Real-time geomagnetic monitoring for space-weather related applications: Opportunities and challenges: Geomagnetic monitoring

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2 authors:

Jeffrey J. Love
United States Geological Survey, Denver, United States

Carol A Finn
United States Geological Survey

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Key Points:
- A summary is given of challenges and opportunities associated with global availability of real-time, ground-level geomagnetic monitoring
- Enhanced monitoring will benefit from leveraging multisector, cross-disciplinary, and international interests and capacities
- Applies to station location coverage, data quality, sampling frequency, transmission promptness, and ease of access and use of data

Correspondence to:
J. J. Love,
jlove@usgs.gov

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Real-time geomagnetic monitoring for space weather-related applications: Opportunities and challenges

Jeffrey J. Love[1,2] and **Carol A. Finn**[1,3]

[1]Geomagnetism Program, U.S. Geological Survey, Denver, Colorado, USA, [2]Formerly served on the INTERMAGNET Executive Council and as Chairman, [3]Serves on INTERMAGNET Executive Council

Abstract An examination is made of opportunities and challenges for enhancing global, real-time geomagnetic monitoring that would be beneficial for a variety of operational projects. This enhancement in geomagnetic monitoring can be attained by expanding the geographic distribution of magnetometer stations, improving the quality of magnetometer data, increasing acquisition sampling rates, increasing the promptness of data transmission, and facilitating access to and use of the data. Progress will benefit from new partnerships to leverage existing capacities and harness multisector, cross-disciplinary, and international interests.

1. Introduction

Around the world, geomagnetic variation and disturbance are monitored from ground-based magnetometer stations [e.g., *Love*, 2008]. The stations are operated by governmental, academic, and commercial institutes in support of basic and applied science projects, including assessing space weather conditions, mapping of geoelectric hazards, directional drilling for oil and gas, and performing aeromagnetic surveys for mineral exploration and geological investigation. Many of these projects could benefit from an enhancement in real-time geomagnetic monitoring. Recognizing this, the Inter-Programme Coordination Team on Space Weather of the World Meteorological Organization and the International Living With a Star Steering Committee of the Committee on Space Research both recommend improving prompt access to data from ground-based magnetometers [*Schrijver et al.*, 2015]; the United States National Space Weather Action Plan identifies real-time ground-based magnetometers as an observational capability that should be expanded [*National Science and Technology Council* (*NSTC*), 2015, Action 6.2.1].

It is important to recognize that the opportunities and challenges that exist for enhancing geomagnetic monitoring are related to institute-to-institute differences in capabilities, cultures, traditions, interests, priorities, and policies, as well as different levels and models of funding [e.g., *Arzberger et al.*, 2004; *Uhlir and Schröder*, 2007]. Enhancement in geomagnetic monitoring can come in a variety of ways. A "top-down" approach concentrates on the negotiation and adoption of high-level agreements with nations and their geophysical monitoring institutes. A "bottom-up" approach seeks to leverage existing multisector, cross-disciplinary, and international capacities for geomagnetic monitoring by (goal 1) expanding the geographic distribution of magnetometer stations, (goal 2) improving magnetometer data quality, (goal 3) increasing acquisition sampling rates, (goal 4) increasing the promptness of data transmission, and (goal 5) facilitating access to and use of real-time magnetometer data.

2. Priority Operational Applications

2.1. Monitoring and Assessment of Space Weather Conditions

Ground-level magnetometer data have led to numerous and seminal discoveries in space weather science, and they are the basis for definitions of the commencement, initial, and main phases of magnetic storms [e.g., *Loewe and Prölss*, 1997]. Given this, it is not surprising that magnetometer data play an important role in operational monitoring of space weather conditions [e.g., *Nagatsuma*, 2013]. They are, for example, described as "priority-1" and "mission critical" in an observation requirements list of the Space Weather Prediction Center (SWPC) of the *National Oceanic and Atmospheric Administration* [2009].

In this context, magnetic indices [e.g., *Menvielle et al.*, 2011] are worthy of special mention. These are simple scalar summary measures of magnetic disturbance and storm intensity that are important for many purposes, including operational evaluation of space weather conditions. Magnetic disturbance tends to be organized by geomagnetic latitude: the auroral electrojet indices *AE* [*Kunitake et al.*, 2002] are produced by the Kyoto World Data Center in near real time [*Meng et al.*, 2004]; the midlatitude regional K and global, midlatitude *Kp* indices are produced by GeoForschungsZentrum; the standard 1 h, low-latitude, ring current index *Dst* [*Sugiura and Kamei*, 1991] is produced by Kyoto in near real time; and a 1 min *Dst* is produced by the U.S. Geological Survey (USGS) in near real time [*Gannon and Love*, 2011]. The U.S. Air Force (USAF) produces versions of the *K* and *Kp* indices [*Gehred et al.*, 1995] in near real time that are used by the USAF and NOAA SWPC [e.g., *Balch et al.*, 2004].

