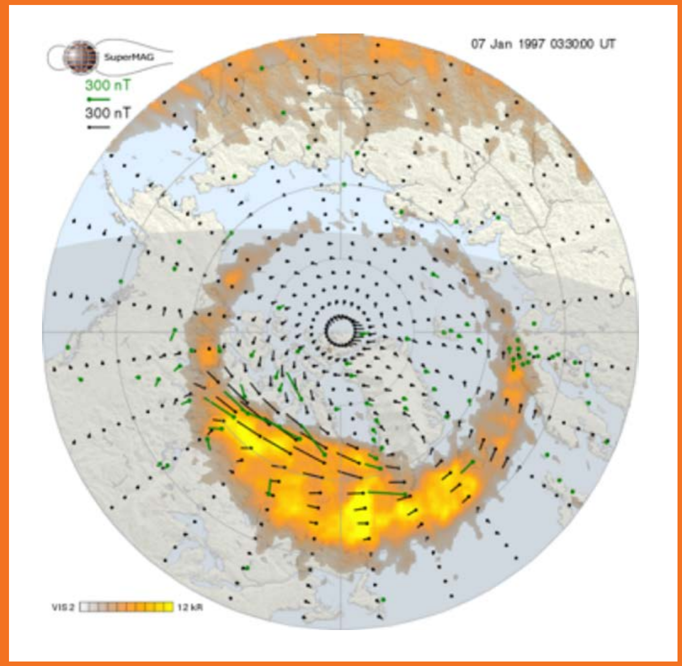

Ground Magnetometer Array Planning: Report of a Workshop

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EXECUTIVE SUMMARY

Ground magnetometer arrays are one of the oldest types of observational tools used to study Earth's space environment, and they continue to provide essential data for a variety of studies of Earth's ionosphere and magnetosphere. These arrays have increasingly been eclipsed in visibility and funding at the National Science Foundation by newer, larger, and more expensive research instruments, but still operate using the organizational and funding structures first put in place several decades ago. In particular, magnetometer array teams continue to compete for funding in NSF's base program against data analysis proposals (which have no equipment or maintenance costs). For many such arrays this has led to lapses in array funding, and slow progress in upgrading instrumentation, achieving near-real-time data transmission from remote sites to the host institutions, and providing the wider space science community with rapid access to data in common formats.

Numerous scientific advisory panels since the early 1990s have stressed the continuing importance of ground magnetometer arrays, and most recently two have suggested new organizational structures as well. The 2013 Solar and Space Physics Decadal Survey suggested placing ground magnetometer arrays in the context of a new model of ground-based observations, Distributed Arrays of Small Instruments (DASI). The 2016 Portfolio Review of the Geospace Section of the Division of Atmospheric and Geospace Science of the National Science Foundation [NSF, 2016] considered how best to operate and support these arrays, and recommended that they be moved toward funding as Geospace Science Facilities, an organizational and funding category first developed for large, single-location ionospheric radars but now used for several other NSF-AGS research efforts in space science as well.

Shortly after the Portfolio Review was first delivered to NSF, NSF-AGS personnel and members of the ground-based magnetometer community began making plans for a workshop to discuss the response of the community to these recommendations, and suggest steps leading to improved array operation and scientific use. This report provides the background for this workshop, held May 5-6, 2016, describes the current state of U.S.-funded ground magnetometer arrays, gives examples of other collaborative ground-based scientific efforts, and presents findings and recommendations developed during the workshop and in subsequent communications among participants.

The recommendations presented below are grouped into three phases, outlining a systematic transition from the largely independent operations of current NSF-funded ground magnetometer array teams to what is hoped will be a more efficient and scientifically productive collaborative effort. These recommendations include a) Initial steps that can be accomplished by the community immediately or within a few months, b) Near-term steps to be implemented by the community and NSF within 1 to 3 years, and c) Longer-term steps to be implemented by the community and NSF within 5-10 years, the time frame by which the Portfolio Review's suggested reprioritization of funding for NSF-AGS Facilities will be completed.

A key characteristic of these recommendations is a stepwise transition from the current model of independently funded array teams, each of which deploy, operate, and maintain magnetometers at remote sites, retrieve their data, process and reformat it as necessary, distribute it via individual web sites and/or one or more centralized data repositories, and perform scientific analyses and prepare higher-level data products as appropriate, to a much more coordinated model of operations funding, separate from funding for scientific analysis.

In the near term, this involves a) establishing a Ground Magnetometer Array Advisory Board of from 4 to 6 members, b) developing and funding one (or a small number of regional) Ground Magnetometer Diagnostics and Response Units that will monitor and support operations and data transmission of all U.S.-funded ground magnetometer arrays, 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, d) developing, in conjunction with the emerging DASI community, global higher level products to support scientific efforts using other ground-based instrumentation, spacecraft missions, and computer simulations, and e) developing improved ground magnetometer array systems (sensors, data recording and storage computers, and data transmission technologies and protocols).

In the longer term, and building on the near-term steps above, we recommend developing and funding one or more multi-institution Class 2 Facilities to operate, monitor, and maintain all NSF-funded ground-based magnetometer arrays. It is expected that operation of this Facility will result in more consistent up-time of arrays and individual stations and possibly in cost savings as well. Also recommended are to install improved, identical magnetometer sensor, recording, and data transmission systems to the extent that this is financially and logistically feasible, following other cited NSF-funded examples such as IRIS, UNAVCO, and SuperDARN.

CHAPTER 1

INTRODUCTION

Since the beginning of the space age, increasingly sophisticated efforts have been made to explore and understand Earth's space environment. The National Research Council's report on the National Geomagnetic Initiative Workshop, held March 16-20, 1992 [*National Geomagnetic Initiative*, 1993], provided a useful summary of the scientific importance of studies of Earth's magnetic field for increasing our understanding of physical processes both in the Earth's interior and in the Earth's surrounding space environment. Because Earth's magnetic field reaches out into space, and electrically charged particles as well as several kinds of plasma waves are guided along magnetic field lines, arrays of ground magnetometers have long been a valued means of remotely monitoring processes in the ionosphere and throughout the magnetosphere.

The Topical Working Group Report on the Magnetosphere, Ionosphere, and Atmosphere in the *National Geomagnetic Initiative* [1993] highlighted both the impact of what is now called "space weather" on both terrestrial and space-based technological and natural systems, and outlined operational considerations for continued and future deployment of ground-based magnetometer arrays.

Many of this report's recommendations for improvements in the use of ground magnetometers for the study of the magnetosphere, ionosphere, and atmosphere are already being implemented by some individual research groups, but the style of research is only gradually changing from performing large studies with a single station or a handful of localized stations to trying to look at simultaneous data from stations at multiple latitudes and local times. However, the value of near-real time data distribution and access is clear, as is the need for extensive collaboration to standardize data formats and to distribute and display ground array data. The digitization of all magnetometer data and the advent of the internet makes this possible.

Since that report was issued, several efforts to integrate all ground magnetometer data have emerged.

By 1993 the INTERMAGNET (International Real-Time Magnetic Observatory Network) program, a voluntary association of geophysical institutes from around the world formed in the late 1980s (Love and Chulliat, 2013), had already collected digital data from 25 ground-based magnetic observatories (which measure both the absolute field and its vector components with high accuracy) at four Geomagnetic Information nodes, but the cadence of this data was at best 1 minute per sample; it now involves 129 stations, and many of these (63) have already upgraded to 1-second sampling. Of those, 46 stations report data to the INTERMAGNET site in near real-time.

ULTIMA (the Ultra-Large Terrestrial International Magnetometer Array), a worldwide consortium of space physics-related magnetometer array programs founded in 2006, acts as a means of international communication between different programs, and has tried to foster integrated support for large missions and global studies that can address scientific questions that could not be answered before. Nearly all of the ULTIMA arrays instruments are so-called variometer arrays; these

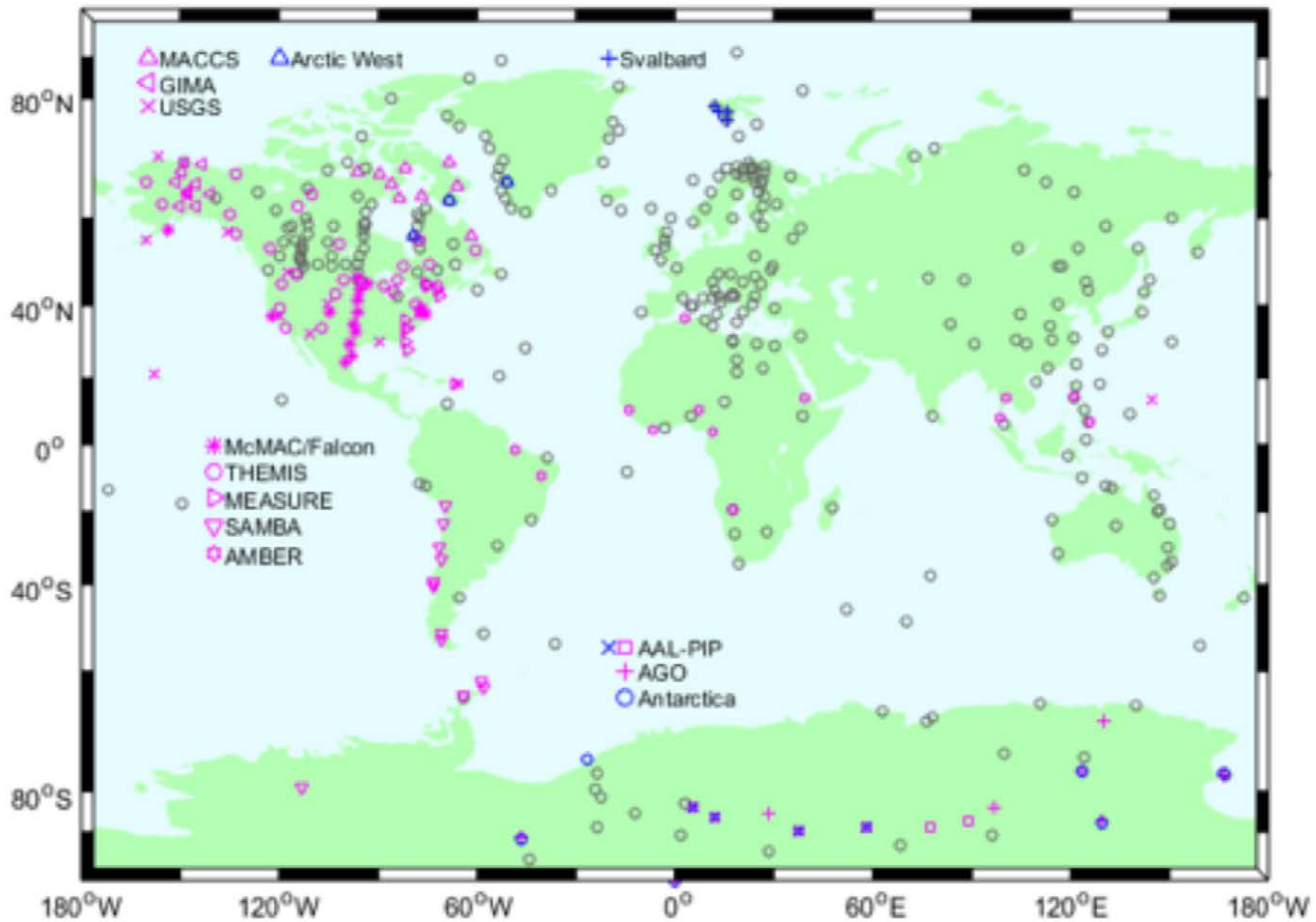

Figure 1.

