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COMMENTARY

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Key Points: • A communiw workshop was cmvened to discuss recanrnendations for the future of ground magnetorneter array research in space physics • Attendees recommended changes in organizational and funding strtrtures, many suggested in the 2016 Geospace Portfolio Review • A variety of new and/or augrnented regional and global data products and visualizations can be facilitated by increased array collaboration

Supporting Information:
• Supporting Information Sl

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Magnetometer Arrays in Support of Space Weather Monitoring and Research

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Abstract A community workshop was held in Greenbelt, Maryland, on 5-6 May 2016 to discuss recommendations for the future of ground magnetometer array research in space physics. The community reviewed findings contained in the 2016 Geospace Portfolio Review of the Geospace Section of the Division of Atmospheric and Geospace Science of the National Science Fcxmdation and discussed the present state of ground magnetometer arrays and possible pathways for a more optimal, robust, and effective organization and scientific use of these ground arrays. This paper summarizes the report of that workshop to the National Science Foundation (Engebretson & Zesta, 2017) as well as conclusions from two follow-up meetings. It describes the current state of U S.-funded ground magnetometer arrays and summarizes community recommendations for changes in both organizational and funding structures. It also outlines a variety of new and/or augmented regional and global data products and visualizations that can be facilitated by increased collaboration ammg arrays. Such products will enhance the value of ground-based magnetometer data to the community's effort for understanding of Earth's space environment and space weather effects.

I . Introduction

Ground magnetometer arrays are one of the oldest types of observational tools used to study Earth's space environment. They continuously provide essential data for studies of Earth's ionosphere and magnetosphere, for monitoring global activity, and for validation of global models and provide necessary support for large satellite missions. However, these arrays have increasingly been eclipsed in visibility and funding at the National Science Foundation (NSF) by newer, larger, and more expensive research instruments. They still operate using the organizational and funding structures put in place several decades ago.

Previous and current practices regarding ground magnetometer deployments in the U.S. have led to a culture of individual arrays having to support both operations and scientific efforts using limited resources. Each team develops their own data recording systems, software, analysis, even data formats. The result has been much duplication of effort and only limited updating of instrumentation and innovation in data products.

Magnetometer array proposals compete for funding in NSF's base program against research proposals with no equipment or maintenance costs, at significant disadvantage. For many arrays this practice has led to lapses in funding and slow progress, if any at all, in upgrading instrumentation. It has also hampered near-real-time data transmission from remote sites, rapid access to data in common formats, and development and provision of higher-level data products to the wider space science community.

Scientific advisory panels since the early 1990s have stressed the importance of continuing operations of magnetometer arrays (Love & Finn, 2017 provide an extensive list). In recognition of society's increasing vulnerability to space weather effects, in 2015 the National Science and Technology Council/Offce of Science and Technology Policy published two documents, the National Space Weather Strategy (2015) and National Space Weather Action Plan (2015) that also stressed the importance of magnetometer arrays for space weather monitoring.

Love and Finn (2017) identify two categories of ground-based magnetometers worldwide: magnetic observatories and variometers. Magnetic observatories are designed to measure Earth's geomagnetic field with great accuracy and long-term stability; they require isolated sites, magnetically clean buildings, frequent calibration, continuous on-site support, and considerable postprocessing to produce "definitive" data.

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Variometer arrays in many cases use the same fluxgate magnetometer sensors as observatories but do not adhere to observatory standards. Their data are sufficient for most studies of ionospheric and magnetospheric phenomena, and they can be established at relatively low cost. It is this latter category that is the focus of this report. The supporting information contains a list and map of these arrays.

Two recent reports recommend new organizational structures for NSF-supported magnetometer arrays. The 2013 Solar and Space Physics Decadal Survey (Solar and Space Physics: A Science for a Technological Society, 2013) recommended operating magnetometer arrays under a new model of ground-based observations, Distributed Arrays of Small Instruments (DASI) (Distributed Arrays of Small Instruments for Solar-Terrestrial Research: Report Of a Workshop, 2006). The 2016 Portfolio Review of the Geospace Section of NSF'S Division of Atmospheric and Geospace Science (NSF, 2016) recommended that a magnetometer DASI be organized as a Class 2 facility with funding from the Geospace (GS) Facilities Program. The GS Facilities Program was created to fund, administer, and review large and expensive single-location ionospheric radars, but now supports the Active Magnetosphere and Planetary Electrodynamics Response Experiment (http:// ampere.jhuapl.edu), the Community Coordinated Modeling Center (https://ccmc.gsfcnasa.gov), the Super Dual Auroral Radar Network (http://vt.superdarn.org), and SuperMAG (http•//supermag.jhuapledu) as well.

