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Global Networks of Ground-Based Magnetometers Enable Cutting-Edge Heliophysics Research, Education, and Space Weather Operations

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Ground-based magnetometers used to measure magnetic fields on the Earth's surface (B) are central to Heliophysics research. We summarize present magnetometer infrastructure, describe research needed to improve our understanding of the causes and consequences of B, and describe infrastructure and policies needed to support this research and related space weather models.

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A white paper for the 2024-2033 Solar and Space Physics Decadal Survey

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Synopsis: Ground-based magnetometers used to measure magnetic fields on the Earth's surface (**B**) have played a central role in the development of Heliophysics research for more than a century. These versatile instruments have been adapted to study everything from polar cap dynamics to the equatorial electrojet, from solar wind-magnetosphere-ionosphere coupling to real-time monitoring of space weather impacts on power grids. Due to their low costs and relatively straightforward operational procedures, these instruments have been deployed in large numbers in support of Heliophysics education and citizen science activities. They are also widely used in Heliophysics research internationally and more broadly in the geosciences, lending themselves to international and interdisciplinary collaborations; for example, ground-based electrometers collocated with magnetometers provide important information on the inductive coupling of external magnetic fields to the Earth's interior through the induced electric field (**E**). The purpose of this white paper is to (1) summarize present ground-based magnetometer infrastructure, with a focus on US-based activities, (2) summarize research that is needed to improve our understanding of the causes and consequences of **B** variations, (3) describe the infrastructure and policies needed to support this research and improve space weather models and nowcasts/forecasts. We emphasize a strategic shift to proactively identify operational efficiencies and engage all stakeholders who need **B** and **E** to work together to intelligently design new coverage and instrumentation requirements.

1.The Central Role of Ground-Based Magnetometers in Heliophysics Research, Education, and Space Weather Monitoring

Measurements of magnetic fields at the Earth's surface (**B**) are used for a wide range of Heliophysics research, education, and space weather monitoring applications. For example, they are used as a remote sensing tool (i.e., ground-based observables providing information about the magnetosphere and ionosphere) for electric currents that define the electrodynamics of Earth's coupled magnetosphere-ionosphere system. They have led to the identification of near-Earth currents associated with magnetic substorms and storms [e.g., Sugiura and Chapman, 1960], as well as those associated with global compressions of the magnetosphere from interplanetary shocks and bow shock-related instabilities [e.g., Zhang et al., 2022]. Global **B** observations have made it possible to track and comprehend the way electromagnetic energy propagates throughout the geospace system after the magnetosphere is impacted by solar wind and embedded interplanetary magnetic field dynamics, and they can also be used to remote sense Ultra Low Frequency wave activity that affects radiation belt dynamics [e.g., Turner et al., 2012] and auroral substorms [e.g., Lester et al., 1984]. It can additionally be used as a plasma mass density diagnostic using magnetoseismology [Menk and Waters, 2013; white paper by Chi et al., 2022]. As a remote sensing tool, **B** observed at ground magnetometer stations complements in situ measurements made by satellites as well as observations from other ground-based remote sensing tools such as radars and optical imagers [Engebretson and Zesta, 2017 and references therein]. For example, they have been used in equatorial regions (where radars/optical imagers are sparsely deployed) to study equatorial electrodynamics [e.g., Yizengaw and Groves, 2018] and the sources of potentially hazardous geomagnetically induced currents [GICs – e.g., Ngwira et al., 2013; Carter et al., 2016].

B is also used to diagnose the current state of the magnetosphere-ionosphere system by being incorporated into global magnetic activity indices that serve as inputs to global research and forecast models and are used in space weather alerts/nowcasts, including the Kp (planetary disturbance level) index and many others [Mayaud, 1980; Engebretson and Zesta, 2017]. As the density of ground magnetometers has increased, new versions of these indices have been generated; for example, the SuperMAG AL index, SML [Newell and Gjerloev, 2011], is now widely used instead of the AL index in substorm-related studies [e.g., Hajra, 2022]. Both local and global **B** measurements are also used to validate global geospace models for research and forecast purposes [e.g., Pulkkinen et al., 2013; Welling, 2019]. **B** is one of the few space weather observables for which there is a long-term record; much of what we know of space weather during storms such as the Carrington event derives from magnetic observatories operating more than 150 years ago [Carrington, 1860; Hapgood, 2019; Hayakawa, 2019; Knipp et al., 2017; Pulkkinen et al., 2017; Ohtani, 2022].