Map of worldwide magnetometer sites and arrays as of Fall 2016: US fluxgates arrays (magenta); US induction coil arrays (blue); and non-US (grey).

measure the vector field but not the absolute field and do not adhere to the rigorous calibration standards required for magnetic observatories [Love and Finn, 2017]. However, the disparate regulations and policies of funding agencies in different countries, and the lack of any funding resources to support the synthesizing of all of this data and providing it in a simple, accessible manner, have prevented full realization of ULTIMA's promise.

Nearly 300 ground-based magnetometers have been installed in over 40 countries worldwide (Figure 1). Of these, 256 are included in arrays that are part of ULTIMA, and there are 132 U.S.-funded fluxgate and induction coil systems (in the U.S. and 15 other countries). As noted below, many of these, including several arrays in the continental U.S., have experienced inconsistent or minimal funding, and some are no longer operational.

A more recent program, SuperMAG, was funded beginning in 2009 in order to integrate as much data as possible to study the currents that flow in the Earth-geospace system. Whether these currents originate in the Earth's crust, the ionosphere, or in the magnetosphere they produce magnetic field perturbations that can be measured by ground-based magnetometers. With care these currents can be monitored by magnetometers distributed around the globe and their spatiotemporal characteristics can be determined.

SuperMAG ingests not only INTERMAGNET data but data from many variometer arrays deployed specifically for space physics studies. The SuperMAG web site (http://supermag.jhuapl.edu/) has become a very useful one-stop web access site for worldwide ground-based magnetometer data (at 1-minute time

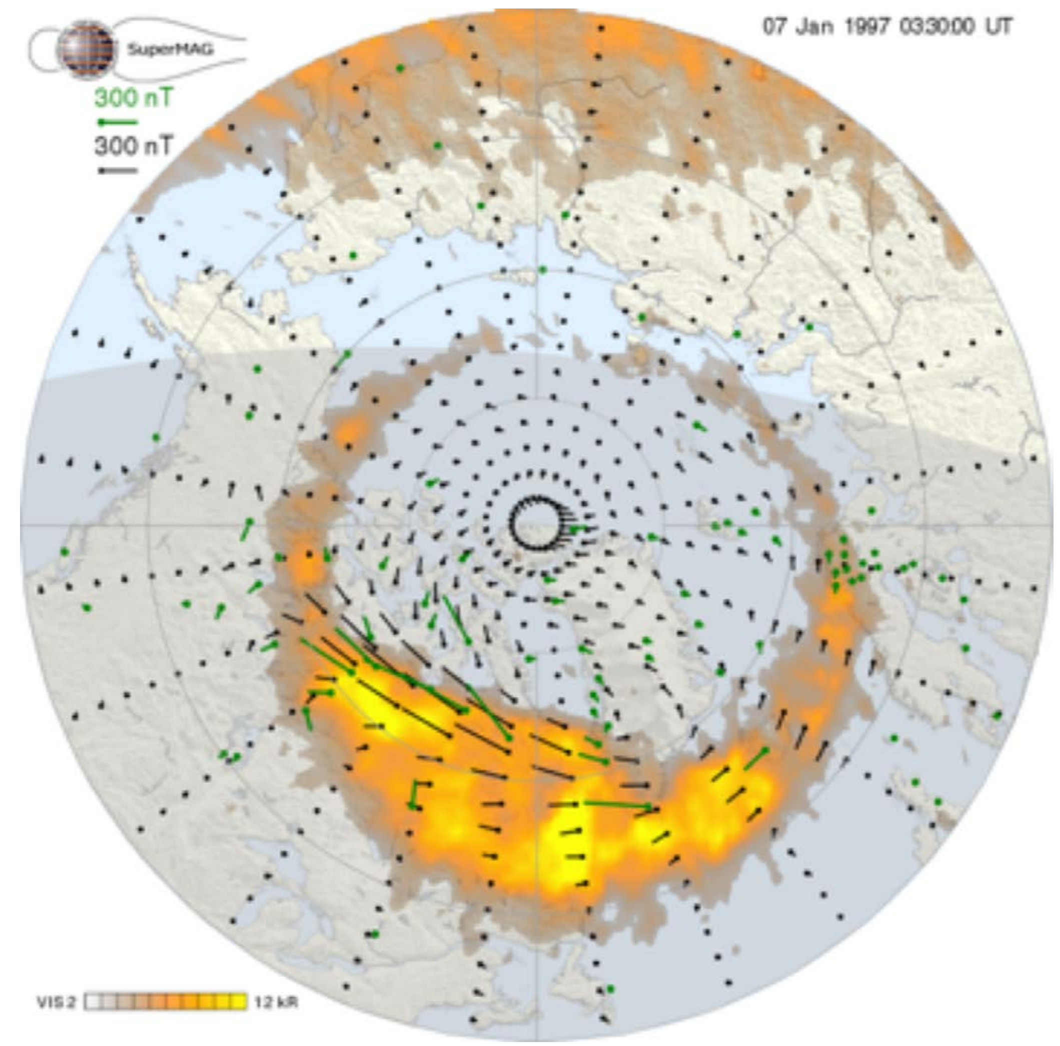

Figure 2.

Global equivalent currents 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.

resolution), global indices, and several higher level data products, such as the northern hemisphere map of equivalent ionospheric currents shown in Figure 2.

However, scientists outside the ground magnetometer community still find it difficult to access data obtained at higher sampling rates, which are essential for studies of the many shorter-period magnetic perturbations and oscillations, because these data sets are in many cases available to the scientific community only through web sites developed by individual arrays (often in nonstandard data formats) or for some arrays through the THEMIS ground magnetometer online data archive (http://themis.ssl.berkeley.edu/data/themis/thg/mirrors/mag/) and NASA's CDAWEB facility (http://cdaweb.gsfc.nasa.gov/.

The scientific importance of ground magnetometer data has continued to be stressed in scientific planning documents. The first three examples below are taken from a draft report by Love and Finn [2017]:

- A 2009 NOAA observation requirements list described ground magnetometer data from each of the three regions of auroral, mid-latitude, and low-latitude as "priority-1" and "mission critical" for space-weather monitoring [NOAA, 2009].

- A 2012 Statement of Guidance for Space Weather Observations conducted by the World Meteorological Organization (WMO) Inter-Programme Coordination Team on Space Weather (ICTSW) recognized the need for ground-based magnetometers for a variety of space-weather applications, and recommended that efforts be made to increase the availability of ground-based magnetometer data with high timeliness [WMO/ICTSW, 2012]

- A 2015 strategic plan commissioned by the Committee on Space Research (COSPAR) of the International Council for Science (ICSU) and the International Living With a Star (ILWS) Steering Committee called for an increase in the availability of ground-based data on the geomagnetic field with "high timeliness" [Schrijver et al., 2015, p. 2770].

- The National Science and Technology Council / Office of Science and Technology Policy in 2015 published two documents, the *National Space Weather Strategy, [2015]* and *National Space Weather Action Plan, [2015]*, that also stressed the importance of ground magnetometer arrays for space weather monitoring.

- The most recent Solar and Space Physics Decadal Survey [*Solar and Space Physics, 2013*], commissioned by the National Academy of Sciences, highlighted the role of real-time ground-based magnetometer data as a "mainstay of the space weather enterprise," and placed them in the context of a new model of ground-based observations: distributed arrays of small instruments (DASI) [*Distributed Arrays of Small Instruments, 2006*]. Integration of data systems and data sets was also given a high priority in that document.

The recent Portfolio Review of the Geospace Section of the Division of Atmospheric and Geospace Science of the National Science Foundation [NSF, *2016*] specifically recognized the importance of magnetometer arrays for research funded by both the Aeronomy and Magnetospheric branches of NSF's AGS Division, considered how best to operate and support these arrays, and encouraged movement toward further integration with a recommendation that they be moved toward funding as Geospace Science Facilities. As is the case for other facilities supported by NSF, the science return from magnetometer arrays cannot be judged simply on the basis of their providing data to the investigators that operate them; the successful operation of these instruments and prompt, easily accessible distribution of their data is also important in providing resources that other scientists can use.

The increasing demands for comparisons between models and observations on a global scale and the related need to provide ground magnetometer observations promptly and efficiently to the worldwide space science community make it imperative that the dissemination of all ground magnetometer data, as well as additional higher level data products and summaries, be provided in a much more accessible manner, and suggest that new, more integrated models of organization and funding be developed in order to do this.

In early 2016, shortly after the Portfolio Review was first delivered to NSF, NSF-AGS personnel and members of the ground magnetometer community began making plans to hold a workshop to discuss the response of the community to the recommendations of the Decadal Survey and Portfolio Review and suggest steps leading to their optimal operation and scientific use. How can NSF support ground-based magnetometer arrays so they can more effectively and efficiently provide data (raw data and higher level data products) to the space science community? This report provides the background for this workshop, held May 5-6, 2016, describes the current state of U.S.-funded ground magnetometer arrays, and presents findings and recommendations developed during the workshop and in subsequent communications among participants.

CHAPTER 2
SCIENTIFIC VALUE OF GROUND MAGNETOMETER ARRAYS

Arrays of ground-based magnetometers have been a part of observational space science since long before the beginning of the space age, and they continue to provide essential physical context for a variety of studies of the ionosphere, magnetosphere, and solar-terrestrial interactions.

