of the Earth, using highly computationally demanding numerical simulations.

The other simpler method, which also uses the physical framework of magnetohydrodynamics, tries to reconstruct as accurately as possible the vector field of the material flow velocities in the depth of the mantle-core interface (or core-mantle boundary - hereafter referred to as CMB).

In addition to these, the reconstruction of the geodynamo process by ensemble modelling using quasi-geostrophic models (having significant simplifications compared to complex numerical simulations) is an increasingly important research direction following the advances of the last decade. This reconstruction attempts to fit the time evolution of the magnetic fields produced by the models of the geodynamo process to the observed time evolution of the geomagnetic field on a statistical, probabilistic basis.

The aim of this research was to develop a method that tries to deal with the reconstruction problem along a different conceptual framework than the three approaches listed above. An essential element in developing the concept was the effort to bridge, at least partially, the gap between the more realistic turbulent geodynamo simulations and the reconstructions which use significant approximations. I have tried to lay the foundations of a procedure that may be able to produce a kind of independent validation and refinement of the picture obtained by current reconstruction experiments.

3. Applied methodology and results

A thorough study of the relevant literature and the results of my own calculations to model the internal processes of the Earth played a key role in my investigations. These have determined the direction and the conceptual framework for method development.

At the beginning of my research, I explored the possibilities offered by numerical simulations of the convective processes inside our planet. As part of this work, I conducted a series of numerical simulations to approximate the thermal convection in Earth's mantle. Here, I have specifically investigated the effect of dynamic viscosity on the convection intensity. I ran into the constraints imposed by this material property and the scale of the process - as viscosity decreased as a function of temperature, finer resolution and higher computational capacity were required in the models. In a later study, I examined the effect of this key parameter, among other factors, under conditions specific to the outer core. I found that viscosity values estimated for the core are comparatively extremely low. This increases the intensity of the magnetohydrodynamic process in the outer core to such an extent that the computational requirements for a hypothetical simulation that accurately models and, most importantly, predicts this process would be far beyond the capabilities of even today's computing power.

For these reasons, I have attempted to develop a concept that complements the abovementioned approaches aiming for a large-scale estimation of processes actually taking place in the core. It attempts to identify local electrical current systems as sources of magnetic field in the geodynamo, which appear in state of the art computationally intensive numerical simulations. This process of inference and identification is more broadly referred to as geophysical inversion. An essential element of the concept was to describe these current systems and their magnetic effects as completely as possible within the framework of a simplified, idealised physical model used for the inversion.

The physical model I used in this current system reconstruction essentially calculated the combined magnetic field of circular currents (current loops) for a given current system configuration. The model calculates the (primary) magnetic field of these current systems under the influence of a constant (steady-state) current in time, and also provides a source-by-source estimate of the magnetic field induced by the high conductivity of the core and the time evolution of the current systems. Finally, the reconstruction is treated as a solution of a mapping problem for each of these models and for the real data. In this interpretation, both the magnetic fields and the distributions of the estimated and true source parameters are represented as maps.

I estimated the possible assumed values of the parameters of the circular currents (their number in the models, latitude, longitude, radius, depth, current, angles of attack, variation of current) using the elementary relations for circular currents and the results of previous calculations on the geomagnetic field.

Each such model contained a randomly parameterized and specified number of current loops within the estimated constraints, and the total magnetic field of the model was always calculated for the CMB reference surface. The solution of each model was therefore computed in the form of a magnetic field map on this surface.

I calculated the primary field of circular currents for each source separately using the analytical solution of the Biot-Savart integral derived by other authors.

I determined the induced magnetic fields around the circular currents emerging due to the surrounding conductive medium of the core using a systematic series of simulations. In these simulations, I fixed the position of the circular currents, always assumed their axes to be radial, and varied the current flowing in them linearly in time. This greatly simplified the simulations and resulted in a static screening field (a secondary contribution) around the primary field of each source (current loop). This screening field depends only on the source parameters and the relative position of observation points on the CMB. Due to computational limitations, I was only able to give an approximate value of this effect at each gridpoint on the map at the CMB surface when performing the estimation task.