Magnetic indices and magnetometer time series are used as input for operational (and potentially operational) models of the space environment: models of ionosphere [e.g., *Richmond et al.*, 1998; *Araujo-Pradere et al.*, 2002; *Schunk et al.*, 2004; *Bilitza et al.*, 2011] can be used to evaluate effects on the accuracy of global positioning systems and over-the-horizon radio communication; models of thermospheric density [e.g., *Storz et al.*, 2005; *Bowman et al.*, 2008] can be used to evaluate spacecraft drag; models of the radiation belts can be used to evaluate spacecraft charging hazards [*Fok et al.*, 2008; *Horne et al.*, 2013].

2.2. Geoelectric Hazard Mapping

Geoelectric fields induced in the Earth's conducting interior during magnetic storms can interfere with the operation of electric power grids [e.g., *Piccinelli and Krausmann*, 2014]. For practical evaluation of geoelectric hazards, estimates of both the local surface impedance and geomagnetic activity are needed [e.g., *Thomson et al.*, 2009; *Love et al.*, 2014]. Real-time maps of storm time geomagnetic activity can be derived from ground magnetometer data [*Pulkkinen et al.*, 2003; *Rigler et al.*, 2014; *NSTC*, 2015, Action 5.5.6]. Impedance is measured at discrete geographic sites during magnetotelluric surveys [e.g., *Unsworth*, 2007]. The time convolution of maps of Earth impedance and geomagnetic activity yields a map of the induced geoelectric field [e.g., *Kelbert et al.*, 2016; *NSTC*, 2015, Action 5.5.6].

2.3. Directional Drilling

Accurate, real-time magnetometer data are used by oil and gas companies for directional drilling—multiple reservoirs can be accessed from a single platform by drilling down and then laterally outward. This reduces both extraction costs and negative impact to the surface environment. Downhole orientation can be accomplished using a magnetometer in an instrument package that follows the drill bit and, also, with simultaneous monitoring of geomagnetic field direction at a nearby ground-based station [e.g., *Buchanan et al.*, 2013; *Nair et al.*, 2015]. At high latitudes, such as in Alaska and the North Sea, the geomagnetic field can be very active, and accurate real-time observatory data can be of critical importance for accurate drilling. Indeed, it is now possible to use magnetic observatory data to accurately drill during a magnetic storm [e.g., *Reay et al.*, 2005].

2.4. Aeromagnetic Surveying

Ground magnetometer data are used for aeromagnetic [e.g., *Pilkington*, 2007] and marine magnetic [e.g., *Tivey*, 2007] surveys that are undertaken for mineral exploration [e.g., *Fletcher et al.*, 2011] and geological investigation. Before performing a survey, a check is made of forecasted geomagnetic disturbance; if this exceeds a given threshold, such as given by a local *K* index, then the survey might be postponed until quiescent conditions are expected to return [e.g., *Watermann et al.*, 2011]. Then, during the survey, magnetometer time series are collected from moving airborne and shipborne magnetometers, which record both spatial variation and temporal geomagnetic field variation, and, simultaneously, from a fixed-site "base station," which records temporal variation. By subtracting the base station time series from the survey time series, a map of magnetic anomalies can be obtained.

2.5. Opportunities and Challenges for Operational Applications

With respect to general improvement (goal 1) in the geographic distribution of magnetometer stations, institutes focused on monitoring and assessment of space weather conditions would generally benefit from receiving magnetometer data acquired from a global distribution of stations. In this respect, then, space weather monitoring projects might usefully receive data from institutes focused on geoelectric hazard mapping, directional drilling, and aeromagnetic surveying, for which data are acquired from a geographically localized distribution of stations. Accomplishing this will require close communication, cooperation, and coordinated planning between institutes from the governmental, academic, and commercial sectors [e.g., *Intriligator*, 2007; *Baker*, 2011], as well as across the traditionally distinct space science and solid Earth disciplines [e.g., *Love et al.*, 2017].

3. Magnetometer Station Types

3.1. Observatories

A magnetic observatory is designed to support continuous and accurate measurements of the local geomagnetic field over a long duration of time [e.g., *Rasson et al.,* 2011]. Since the 1970s and 1980s, observatory institutes have been collecting digital data with a 1 min sampling interval using fluxgate (variometer) magnetometer sensor systems [e.g., *Primdahl*, 1979]. These data are available with different quality levels, and they are available for use after different time delays. Raw variometer time series have not been inspected by a geophysicist and, in particular, not calibrated in any rigorous sense, and as such they are considered "preliminary." Many observatory institutes "adjust" their variometer data so that they have a rough calibration; often, this is just a rotation factor applied to correct for installation orientation defined by the prevailing geomagnetic meridian (the deviation from geographic north is declination). Additional processing is required to produce more "definitive" data; these have been cleaned of spikes and offsets, and they have been calibrated for slow drift in variometer response using auxiliary "absolute" data [e.g., *Jankowski and Sucksdorff*, 1996].

