Space-Based Observations for Geomagnetic Modeling

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Summary: *Over the past fifteen years, thanks to three very successful European satellite missions, geomagnetic field modeling has made tremendous progress but also become heavily reliant on space-based observations. Using high-precision data from the Low Earth Orbit Ørsted, CHAMP and Swarm missions, the National Oceanic and Atmospheric Administration (NOAA) has developed enhanced operational models addressing the ever-increasing needs of accuracy sensitive users in government and industry. The same data have also brought new insights into the geodynamo and the various sources of the Earth's magnetic field, prompting new research questions for geomagnetism and Earth System science. However, the current Swarm mission is likely to end in 2021, putting at risk the performance of future models supporting NOAA, Department of Defense, and Federal Aviation Administration operations and further progress in geomagnetic research. Neither ground-based magnetic measurements nor magnetic data from non-dedicated satellite missions can provide a viable alternative to Swarm-like data. We argue for the need to launch a new constellation of magnetic satellites that would build upon the knowledge acquired from Swarm, ensure the continuous support of enhanced navigation, resource exploration and directional drilling by research and operational models and further our understanding of geomagnetic sources.*

1) What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

Geomagnetic field models are mathematical representations of the Earth's magnetic field inferred from ground and space-based observations. They are widely used for investigating the spatial and temporal characteristics of the geomagnetic field and its sources, but also in an operational context, for orienting a satellite, positioning a submarine or navigating a drill bit. Over the past fifteen years, enormous progress has been made in the field of geomagnetic modeling thanks to a stream of high-precision, Low Earth Orbit (LEO) magnetic satellite missions launched by Denmark (Ørsted, 1999-2013), Germany (CHAMP, 2000-2009) and the European Space Agency (Swarm, since 2013). Data-based models of increasing spatial and temporal resolutions have been developed, furthering the use of operational models by government and industry and opening up new scientific questions.

A key operational challenge: developing and improving NOAA's operational geomagnetic models

The National Oceanic and Atmospheric Administration (NOAA)'s National Centers for Environmental Information (NCEI) have the responsibility of developing operational geomagnetic models for government and industry. These models support enhanced navigation, resource exploration and directional drilling. Three models are currently being produced by NOAA:

- The World Magnetic Model (WMM) is a low-resolution model (up to degree 12 of the spherical harmonic expansion), produced at 5-year intervals (Chulliat et al., 2015). It is used extensively by the Department of Defense (DoD) in a wide range of positioning and navigation system applications, including all aircraft, ships, submarines, and GPS units within DoD and the North Atlantic Treaty Organization (NATO). The WMM is also widely used by the International Hydrographic Organization (IHO), the Federal Aviation Administration (FAA), NOAA, and in a very large number of hand-held devices, including over one billion smartphones. It is a joint product of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defence Geographic Centre (DGC), and is jointly developed by NCEI and the British Geological Survey (BGS). The current WMM has been downloaded over 16000 times since its release in December 2014 and the WMM online calculators receive about 10 million hits/yr.
- The Enhanced Magnetic Model (EMM) is a higher resolution model, resolving anomalies down to 56 km wavelength and addressing the needs of accuracy-sensitive users such as the DoD and the resource exploration industry. The latest EMM was released in May 2015 and has already been downloaded over 900 times.
- The High Definition Geomagnetic Model (HDGM) is a global, high-resolution model coming with software tailored to the needs of the directional drilling industry and is updated every year. It is used by over 20 companies worldwide.

Magnetic models need to be regularly updated, due to the slow but unpredictable secular variation of the core field. Moreover, there is a constant demand from government and industry for higher accuracy and higher resolution. Addressing such needs will require further development of integrated models of the crustal magnetic field, combining marine trackline data, aeromagnetic survey data and satellite data. In addition to the improved spatial resolution, more sophisticated models, including models updated in real-time, are needed to describe the rapidly varying magnetic fields generated by electric currents in the ionosphere and magnetosphere. As will be explained in section 3 below, this cannot be done without the continuous availability of high-precision, space-based geomagnetic observations in the coming decade.

