Modeling Earth's Ever-Shifting Magnetism

The World Magnetic Model, updated every 5 years through an international collaboration, supports numerous technologies that help us find our way.

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By Arnaud Chulliat, William Brown, Patrick Alken, Susan Macmillan, and Michael Paniccia 3 hours ago

On a day-to-day basis, most of us probably take for granted how much Earth's deep inner workings affect some of modern life's conveniences, like the relative ease with which we find our way from place to place by plane, boat, or automobile or on foot. Roughly 2,900 kilometers below the planet's surface, convection of molten iron and nickel in the outer

Tracking Magnetic Fields

core generates Earth's magnetic field, which guides navigation technology from handheld compasses to complex automated systems.

To help these systems make sense of the magnetic field—which constantly shifts about (https://eos.org/features/the-herky-jerky-weirdness-of-earths-magnetic-field), sometimes gradually and sometimes not—and navigate accurately, they make use of models that provide assessments of the current state of the magnetic field and predictions of how it will change in the future. One such model is the World Magnetic Model (https://www.ngdc.noaa.gov/geomag/WMM/) (WMM), a geomagnetic reference model representing the main component of the magnetic field—that is, the field produced by Earth's outer core geodynamo.

The WMM is widely used by government, industry, and the public for orientation and navigation. For example, the U.S. Federal Aviation Administration relies on the WMM to provide accurate magnetic field referencing in the National Airspace System, including for runway numbering. NOAA uses the WMM in nautical charts and for orienting ocean reference station buoys. It is also used by government and industry in antenna tracking, attitude control of aircraft and spacecraft, surveying, and mapping. And as the WMM is embedded in billions of handheld electronic devices, including in navigation apps on smartphones, it is a truly ubiquitous scientific product.

The model, first named the World Magnetic Model in 1990, is a modern successor to magnetic field mapping efforts dating back to 1701, when Edmond Halley first published (https://www.tandfonline.com/doi/abs/10.1080/03085694.2017.1242841?journalCode=rimu20) a magnetic chart. Today's WMM is developed in a partnership between NOAA's National Centers for Environmental Information (NCEI) and the British Geological Survey (BGS) and is a joint product of the U.S. National Geospatial-Intelligence Agency (NGA) and the U.K.'s Defence Geographic Centre.

Monitoring the magnetic field and maintaining the WMM to support all these applications is a continuous effort for these agencies and one that occasionally poses unexpected and timely challenges.

Under the Hood of the WMM

Mathematically, the WMM is a spherical harmonic model (https://academic.oup.com/gji/article/206/1/142/2606501) (of degree and order 12) that provides a snapshot of the core-generated magnetic field as well as its time-varying change, known as secular variation, at a given time. The snapshot and time-varying parts of the model each comprise 168 coefficients—yielding a total of 336 coefficients for the complete model—that describe the direction and intensity of the field. The model captures spatial features in the field to a resolution of about 3,000 kilometers at Earth's surface, and it is updated every 5 years, providing a linear extrapolation of the magnetic field 5 years into the future based on the field's rate of change at the time the model is updated.