Earth's magnetic field consists of an internal component, driven by its planetary dynamo, and external perturbations that result from interactions of the internal field with the continuous but highly variable flow of particles and fields from the Sun (the solar wind). As with any magnetized planet, a magnetic field plays an essential role in supporting life on the planet by shielding its atmosphere from solar wind ablation; indeed, the possible disappearance of a Martian atmosphere is thought to be specifically due to the collapse of its magnetic field.

Internal dynamo processes within the Earth create slowly changing magnetic fields with time scales of centuries, and transient impulses due to solar events produce ground-level magnetic disturbances that can occur in minutes, by affecting the complex current systems in and near the Earth's atmosphere. As a result, the magnetic field on the Earth's surface is different from location to location, and it changes over time.

"Magnetic observatories were first established in the early 19th century in response to the influence of Alexander von Humboldt and Carl Friedrich Gauss. Since then, magnetic measurement has advanced significantly, progressing from simple visual readings of magnetic survey instruments to include automatic photographic measurement and modern electronic acquisition. To satisfy the needs of the scientific community, observatories are being upgraded to collect data that meet ever more stringent standards, to achieve higher acquisition frequencies, and to disseminate data in real time." [Love, 2008]

Ground magnetometer observations have played a major role in the development of space science, by remotely measuring currents that define the dynamics of the magnetosphere and Earth's ionosphere. They have led to the identification of ionospheric currents associated with magnetic substorms and storms, as well as those associated with global compressions of the magnetosphere from interplanetary shocks and bow shock-related instabilities. Ground magnetometer observations have made it possible to track and comprehend the way reconfigurations of currents and convection are propagated globally after the magnetosphere is impacted by solar wind and/or interplanetary magnetic field dynamics. In addition, ground magnetometer observations continue to be used to track energy propagation through the magnetosphere via magnetospheric Alfven waves (including long-period field line resonant oscillations as well as higher-frequency electromagnetic ion cyclotron waves). Although ground magnetometers have contributed to space science for over a century, they continue to play an essential role. The continuous data that these worldwide arrays provide complements the necessarily local measurements made by orbiting research spacecraft as well as observations from other ground-based instruments such as radars and optical imagers. In fact, global ground magnetometer observations provide the most fundamental and necessary context that needs to exist if any of the current and future missions are to provide new discovery science within near-Earth Geospace. While their role as a continuous monitor and context-providing source is paramount, their continuous operation on a now-global scale provides the means for research science at the systems level never before possible.

Ground magnetometers continue to be the primary means of measuring / monitoring electrical currents in the ionosphere, including equatorial electrojet and auroral currents in the ionosphere, as well as the magnetospheric ring current. Magnetic perturbations measured by these magnetometers are incorporated into various global magnetic activity indices: Kp (planetary disturbance level), AE, AU, and AL (auroral electrojet indices, indicative of substorms and other high-latitude disturbances), Dst, SYM/H, SYM/D, ASY/H, ASY/D (ring current intensity and asymmetry), and PC (polar cap magnetic activity), and also provide direct observations of geomagnetic pulsations with frequencies ranging from 0.001 Hz to ~ 5 Hz in the ultra-low-frequency (ULF) range that originate in Earth's magnetosphere. These pulsations transfer energy both between regions within the magnetosphere and ionosphere and between various populations of magnetospheric plasmas (including the Van Allen Radiation belts), and also serve as diagnostics of various plasma instabilities. These magnetometers also provide information on the convection electric fields that redistribute ionospheric plasma in the polar regions and generate Joule heating of 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 the ionosphere that control ionospheric plasma distributions, which directly affect navigation and communication systems [Yizengaw et al., 2014; Anderson et al., 2004)]. For example, the unstable plasma distributions in the equatorial ionosphere, which are mainly caused by equatorial electrodynamics, can cause disruptions of the detection and tracking of aircraft, missiles, satellites, and other targets; distort communication and navigation systems [Doherty et al., 2004]; and interfere with global command, control, and surveillance operations. At middle latitudes during geomagnetic storms penetration electric fields can increase or decrease ionospheric plasma densities and generate steep horizontal gradients affecting WAAS and LAAS navigation system accuracy. Magnetometers provide insight into this global electrodynamic interaction of the earth's ionosphere and magnetic field.

Magnetometer array data have for many years also been used as input into the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure [Kamide et al., 1981; Richmond and 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 various Global Assimilation of Ionospheric Measurements (GAIM) models and the Ionospheric Dynamics and Electrodynamics Data (IDED) assimilation model (Schunk et al., 2014)

Several additional examples of more detailed and emerging uses of arrays of ground magnetometer data are given below:

1) Mesoscale and closely spaced two-dimensional arrays in the auroral zone have been used to determine the spatial distribution of field-aligned currents (e.g., Weygand et al., [2011]), the time and location of substorm onsets (e.g., Murphy et al., [2009]), and the synoptic variation of the magnetospheric open-closed boundary [Urban et al., 2011].

2) Mesoscale and closely spaced two-dimensional arrays in the polar cap have been used to study ULF waves in the solar wind, polar cap heating, and magnetic coordinate systems [Urban et al., 2016]

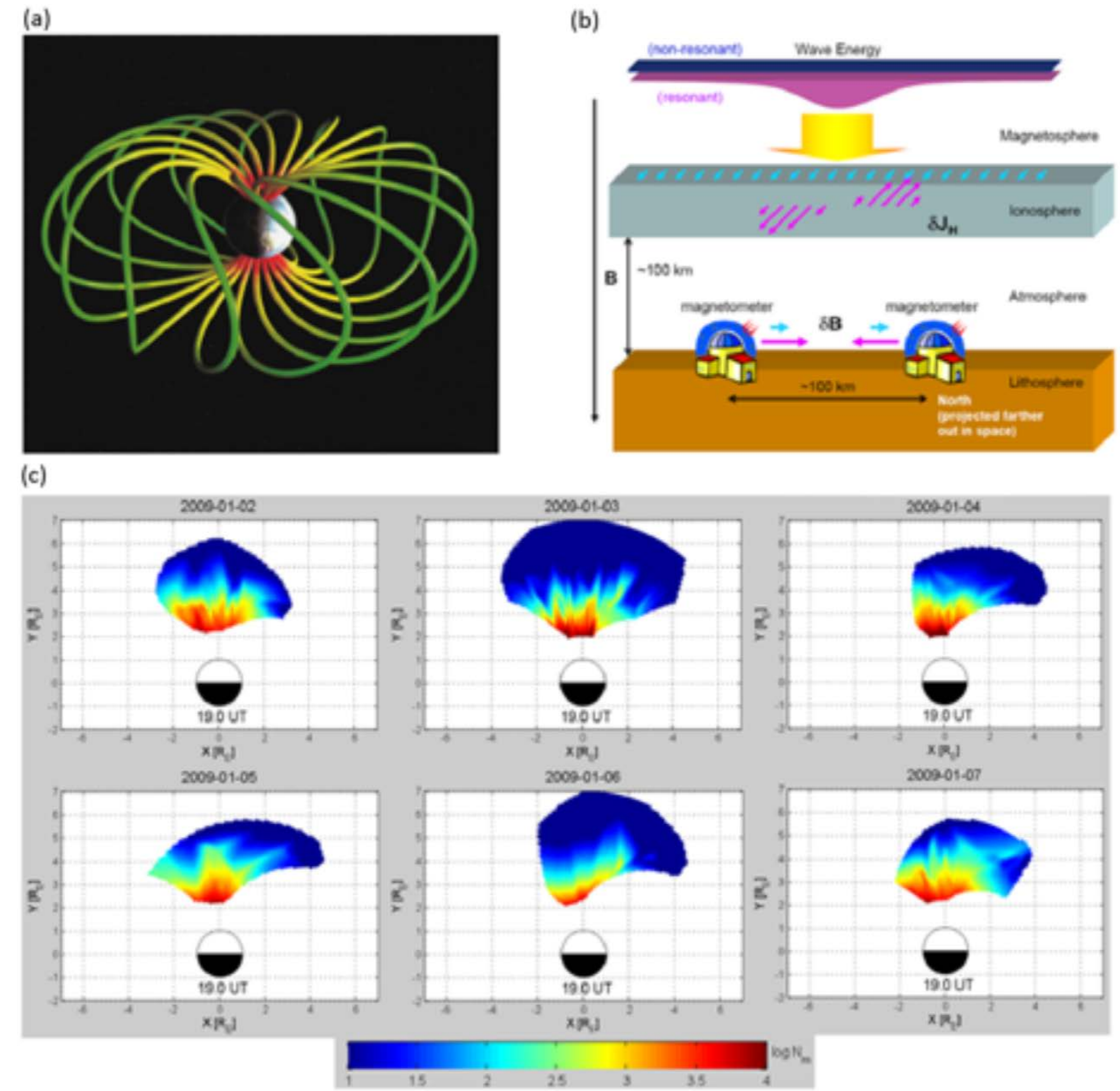

Figure 3. (a) Toroidal oscillations of magnetospheric field lines as a result of field line resonance (FLR). Taken from the front cover of Takahashi et al. [2006]. (b) A schematic diagram of how magnetospheric oscillations are detected by ground-based magnetometers. A pair of ground stations separated by a distance comparable to the ionospheric height can identify the gradient of wave phase due to FLR. (c) The equatorial density distributions inferred from FLR frequencies observed by ground-based magnetometers in North America.

3) Mesoscale latitudinal arrays have been used to remotely sense the magnetospheric mass density using field line resonance sounding (Figure 3), including remote sensing of the radial location of the plasmapause (e.g., Chi et al. [2013], Boudouridis et al. [2007]).

4) Latitudinal arrays at magnetically conjugate regions in both the northern and southern hemisphere have been used to study interhemispheric processes and understand the way energy from the solar wind is transmitted asymmetrically to Earth's high latitude regions (e.g., Kim et al. [2013, 2015], Zesta et al. [2016]).

5) Low latitude and equatorial latitude arrays have been used to monitor and study the signatures of atmospheric tides [Tarpley, 1970a,b; Eccles et al., 2011].

6) Worldwide arrays have been used to determine the spatial pattern and extent of ULF waves, which are often highly localized, and can appear very differently at different locations, especially during geomagnetic storms [Posch et al., 2003; Engebretson et al., 2015], to produce a global index of long-period ULF activity that has been used to study the influence of these waves on radiation belt fluxes [Kozyreva et al., 2007], and to produce statistical maps of geomagnetic perturbations as a function of the interplanetary magnetic field [Weimer et al., 2010] and during substorm onset and recovery [Pothier et al., 2015].