Shortly after the Portfolio Review was first delivered, NSF-Atmospheric and Geospace Sciences (AGS) personnel and members of the ground-based magnetometer community planned a workshop to discuss the response of the community to these recommendations and suggest steps toward improved array operation and scientific use. Recommendations would address a stepwise transition from the current model of independently funded array teams to a coordinated model of funding operations and data-product generation, separate from research funding.

Such a transition reflects the scientific community's needs. Rarely now do research studies depend solely on a single ground station or even a single magnetometer chain. Science questions are investigated with multistation magnetometer observations covering wide latitude and local time ranges, as well as space observations and other ground instrumentation. Effective response of the ground magnetometer community to these research and societal needs requires three elements: (1) continuous operation of magnetometer stations with good spatial coverage over the Western Hemisphere across all latitudes, (2) near-real-time monitoring capabilities, and (3) prompt availability of ground magnetometer data in a standardized format, as well as higher-level products for research and forecasting.

2. Scientific Value of Ground Magnetometer Arrays for Space Weather

Ground magnetometer observations have played a major role in the development of space science, by remotely measuring currents that define the coupled dynamics of Earth's magnetosphere and ionosphere (Glassmeier, 1987; Kamide et al., 1981). They have led to the identification of ionospheric currents associated with magnetic substorms and storms (Akasofu, 1963; Baumjohann et al., 1981), as well as those associated with global compressions of the magnetosphere from interplanetary shocks and bow shock-related instabilities (Araki, 1994; Boudouridis et al., 2003; Sibeck, 1990). Ground magnetometer observations have made it possible to track and comprehend the way energy is propagated globally after the magnetosphere is impacted by solar wind and/or interplanetary magnetic field dynamics (Mathie et aL 1999; Zesta & Sibeck, 2004). Magnetic perturbations are incorporated into global magnetic activity indices that serve as inputs to global research and forecast models Davis & Sugiura, 1966; Sugiura, 1964; Troshichev et aL 2006). Routinely available indices include KP (planetary disturbance level); AE, AJ, and AL (auroral electrojet indices, indicative of substorms, and other high latitude disturbances); Dst, SYM/H, SYM/D, ASY/H, and ASY/D (ring current intensity and asymmetry); and PC (polar cap magnetic activity). Data from worldwide arrays complement in situ local measurements made by orbiting satellites as well as observations from ground radars and optical imagers. While their role as a continuous monitor and context-providing source is paramount, their operation on a now-global scale holds the potential to provide system-level data products heretofore unavailable. These magnetometers also provide information on the convection electric fields that redistribute ionospheric plasma in the polar regions and generate Joule heating in the atmosphere during geomagnetic storms, which increases atmospheric drag on satellites and complicates the important task of tracking space debris (Orbital Debris: A Technical Assessment, 1995).

Magnetometer observations at middle and low latitudes have also become valuable assets to monitor and understand the electrodynamics of ionospheric plasma motions and distributions, which directly affect navigation and communication systems (Anderson et al., 2004; Yizengaw et aL 2014).

Time History of Events and Macroscale Interactions during Substorms (THEMIS) (Angelopoulos, 2008) was the first and so far the only NASA mission that incorporated ground magnetometer instrumentation along with its five satellites as a requirement for mission success, demonstrating the value of ground magnetometers to missions if properly organized and funded. THEMIS funded and operated a series of ground magnetometers in addition to the already existing ones in North America (Russell et al., 2008). There is now a community effort to implement similar support for the ICON, GOLD, and COSMIC-2 missions (Solomon, 2016). The most recent Solar and Space Physics Decadal Survey (Solar and Space Physics: A Science for a Technological Society, 2013) has urged enhanced collaboration between NASA and NSF through the Diversify, Realize, Integrate, Venture and Educate initiative. Such coordinated support is expected to be the norm in the future.