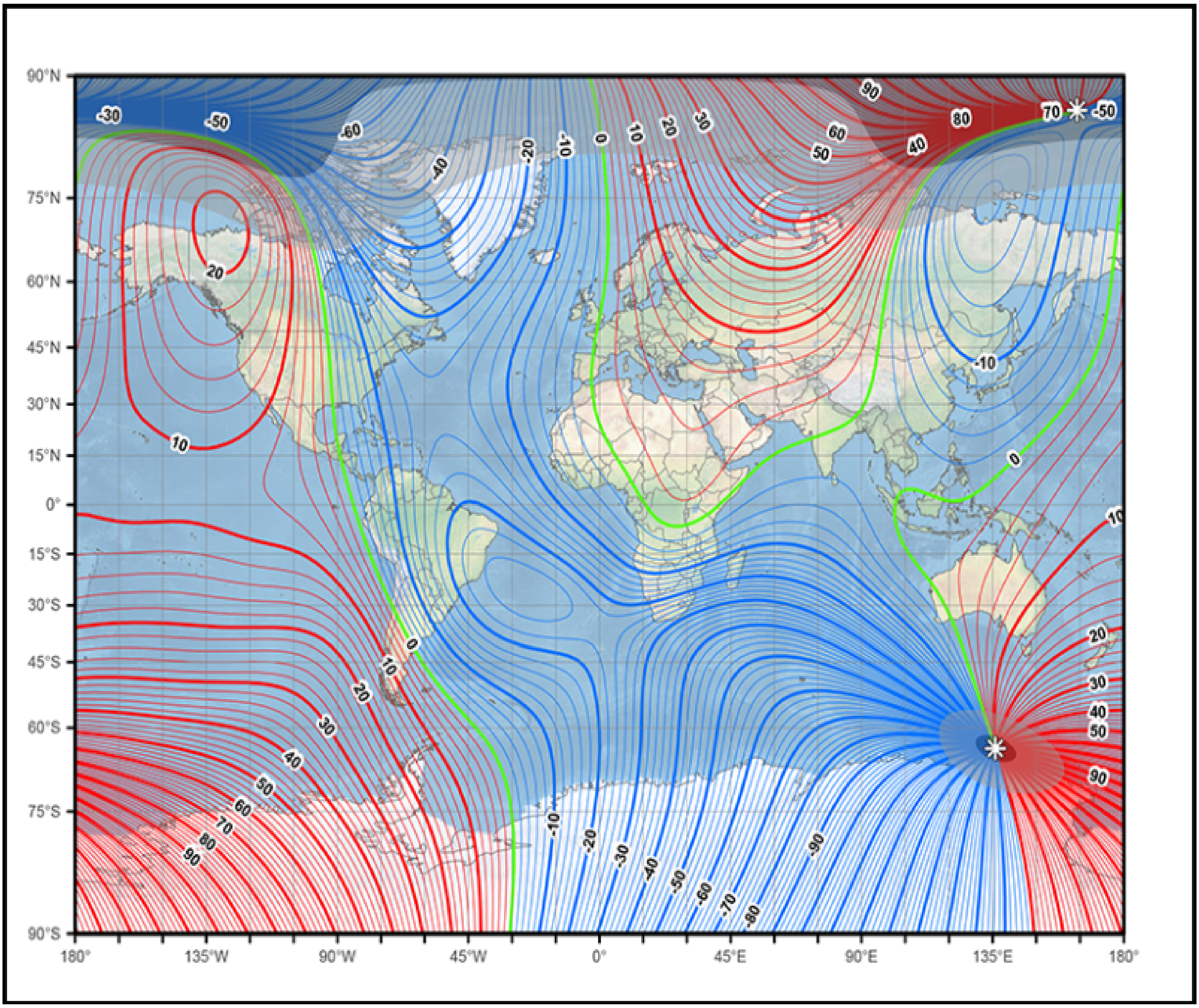

Fig. 1. Magnetic declination at the surface of the World Geodetic System (WGS 84) ellipsoid on 1 January 2020 as predicted by the most recent World Magnetic Model (WMM2020) is shown in this

Miller projection. The contour interval is 2°. Red contours are positive (east), blue are negative (west), and green represent the zero (agonic) line. White stars indicate the 2020.0 positions of the dip poles. Blackout zones are shown as dark shaded areas.

The latest update, WMM2020, was released in December 2019 and is valid until 31 December 2024 [*Chulliat et al.* (https://doi.org/10.25923/ytk1-yx35), 2020]. WMM2020 provides the vector magnetic field everywhere from 1 kilometer below the World Geodetic System (WGS 84 (https://earth-info.nga.mil/GandG/update/index.php?dir=wgs84&action=wgs84)) ellipsoid—a standardized approximation of Earth’s surface—to approximately 850 kilometers above it. Figure 1, for example, shows the magnetic declination (the angle between the direction of geographic north and the local direction of the horizontal magnetic field) predicted by WMM2020 on 1 January 2020 at the surface of the WGS 84 ellipsoid.