7) Worldwide arrays have also been used to study the flow of energy from high latitudes to low latitudes via waves and penetrating electric fields [Yizengaw et al., 2016; Fejer et al., 2007; Huang et al., 2005], and have also been used very recently to study the drivers of geomagnetically induced currents that can cause severe damage to terrestrial power grids during major magnetic storms [Carter et al., 2015; 2016], and determine their latitudinal profiles [Woodroffe et al., 2016].

8) Worldwide arrays are increasingly being used to provide ground support for spaceflight missions. This was done very successfully with THEMIS, and there is a community effort to implement similar support for the ICON, GOLD, and COSMIC-2 missions [Solomon, 2016] and MMS. With the Decadal Survey decreeing enhanced collaboration between NASA and NSF, such actions and mission support projects are expected to be the norm.

9) Ground magnetometer data are increasingly being used to validate global magneto-hydrodynamic (MHD) models.

CHAPTER 3

CURRENT ORGANIZATIONAL AND FUNDING / FINANCIAL CHALLENGES

Although magnetometer arrays over the globe are supported by scientific agencies in many countries, the current organizational and funding situation of such arrays in the U.S. by the National Science Foundation has not been cohesive, and is not adequate to address current and emerging data and science needs. Rapid progress in cyber infrastructure and capabilities has been quickly followed by continuously increased needs for steady provision and access to this data and related derived products. The forefront of research requires quick, reliable, uniform, and global access to all these data as well as to derivative forms (data products). The ground magnetometer community must respond to this need with a new model of operations and data distribution, one that supports efforts to understand ionospheric and magnetospheric processes on global scales with high spatial and temporal resolution, all while taking advantage of economies of scale.

Previous and current practice has led to a ground magnetometer culture of individual array PIs using at least 5 different kinds of fluxgate magnetometers and two kinds of induction magnetometers (e.g., Figures 4-6) and developing their own data recording systems, software, and even data formats, and leads to individual proposers supporting both operations and scientific efforts based on that data. Magnetometer array proposals compete in the base program against data analysis proposals, and the cost of operations has placed them at a disadvantage. Several U.S. arrays are in place but are not currently funded. Unfunded existing chains are mostly not operating and await much needed maintenance, which deprives the community of valuable data that could be maintained at relatively low cost. While some magnetometer arrays may support specific objectives that require only a limited duration of operation (e.g., for magnetotelluric studies of ground

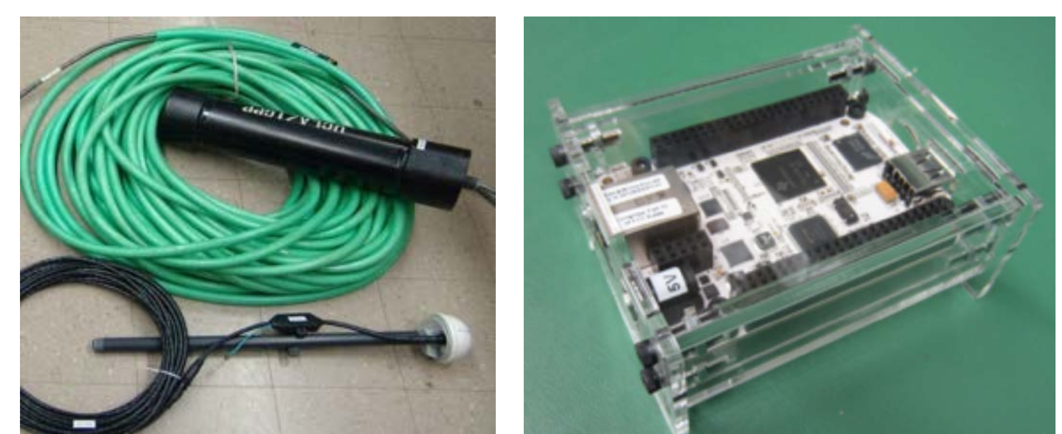

Figure 4.

UCLA magnetometer sensor and GPS antenna with cables (left) and miniaturized Beaglebone controller/ recording system (right). These instruments are used by the AMBER, SAMBA, MEASURE, and THEMIS arrays.

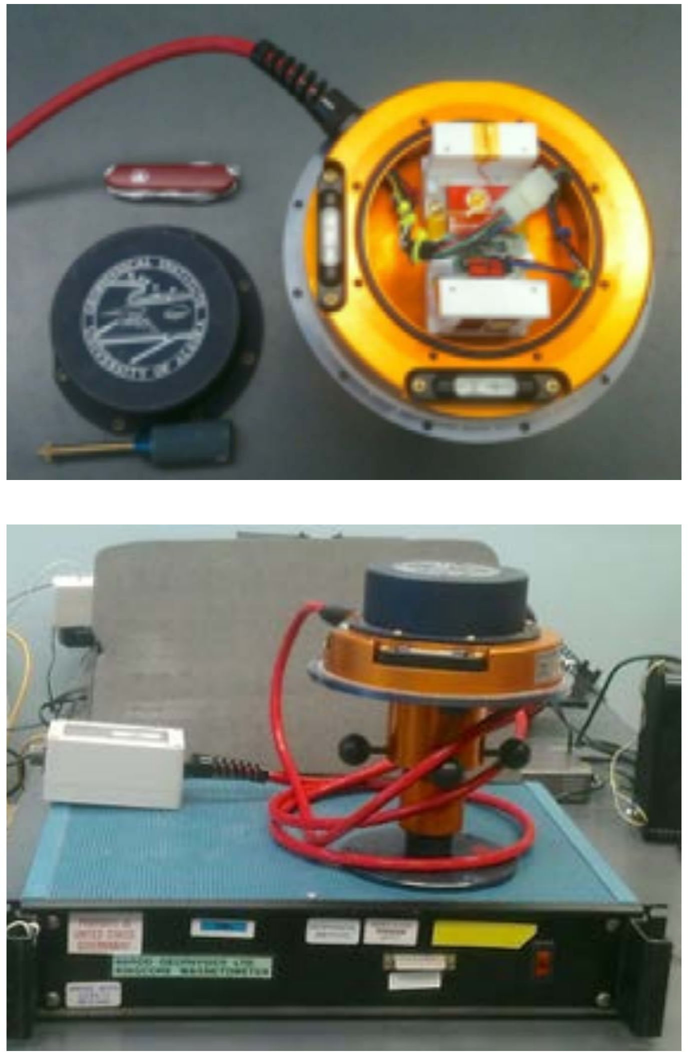

Figure 5. Narod fluxgate magnetometer sensor (top) and controller (bottom): These instruments are used by the USGS, GIMA (Alaska), and MACCS arrays.

conductivity that are important for determining the influence of space weather on ground-induced currents), many, if not most, magnetometer arrays should not be viewed as something to be installed once in a particular location and then moved to the next location. Instead, they need to be run effectively as a facility so there is sufficient continuity of data to determine the optimum spatial resolution for long term space weather monitoring tasks, for supporting different spaceflight missions, and for providing different necessary products.

Because of the distributed and often remote locations of ground magnetometer sites, array teams often face more severe logistical challenges than do larger, more centralized ground-based instrument teams Figures 7-9 show examples of the variety of remote sites worldwide where U.S. - funded ground magnetometers are currently operating.

The level of support for ground-based magnetometers covers a wide range. Instruments operated by the U.S. Geological Survey are tended by full-time personnel who monitor the operation of the instruments and perform regular instrument checks and calibrations consistent with standards of the INTERMAGNET international geomagnetic observatory community. Similarly, full-time personnel at manned U.S. research stations in Antarctica and Greenland monitor magnetometers at those sites to ensure that they are operating and recording data. However, at several remote sites in Antarctica magnetometers and other instruments operate for a year or more with no human presence, and at nearly all arrays in North and South America supported by the National Science Foundation, the support of operations is provided largely by unpaid non-scientist volunteer operators where available, or by local institutions that collaborate with the PI. The result is that operations are largely dependent on personal relationships, on local politics and dynamics, and are inconsistent and often difficult. A centralized entity, like a facility, that would be sanctioned by NSF would be much better placed to negotiate such operations with local institutions and have better resources to provide for smoother and continuous operations.

Although ground-based magnetometer sensors have often proven to be very reliable, the instrumentation needed to power them and record and transmit their data (often in harsh, remote environments) is not nearly as robust. Robert Strangeway's experience