In the design of the estimation (inversion) algorithm, it was essential that it could solve the basic problem of estimating parameters of current systems using only their surface magnetic fields (synthetic data), which were in this case generated by the models I built. Since even the solution of this basic task is already made difficult by significant equivalence problems (different source configurations can produce very similar magnetic fields), I heavily relied on machine learning methods, mainly image processing neural networks, when implementing the algorithm. This meant that I essentially taught an image processing network to map the relationship between the magnetic fields generated by the models and the corresponding source configurations and source parameters.

The final implementation variant, which also processes real geomagnetic data, has resulted in a neural network based estimation algorithm that can reconstruct the distribution maps of all source parameters and the geographic locations of the sources. Finally, the parametrisation of the actual reconstructed physical model was derived by a genetic algorithm using data from these distribution maps.

The final result of the study was a source model reconstruction based on magnetic field maps generated from a dataset containing real geomagnetic data. The main conclusion is that the current system model carrying a time-varying current as a source model is capable of reproducing the main characteristics of the internal geomagnetic field, but is not able to track the variation of the field over time. This essentially means that using such a source model cannot simultaneously account for the field values and the time variations observed in the geomagnetic field. The reason for this discrepancy is that a change in the source currents that could reproduce the known temporal variation of the field field would have resulted in secondary (induced) contributions in the model that would have significantly exceeded the magnitude of the actual geomagnetic field itself. The output of this analysis may have wider relevance to the methods, outlined in the previous section about the research backgroud, which use the laws of magnetohydrodynamics to describe the temporal variation of the magnetic field as a result of an interplay between advection and magnetic diffusion (decay).

4. Summary, theses

1) As a starting point for the research, I modelled the thermal convection of the mantle in a 2-dimensional geometry using finite element methods. In a paper presenting the results of this study, I describe how the intensity of convection, in particular the role of dynamic viscosity, increases the number of elements in the computational mesh and the computational complexity. I find that this feature of thermal convection, which depends on viscosity as a key parameter, leads to a much more significant increase in computational complexity for the magnetohydrodynamic process in the Earth's core, which, even with the infrastructure available today, makes the reliability of reconstructions and predictions concerning the actual geodynamo process questionable.

   Related publications: [1] [2]

2) Consistent with results of geodynamo simulations reported in the literature, I have created an equivalent source model of the internal geomagnetic field by assuming the sources to be circular current loops of given radii, depths and spatial positions, carrying steady-state (stationary) currents. I have shown the applicability of the method in a geometric setting representing the Earth's core.

Related publications: [1]

3) I have developed a method based on an image processing neural network and genetic algorithm to invert all source parameters and source distributions in case of stationary current loop models from their magnetic induction vector fields given at the CMB reference surface, when the currents' axes had arbitrary angles of incidence. I showed that the inversion can be applied effectively on synthetic data.
Related publications: [1]

4) I have developed a method based on a series of simulations which allows to take into account, the effect of electrical conductivity in the Earth's core, and thus the induced secondary contribution, on the magnetic field of the sources included in the circular current model. Moreover, I did this in such a way which was computationally feasible in the inversion estimation, provided that the sources of the model conduct currents of linearly varying strength in time and their axes point in a radial direction (perpendicular at each point tot he CMB). I have demonstrated the viability of the method on synthetic data.

5) I have developed a method based on the use of image processing neural networks to estimate the effect of an induced current system in a conductive core during a joint inversion of the source parameters. I demonstrated the functionality of the inversion both on synthetic test data and a real geomagnetic data set.
Related publications: [1]

5. Scientific publications related to the topic of the thesis

Journal articles

[1] Kuslits, L.; Lemperger, I.; Horváth, A.; Koronczay, D.; Wesztergom, V. (2020) Recent progress in identification of the geomagnetic signature of 3D outer core flows, ACTA GEODAETICA ET GEOPHYSICA 55: 3 pp. 347-370., 24 p. DOI: 10.1007/s40328-020-00307-3

Independent citation:

Liu, H.; Bin, J.; Liu, Y.; Dong, H.; Liu, Z.; Mrad, N.; Blasch, E. (2021) SGCast: A New Forecasting Framework for Multilocation Geomagnetic Data With Missing Traces Based on Matrix Factorization IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT 70 Paper: 9700311, 11 p.