Prior to the satellite era, the global network of magnetic observatories was the primary source of high-quality data for the WMM, combined with data collected from boats and planes.
WMM coefficients are inferred from the best magnetic field measurements available at the time of model development. Since 1999, high-quality measurements have been collected almost without interruption by various low-Earth orbit (LEO) scientific satellites such as Ørsted (https://www.space.dtu.dk/english/research/projects/project-descriptions/oersted), CHAMP (https://www.gfz-potsdam.de/en/section/geomagnetism/infrastructure/champ/) (Challenging Minisatellite Payload), SAC-C (https://directory.eoportal.org/web/eoportal/satellite-missions/s/sac-c) (Satélite de Aplicaciones Científicas-C), and the European Space Agency’s ongoing Swarm (https://earth.esa.int/eogateway/missions/swarm?text=swarm) mission. Because of their global coverage and high accuracy, these data have greatly facilitated the development of successive WMMs over the past 2 decades.

Prior to the satellite era, the global network of magnetic observatories (under the auspices of the International Association of Geomagnetism and Aeronomy (http://www.iaga-aiga.org/) and the International Real-time Magnetic Observatory Network (https://intermagnet.github.io/)) was the primary source of high-quality data for the WMM and other similar reference models, combined with data collected from boats and planes in areas poorly covered by observatories. Magnetic observatories are specifically designed to track geomagnetic secular variation over a long period of time, and some date back to the early stages of continuous magnetic field measurements made in Europe in the 1830s. Today magnetic data from observatories are still heavily used in WMM development, for example, in helping select which satellite data are used on the basis of global geomagnetic activity and to improve local time coverage.

Accounting for Model Omissions

Criteria to be met by the WMM for its operational use are established in a U.S. Department of Defense (DOD) specification [*Department of Defense* (http://everyspec.com/MIL-PRF/MIL-PRF-080000-

99999/MIL-PRF-89500B_56010/), 2019], which is also referred to by a NATO standard [*NATO Standardization Agency*, 2011]. The specification was recently updated, but the model format, including the coefficients that describe it, hasn't changed in decades. The permanence of the model format facilitates easy adoption of regular model updates by users, which is critical in maintaining the model's performance and in meeting the DOD criteria. However, it also means that the model has limitations compared with other, more sophisticated geomagnetic reference models, such as NOAA's High Definition Geomagnetic Model (https://ngdc.noaa.gov/geomag/HDGM/index.html) and the BGS Global Geomagnetic Model (https://geomag.bgs.ac.uk/data_service/directionaldrilling/bggm.html).

Magnetic field features smaller than about 3,000 kilometers are omitted from the model. They include some core field contributions as well as most features generated by magnetism in Earth's crust. The corresponding error in the WMM from these omissions is highly variable with geography and can reach up to several thousand nanoteslas near intense crustal magnetic anomalies.

Even a seemingly small error in the model can lead to large errors in navigation, so it is important to understand and characterize the sources of error to inform users about these limitations.
The model does not account for magnetic fields generated outside the solid Earth, including, for example, by electric currents in the ionosphere and magnetosphere. Such so-called disturbance fields are only a few nanoteslas at night during geomagnetically quiet times at middle and low latitudes but can reach thousands of nanoteslas at high latitudes during magnetic storms. They are accompanied by induced magnetic fields in electrically conducting layers of the solid Earth, like the mantle and the ocean. Induced fields are generally omitted by the WMM, unless their timescales are greater than a few years, in which case they are indistinguishable from the linear secular variation of the core field.

Although the core field varies slowly in time, it can also display nonlinear changes over periods of a few years. The amplitudes of such variations are generally small (less than a few tens of nanoteslas) but, nonetheless, are detectable both in long-term recordings made by ground-based magnetic observatories and in LEO satellite measurements. With its 5-year predictive outlook, the WMM is not designed to account for such quick changes.