New research questions

Despite progress in observations and numerical simulations over the past decade, understanding how the geodynamo works remains one of the biggest questions in Earth science. For example, we are still unable to predict how long the current decay of the dipole field will last, or when the next geomagnetic reversal will occur. These questions are intimately linked to our understanding of the outer core structure and dynamics and of the Earth energy budget as a whole. They also have practical implications, as the geomagnetic field is shielding the Earth from charged particles coming from the Sun and the outer space. Recent advances in geomagnetic modeling have led to new questions regarding the geodynamo but also the other sources of the Earth's magnetic field.

a. *Understanding short-term fluctuations in the geodynamo.* Over the past decade, space-based magnetic measurements have made it possible to model not only the core field and its secular variation, but also the rapid fluctuations in the secular variation, of time scales of only a few years. Global models have revealed the existence of core field pulses at three-year interval (Chulliat et al., 2010; Finlay et al., 2015), which might be the result of magnetic Rossby waves propagating in a stably stratified layer at the top of the core (Chulliat et al., 2015). The existence of such a layer would be in agreement with recent results from seismic data (Hellfrich and Kaneshima, 2010) and observations of MAC waves from historical magnetic data (Buffett, 2014), but in contradiction to the dominant scenario of a fully-mixed outer core. Key research questions in the coming years will be to understand what produces rapid fluctuations in the core field and investigate to which extent such fluctuations can be forecasted.
b. *Improving the separation of internal and external magnetic fields.* The geomagnetic field is comprised of many sources, some of which originate in the Earth's interior (internal sources), while others originate in the upper atmosphere and magnetosphere (external sources). When investigating core flows, secular variation and acceleration, mantle resistivity and induction, or small-scale crustal fields, great care must be taken to separate the source of interest from the complex external fields. In the past decade, data from the CHAMP and Swarm satellites enabled the detection and characterization of various ionospheric current systems (e.g., Stolle et al, 2006; Alken and Maus, 2010; Iyemori et al, 2015) and the global modeling of the large-scale magnetospheric field and its induced counterpart at ground and LEO altitudes (Maus and Lühr, 2005). These progresses have led to new questions regarding the spatial structure of the many different ionospheric and magnetospheric current systems, their temporal evolution during quiet and disturbed times and how our knowledge of these currents can be used to improve geomagnetic models.
c. *Detecting ocean circulation generated magnetic signals.* The Ocean's salinity provides it a significant electrical conductivity. All forms of ocean flow pass through the Earth's main magnetic field generating electrical currents that in turn induce secondary electromagnetic field bearing the signature of the water transport. The oceanic motion induced magnetic anomalies have been predicted at sea level and at satellite altitudes (e.g., Manoj et al. 2006). The tidal ocean signal has been recognized from the magnetic measurements of the CHAMP satellite (Tyler et al. 2003). But magnetic anomalies from the non-tidal part of the oceanic circulation have not yet been detected in satellite magnetic data. Identification of magnetic signals from the ocean circulation in satellite data could help further our knowledge on global transport of heat, chemicals (e.g. CO2) and nutrients for marine life.

2) Why are these challenges/questions timely to address now especially with respect to readiness?

Today, NOAA's models are in high demand by government and industry. The WMM is DoD's standard model and its performances have to meet military specification MIL-89500. Advanced models, such as the EMM and HDGM, are part of a broader research field investigating alternate (non-GPS) navigation technologies relying on a naturally occurring measurement sources. Further development and improvement of the EMM and HDGM will be needed to harness the full potential of geomagnetic models for navigation in both the military and civilian realms. Basic research on the various geomagnetic sources, and particularly the questions outlined in section 1, is a prerequisite to achieving such improvements. This is all the more true now that the research focus is on the smallest contributions to the total geomagnetic field, which are harder to properly characterize and separate from each other.

After 15 years of nearly-continuous space-based observations, several research groups in the U.S. and in Europe have established themselves as experts in geomagnetic modeling. The preparation of the ongoing Swarm mission catalyzed collaborations among these groups, many of whom are part of Swarm's Satellite Constellation Application and Research Facility (SCARF) consortium (Olsen et al., 2013). It led to the emergence of constellation-based geomagnetic modeling as a new technique whose potential has yet to be fully realized. Moreover, after three successful missions (Ørsted, CHAMP and Swarm), the technology of high-precision magnetic measurements in LEO is mature and could easily be reused in future missions.

3) Why are space-based observations fundamental to addressing these challenges/questions?

None of the challenges/questions listed in section 1 can be successfully addressed without a nearly-continuous stream of high-precision, global, space-based magnetic measurements in the coming decade. This applies both to ensuring continuity of the WMM and improving the EMM and HDGM.

Today, space-based observations are provided by the European Space Agency (ESA) Swarm mission, which comprises three LEO satellites. Swarm was launched in November 2013 and will fly until 2018, with possible extension until 2021 (to be decided in 2017). It provides unrestricted data access to U.S. scientists and effectively meets current needs for space-based geomagnetic observations. However, there currently is no funded magnetic satellite project for the second part of the upcoming decade.

Figure 1 shows what the impact would be on the WMM if no satellite were to be launched by 2025. The model would be unable to meet the military specification for the declination a high-latitudes, even at the beginning of the validity interval. This is because, in the absence of satellite data, models such as the WMM are solely based upon ground data that are too geographically sparse to enable accurate determination of the smaller spatial scales. Ground data are provided by the global network of magnetic observatories, including the 14 observatories operated by the United States Geological Survey (USGS). It is worth noting that observatory data, although not sufficient to build accurate global models, are included in many such models and extensively used in validating them.