The International Real-time Magnetic Observatory Network (INTERMAGNET) is a voluntary consortium of institutes which promotes the operation of observatories according to a common set of modern standards, checks, and certifies observatory data and facilitates their dissemination [e.g., *Love and Chulliat*, 2013]. Most observatories within the INTERMAGNET consortium are operated by governmental (geological, meteorological, and space) institutes, a few are operated by universities, and several by companies. There are 57 INTERMAGNET member institutes; they come from 42 countries and support the operation of 120 observatories. INTERMAGNET observatories are operated with a high level of temporal continuity, in some cases more than 99% complete/year. As of December 2016, data from 20 INTERMAGNET observatories are openly available within 15 min of acquisition; data from another 22 observatories are available within 1 h of acquisition.

3.2. Variometer Stations

In comparison to operating an observatory, it is much simpler to operate a variometer station—their data are not normally laboriously cleaned and rigorously calibrated for absolute accuracy. Variometer data are sufficient for certain space physics research projects focused on analysis of the ionosphere and magnetosphere [e.g., *Lühr et al.*, 1998; *Yumoto and Magdas Group*, 2006; *Chi et al.*, 2013]. In particular, variometer stations can be established at relatively low cost, high density, and, more generally, with flexibility. Institutes supporting variometer systems have pioneered routine acquisition of 1 s and higher-frequency data that observatory institutes have only recently begun to achieve. Some variometer and some observatory institutes operate search-coil (induction-coil) magnetometer systems [*Tumanski*, 2007] that permit data acquisition up to about a 0.01 s (100 Hz) sampling rate.

The Ultra Large Terrestrial International Magnetic Array (ULTIMA) is a voluntary consortium of academic institutes promoting collaborative, space physics research through the use of ground-based magnetometers [e.g., *Yumoto et al.*, 2012]. As of 2015, ULTIMA encompasses 17 principal investigator members from 17 universities and 6 countries, supporting the operation of a large number of variometer stations. Many of the variometers operated in North America are supported by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Canadian Space Agency (CSA).

3.3. Opportunities and Challenges Regarding Magnetometer Stations

It is worth emphasizing that observatories and variometer stations are complementary. In particular, variometer deployments can help fill in gaps between the sparse distribution of observatories, thus helping to address (goal 1) needed improvements in the geographic distribution of magnetometer stations. Regarding data quality (goal 2) variometer projects might consider reporting the (approximate) declinational orientation of their magnetometers—this would increase the utility of their data for the calculation of indices, mapping of geomagnetic activity, directional drilling, and aeromagnetic surveying. More generally, both INTERMAGNET and ULTIMA can promote (goal 1) the geographic distribution of magnetometer stations and facilitate inter-institute communication to (goal 2) improve data quality and (goal 3) increase acquisition sampling rates. Progress here will benefit from close communication, cooperation, and coordination between the observatory and variometer communities [e.g., *Engebretson and Zesta*, 2017, p. 22].

4. Data Management

Archival databases of magnetometer data include one supported by INTERMAGNET, the NSF-sponsored SuperMAG [*Gjerloev*, 2009], the NASA-sponsored Time History of Events and Macroscale Interactions during Substorms (THEMIS) [*Russell et al.,* 2009], NASA's Coordinated Data Analysis Web (CDAWEB) [*Candey*, 2010], the World Data System (WDS) which supports long-term archives of observatory data, and several others supported by individual observatory and variometer institutes. It is noteworthy that real-time data from several observatory institutes can, right now, be accessed through the INTERMAGNET website.

Just as research data should be accompanied by informative metadata, real-time data should as well [e.g. *Reeve*, 2013, chap. 17]. An important part of metadata is persistent identifying information that can, conceivably, allow for retrospective evaluation of the real-time operational performance. Data files obtained through INTERMAGNET have a metadata header [e.g., *Reay et al*., 2011]. United States institutes supporting magnetometer operations have data plans that prioritize the use of metadata [e.g., *National Aeronautics and Space Administration (NASA)*, 2014; *National Science Foundation* (*NSF*), 2015; *U.S. Geological Survey* (*USGS*), 2016].

4.1. Opportunities and Challenges for Data Management

INTERMAGNET can facilitate the organization of real-time data feeds and, thus, promote their (goal 5) access and use. The INTERMAGNET website already supports a real-time service, through which a number of institutes promptly release their magnetometer data. This is important and worthy of further development; it might also be more widely advertised and made more visible to potential users on the INTERMAGNET website. More generally, progress on (goal 5) can be made by ensuring that archival services (for both observatories and variometer stations) have sufficient resources for facilitating access to and use of real-time magnetometer data.