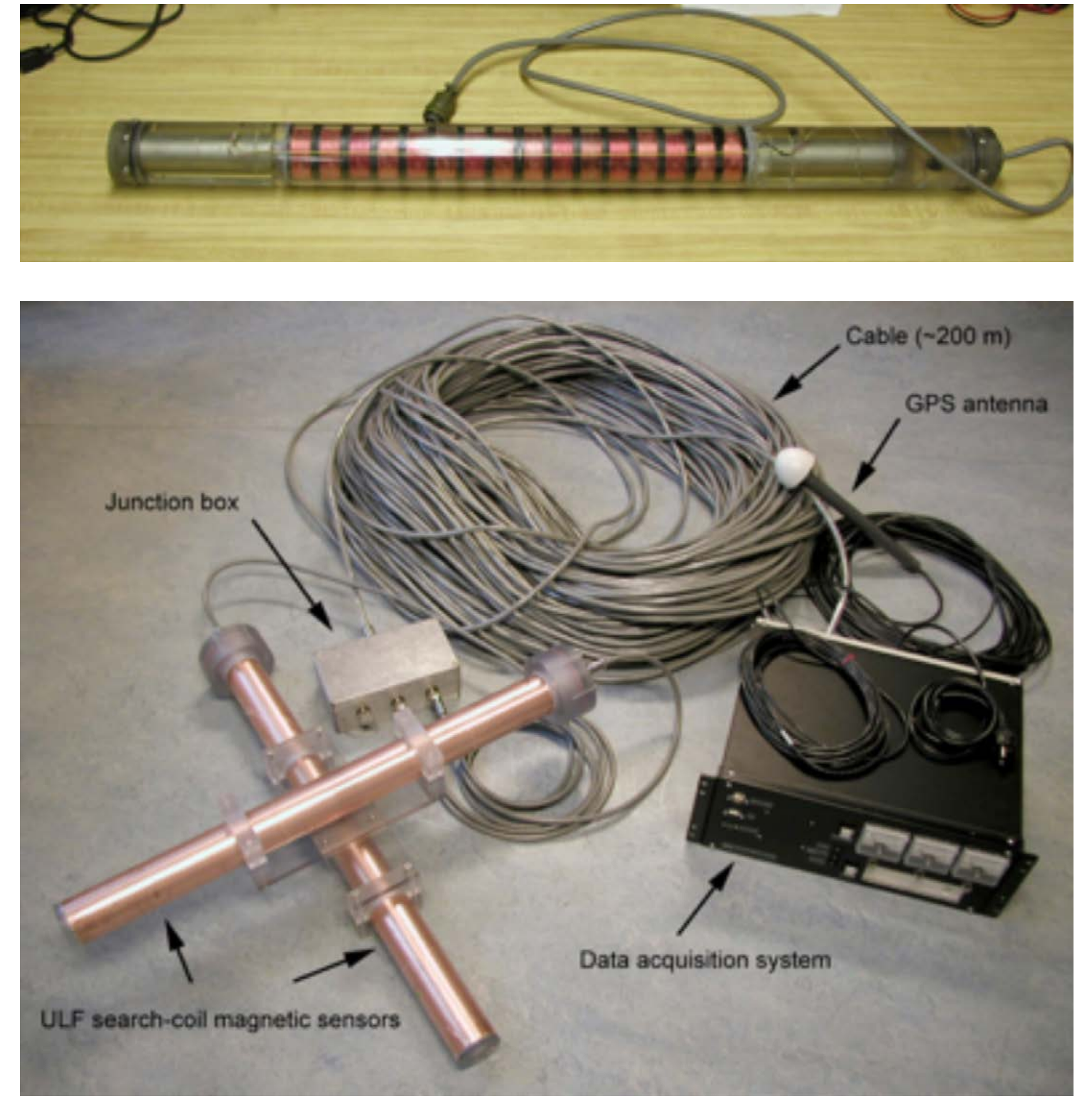

Figure 6. University of New Hampshire induction coil magnetometer: Single-axis sensor (top) and Full Instrument (bottom).

with ground-based magnetometers at remote sites is typical: from 10 to 20% of ground magnetometers were damaged within 5 years after installation by either natural (e.g., lightning) or human- or animal-caused (e.g., cutting through cables) mishaps. Untrained local operators can be asked to check for obvious damage and reboot computers and modems after power outages, but in most cases cannot help array managers diagnose the cause of system failures. Because of the high cost of travel to remote sites, funding constraints thus often result in only yearly maintenance and repair visits, thus substantially hindering the goal of nearly constant data coverage from each station. Travel to remote sites also puts additional pressure on low-cost ground magnetometer projects, causing them to shift funds and trained personnel from quality checks and database / web server development to cover necessary repairs. As a result, the quality and continuity of data is not always at the desired level.

Many current magnetometer sensors are over 25 years old, but there has been little organized investment in the U.S. in improved sensor technologies for ground-based arrays, and little attention paid to replacing aging systems. In addition, although the sampling cadences of most ground-based magnetometers worldwide have increased from typical values of 1 minute or 10 seconds to 1 second, current arrays of fluxgate magnetometers cannot sample rapidly enough to cover the full ULF frequency range (EMIC waves need at least 10 Hz sampling) because of both limited instrument sensitivity and limited capacity of data collection and transmission systems. Few U.S.-funded induction coil systems (with higher sampling rates and capable of detecting EMIC waves) are currently in place – mostly at very high latitudes (Table 1). (There is also possible synergy with the atmospheric electricity community in looking at Schumann resonances, for which sampling rates of 20 Hz or slightly higher are needed.)

Several array teams have recently developed and begun to install upgraded data collection systems based on low-power miniaturized single-board computers that can readily support higher sampling cadences. It is possible that new technologies designed for small satellites and rockets might lead to more sensitive instruments that can be utilized for ground-based research, but no single instrument yet available can cover the entire frequency range from DC to 10 Hz. More critically, we note that the desirability of replacing aging magnetometers and replacing/upgrading data collection and transmission systems so that all sites can record and transmit data with at least a 1 Hz cadence, and do so in near real time, has not been matched by availability of funding.

Figure 7. MACCS magnetometer sensor (inside the white box) at Cape Dorset during Arctic summer. MACCS consists of two approximately east-west chains at 75° and 80° north geomagnetic latitude in eastern Arctic Canada. Each system is located at an Inuit village (often near the airport, as at Cape Dorset, or other public infrastructure facility) where power and local volunteer support can be provided. MACCS data were originally recorded on tape cassettes mailed to the U.S. monthly; currently data are transmitted in near real time via village wireless internet, or in two cases via the Iridium satellite telephone system.

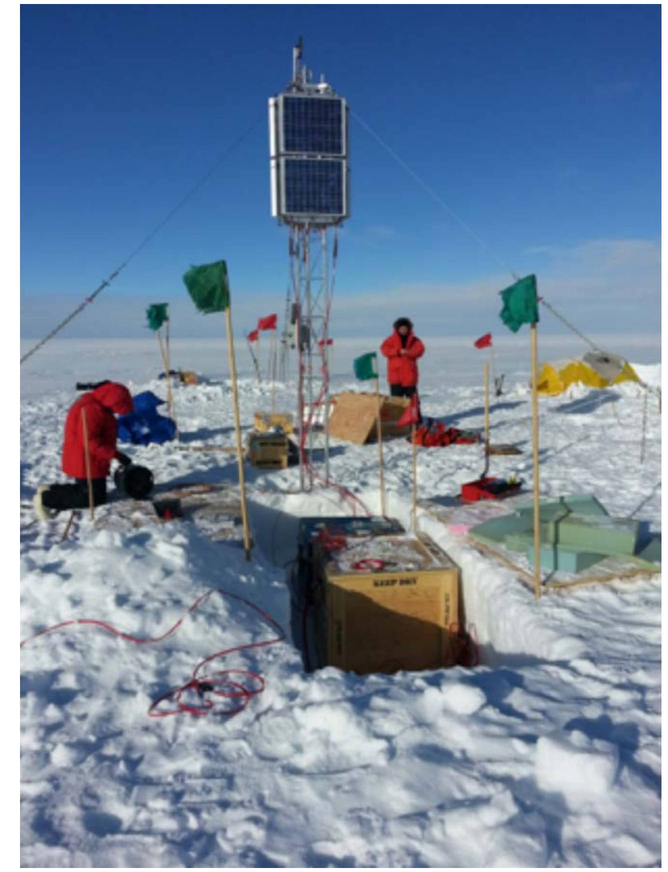

Figure 8. Installation of the Autonomous Adaptive Low-Power Instrument Platform (AAL-PIP) PG5 on the East Antarctic Plateau during January 2016. This station is the final and most equatorward of the high-latitude 6-station chain along the Antarctic 40-degree magnetic meridian, conjugate to Arctic magnetometer stations along the west coast of Greenland. The platform supports fluxgate and induction magnetometers, dual-frequency GPS receiver for ionospheric TEC and scintillation studies, and an HF-radio propagation experiment. Data acquisition and station control utilize Iridium satellite communication links. The equipment and 4-person installation team are carried to the site via Twin Otter aircraft and camp during the 3 - 5 day installation period. Challenges for the installations are the limited cargo capacity of the aircraft, aircraft range limitations requiring the deployment of fuel caches, limited weather information to support the aircraft operations, and very low temperatures and very high altitude of the AAL-PIP sites

Figure 9. AMBER magnetometer sensor that was deployed on the premises of the Centre de Recherche Scientifique de Conakry Rogbanè (CERESCOR) in Conakry, Guinea, Africa. The PI of the AMBER project and an engineer from UCLA carried out the physical deployment in August 2013. The deployment process took 3 days at the site. The most difficult part of the installation was to identify a magnetically quiet site close to a shelter that has electrical power and an internet connection. In addition to providing new science data to the broader community from a region that had been devoid of ground-based instruments, the AMBER magnetometer in Conakry is the first space science instrument ever deployed in Guinea. Thus, it enjoyed full support from the government officials as well as attracting considerable media attention. Since AMBER was deployed in that country, the interest and participation of the local community (especially young students) to space science education and research has increased. Some students have already started their postgraduate studies in space science under the supervision of professors from Cocode University in Abidjan, Ivory Coast (another French speaking country).

CHAPTER 4

ISSUES ADDRESSED AT THE WORKSHOP

The intent of this workshop was to suggest elements of a transition plan toward optimal operation and scientific use of these ground arrays. Higher levels of up-time of array stations, near real time transmission and easier access to data, and a variety of data products from the traditional vector time series obtained at individual stations to regional and/or global derived products and visualizations, can all be expected to enhance the value of ground-based magnetometer data, and ultimately lead to increased understanding of Earth's space environment.

The workshop began with the presentation of five questions:

1. Could technical staffing efforts from individual smaller programs be merged to provide higher 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?

Following this presentation, representatives of various magnetometer arrays presented descriptions of the current state of their programs, including locations, scientific goals and applications, technical details (sampling rates, data communications) and operational concerns. A breakout group of array managers and engineers also discussed new sensor and data recording systems. Other attendees discussed their uses of ground magnetometer data and their suggestions and concerns regarding its provision and optimal use.

Much of the second day of the workshop was devoted to addressing proposed changes in array funding and management, focusing especially on the challenges listed in section 3; the recommendations of the Geospace Portfolio Review (listed in section 5 below); and examples of organization and funding models used in other NSF-funded geoscience facilities (listed in section 6 below).

CHAPTER 5

RECOMMENDATIONS OF THE GEOSPACE PORTFOLIO REVIEW

Listed here are selected findings and recommendations from the 2016 Geospace Portfolio Review commissioned by the NSF [NSF, 2016]. Acronyms used in this report are listed at the end of this section.