Finally, ground magnetometer observations are used to validate several global models of geospace dynamics for both research and forecast purposes (e.g., Pulkkinen et al., 2013; Shi et al., 2008; Weygand et al. 2011 ; Yu & Ridley, 2008). The increasing demand for such comparisons again requires the prompt dissemination of all ground magnetometer data, as well as additional higher-level data products.

3. Organizational and Funding Challenges

In this section we outline the most prevalent problems with the existing structure of magnetometer array funding and operations and identi$' how such problems can be addressed.

The first community problem is the lack of consistency in operations and data return across the different magnetometer chains. Operations of observatories supported by the U.S. Geological Survey (USGS) or variometers at manned stations supported by the U.S. Antarctic Program are attended by full-time on-site personnel. In contrast, at nearly all the NSF-AGS-funded sites in North and South America, operational support is provided by unpaid nonscientist volunteers or by local institutions that collaborate with the principal investigator (PI). Many of these sites are in remote locations, often in harsh environments (e.g., Antarctica and Arctic). Array PIs report that 20% or more of ground magnetometers are damaged within 5 years after installation by either natural (e.g., lightning) or human- or animal-caused mishaps cutting through cables). Untrained local volunteers can only diagnose obvious damage, and with travel costs to these remote locations prohibitive, damaged stations can remain inoperative for months or a year. Remote-site travel puts pressure on low-cost ground magnetometer projects, forcing them to shift funds and trained personnel from quality checks and database/Web server development to necessary repairs. The result is data return and quality far from optimal and often poor. Research and publication returns also suffer.

A second problem is that US. ground magnetometer sensors are agirv. Most sbtions have not been upgraded for over two decades. Funds for new sensor development have been difficult to obtain, even though current instruments have limited capacity for measurements at >1 Hz, for example, electromagnetic ion cyclotron wave observations, which require > 10 Hz sampling (eg., Kim et al., 2017). Data collection systems are the most common culprit in system failures. Compounding this difficulty is that U.S.-kd arrays use at least five different kinds of fluxgate magnetometers and two kinds of induction magnetometers. Thus, small upgrades or new developments cannot be implemented across all arrays due to the lack of similar instrumentation and a cohesive nanagement structure. A few array teams have begun installing upgraded data cdlection systems based on Imv-power miniaturized single-board computers that can support high sampling rates. New sensor technologies designed for small satellites and rockets may lead to more sensitive instruments that can be utilized for ground-based research. New ground-based magnetometer and data collection systems could reduce duplication and promote best practices for hardware and software development in both communities.

The third important problem the ground magnetometer community faces is its limited provision of higherlevel data products. Most arrays have resources and time to collect only their own data, process it, and make it available to the community as digital data files and time series plots, in some cases after long delays. The current needs for near-real-time monitoring and prompt production of higher-level products cannot be met under the current model for funding and operation of these arrays.

While increased levels of funding can address some aspects of these problems, cohesion in array operations requires a more centralized management approach. The fact that funding levels are fixed or even dropping makes the need for coordinated efforts all the more critical.