5. Some Example Networks

5.1. North America

For insight, let us consider some individual magnetometer networks. Starting with North America, the USGS Geomagnetism Program operates 14 magnetic observatories in the United States and Territories [*Love and Finn*, 2011]. Data from each observatory are transmitted to Program headquarters in Golden, Colorado, within about 5 min of acquisition; they are then made promptly available to users without "embargo" [*USGS*, 2016, p. 9], such as NOAA SWPC and the USAF; all USGS data are available for viewing and download from the USGS and INTERMAGNET websites without restriction. With respect to variometer stations in the continental United States, such as those of McMAC [e.g., *Chi et al*., 2013], many are funded by the NSF and NASA. These variometer operations are not necessarily intended to provide a long-term, real-time data service, nor are their operations funded sufficiently to maintain a high level of operational continuity: a search of the SuperMAG database for data acquired at variometers operated in the continental United States, and on the first universal day of each calendar month in 2015, identified data from no more than 11 stations (although 32 are listed); for 1 December 2015, data from only two stations were found.

Data from relatively numerous magnetometer stations are available from Canada, though real-time data are only available from a minority of these stations. Data from the Autumn and Autumnx variometer networks are available within 1 h of acquisition [*Connors et al*., 2016]. Data from 13 observatories operated by Natural Resources Canada (NRCan) [*Lam*, 2011] are transmitted to their Program headquarters in Ottawa within about 5 min of acquisition; these are then transmitted to selected users, including the USGS, NOAA SWPC, and the USAF; data from 11 observatories can be almost immediately viewed as plots on the INTERMAGNET website, but as of January 2017 the data are only available for download through INTERMAGNET after a delay of 1 day. Data from other networks, such as MACCS and CARISMA [e.g., *Engebretson et al*., 1995; *Mann et al*., 2008] are available 1 day after acquisition, though procedures could be modified to make some of these data available more promptly (I. R. Mann and M. J. Engebretson, private communication, 2016).

In 2016, the United States Federal Energy Regulatory Commission directed the North American Electric Reliability Corporation to collect magnetometer data and to make these data publically available (TPL-007-1). Exactly how this will be implemented is not yet clear, we imagine that some data collection and organizational responsibility might involve the Electric Power Research Institute, which already supports the SUNBURST network for monitoring geomagnetically induced currents in power grid systems [*Lesher et al.*, 1994]. Outside of space weather, magnetometer systems are deployed near seismically active regions in California in support of earthquake research projects [e.g., *Cutler et al.*, 2008; *Creasy et al.*, 2013].

5.2. Other Geographic Areas

Two French institutes, the Institut de Physique du Globe in Paris (IPGP) and the Ecole et Observatoire des Sciences de la Terre in Strasbourg (EOST), together support, directly or through collaboration, 17 observatories [*Chulliat and Chambodut*, 2014]. As of January 2017, data from three of these observatories are available from the INTERMAGNET database within 15 min of acquisition: data from 1 are available within 1 h. Reporting delays are due to the practical limitations in transmitting data from remote locations; national policies restrict real-time data transmission from collaborative observatories in Russia and China.

The British Geological Survey (BGS) operates nine observatories, some in collaboration with other institutes, including an oil-and-gas drilling company [*Thomson*, 2015]. Data are available at BGS within 5 min of acquisition. As of January 2017, data from three observatories are available from the INTERMAGNET database within 1 h of acquisition; proprietary delays limit the availability of data from other stations by up to 2 weeks.

Continuous and prompt international access to magnetometer data from Russia has been described as a “difficulty” [*Meng et al.*, 2004]. Both the Russian Academy of Sciences [*Gvishiani et al.*, 2014] and RosHydroMet [*Troshichev et al.*, 2010] support magnetometer operations there; real-time data are made available from RosHydroMet stations to selected users; a 1 day delay is placed on data transmitted from stations associated with the Russian Academy of Sciences. In China, real-time space weather operations are being pursued [*Wang*, 2010], though observatory data are only available through INTERMAGNET after a delay of 1 or more days.

5.3. Opportunities and Challenges Regarding Networks

The preceding discussion of different magnetometer networks highlights some issues affecting (goal 4) prompt data transmission, and (goal 5) prompt access to and use of real-time data. Consider, first, national and government agency policies. The United States Federal Government promotes a free and open-access policy for unclassified data sets that have been acquired at taxpayer expense (Executive Order 13642); the Canadian Government has a similar policy (Action Plan on Open Government, Commitment 6). How these policies translate into access to real-time data is not always especially clear. The USGS policy, for example, is to make its data products available as quickly as possible [*USGS*, 2016, p. 9]; the CSA has a similar policy [*Canadian Space Agency*, 2013, p. 2], but other institutes accommodate temporary embargoes for academic research [*NSF*, 2015, p. 19], and some institutes do not have policies regarding the promptness of reporting data.

In Europe [e.g., *Weiss*, 2004, p. 71] and China [e.g., *Wan*, 2015], government agencies sometimes charge a fee for the use of their data in order to generate revenue; some government agencies in some countries might even charge for foreign national use of their data [*Chuang*, 2004, p. 75]. Some companies collect magnetometer data to support their for-profit projects, and they are usually reluctant to release their data, especially real-time data because they might be exploited by a competitor. Some magnetometer institutes are simply not accustomed to sharing their data with an outside user, and some institutes, especially in economically developing countries [e.g. *Mathae and Uhlir*, 2012], lack the resources to sustain real-time data transmission.