Chapter 6: GS Core and Strategic Grants Program

"**Recommendation 6.3.** AER/MAG/STR grants research also should continue to serve as a technology incubator, funding modest-scale projects in experimental instrument development with a focus on new scientific capabilities. As these development efforts mature, their funding source should transition from the core programs to programs such as the recommended Innovation and Vitality (Section 7.4.1) and DASI (Section 7.4.3) programs and the CubeSat program. The GS should also encourage instrument development projects to seek funding through the NSF-wide MRI and MREFC programs when appropriate." (p. 55)

"**Recommendation 6.9.** The GS should encourage and fund AER research projects, in collaboration with the MAG community, for early development of DASI concepts for diagnosing upper atmospheric, ionospheric and magnetospheric processes, as well as the development of self-consistently coupled physics-based models. As the DASI concepts mature, their funding source should migrate to the GS Facilities program (Section 7.4.3)." (p. 57)

PR: "**Recommendation 6.11.** The GS should encourage and fund MAG research projects, in collaboration with the AER community, for early development of DASI concepts for diagnosing upper atmospheric, ionospheric and magnetospheric processes. As the concepts mature, their funding source should migrate to the GS Facilities program." (p. 59)

Chapter 7: GS Facilities and Infrastructure

7.2.1 Definition of a Community Facility

"The Committee found that NSF/GS does not have a clear definition of a Community Facility – what it should provide and how it should interact with its users. The contribution of each facility to GS program goals and objectives does not appear to be consistently evaluated, nor its performance in serving its user community. The contractual arrangements between facility PIs and NSF vary significantly from facility to facility, and funding for science under the primary grant or cooperative agreement of each facility also varies significantly among the facilities. This practice has meant that the expectations of the facilities and their management is not clear or transparent."

As a result of its examination of NSF/GS practices regarding facilities, the Committee has identified the essential characteristics of a NSF GS facility.

"**Recommendation 7.1.** A facility should exhibit the following functions:

1. Serve a community of users well beyond a single PI or small group of investigators, i.e., at least national but may be international;
2. Be operated in such a way as to ensure responsiveness to the needs of the research community to sustain international-class scientific productivity; thus each facility is expected to have both an advisory group and a user forum, with membership not selected by facility management;
3. Operate for more than one award cycle and typically substantially longer if warranted by the Senior Review Process (see Section 7.8);
4. Make all data openly available and accessible in a timely fashion according to a published data distribution and dissemination plan;
5. Develop and deliver an effective long-term plan to maintain the facility at an international cutting-edge level;
6. Carry out a limited amount of science funded from the Maintenance and Operations (M & O) contract (see section 7.5.2);
7. Support the deployment and operations of co-located instruments with the full costs covered by each co-located instrument Principal Investigator;
8. Deliver substantial education, outreach, and diversity programs; and
9. Provide cost-effective operations." (pp. 74-75)

Comments of the appropriateness of this list to proposed ground magnetometer facilities are presented in section 9 below.

7.2.3 Class 1 and Class 2 Community Facilities

"The PRC found it helpful to consider the Community Facilities in two classes. A Class 1 facility is a major, complex facility at a single site. Its investment over time typically reaches many $10sM, requires significant M&O funds and accommodates a variety of complementary instruments at or very near the site. Class 1 facilities might be expected to have a lifetime of 20+ years from first deployment. In the current portfolio, all the incoherent scatter radars (ISRs) are considered to be Class 1.

"Class 2 facilities are more modest and diverse investments. They include distributed networks of instruments that are simpler to operate than ISRs (e.g. SuperDARN), facilities producing value-added products from data from other sources (e.g. SuperMAG and AMPERE), model support for the community (e.g. CCMC) and data management (Madrigal Database, currently funded through the Millstone Hill ISR contract)." (p. 75)

7.3.4 Class 2 Facilities: Findings and recommendations

"***Finding.*** *Several magnetometers and magnetometer arrays are funded through research projects.*

"**Recommendation 7.16.** The GS should assess if the era may now exist wherein greater scientific synergies and optimization of operations could be obtained if all GS-sponsored magnetometers were managed as a single array. Such an array could thus evolve into a Class 2 facility (see Section 7.4.3 for more details on DASI)." (p. 81)

7.4.3 Distributed Arrays of Small Instruments (DASI)

"The DASI concept was recommended in the first decadal survey of solar and space physics research *The Sun to the Earth and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2003). DASI would provide the temporal and spatial coverage of many atmospheric and ionospheric parameters that complement measurements from other ground- and space-based facilities. The DASI concept was subsequently examined by a National Academies workshop.[25]

25 http://www.nap.edu/catalog/11594/distributed-arrays-of-small-instruments-for-solar-terrestrial-research-report

"In the last decade, the DASI concept has not evolved as rapidly as originally envisaged. This shortcoming has been due to a variety of factors, including a lack of funding opportunities, inadequate community experience in cultivating the required international collaborations, and inadequate experience in developing robust capabilities for unmanned and energy-efficient operation of distributed instruments and for automated data processing, analysis and transfer. Nevertheless, some members of the US scientific community have forged ahead with the development and improvement of new ground-based instrumentation and the deployment of small networks. These activities have been sponsored by diverse funding streams including NSF MRI, GS Core, the Office of Naval Research, and the Department of Defense University Research Instrumentation Program (DURIP).

...

"The types of instruments deployed in DASI-type networks include but are not limited to Global Positioning System receivers giving total electron content (TEC) and scintillation activity, Fabry-Perot interferometers measuring winds and temperatures at mesospheric and/or thermospheric altitudes, magnetometers, meteor wind radars, digital ionosondes, LIDARs, optical imagers, photometers, riometers and VLF radio receivers.

"***Finding.*** *With growing recognition for the importance of geospace system science, the geospace community can expect, in the next decade, an increasing demand for higher spatial and temporal resolution in measurements, not only to determine the local, regional and global scale of processes but also for data assimilation into geospace models.*

"**Recommendation 7.24.** The GS should create a "DASI" fund with two purposes: (i) to develop and build new "small" instrumentation suitable for deployment in a DASI network and (ii) to provide M&O funds to maintain the network once created." (p. 84)

Chapter 8. Partnerships and Opportunities

8.3 International Partnerships

"***Finding.*** *US funding for engagement in international partnerships provides excellent leverage for additional data, access to an expanded base of scientific and technical skills and knowledge, and to new and innovative software and hardware. Significant benefits accrue to all partners." (Examples included SuperDARN and the MACCS magnetometer array. Other examples could include SAMBA, AMBER, LISN, THEMIS GMAG, and various international partnerships for U.S.-built induction magnetometers, which already involve the U.K., Norway (Svalbard), South Korea, and Germany.*

"Recommendation 8.16. The GS should continue to sponsor highly-rated proposals to develop, deploy, and operate new instruments, instrument networks and data acquisition, especially when GS resources for the project are leveraged through international partnerships." (p. 103)

Chapter 9. Recommended GS Portfolio

9.4 GS Facilities Program

"The DRIVE initiative of the DS directs NSF to provide funding sufficient for essential synoptic and multiscale observations. Distributed measurements are required to provide synoptic ground based observations of geospace phenomena. DASI networks can fulfill this requirement. The recommended portfolio includes an explicit line item for DASI development, deployment and operation.

"**Recommendation 9.12.** The GS should create a new ***DASI Facilities Program*** with a $1.6M annual budget. This fund should be used initially to develop and implement one or more DASI Class 2 facilities with concept selection determined by peer review. For a fully operational DASI to transition to a Class 2 facility, it must satisfy the criteria for a community facility as defined in Section 7.2." (p. 110)

List of Acronyms and Abbreviations used in the Geospace Portfolio Review

AER	Aeronomy program, within NSF's Geospace Section
AGS	Division of Atmospheric and Geospace Science of the National Science Foundation
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
CCMC	Community Coordinated Modeling Center
DASI	Distributed Arrays of Small Instruments for Solar-Terrestrial Research
DS	Solar and Space Physics Decadal Survey
DRIVE	Diversify, Realize, Integrate, Venture, Educate
GS	Geospace Section of the Division of Atmospheric and Geospace Science (AGS) of the National Science Foundation
ISR	Incoherent Scatter Radar
MAG	Magnetospheric Physics program, within NSF's Geospace Section
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation Program
M&O	Maintenance and Operations
NSF	National Science Foundation
PRC	Portfolio Review Committee
STR	Solar-Terrestrial Research program, within NSF's Geospace Section

CHAPTER 6

EXAMPLES OF GOVERNANCE AND ORGANIZATION IN OTHER SCIENTIFIC FACILITIES

In this section we review four examples of organizations currently funded by NSF to coordinate distributed scientific instruments and research programs: EarthScope, IRIS, UNAVCO, and SuperDARN. Only SuperDARN falls within the GS branch of NSF. The others, however, deal with small, distributed sensors.

6.1 EarthScope:

EarthScope is a program of the National Science Foundation that deploys thousands of seismic, GPS, and other geophysical instruments to study the structure and evolution of the North American Continent and the processes that cause earthquakes and volcanic eruptions. It comprises three interlinking components: 1) the EarthScope Facility operated by the UNAVCO and IRIS consortia (see below), 2) a research program that supports PI-led investigations, and 3) an investigator community, coordinated by an academic EarthScope National Office, that actively participates in science planning, research, and facility governance. The EarthScope National Office (ESNO) is a rotating, university-based organization that facilitates scientific planning and coordinates education and outreach efforts for the EarthScope community. The ESNO also organizes the EarthScope National Meeting and several scientific workshops held throughout the year, supports and facilitates EarthScope Synthesis Workshops, provides opportunities for community planning, and maintains and updates an EarthScope web site to highlight key science, education, and outreach results.

6.2 IRIS (Incorporated Research Institutions for Seismology)

IRIS is a nonprofit consortium of over 120 US universities dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data. The IRIS governance and management structure is an interface among the scientific community, funding agencies, and IRIS programs. The structure is designed to ensure close involvement of the research community in the development of IRIS facilities, focus scientific talent on common objectives, encourage broad participation, and effectively manage IRIS programs. Each year, over 50 scientists from member institutions participate in IRIS management through its Board of Directors, eight regular committees, and ad hoc advisory groups. Standing committees maintain community oversight while program managers are responsible for day-to-day activities. Committee scientists work with a professional staff at IRIS led by the President, Director of Planning, Director of Project Administration, Director of Finance and Administration, and the five program managers. Representatives of the full set of member institutions elect the nine-member Board of Directors. IRIS also maintains an Advisory Council, Science Advisory Committees, and a Coordinating Committee.

6.3 UNAVCO

UNAVCO was created in 1984 in response to the challenge of applying GPS to geosciences. At that time it was called the University NAVSTAR Consortium. Managed by a Board of Directors, UNAVCO periodically develops a Strategic Plan, and provides GPS/GNSS receivers, seismometers, tiltmeters, etc. for purchase or loan. Following installation, UNAVCO tests and troubleshoots the instruments and the data collection, power and communications systems required to record and access data from continuously operating and often remote sites. It also provides network monitoring for several networks from which UNAVCO downloads data. UNAVCO has three Standing Committees (Audit and Finance, Nominating, Membership), five Advisory Committees to the Board (Education and Community Engagement, Geodetic Data Services, Geodetic Infrastructure, Polar Networks, and WinSAR Executive Committee), and two Working Groups (COCONet and Terrestrial Imaging Geodesy).

