Predicting the next global geomagnetic reversal using machine learning

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Background

The Earth's magnetic field, generated by turbulent convection in the liquid outer core, has reversed many times over its 3.5 billion-year history, at a present rate of about 2-3 times per million years (Stern, 2002) The last global reversal took place 780,000 years ago, leading to speculation that we are "overdue". This fact, coupled with the observations that the field is weakening in the south Atlantic (the so-called south Atlantic anomaly) and the dipole is presently decaying at a rate of 5% per century, suggests that the magnetic field may be headed for a reversal. However, predicting future magnetic field variations is challenging, in part because we don't yet have a complete physical description of the geodynamo within the core.

Despite these challenges, at our disposal is a large set of observations of the Earth's magnetic field, describing its polarity state over millions of years, and in more recent centuries higher resolution observations from shipping records and ground-based observatories which have enabled maps of the field to be reconstructed (see figure 1). Since the beginning of the satellite era, several decades of very high quality satellite data now show the evolution of the geomagnetic field in unprecedented detail (e.g. Finlay et al., 2016). To date, studies using data to constrain the geodynamo process within the core have been reliant on a mix of human subjectivity and physics-based models.

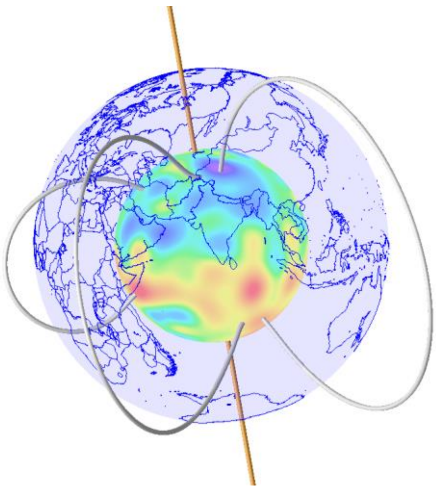

Figure 1: Observations of the Earth's internal field taken from the surface constrain the structure at the edge of the core (the source region), shown by selected field lines. The sign of the outwards/inwards pointing magnetic field is shown as red/blue. The future structure of the magnetic field is the focus of this project.

The novel aspect of this project is to apply recent advances in machine learning to the prediction of Earth's magnetic field. Machine learning is a technique in which computers 'learn' to interpret data via an explicit training process, using neural networks for example. Such algorithms have been used with great success in, for example, spotting patterns in consumer spending, speech recognition and in recommending movies within Netflix (e.g. see the Wikipedia page). In some studies, machine learning has been shown to predict the next frames of video from a static image (Vondrick et al. 2016). In this project, we will train neural networks to learn how the magnetic field has changed, and to assess its predictability. The algorithms are entirely data-driven and do not rely on any physical model or numerical simulation. The key idea behind the project is that such trained neural networks may be able to spot patterns in the data that have so far either not been noticed or have been too complex to interpret; such networks may be able to supply accurate short-time forecasts of the internally generated magnetic field. Ultimately, the goal is to assess evidence for whether the geomagnetic field is likely to reverse.

The objectives of the PhD project are as follows:

1. Assess predictability for the million-year evolution of the geomagnetic dipole using the model PADM2M (Ziegler et al., 2011) using hindcasting, and compare with other predictions (e.g. Buffett and Davis, 2018).
2. Investigate predictability of the global magnetic field using a 400-yr observation-derived model (gufm1, Jackson et al. 2000) using a technique that predicts the next frames of a global movie of the evolving magnetic field (e.g. Vondrick et al. 2016). These or similar techniques will also be applied to observatory data sets and the latest satellite data using virtual observatories (Mandea & Olsen, 2006) to assess the predictability of features in the magnetic field such as geomagnetic jerks (e.g. Cox and Brown, 2013).
3. Assessment of predictability of a neural network trained not on real geomagnetic data, but on the output of a numerical simulation of Earth's magnetic field: for example, the coupled Earth model of Aubert et al., 2013 or the database of simulated magnetic reversals under development at Leeds. A prediction of the trained network based on a past static image of the real geomagnetic field will allow us to quantify whether or not the training data is compatible with Earth's true dynamics, in other words, it will provide an important measure on whether or not the numerical models are a faithful representation of the Earth's core.