The negotiation and adoption of policies at high levels in national institutes and international organizations that prioritize access to real-time geophysical data are certainly worthwhile. So, for example, the International Council for Science and its Committee on Data for Science and Technology (CODATA) has helped increase access to real-time seismic data from China. CODATA might consider the present challenge in obtaining access to real-time magnetometer data from China (and Russia). At the same time, progress can also come by encouraging magnetometer institutes that already have open-access data policies to make their data more promptly available. Magnetometer institutes that charge for commercial use of their data [e.g., *Newitt*, 2007] might consider making their data available in real time on the condition that they are only used for nonprofit projects. Real-time transmission of magnetometer data from economically developing countries could be supported through a program that allows for the international exchange of modest amounts of money.

6. Looking Forward

Substantial progress has been made with respect to real-time geomagnetic monitoring, and some respectable capacities have been established. Still, significant potential remains unmet, and much work remains to be done. As with other aspects of the broad subject of space weather, enhancement in real-time geomagnetic monitoring will benefit from new partnerships to leverage existing capacities and harness multisector, cross-disciplinary, and international interests. We look forward to a future in which enhanced real-time geomagnetic monitoring results in improved support for operational projects of importance for national economies and security.

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References

Araujo-Pradere, E. A., T. J. Fuller-Rowell, and M. V. Codrescu (2002) STORM: An empirical storm-time ionospheric correction model: 1. Model description, *Radio Sci.*, *37*(5), 1070, doi:10.1029/2001RS002467.

Arzberger, P., P. Schroeder, A. Beaulieu, G. Bowker, K. Casey, L. Laaksonen, D. Moorman, P. Uhlir, and P. Wouters (2004), An international framework to promote access to data, *Science*, *303*(5665), 1777–1778, doi:10.1126/science.1095958.

Baker, D. N. (2011), The role of universities in a vigorous National Space Weather Program, *Space Weather*, *9*, S05001, doi:10.1029/2011SW000673.

Balch, C., et al. (2004), *Service Assessment: Intense Space Weather Storms October 19–November 07, 2003*, pp. 1–50, U.S. Dep. Commerce, NOAA, Silver Spring, Md.

Bilitza, D., L.-A. McKinnell, B. Reinisch, and T. Fuller-Rowell (2011), The international reference ionosphere today and in the future, *J. Geod.*, *85*, 909–920, doi:10.1007/s00190-010-0427-x.

Bowman, B., W. K. Tobiska, F. Marcos, C. Huang, C. Lin, and W. Burke (2008), A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, August, 18-21, Honolulu, Hawaii, AIAA-2008-6438, doi:10.2514/6.2008-6438.

Buchanan, A., et al. (2013), Geomagnetic referencing—The real-time compass for directional drilling, *Oilfield Rev.*, *25*(3), 32–47.

Candey, R. M. (2010), Common Data Format (CDF) and Coordinated Data Analysis Web (CDAWeb), Abstract presented at VISualize 2010: Second Annu. Data Analysis and Visualization Symp., Washington, D. C., 19–20 May.

Chi, P. J., et al. (2013), Sounding of the plasmasphere by Mid-continent MAgnetoseismic chain (McMAC) magnetometers, *J. Geophys. Res. Space Physics*, *118*, 3077–3086, doi:10.1002/jgra.50274.

Chuang, L. (2004), Recent developments in environmental data access policies in the People's Republic of China, in *Open Access and the Public Domain in Digital Data and Information for Science*, *Nat. Acad. Sci.*, edited by J. Esanu and P. F. Uhir, pp. 74–76, Natl. Acad. Press, Washington, D. C., doi:10.17226/11030.

Chulliat, A., and A. Chambodut (2014), *Bureau Central de Magnétisme Terrestre Strategic Plan 2014–2018*, pp. 1–23, Bureau Central de Magnétisme Terrestre, Paris, France.

Connors, M., I. Schofield, K. Reiter, P. J. Chi, K. M. Rowe, and C. T. Russell (2016), The AUTUMNX magnetometer meridian chain in Québec, Canada, *Earth Planets Space*, *68*, 2, doi:10.1186/s40623-015-0354-4.

Creasy, N., J. Gardner, J. M. Spritzer, I. Keneally, J. M. Glen, D. McPhee, and S. L. Klemperer (2013) Field testing, installation, and calibration of a new data acquisition system for the USGS-Stanford-Berkeley Ultra-Low Frequency Electromagnetic (ULFEM) Array, Abstract NH31B-1604 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9–13 Dec.

Cutler, J., J. Bortnik, C. Dunson, J. Doering, and T. Bleier (2008), CalMagNet—An array of search coil magnetometers monitoring ultra low frequency activity in California, *Nat. Hazards Earth Syst. Sci.*, *8*(2), 359–368, doi:10.5194/nhess-8-359-2008.