[2] Kuslits, LB; Farkas, MP; Galsa, A. (2014) Effect of temperature-dependent viscosity on mantle convection, ACTA GEODAETICA ET GEOPHYSICA 49: 3 pp. 249-263., 15 p. DOI: 10.1007/s40328-014-0055-7

Independent citation:

Zhu, T.; Guo, Y. (2021) Asthenospheric rheology beneath mainland China inferred from mantle flow simulation and shear-wave splitting measurements.TECTONOPHYSICS 819 Paper: 229088, 14 p.

Conference reports

Kuslits, L. B., Lemperger, I., Beggan, C., Prácser, E., Bozsó, I., & Wesztergom, V. (2019). An equivalent current system method and its application to Earth's core field. In *27th IUGG General Assembly: Beyond 100: The next century in Earth and Space Science* (p. IUGG19-2229).

Kuslits, L., Lemperger, I., Beggan, C., Prácser, E., Bozsó, I., Szalai, S., & Wesztergom, V. (2019). Machine learning equivalent source model of the Earth's magnetic field. In *Hungarian Space Research Forum 2019 - Abstracts of presentations* (p. 49).

Kuslits, L. B., Lemperger, I., Beggan, C., Prácser, E., Wesztergom, V., & Bozsó, I. (2018) An equivalent current system method and its application to Earth's core field. In *AGU Fall Meeting 2018* (p. DI21B-0003).

Kuslits, L., Wesztergom, V., Lemperger, I., & Prácser, E. (2018). Understanding the non-dipole part of the geomagnetic field by inversion. 7th IAGA/ICMA/SCOSTEP Workshop on Vertical Coupling in the Atmosphere-Ionosphere System, Potsdam

Kuslits, L., Wesztergom, V., Prácser, E., & Lemperger, I. (2018). On the possibility of assessing processes in planetary dynamos based on the recunstruction of current density distribution using a combined machine learning - genetic algorithm inversion approach. *GEOPHYSICAL RESEARCH ABSTRACTS, 20*.

Kuslits, L., Prácser, E., & Lemperger, I. (2017) On the recovery of electric currents in the liquid core of the Earth. *GEOPHYSICAL RESEARCH ABSTRACTS, 19*.

6. My publications indirectly related to my thesis

Horváth, A. , Timkó, M., Kiszely, M., Bozóki, T., Bozsó, I., & Kuslits, L., (2022). Classifying earthquakes and mining activity with deep neural networks. In *EGU General Assembly 2022: EGU22-7133*. http://doi.org/10.5194/egusphere-egu22-10382

Czirok, L., Kuslits, L., Bozsó, I., Radulian, M., & Gribovszki, K. (2022). Cluster Analysis for the Study of Stress Patterns in the Vrancea Zone (SE-Carpathians). *PURE AND APPLIED GEOPHYSICS*, *179*(10), 3693-3712. http://doi.org/10.1007/s00024-022-03159-w

Magos, L., Bozóki, T., Bozsó, I., Bór, J., Horváth, A. , Kuslits, L., ... Buzás, A. (2022). Digitizing archive atmospheric electric potential gradient data for scientific research. In *EGU General Assembly 2022: EGU22-7133*. http://doi.org/10.5194/egusphere-egu22-5228

Bozóki, T., Bór, J., Szabóné André, K., Buzás, A., Sátori, G., Steinbach, P., ... Timkó, M. (2022). AC/DC Global Electric Circuit response to the Hunga Tonga eruption. In *3rd URSI Atlantic / Asia-Pacific Radio Science Meeting Abstracts*.

Bozóki, T., Młynarczyk, J., Bozsó, I., Horváth, A., Kuslits, L., Timkó, M., Szabóné André, K., Buzás, A. , Bór, J., (2022) Towards machine learning-based classification of ELF transients. In *17th International Conference on Atmospheric Electricity - Abstracts of the Presentations*.