6.4 SuperDARN

The U.S. portion of SuperDARN (the Super Dual Auroral Radar Network) is a recognized Class 2 facility, consisting of a collaboration of 4 institutions (Virginia Tech, JHU/APL, Dartmouth College, and the University of Alaska Fairbanks), for which one collaborative proposal is written. This base award from the Space Weather Research Program covers the operation of about 10 HF coherent-scatter radars, the processing and distribution of data to SuperDARN partners, and the provision of support to data users, in addition to modest amounts for developing new research lines with the data. The scientific staff of the SuperDARN groups separately pursue support for research from NSF, NASA, and other sources in both base and targeted programs. Economies of scale are realized in that technical progress by one group benefits the others and there are notable leveraging benefits in that the U. S. partners and the U.S. research community gain access to the entire SuperDARN data archive which is generated from about 35 radars. The costs of the non-U.S. operations are supported by the funding agencies of the other participating countries. Importantly, the partners agree on common protocols for operating the radars and processing the data into a single shared format.

Comparison of SuperDARN and Ground-based Magnetometer Arrays

- Both are examples of distributed, always-on, arrays of distributed instruments that produce a uniform 'product'.
- Their data are important for a big-picture view of Magnetosphere-Ionosphere-Thermosphere coupling processes.
- Their measurements relate directly to fundamental ionospheric parameters (electric fields and currents).
- They are different in terms of development path - all SuperDARN radar designs derive from the original radar (Goose Bay) and new groups have adopted the established operating and software protocols. Ground magnetometer arrays have developed largely independently; they use 5 different types of fluxgate instruments, many different types of controllers and data recording systems, produce data in several different formats and at different sampling rates, and provide their data mostly via a number of array-specific web sites.
- They are also vastly different in the fields of view of individual instruments: each ground magnetometer has an effective omnidirectional range of ~100 km, while each SuperDARN radar has a radial range from 180 km to ~3500 km and an azimuthal range of ~30°-60°.
- Web tools exist to facilitate viewing of all SuperDARN data and higher level products (by both experts and non-experts). With the exception of SuperMAG, ground-based magnetometer data are consulted in a more ad hoc and disjointed way.

Internationally the SuperDARN collaboration is managed by the SuperDARN Executive Council, which is comprised of Principal Investigators (PIs) from the partner nations. The Executive Council oversees the joint operations of the radars, implements new initiatives brought forward by the various working groups and individuals, and ensures timely access for users to high quality data. The SuperDARN Principal Investigators' Agreement specifies that the PIs are responsible for one or more SuperDARN radars, managing all radar operations in the various countries, leading the engineering and technical teams, handling day-to-day radar operations, raising necessary funds, and are to be the point of contact for users. The Executive Council holds a face-to-face meeting at the annual international SuperDARN workshop.

The annual workshop is the principal venue for the PI Council to coordinate the activities of various working groups that maintain consistency across the collaboration. These include working groups to coordinate radar scheduling, data distribution, and coordination with satellite missions. The working groups operate year-round and maintain communications by emailing and dedicated web sites. They are also tasked with developing and testing new experimental capabilities and ensuring high data quality and reliable data distribution and archiving.

6.5 Polar Engineering Development Center (PEDC)

The PEDC, housed at the New Jersey Institute of Technology (NJIT) and operating collaboratively with Merrimack College and the University of New Hampshire, consists of collegiate professors, research scientists, electrical and mechanical engineers, and technicians experienced in instrument and hardware design for deployment in high latitude/polar regions. The original group was formed in the 1980s as part of the NSF-supported Automatic Geophysical Observatory (AGO) program which operates to this day on projects active across the Antarctic ice shelf. The PEDC is a community resource for the Antarctic astrophysical and geospace communities, thus serving the analogous role that the UNAVCO or IRIS-PASCAL programs serve to the Antarctic Earth Sciences Program, by providing support in the areas of (a) sustainable "green" power generation in the 10-W to 100-W range, (b) power conditioning and control, (c) robust engineering for polar climates, (e) data acquisition techniques, units, and transmission services, and (f) general polar field support. Many of the U.S. Antarctic magnetometer systems are currently operated by the PEDC.

CHAPTER 7

FINDINGS AND RECOMMENDATIONS

Making the transition to a Class 2 ground magnetometer facility, following current examples such as SuperDARN, will involve changes in the organization and funding of P.I.-led magnetometer arrays, but brings the promise of achieving critically important long-term stability and scientific productivity for these arrays, including the development of an easily accessible, long term archive of the data. At the most basic level, this involves splitting facility/operations budgets from science budgets for each magnetometer array. In the near term, facility/operations budgets might themselves be split or divided out, so that PIs install and maintain the hardware, while one or two categories of cooperative organizations – a "diagnostics and response unit" and an "augmented data center" – would be responsible for monitoring of routine operations (data recording and transmission) and storage and distribution of data and production of data products, respectively.

Suggested Initial Steps (within months)

1. Increase coordination among array managers via blogs, e-mail lists, or similar easy-access means regarding operational issues such as coordination of repair and maintenance visits and technical issues such as development of new miniaturized data systems and compatible data formats. Also increase discussions of these matters with the wider user and instrument communities and NSF staff in the Division of Atmospheric and Geospace Sciences (AGS, Aeronomy, Magnetosphere) and Office of Polar Programs (OPP).

2. Encourage individual array programs to prepare data in standard formats and to transmit them in near real time (if this is not currently done) to data centers such as SuperMAG, THEMIS, and CDAWEB. Efforts to achieve these objectives, if needed, should be part of any renewal proposals for funding in the near future.

3. Proposals for renewed funding of magnetometer arrays in the near future should clearly designate facility/operations budgets and person-months separately from science budgets.

4. Schedule a followup workshop for all members of the ground magnetometer array community, to be held during or immediately before or after the summer 2017 GEM Workshop, to develop plans for implementing the near-term steps below.

Near-term Steps (1-3 years)

1. Establish a Ground Magnetometer Array Advisory Board (4-6 members) tasked to periodically evaluate the operations and effectiveness of all U.S.-funded ground magnetometer arrays, suggest possible additional magnetometer locations in consultation with USGS and the international ground magnetometer community (including ULTIMA), and develop plans in conjunction with NSF-AGS, NSF-OPP, and the ground magnetometer community to transition toward more complete implementation (as appropriate) of the DASI model, leading toward partial or full funding of arrays from the Geospace Facilities Program. (Portfolio Review recommendations 6.9, 6.11, and 7.16) As was pointed out in that review, further studies are needed to quantify the cost/benefit value, if any, of multi-instrument DASI networks: feeding data from various types of sensors into a common power, data recording, and data transmission system, either at remote sites (often at high latitudes and/or in extreme environments) or at less challenging locations.

2. Fund a team, selected by the Advisory Board, via a small grant to gather information about operational costs of all NSF-supported magnetometer arrays, including person-months; instrument down time and causes; mode of data transfer; and use of array data, including number of publications. The funding logistics could be satisfied by a small supplement to an existing grant.

3. Provide sufficient support to SuperMAG to enable it to ingest, store, and serve the full set of data from both fluxgate and induction coil magnetometers, at their original sampling rates (currently only 1-min data are provided by SuperMAG).

4. Develop and fund one (or a small number of regional) Ground Magnetometer Diagnostics and Response Units (GMDRUs) that share common technologies (e.g., instrument types and manufacturers) or geographic regions (e.g., polar, midlatitude, low latitude). These Units will support operations and data transmission of all U.S.-funded ground magnetometer arrays currently supported only by grants to individual arrays. GMDRU personnel will monitor instrument operation, data quality, and volume of data transmitted on a daily basis, and notify responsible array personnel of any problems. Because it is not immediately clear how such a transition will work for each GMDRU, it was considered inadvisable at the outset to move the responsibility of performing necessary repair and maintenance tasks at individual sites from the current array management to its GMDRUs, but we recommend a transition toward this end. As part of this step, we recommend that the Ground Magnetometer Array Advisory Board develop a set of metrics to measure the performance of GMDRUs and any improvements in array function that they contribute. Figure 10 shows a possible transitional

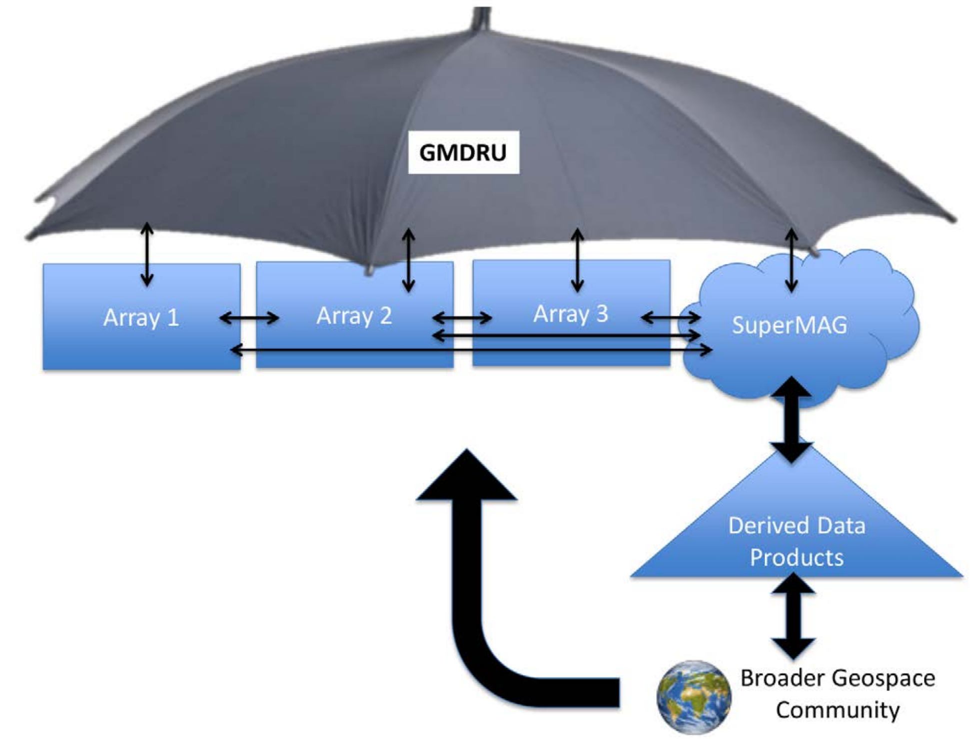

Figure 10. Sketch of a possible interim organizational structure for the U.S. ground magnetometer community, adapted from a diagram developed by Dr. Andy Gerrard of the New Jersey Institute of Technology.

configuration. Three (or more) magnetometer array groups receive monitoring and maintenance support from a GMDRU, and either directly or via the GMDRU they transmit their data to a central repository such as SuperMAG that also prepares derived data products, and makes all the data easily available to the geospace community. Initially several array groups and GMDRUs may form; initial experience with these configurations, as well as optimization studies, may lead to modifications as the ground magnetometer community moves toward a more unified operational structure.