Canadian Space Agency (2013), Geospace Observatory (GO) Canada: Data policy, Canadian Space Agency.

Engebretson, M. J., W. J. Hughes, J. L. Alford, E. Zesta, L. J. Cahill Jr., R. L. Arnoldy, and G. D. Reeves (1995), Magnetometer array for cusp and cleft studies observations of the spatial extent of broadband ULF magnetic pulsations at cusp/cleft latitudes, *J. Geophys. Res.*, *100*(A10), 19,371–19,386, doi:10.1029/95JA00768.

Engebretson, M., and E. Zesta (2017), *Ground Magnetometer Array Planning: Report of a Workshop*, 35 pp., Augsburg College, Minneapolis, Minn.

Fletcher, K. M. U., J. D. Fairhead, A. Salem, K. Lei, C. Ayala, and P. L. M. Cabanillas (2011), Building a higher resolution magnetic database for Europe for resource evaluation, *First Break*, *29*(4), 95–101.

Fok, M.-C., R. B. Horne, N. P. Meredith, and S. A. Glauert (2008), Radiation Belt environment model: Application to space weather nowcasting, *J. Geophys. Res.*, *113*, A03S08, doi:10.1029/2007JA012558.

Gannon, J. L., and J. J. Love (2011), USGS 1-min *Dst* index, *J. Atmos. Solar Terr. Phys.*, *73*(2–3), 323–334, doi:10.1016/j.jastp.2010.02.013.

Gehred, P. A., W. Cliffswallow and J. D. Schroeder III (1995), A comparison of USAF *Ap* and *Kp* indices to Gottingen indices, *Tech. Memo. ERL SEL-88*, pp. 1-26, NOAA, Silver Spring, Md.

Gjerloev, J. W. (2009), A global ground-based magnetometer initiative, *EOS Trans. Am. Geophys. Union*, *90*(27), 230–231, doi:10.1029/2009EO270002.

Gvishiani, A., R. Lukianova, A. Soloviev, and A. Khokhlov (2014), Survey of geomagnetic observations made in the northern sector of Russia and new methods for analyzing them, *Surv. Geophys.*, *35*(5), 1123–1154, doi:10.1007/s10712-014-9297-8.

Horne, R. B., S. A. Glauert, N. P. Meredith, D. Boscher, V. Maget, D. Heynderickx, and D. Pitchford (2013), Space weather impacts on satellites and forecasting the Earth's electron radiation belts with SPACECAST, *Space Weather*, *11*, 169–186, doi:10.1002/swe.20023.

Intriligator, D. (2007), Collaboration between government and commercial space weather information providers, *Space Weather*, *5*, S10002, doi:10.1029/2007SW000348.

Jankowski, J., and C. Sucksdorff (1996), *Guide for Magnetic Measurements and Observatory Practice*, pp. 1–235, Int. Assoc. of Geomagn. and Aeron, Warsaw, Poland.

Kelbert, A., C. Balch, A. Pulkkinen, G. D. Egbert, J. J. Love, E. J. Rigler and I. Fujii (2016), Methodology for time-domain estimation of storm-time electric fields using the 3D Earth impedance, Abstract GP23D-02 presented at 2016 Fall Meeting, AGU, San Francisco, Calif., 12–16 Dec.

Kunitake, M., H. Ishibahi, T. Nagatsuma, T. Kikuchi, and T. Kamei (2002), Real-time geomagnetic data acquisition from Siberia region and its application—PURAES project, *Comm. Res. Lab.*, *49*(4), 87–97.

Lam, H.-L. (2011), From early exploration to space weather forecasts: Canada's geomagnetic odyssey, *Space Weather*, *9*, S05004, doi:10.1029/2011SW000664.

Lesher, R. L., J. W. Porter, and R. T. Byerly (1994), SUNBURST—A network of GIC monitoring systems, *IEEE Trans. Power Delivery*, *9*(1), 128–137, doi:10.1109/61.277687.

Loewe, C. A., and G. W. Prölss (1997), Classification and mean behavior of magnetic storms, *J. Geophys. Res.*, *102*(A7), 14,209–14,213, doi:10.1029/96JA04020.

Love, J. J. (2008), Magnetic monitoring of Earth and space, *Phys. Today*, *61*(2), 31–37, doi:10.1063/1.2883907.

Love, J. J., and A. Chulliat (2013), An international network of magnetic observatories, *EOS Trans. Am. Geophys. Union*, *94*(42), 373–374, doi:10.1002/2013EO420001.

Love, J. J., and C. A. Finn (2011), The USGS Geomagnetism Program and its role in space weather monitoring, *Space Weather*, *9*, S07001, doi:10.1029/2011SW000684.

Love, J. J., E. J. Rigler, A. Pulkkinen, and C. C. Balch (2014), Magnetic storms and induction hazards, *EOS Trans. Am. Geophys. Union*, *95*(48), 445–446, doi:10.1002/2014EO480001.