Czirok, L., Kuslits, L., & Gribovszki, K. (2021). Cluster analysis in the studying of stress relation in the Vrancea zone. In *EGU General Assembly 2021: Conference Abstracts.* http://doi.org/10.5194/egusphere-egu21-9749

Lemperger, I., Szendrői, J., Szabó, Cs., Kuslits, L., Kiss, A., Szalai, S., ... Wesztergom, V. (2021). Geomagnetic observation system in the Széchenyi István Geophysical Observatory. In *Geophysical Observatory Reports* (pp. 26-35).

Czirok, L., Kuslits, L., Bozsó, I., Radulian, M., & Gribovszki, K. (2021). Clustering-based stress inversions in the SE-Carpathians. In *37th General Assembly of the European Seismological Commission ESC 2021 - Book of Abstracts*.

Szalai, S., Mátyás, K. B., Attila, K., Kuslits, L., Gábor, F., Gribovszki, K., ... Szarka, L. (2020). Chapter 7, Characterisation of Fractures and Fracture Zones in a Carbonate Aquifer Using Electrical Resistivity Tomography and Pricking Probe Methods. In *International Research in Environment, Geography and Earth Science Vol. 6* (Vol. 6, pp. 77-96).

Czirok, L., Kuslits, L., Bozsó, I., Gribovszki, K., & Bányai, L. (2019). Seismotectonic analysis using GIS and stress inversions in the SE-Carpathians. Presentation on Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations, ICTP, Trieste, Italy.

Czirok, L., Kuslits, L., & Bozsó, I. (2019). Effects of the Different Types of Earthquake-Classifications on Stress Inversions (in the SE-Carpathians). In *27th IUGG General Assembly: Beyond 100: The next century in Earth and Space Science* (p. S20p-142).

Czirok, L., Bozsó, I., Kuslits, L., & Bányai, L. (2019). A Seismo-tectonic Information System for monitoring the tectonic variations in the Carpathian Bend. *GEOPHYSICAL RESEARCH ABSTRACTS*, *21st*, Paper: EGU2019-6933 (2019)

Erdős, G., Hevesi, L., Kuslits, L., Lemperger, I., Lichtenberger, J., Németh, Z., ... Wesztergom, V. (2019). Establishment of a Magnetic Zero Field Laboratory (ZBL). In *Hungarian Space Research Forum 2019 - Summaries of presentations* (pp. 29-29).

Kiss, Á., Lemperger, I., Michel, M., Novák, A., Wesztergom, V. & Kuslits, L., (2018) A Long Term Study of the Electromagnetic and Vertical Magnetic Transfer Function, In *AGU Fall Meeting 2018* (p. 1).

Czirok, L., & Kuslits, L. (2018). Effects of earthquake data-clusterization on stress inversions. In *Book of Abstracts of 36th General Assembly of the European Seismological Commission (ESC2018)* (pp. 296-296). http://doi.org/10.13140/RG.2.2.34459.72480

Czirok, L., & Kuslits, L., (2018). Effects of earthquake data clustering on the results of stress inversions.*GEOSCIENCES AND ENGINEERING: A PUBLICATION OF THE UNIVERSITY OF MISCOLC*, *6*(9), 127-141.

Szalai, S., Kovács, A., Kuslits, L., Facskó, G., Gribovszki, K., Kalmár, J., & Szarka, L. (2018). Characterisation of Fractures and Fracture Zones in a Carbonate Aquifer Using Electrical Resistivity Tomography and Pricking Probe Methods. *JOURNAL OF GEOSCIENCE AND ENVIRONMENT PROTECTION*, *6*(4), 1-21. http://doi.org/10.4236/gep.2018.64001

Lemperger, I., Wesztergom, V. Michel, M., Szalai, S., Kiss, A., Novák, A., ... Kuslits, L., (2016). Effect of ionospheric current system geometry on local surface EM observation - a theoretical model. In *AGU Chapman Conference*.