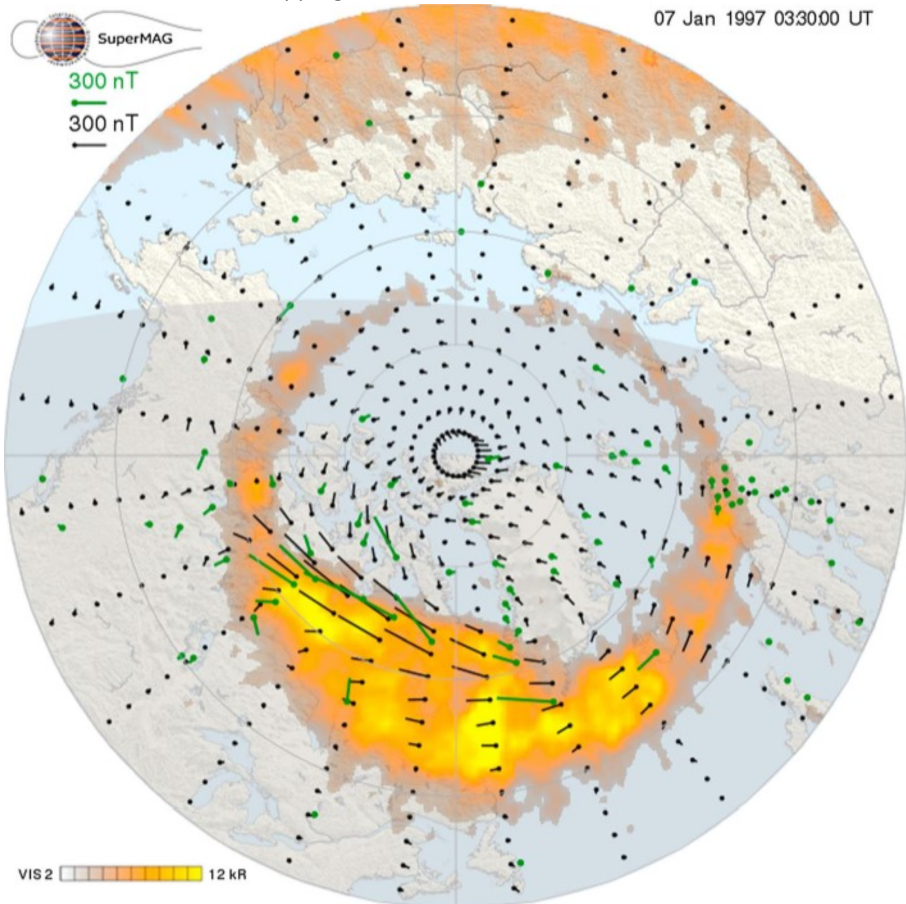

Figure 1 . Global equivalentcurrents in the Northern Hemisphere during an auroral substorm, from the SuperMAG Web site, superposed on a simultaneous Polar VIS Earth camera image. Measured vectors are shown in green and derived global equivalent currents in black.

There have been three efforts so far to unify ground magnetometer arrays and enhance their scientific outputs:

The INTERMAGNET (International Real-Time Magnetic Observatory Network) program, a voluntary association of geophysical institutes from around the world, was formed in the late 1980s. It now involves 129 stations, and many of these (63) have upgraded to 1 s sampling. Of those, 46 stations report data to the INTERMAGNET site in near real time. Although these observatories are widely spaced, they provide consistent high-quality data, rapid reporting, and worldwide coverage (Love & Finn, 2017).

ULTIMA, the Ultra-Large Terrestrial International Magnetometer Array (Yumoto et al., 2012), a worldwide consortium of space physics-related magnetometer arrays (nearly all of them are variometers) was founded in 2006. ULTIMA enables communication between international programs and has tried to foster integrated support for large space missions and global scientific studies. Currently, ULTIMA encompasses 256 stations, including 132 U.S.-funded fluxgate and induction coil systems (in the U.S. and 15 other countries). Unfortunately, the disparate regulations and funding agency policies in different countries and a lack of resources have prevented ULTIMA from realizing worldwide data synthesis and fusion. Many of the arrays within ULTIMA, including several in the continental U.S., have experienced inconsistent funding, and some are no longer operational.

SuperMAG was first funded by NSF in 2009 to ingest and integrate all available ground magnetometer data and to provide estimates of ionospheric equivalent currents flowing in the Earth-geospace system (Gjerloev, 2009, 2012). SuperMAG is the first project to focus on provision of higher-level data products from ground magnetometers. Its funding as a Class 2 Geospace Facility has enabled development and maintenance of a Web site (http://supermag.jhuapl.edu/) that is quickly becoming the most widely used one-stop repository for worldwide ground-based magnetometer data (at 1 min time resolution), global indices, and maps of equivalent ionospheric currents such as that shown in Figure 1.

4. Workshop Topics and Recommendations

The intent of this workshop was to suggest elements of a transition plan toward optimal operation and scientific use of these ground arrays. The workshop began with presentation and discussion of five questions:

1, Could technical staffing efforts from individual smaller programs be merged to provide more complete data coverage, economies of scale, more rapid and uniform data dissemination, and continuity during lapses of funding of individual arrays?
2. Would integrated support for maintenance across the various instrument and data acquisition platforms be possible and desirable?
3. Would new types of instruments and/or instrument capabilities improve the scientific return from magnetometer arrays?
4. Should operations be separated from scientific analysis in both the organization and funding of magnetometer teams?
5. Global higher-level products are becoming increasingly important, particularly in the context of supporting other ground-based instrumentation, spacecraft missions, and computer simulations. How can such products best be produced and disseminated? What additional products should be generated?