Love, J. J., P. A. Bedrosian, and A. Schultz (2017), Down to Earth with an electric hazard from space, *Space Weather*, *15*, 658–662, doi:10.1002/2017SW001622.

Lühr, H., A. Aylward, S. C. Bucher, A. Pajunpää, K. Pajunpää, T. Holmboe, and S. M. Zalewski (1998), Westward moving dynamic substorm features observed with the IMAGE magnetometer network and other ground-based instruments, *Ann. Geophys.*, *16*(4), 425–440, doi:10.1007/s00585-998-0425-y.

Mann, I. R., et al. (2008), The upgraded CARISMA magnetometer array in the THEMIS era, *Space Sci. Rev.*, *141*(1), 413–451, doi:10.1007/s11214-008-9457-6.

Mathae, K. B., and P. F. Uhlir Eds (2012), *The Case for International Sharing of Scientific Data: A Focus on Developing Countries*, *Proc. Symp., Nat. Acad. Sci.*, 180 pp., Natl. Acad. Press, Washington, D. C., doi:10.17226/17019.

Meng, C., K. Takahashi, M. Kunitake, T. Kikuchi, and T. Kamei (2004), Near-real-time auroral electrojet index: An international collaboration makes rapid delivery of auroral electrojet index, *Space Weather*, *2*, S11003, doi:10.1029/2004SW000116.

Menvielle, M., T. Iyemori, A. Marchaudon, and M. Nosé (2011), Geomagnetic indices, in *Geomagnetic Observations and Models*, edited by M. Mandea and M. Korte, pp. 183–227, Springer, New York, doi:10.1007/978-90-481-9858-0_8.

Nagatsuma, T. (2013), New ages of operational space weather forecast in Japan, *Space Weather*, *11*, 207–210, doi:10.1002/swe.20050.

Nair, M., A. Woods, A. Chulliat, P. Alken, and N. Boneh (2015) A real-time magnetic disturbance model to improve drilling accuracy in low and mid latitudes of the Earth, Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) 42nd meeting, October 1st 2015, Houston, Tex.

National Aeronautics and Space Administration (NASA) (2014), *NASA Plan for Increasing Access to the Results of Scientific Research: Digital Scientific Data and Peer-Reviewed Publications*, pp. 1–21, Natl. Aeronaut. and Space Admin., Washington, D. C.

Newitt, L. (2007), Survey of magnetic observatory charging practices, *Publs. Inst. Geophys. Pol. Acad. Sci.*, *C-99*(398), 308–314.

National Oceanic and Atmospheric Administration (2009), *Consolidated Observation Requirements List, NOAA Program Observation Requirements Document, WW-SWX*, 31 pp., NOAA Tech. Plann. Integr. Office, Silver Spring, Md.

National Science Foundation (NSF) (2015), *Today's Data, Tomorrow's Discoveries: Increasing Access to the Results of Research Funded by the National Science Foundation*, pp. 1–31, Natl. Sci. Found., Washington, D. C.

National Science and Technology Council (NSTC) (2015), *National Space Weather Action Plan*, pp. 1–38, Executive Office, Natl. Sci. and Technol. Counc., Washington, D. C.

Piccinelli, R., and E. Krausmann (2014), *Space Weather and Power Grids—A Vulnerability Assessment*, pp. 1–53, European Union, Luxembourg.

Pilkington, M. (2007), Aeormagnetic surveying, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by D. Gubbins and E. Herrero-Bervera, pp. 1–3, Springer, Dordrecht, Netherlands, doi:10.1007/978-1-4020-4423-6_1.

Primdahl, F. (1979), The fluxgate magnetometer, *J. Phys. E Sci. Instrum.*, *12*(4), 241–253, doi:10.1088/0022-3735/12/4/001.

Pulkkinen, A., O. Amm, A. Viljanen, and BEAR working group (2003), Ionospheric equivalent current distributions determined with the method of spherical elementary current systems, *J. Geophys. Res.*, *108*(A2), 1053, doi:10.1029/2001JA005085.

Rasson, J., H. Toh, and D. Yang (2011) The global geomagnetic observatory network, in *Geomagnetic Observations and Models*, edited by M. Mandea and M. Korte, pp. 1–25, Springer, New York, doi:10.1007/978-90-481-9858-0_1.

Reay, S. J., W. Allen, O. Baillie, J. Bowe, E. Clarke, V. Lesur, and S. Macmillan (2005), Space weather effects on drilling accuracy in the North Sea, *Ann. Geophys.*, *23*(9), 3081–3088, doi:10.5194/angeo-23-3081-2005.

Reay, S. J., D. C. Herzog, S. Alex, E. P. Kharin, S. McLean, M. Nosé, and N. A. Sergeyeva (2011), Magnetic observatory data and metadata: Types and availability, in *Geomagnetic Observations and Models*, edited by M. Mandea and M. Korte, pp. 149–181, Springer, New York, doi:10.1007/978-90-481-9858-0_7.