From a practical point of view, these limitations can affect the accuracy of navigation systems and other applications relying on the WMM. Even a seemingly small error of a single degree in the declination described by the model, for example, can lead to large errors in navigation. So it is important to understand and characterize the sources of error in the WMM and to inform users about these limitations.

Recently, NCEI and BGS performed a comprehensive uncertainty analysis of the model [*Chulliat et al.* (https://doi.org/10.25923/ytk1-yx35), 2020]. Both groups independently determined the error associated with omitting the crustal magnetic field by comparing model outputs with data from marine track lines and ground observatories collected since 2000 along with repeat station data collected since

1980. (Repeat stations are permanently marked sites where the geomagnetic field is measured every few years.) Error from omitting disturbance fields was also estimated by comparing model outputs with observatory data since 2000. And the model commission error, defined as the error in model coefficients, was determined by comparing core field models calculated by both groups and by retrospectively comparing the 5-year predictions from old WMM versions with those from recent models calculated using all the data available over the past 20 years.

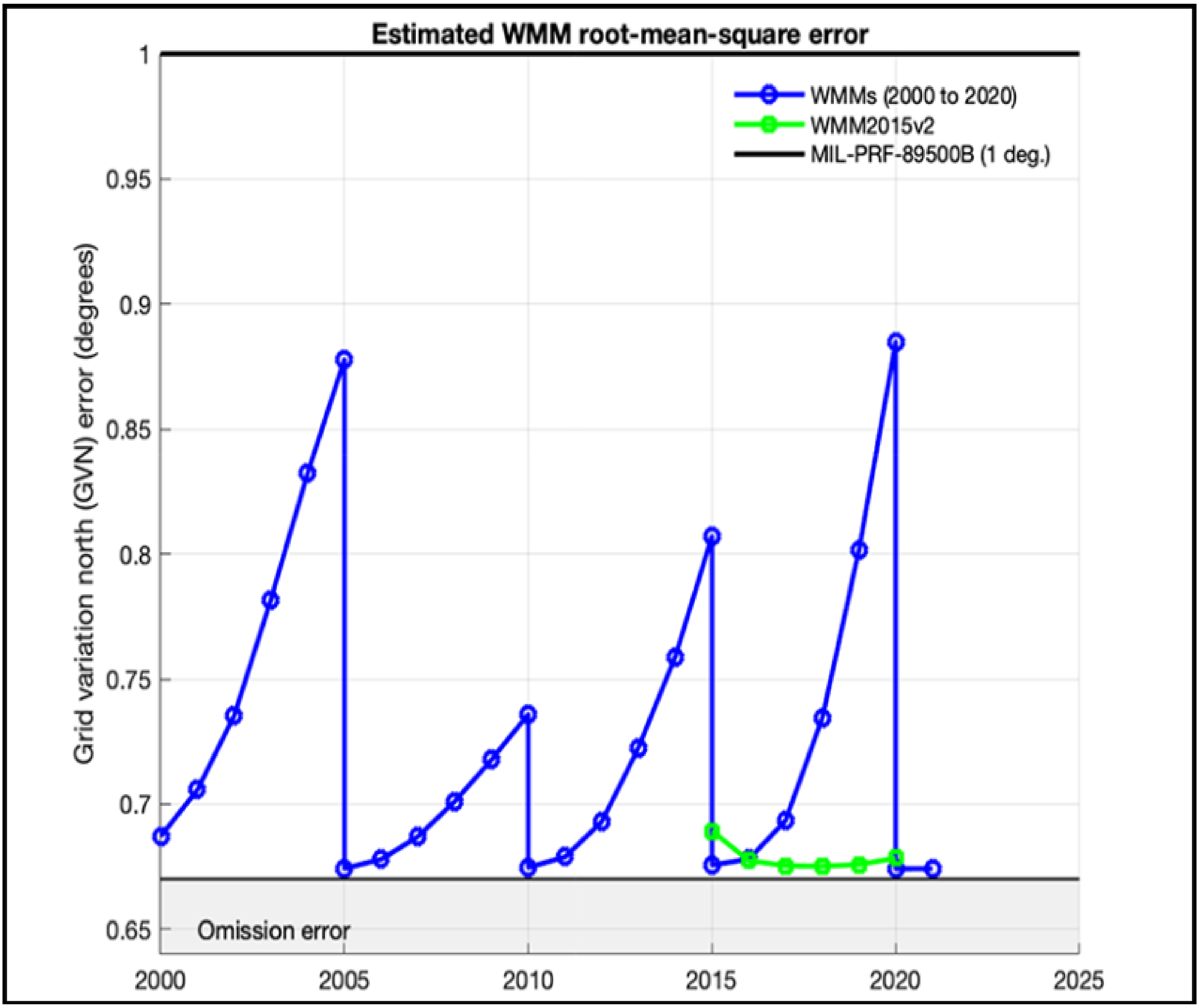

Fig. 2. The time evolution of the global RMS grid variation error in the Northern Hemisphere for all WMMs since 2000 is shown in this figure. The omission error, assumed to be constant over time, is shown as a gray rectangle at bottom.

The combined error for each magnetic field component (e.g., in *X*, *Y*, and *Z* coordinates, in declination, etc.) in the WMM, obtained by adding all errors from the contributing sources described above, has a characteristic sawtooth-like shape. Figure 2 shows an example of a sawtooth diagram for the grid variation in the Northern Hemisphere. (Grid variation is defined as the difference between declination and local longitude above 55° latitude; its error is the same as that of the declination.)

When a new version of the model is released every 5 years, the total error reflects the sum of all omission errors and the very small commission error at the time. Note that this total error was larger in 2000, before high-quality LEO magnetic field measurements became available. Over time, the combined error increases, mostly from the cumulative effects of nonlinear secular variation.

Corrections and Improvements