Workshop participants recognized the value of the Geospace Portfolio Review's recommendations to transition magnetometer array operations to a Class 2 facility. This transition will involve changes in the organization and funding of PI-Ied magnetometer arrays. At the same time, it brings the promise of important long-term stability and scientific productivity for these arrays.

At the most basic level, the transition should separate facility/operations budgets from science budgets for each array. In the near term, facility/operation budgets might be split, so that PIs install and maintain their hardware, while one or more cooperative "Diagnostics and Response Unit for Magnetometers" (DRUM) organizations are responsible for monitoring routine operations (data recording and transmission), and an "Augmented Data Center" (ADC) is responsible for storage and distribution of data and production of data products.

Specific near-term recommendations included (a) establishing a Ground Magnetometer Array Advisory Board, (b) developing and funding one (or a small number of regional) DRUM that will monitor and support operations of all U.S.-funded ground magnetometer arrays, and (c) providing sufficient support to SuperMAG, a current Class 2 Facility within NSF-AGS, to enable it to ingest, store, and serve the full set of data from all U.S.-funded fluxgate and induction coil magnetometers at their original sampling rates.

Recommended both immediately and over the longer term are (d) preparing data in standard formats and transmitting them in near real time (if this is not currently done) to data centers such as SuperMAG, THEMIS (http•.//themis.sslberkeley.edu/overview_datashtml), and Coordinated Data Analysis Web (https:// cdawebsci.gsc.nasagov); (e) developing improved ground magnetometer array systems (sensors, data recording and storage computers, and data transmission technologies); and (f) continuing to develop regional and global higher-level products to support scientific efforts, spacecraft missions, and model simulations. The Ground Magnetometer

Array Advisory Board was formed and tasked to periodically evaluate the operations and effectiveness of all U.S.-funded ground magnetometer arrays. The board will prioritize magnetometer locations in consultation with USGS and the international ground magnetometer community (including ULTIMA), and it will develop plans in conjunction with NSF-AGS, NSF-Offce of Polar Programs, and the ground magnetometer community to transition toward a DASI model.

One (or a few regional) DRUM(s) that share common technologies (e.g., instrument types and manufacturers) or geographic regions (e.g., polar, midlatitude, and low latitude) will support operations of all U.S.-funded ground magnetometer arrays currently supported by individual array grants. DRUM personnel will monitor

instrument operation, data quality, and volume of data transmitted on a daily basis and notifr responsible array personnel of any problems.

Recommended in the longer term, and building on the near-term steps above, is the development and funding of one or more multi-institution Class 2 facilities to operate, monitor, and maintain all NSF-funded ground-based magnetometer arrays. It is expected that this will result in consistent up-time of sites as well as cost savings. In order to address instrument and data recording system development and unification, participants recommended that NSF encourages efforts to develop improved ground magnetometer array systems (sensors, data recording and storage computers, data transmission technologies, and protocols) through existing and possibly new funding channels. For fluxgate magnetometers these developments would include higher sampling rates, lower noise and digitization levels, and ideally miniaturized footprints, lower power consumption, and environmentally robust operation (e.g., for use in polar regions and at remote sites). In addition, the ground-based magnetometer community should develop a standardized raw data format and consider developing a "Mag OS" magnetometer operating system that all teams could use.

Finally, the ADC(s), in conjunction with the emerging DASI community, the magnetic observatory community, and leaders of ground-based magnetometer arrays will be tasked to develop additional global higherlevel products to support scientific efforts using other ground-based instrumentation, spacecraft missions, and model simulations.

5. Higher-Level Data Products

Global and higher-level data products based on ground-based magnetic field data such as Kp, AE, and Dst have for many years been used for both quick-look and more in-depth studies of magnetospheric and ionospheric phenomena and are used as inputs to a variety of research and forecast models. Although these earlier indices were derived using only a small number of stations, advances in data communications and increases in the number of magnetometers worldwide in the past decade have made it possible to generate additional indices and more complex data products. The SuperMAG team has used worldwide ground magnetometer data to develop, in addition to their much used equivalent ionospheric current maps (Figure 1), auroral indices (SuperMAG SME, SMIJ, and SML) utilizing many more stations than the standard auroral electrojet indices AE, AL, and AU (Newell & Gjerloev, 2011).