Reeve, A. (2013), *Managing Data in Motion: Data Integration Best Practice Techniques and Technologies*, 204 pp., Morgan Kaufmann, Elsevier, Waltham, Mass.

Richmond, A. D., G. Lu, B. A. Emery, and D. J. Knipp (1998), The AMIE procedure: Prospects for space weather specification and prediction, *Adv. Space Res.*, *22*(1), 103–112, doi:10.1016/S0273-1177(97)01108-3.

Rigler, E. J., A. A. Pulkkinen, C. C. Balch, and M. J. Wiltberger (2014), Dynamic geomagnetic hazard maps in space weather operations, Abstract SM31A-4178 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.

Russell, C. T., et al. (2009), THEMIS ground-based magnetometers, in *The THEMIS Mission*, edited by J. L. Burch and V. Angelopoulos, pp. 389–412, Springer, New York, doi:10.1007/978-0-387-89820-9_17.

Schrijver, C. J., et al. (2015), Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS, *Adv. Space Res.*, *55*(12), 2745–2807, doi:10.1016/j.asr.2015.03.023.

Schunk, R. W., et al. (2004), Global Assimilation of Ionospheric Measurements (GAIM), *Radio Sci.*, *39*, RS1S02, doi:10.1029/2002RS002794.

Storz, M. F., B. R. Bowman, J. I. Branson, S. J. Casali, and W. K. Tobiska (2005), High accuracy satellite drag model (HASDM), *Adv. Space Res.*, *36*(1), 2497–2505, doi:10.1016/j.asr.2004.02.020.

Sugiura, M., and T. Kamei (1991), *Equatorial Dst* Index 1957–1986, *IAGA Bull*, vol. 40, 246 pp., ISGSI Publ. Office, Saint-Maur-des-Fossess, France.
Thomson, A. W. P., A. J. McKay, and A. Viljanen (2009), A review of progress in modeling induced geoelectric and geomagnetic fields with special regard to induced currents, *Acta Geophys.*, *57*(1), 209–219, doi:10.2478/s11600-008-0061-7.
Thomson, A. W. P. (Ed.) (2015) *Geomagnetism Review 2014*, pp. 1–34, British Geol. Surv., Edinburgh, U. K.
Tivey, M. A. (2007), Magnetic surveys, marine, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by D. Gubbins and E. Herrero-Bervera, pp. 542–546, Springer, Dordrecht, Netherlands, doi:10.1007/978-1-4020-4423-6_184.
Troshichev, O. A., A. S. Janzhura, and K. Takahashi (2010), Significance, present status and perspectives of the auroral zone magnetic activity monitoring by the Russian arctic magnetometer network, Abstract SM41C-1896 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13–17 Dec.
Tumanski, S. (2007), Induction coil sensors—A review, *Meas. Sci. Technol.*, *18*(3), R31, doi:10.1088/0957-0233/18/3/R01.
Uhlir, P. F., and P. Schröder (2007), Open data for global science, *Data Sci. J.*, *6*, 0D36-OD53, doi:10.2481/dsj.6.OD36.
Unsworth, M. (2007), Magnetotellurics, in *Encyclopedia of Geomagnetism and Paleomagnetism*, edited by D. Gubbins and E. Herrero-Bervera, pp. 670–673, Springer, Dordrecht, Netherlands, doi:10.1007/978-1-4020-4423-6_207.
U.S. Geological Survey (USGS) (2016), *Public Access to Results of Federally Funded Research at the U.S. Geological Survey: Scholarly Publications and Digital Data*, pp. 1–22, U.S. Geol. Surv., Reston, Va.
Wan, Z. (2015), China's scientific progress hinges on access to data, *Nature*, *520*(7549), 587, doi:10.1038/520587a.
Wang, C. (2010), New chains of space weather monitoring stations in China, *Space Weather*, *8*, S08001, doi:10.1029/2010SW000603.
Watermann, J., H. Gleisner, and T. M. Rasmussen (2011), A geomagnetic activity forecast for improving the efficiency of aeromagnetic surveys in Greenland, *Adv. Space Res.*, *47*(12), 2172–2181, doi:10.1016/j.asr.2010.02.005.
Weiss, P. (2004), Borders in cyberspace: Conflicting public sector information policies and their economic impact, in *Open Access and the Public Domain in Digital Data and Information for Science*, *Nat. Acad. Sci.*, edited by J. Esanu and P. F. Uhlir, pp. 69–73, Natl. Acad. Press, Washington, D. C., doi:10.17226/11030.
Yumoto, K., and Magdas Group (2006), MAGDAS project and its application for space weather, Abstract 2210 presented at 2006 COSPAR Scientific Assembly, Beijing, China, 16–23 July.
Yumoto, K., et al. (2012), ULTIMA of ground-based magnetometer arrays for monitoring magnetospheric and ionospheric perturbations on a global scale, Abstract SM14A-01 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 9–13 Dec.