Milestones

Year 1: Familiarisation with neural networks, geomagnetic observations and the theory of the dynamics of Earth's core. Assessment of the dipole time series PADM2M.

Year 2: Application of machine learning to global geomagnetic data sets and assessment of predictability.

Year 3: Application of machine learning algorithms applied to the output of numerical simulations of the Earth's core; comparison to the real geomagnetic signal.

Potential for high impact outcome

Explaining important features in the Earth's magnetic field is an international endeavour and of wide interest. Studies of models of the dynamics of Earth's core date back to the 1950's and have been published in high impact journals such as Nature and Science. Being able to predict the Earth's magnetic field would be paradigm changing.

Training

The student will learn techniques of machine learning using both Matlab and Python, and will have the opportunity to take relevant specific undergraduate or masters level courses. The student will also have access to a broad spectrum of training workshops at Leeds that include techniques in numerical modelling, through to managing your degree and preparing for your viva. The student will be a part of the deep Earth research group, a vibrant part of the Institute of Geophysics and Tectonics, comprising staff members, postdocs and PhD students. The deep Earth group has a strong portfolio of international collaborators which the student will benefit from.

Although the project will be based at Leeds, there are project partners in both Edinburgh and Copenhagen who the student will visit. There will also be opportunities to attend international conferences (UK, Europe, US and elsewhere), and other possible collaborative visits within Europe.

Requirements
We seek a highly motivated candidate with a strong background in mathematics, physics, computation, geophysics or another highly numerate discipline. Knowledge of geomagnetism is not required, and training will be given in all aspects of the PhD. For further information please contact Phil Livermore (p.w.livermore@leeds.ac.uk) or Chris Davies (C.Davies@leeds.ac.uk).

Other opportunities
The Deep Earth Research Group in Leeds (http://www.see.leeds.ac.uk/research/igt/deep-earth-research/) is one of the largest groups of scientists studying the structure and dynamics of Earth's core and mantle in the world. Research topics include the dynamics and structure of the Earth's magnetic field and convection in the outer core, material properties under high pressure and temperature and Global Seismology. The Group collaborates closely with the Department of Applied Mathematics in Leeds and Deep Earth research groups worldwide. Dr Livermore is interested in the dynamics of the core and geomagnetism. Please contact him (p.w.livermore@leeds.ac.uk) to discuss further PhD opportunities.

References

Aubert, J., Finlay, C. C., & Fournier, A. (2013). Bottom-up control of geomagnetic secular variation by the Earth's inner core. *Nature*, *502*(7470), 219–223. http://doi.org/10.1038/nature12574

Cox, G A, and Brown, W J. 2013. Rapid dynamics of the Earth's core *Astronomy and Geophysics*, 54(5)5.32-5.37

Buffett, B., & Davis, W. (2018). A Probabilistic Assessment of the Next Geomagnetic Reversal. *Geophysical Research Letters*, *45*(4), 1845–1850. http://doi.org/10.1002/2018GL077061

Finlay, C. C., Olsen, N., Kotsiaros, S., Gillet, N., & Tøffner-Clausen, L. (2016). Recent geomagnetic secular variation from Swarm and ground observatories as estimated in the CHAOS-6 geomagnetic field model. *Earth Planets and Space*, *68*(1), 1–18. http://doi.org/10.1186/s40623-016-0486-1

Jackson, A., Jonkers, A., & Walker, M. (2000). Four centuries of geomagnetic secular variation from historical records. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences*, *358*(1768), 957–990.

Mandea, M., & Olsen, N. (2006). A new approach to directly determine the secular variation from magnetic satellite observations. *Geophysical Research Letters*, *33*(15), L15306. http://doi.org/10.1029/2006GL026616

Stern, D. A (2002) Millennium of Geomagnetism, online material: http://www.phy6.org/earthmag/mill_1.htm

Vondrick, C., Pirsiavash, H. & Torralba, A. (2016) Generating Videos with Scene Dynamics, NIPS https://arxiv.org/abs/1609.02612

Ziegler, L. B., Constable, C. G., Johnson, C. L., & Tauxe, L. (2011). PADM2M: a penalized maximum likelihood model of the 0-2 Ma palaeomagnetic axial dipole moment. *Geophysical Journal International*, *184*(3), 1069–1089. http://doi.org/10.1111/j.1365-246X.2010.04905.x