Magnetometer array data have been used for many years as input into the Assimilative Mapping of Ionospheric Electrodynamics procedure (Kamide et aL 1981; Lu, 2017; Richmond & Kamide, 1988) to characterize high-latitude ionospheric electric fields, and more recently as input into physics-based data-assimilation models of the global ionosphere such as the Global Assimilation of Ionospheric Measurements models and the Ionospheric Dynamics and Electrodynamics Data assimilation model (Schunk et al., 2014).

Workshop participants suggested several other quantitative and/or visual data products that could provide easily accessible and understandable summaries of magnetospheric and ionospheric activity. These products are listed below, along with references to existing or developing examples of their generation:

1. New mapping products
   a. Global maps of magnetospheric mass density as a function of L and local time including location and characterization of the plasmapause, based on field line resonance-based remote sensing Chi et aL 2013; Menk & Waters, 2013).

b. Global and/?or regional maps of equatorial electrojets (Yizengaw et aL 2014, 2016) and auroral zone equivalent currents (Weygand et al., 2011).
c. Routine production of maps of global equivalent current data from magnetometers and other instruments such as the SuperDARN radars. Derivation of the full vector electric current system in the ionosphere requires simultaneous magnetic field data from space and the ground (Lotko, 2017).
d. Maps of magnetic perturbations and the synoptic open/?closed boundary of the magnetosphere in both polar caps (Urban et al., 2011).
e. Statistical maps of magnetic perturbations (Pothier et aL 2015; Weimer et al., 2010) and various categories of ULF waves as functions of solar wind/?IMF drivers and/?or geomagnetic activity.

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f. Quick-look event-specific maps and/or magnetic keograms of Pc5 ULF waves (Kozyreva et al., 2016) and other ULF wave categories superposed on magnetospheric regions such as the polar cap, auroral zone, plasmatrough, and plasmasphere.
g. Global and regional maps and parameterizations of geomagnetic disturbances (and time derivatives) that drive ground-induced currents (e.g., Carter et al., 2016; Love et al., 2016; Woodroffe et al. 2016).
h. Interhemispheric comparisons of regional ULF wave activity (eg., Kim et al., 2013, 2015; Zesta et al., 2016), electrojet currents, and cusp and substorm phenomena, in order to understand the way energy from the solar wind is transmitted asymmetrically to Earth's high-latitude regions.

2. New activity indices, indicators, and tools

a. Regional activity indices (K indices) specifying localized activity.
b. Stacked plots of time series of "virtual magnetometers" at fixed local times.
c. Visual products using the ULF index (Kozyreva et al., 2007; Pilipenko et al. 2017).
d. Development of more "interpretive" capabilities such as automated identification and location of substorms (Murphy et al., 2009) and Pi2 pulsations.
e. Shared software tools for analysis of magnetometer data, as is done, for example, in the seismic and astrophysical communities.

6. Summary and Conclusions

This report represents the U.S. ground magnetometer community's efforts to collaborate in responding to the current needs of the research community and society in advancing the science of Space Weather. It responds to the NSF Portfolio Review recommendations with a projected path and actions toward a new model of operating all ground magnetometers as a Class 2 facility in order to provide prompt monitoring and higher-level products that support the research community, satellite missions, and our nation.

Ground magnetometers provide the most fundamental space environment measurement with a continuity of more than 150 years, allowing for the only long-term, multicycle studies in space physics. The need of continuous supply of global ground magnetometer data is paramount for both research and monitoring purposes, and it is how a limited number of worldwide magnetometer stations have been used for many decades. The world's (and our nation's) current reliance on space assets for communication and financial transactions makes the need for regular, continuous, global observations more profound than ever. Organizing and funding the ground magnetometer community as a facility will enable it to much more effectively respond to these needs and provide the community and nation with a variety of higher-level data products that can be directly ingested into decision making processes. While the ground magnetometer community is going through this transition path, we seek the larger community's support and their feedback on how to best serve their needs.

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