Magnetic observations from non-dedicated satellite missions, such as the Defense Meteorological Satellite Program (DMSP), are also useful for geomagnetic modeling and have recently been used to bridge a gap in data availability between the CHAMP and Swarm missions (Alken et al, 2014). However, the precision of such observations is not enough to address the research questions outlined in section 1 and operational models derived from them would be of significantly degraded quality compared to current models.

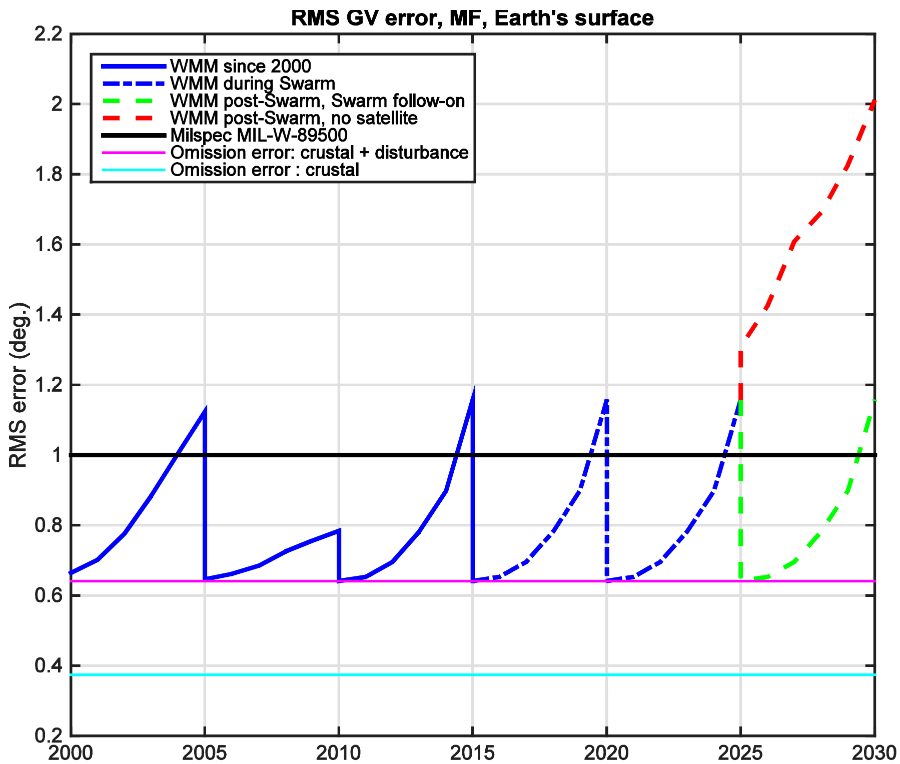

Figure 1: Root-mean-square declination error of the WMM at high latitudes (>±55°). The total error is the superposition of the error made by omitting the crustal and external fields in the model, and the error of the model itself. The latter is very small at model epochs (2000, 2005, etc.) but increases in time due to the forecast error. The actual error (inferred a posteriori) is shown from 2000 to 2015 (in blue). The military specification for the WMM is shown as a black line. Estimated errors are shown after 2015, assuming Swarm continues until at least 2020, and a Swarm follow-on mission is launched (in green) or not (in red) before 2025.

Single satellites can rapidly orbit the planet, allowing the study of the geomagnetic field at many different length scales, however only multi-satellite missions, sampling the field simultaneously at different local times can also achieve the recovery of the temporal structure, which is crucial for separating the many contributions to the total field, which all vary on different temporal and spatial scales. Moreover, a pair of satellites flying side-by-side in an East-West configuration such as in Swarm allows the use of the gradient information for detecting the smallest signals generated in the crust and oceans. Improved models of various internal and external fields are already being developed based upon Swarm data (e.g., Olsen et al, 2015) and the next generation of models will need to rely upon future constellation missions.

In 2002, NASA's Solid Earth Science Working Group (SESWG) made the case for continuous, space-based geomagnetic observations and recommended the launch of constellations of magnetic satellites in varying orbits (SESWG, 2002). This report was later reviewed by NRC, which "strongly supported these recommendations and noted that the Swarm mission (…) planned for launch by the European Space Agency in 2009 would largely satisfy the SESWG goals" (NRC, 2007). Fifteen years later, and as no Swarm follow-on is planned, the case made by the SESWG is still valid and even further strengthened by the new questions and challenges outlined in section 1. A future U.S. mission could build upon the experience accumulated during the Swarm mission and aim for an even better designed constellation.

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