Performance of the WMM is carefully monitored by NCEI and BGS. Every year, both organizations develop research core field models from the most recent data available to estimate the current error of the WMM and update the "sawtooth" error diagram for each component. In 2018, NCEI, BGS, and NGA projected that the WMM root-mean-square (RMS) error in grid variation would exceed 1°, the maximum level of allowable error set by the DOD specification for the model. The rapidly rising error was mostly a result of the occurrence of intense nonlinear core field variations following the release of WMM2015. The effect of such variations on the declination error was geometrically amplified near magnetic dip poles, locations where the magnetic field is exactly vertical (and therefore where declination is undefined).

With every scheduled—and unscheduled—release of the WMM, the developers are looking for ways to improve the model and incorporate data from different sources.
To bring the model back into line with the specification, an out-of-cycle updated WMM (https://www.ncei.noaa.gov/news/world-magnetic-model-out-cycle-release) was released (WMM2015v2) [*Chulliat et al.* (https://doi.org/10.25921/xhr3-0t19), 2019]. The WMM specification was also revised with the introduction of so-called blackout zones [*Department of Defense* (http://everyspec.com/MIL-PRF/MIL-PRF-080000-99999/MIL-PRF-89500B_56010/), 2019] (Figure 1), which are areas in the vicinity of magnetic dip poles where WMM declination values are inaccurate and compasses cannot be trusted. Blackout zones are no longer considered in WMM error calculations (e.g., Figure 2), thus making the specification more robust to nonlinear core field variations while providing better guidance to navigators using the WMM at high latitudes.

With every scheduled—and unscheduled—release of the WMM, the developers are looking for ways to improve the model and incorporate data from different sources. For example, NGA recently concluded (https://www.nga.mil/news/1602596787476_NGA_announces_winning_teams_from_the_$21_million_M.html) MagQuest, a three-phase prize challenge open to industry and academia to develop designs for a future system to collect global geomagnetic data for the WMM. A total of $2.1 million was awarded across the phases to companies and universities around the world, including three winning teams whose designs all incorporated CubeSats. The results of MagQuest will inform NGA's strategy for the WMM going forward, with an expected procurement of a new system that can be operational by 2027.

With continuing efforts like these, future versions of the WMM should prove increasingly accurate and better support technologies that help us get from place to place around the planet or even just within our communities.

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