5. Make funds available to ground magnetometer array projects to reimburse local hosts (currently often unpaid volunteers) for their support of magnetometer systems at remote sites.

6. Either in the GMDRUs or as a whole, the ground-based magnetometer community should consider the possibility of moving toward a standardized raw data format, and if the move to single-board systems running variations of the unix operating system permits, consider developing a "Mag OS" magnetometer operating system that all teams could use.

7. Develop, in conjunction with the emerging DASI community and the magnetic observatory community, additional global higher level products to support scientific efforts using other ground-based instrumentation, spacecraft missions, and computer simulations, and enable them to be displayed using community-supported graphic tools such as Autoplot.

8. Encourage efforts to develop improved ground magnetometer array systems (sensors, data recording and storage computers, data transmission technologies and protocols) through both existing and possibly new NSF funding channels. (Program Review Recommendation 6.3) For fluxgate magnetometers this would include higher sampling rates, lower noise and digitization levels, and ideally miniaturized footprint, lower power, and environmentally robust operation (e.g, for use in polar regions and at remote sites). In the ideal case a single instrument would provide both vector and total field (scalar) measurements with high accuracy, and be used to replace the currently separate vector (fluxgate and induction coil) and scalar instruments at magnetic observatories worldwide.

Longer-term Steps (5-10 years)

1. Develop and fund one or more Class 2 facilities to operate, monitor, and maintain all NSF-funded ground-based magnetometer arrays (Program Review recommendations 6.9, 6.11, and 7.16). Steps in this direction are already underway within the U.S. Antarctic Program (e.g., the Polar Engineering Development Center). The creation of GMDRUs will be an initial step in this direction and, if successful, will enable the ultimate creation of the overall Class 2 facility or facilities. Planning for this/these facilities should also take into account the necessity of working with international partners (Program Review recommendation 8.16).

2. Provide funding to install improved, identical magnetometer sensor, recording, and data transmission systems to the extent that this is financially and logistically feasible. (As long as equipment continues to vary from one array to another, the effectiveness of a single Class 2 facility in operating, monitoring, and especially maintaining all participating arrays will be diminished.)

3. Continue to develop global higher level data products to support scientific efforts using other ground-based instrumentation, spacecraft missions, and computer simulations. (See the next section for examples of such products.)

CHAPTER 8

DERIVED DATA PRODUCTS

Global and higher level data products such as Kp, AE, and Dst, based on ground-based magnetic field data have for many years been used for both quick-look and more in-depth studies of magnetospheric and ionospheric phenomena. They can be used in support of studies using other ground-based instrumentation, spacecraft missions, and computer simulations. 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 make it practical to generate additional indices and more complex data products. The SuperMAG team has used worldwide ground magnetometer data to develop indices utilizing many more stations than the standard auroral electrojet indices (SuperMAG SME, SMU, and SML vs. AE, AU, and AL).
Visual / graphical products have significant value to the space physics community both as quick-look indicators of activity and as detailed displays of spatially extended scalar and vector variations. Products developed by SuperMAG also include graphical displays such as Figure 2 showing, for example, ionospheric convection (derived from magnetic perturbations) and auroral activity.

Higher-level Data Products

Scientific Value of Higher-level Products

- Provides basis for large-picture, system-level science for showing connections between domains
- Assists in developing first-principles MHD models
- Enables space weather science and applications

Helpful Attributes of Higher-level Products:

- Easy to access and understand
- Underlying data are available for more refined analysis
- Supported by easily accessible expertise (a knowledgeable person)

Possible additional data products:

a. Global field-line resonance-based calculations of mass density as a function of L and local time (e.g., extensions of those shown in Figure 3), including location and characterization of the plasmapause.

b. SuperMAG currently produces its own versions of the auroral electrojet indices AE, AU, and AL, designated SME, SMU, and SML. It could also produce local time indices, and regional K indices (regional activity indices specifying localized activity across a particular area over earth).

c. Global equivalent currents and electrojets, equatorial and auroral electrojet variability in longitude, and possible regional products.

d. Routine production of spatial plots (maps) of simultaneous data from magnetometers and other instruments such as the SuperDARN radars.

e. Maps of the synoptic open/closed boundary of the magnetosphere.

f. Quick-look global maps (magnetic keograms) of perturbations and ULF waves: "Is there any activity? Where?" Maps of ΔB and Pc5 wave amplitudes (broadband, narrowband, or combined, possibly using the ULF index database), EMIC waves, etc. Also, stacked plots of time series of "virtual magnetometers" at fixed local times.

g. Comparisons of interhemispheric perturbations; conjugate maps of electrojet currents, ULF wave activity at least in the Pc5 band, and at least at well-instrumented longitudes; conjugate maps of cusp and substorm phenomena.

h. Development of more 'interpretive' capabilities such as automated identification and location of substorms and Pi2s.

i. Joint data products with USGS for Space Weather diagnostics, and that the global GIC (ground-induced currents) community can use. (INTERMAGNET routinely provides time series plots of dB/dt at each station.)

j. Shared software tools for analysis of magnetometer data, as is done, for example, in the seismic and astrophysical communities. These might include standardized error detection and mitigation software for secular variation baseline jumps and drifts. (See the example of Quakefinder, which has deployed a network of induction coil systems to search for earthquake precursors.)

CHAPTER 9

CLASS 2 FACILITY CONSIDERATIONS

As noted in section 5 above, the Portfolio Review included a proposed list of nine items that would characterize every Facility, presumably both Class 1 and Class 2, supported by NSF-AGS. In this section we briefly note our understanding of the potential fit of both A) the proposed GMDRUs, and B) a full ground magnetometer array DASI structure:

1. Serve a community of users well beyond a single PI or small group of investigators, i.e., at least national but may be international. A: No B: Achievable

2. Be operated in such a way as to ensure responsiveness to the needs of the research community to sustain international-class scientific productivity; thus each facility is expected to have both an advisory group and a user forum, with membership not selected by facility management; A,B: Achievable for both

3. Operate for more than one award cycle and typically substantially longer if warranted by the Senior Review Process (see Section 7.8). A,B: Achievable for both

4. Make all data openly available and accessible in a timely fashion according to a published data distribution and dissemination plan. A,B: Achievable for both

5. Develop and deliver an effective long-term plan to maintain the facility at an international cutting-edge level. A,B: Achievable for both

6. Carry out a limited amount of science funded from the Maintenance and Operations (M & O) contract (see section 7.5.2). A,B: This task seems more appropriate for Class 1 Facilities.

7. Support the deployment and operations of co-located instruments with the full costs covered by each co-located instrument Principal Investigator. A: No B: Achievable

8. Deliver substantial education, outreach, and diversity programs. A,B: This task seems more appropriate for Class 1 Facilities.

9. Provide cost-effective operations. A,B: Achievable for both

One additional task of the Ground Magnetometer Array Advisory Board or its successor will be to work with NSF-AGS staff to develop an appropriate and feasible version of the above list that can be used to guide the operations and management of the GMDRUs and future full ground magnetometer array DASI structure(s).

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U.S. GROUND-BASED MAGNETOMETER ARRAYS AND PROGRAMS AS OF FALL 2016

Array	Location	Instruments	Manufacturer	No. of Locations
AAL-PIP	Antarctica	Fluxgate	Korepanov	6
	Antarctica	Induction coil	UNH	6
AMBER/iMAGS	Africa	Fluxgate	UCLA	7
	South America	Fluxgate	UCLA	2
	East Asia	Fluxgate	UCLA	4
Falcon	Continental US	Fluxgate	UCLA	6
GIMA	Alaska	Fluxgate	Narod	9
IGPP-LANL	Continental US	Fluxgate	UCLA	2
Jicamarca	South America	Fluxgate	UCLA/Jicamarca	4
LISN	South America	Fluxgate	Jicamarca	6
MACCS	Arctic Canada	Fluxgate	Narod	8
McMAC	Cont. US & Mexico	Fluxgate	UCLA	9
MEASURE/iMAGS	Cont. US	Fluxgate	UCLA	6
SAMBA/iMAGS	South America	Fluxgate	UCLA	7
	Antarctica	Fluxgate	UCLA	3
THEMIS	Canada	Fluxgate	UCLA	22
U.S. Geological Survey	U.S. & Territories	Fluxgate	Narod	14
NJIT / AGO	Antarctica	Fluxgate	Bell Labs	7
	Antarctica	Induction coil	Tohoku U.	5
MICA - North	Alaska, Canada, Greenland, Svalbard	Induction coil	UNH/Augsburg	8
MICA - South	Antarctica	Induction coil	UNH/Augsburg	3

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LIST OF GROUND MAGNETOMETER ARRAY WEB SITES SERVING MAGNETOMOETER DATA

AAL-PIP	http://mist.nianet.org/index.html
Antarctic Geospace	https://antarcticgeospace.njit.edu/
CDAWEB	http://cdaweb.gsfc.nasa.gov/
GIMA	https://www.asf.alaska.edu/magnetometer/
INTERMAGNET	http://www.intermagnet.org/data-donnee/download-eng.php
LISN	http://lisn.igp.gob.pe/
MACCS	http://space.augsburg.edu/maccs/index.html
Search Coils (Augsburg)	http://space.augsburg.edu
Search Coils (UNH)	http://mirl.sr.unh.edu/projects_ulf.html
SAMBA-AMBER	http://magnetometers.bc.edu/index.php/78-magnetometers/78-home
USGS	http://geomag.usgs.gov/products/
SuperMAG	http://supermag.jhuapl.edu/
THEMIS GMAG	http://themis.ssl.berkeley.edu/data/themis/thg/mirrors/mag/
World Data System	http://wdc.kugi.kyoto-u.ac.jp, http://www.wdc.bgs.ac.uk

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