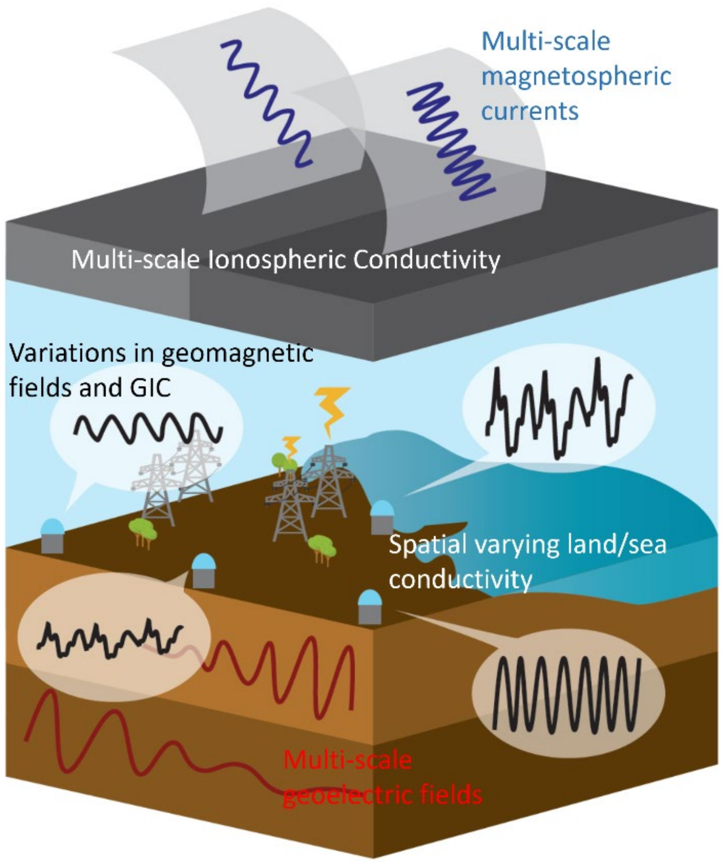

Figure 1 - Multi-scale currents in the magnetosphere interact with the spatially varying ionosphere and ground conductivity to produce non-uniform geomagnetic fields, geoelectric fields, and GICs. Adapted from Gannon, [2016]. Credit: Michelle Salzano and Ayomide Olabode

Space weather conditions on the ground generally originate from the interaction of the solar wind with the magnetosphere, which propagates down to the ionosphere and ground via magnetic field lines. GICs are set up by a geoelectric field (**E**) which arises from time variations in **B** caused by ionospheric and magnetospheric currents and the conductive properties of the ground (Figure 1). Extreme **B** can be generated with a variety of spatial scales; for example, they can occur in the auroral zone with fine spatial scales (<~100 km) or be excited by interplanetary shocks with global scales [Ngwira et al., 2015; Belakhovsky et al., 2018, 2019; Engbretson et al. 2019]. Forecasting large GIC remains challenging as the largest GIC are not always concurrent with the largest geomagnetic depressions [Dimmock et al., 2018] or elevated geomagnetic activity levels [e.g., Engebretson et al., 2021]. Ground magnetometers have proven essential in this area for both research and real-time monitoring of **B** that drives GIC.

Ground-based magnetometers and **B** are also central to many other areas of geophysics research, including magnetotellurics/exploration geophysics, seismology, and geomagnetism. Some of these areas have direct connections to Heliophysics research. For example, the geomagnetism community uses **B** to constrain and update the IGRF model which is in turn used in many areas of Heliophysics research (e.g., radiation belt models). As another example, the magnetotelluric (MT) survey from the NSF EarthScope and follow-on NASA and USGS MTArray initiative has proven indispensable for GIC research and is currently used by the NOAA Space Weather Prediction Center (SWPC) to provide nowcasts of geoelectric fields [Kelbert, 2020]. By combining **B** and **E** measurements in the magnetotelluric configuration, the derived impedances provide improved boundary conditions for fully coupled Heliosphere/Magnetosphere/Geosphere models. Low-cost combined **B** and **E** instruments with real-time telemetry have also been developed to facilitate permanent arrays of magnetotelluric monitoring to complement magnetometer arrays.

Many recently developed ground-based magnetometers are low-cost (as low as ~$100-200, e.g., Beggan and Marple, 2020) and straightforward to deploy and operate, making them an ideal tool for use in Heliophysics education and citizen science projects. For example, they were used in the THEMIS Education and Public Outreach Program [Peticolas et al., 2008; Russell et al., 2008] which incorporates Heliophysics in high school education programs through teacher training, deployment of magnetometers at high schools that were ultimately used in numerous publications, and involvement of students in Heliophysics research. Recent programs include the Space Weather Underground project to work with high schools across the Northeastern US and Alaska (SAM-III magnetometer), the RaspberryPi magnetometer network in the UK [Beggan and Marple, 2020], the Personal Space Weather Station project as part of the Ham Radio Science Citizen Investigation (https://hamsci.org/) involving amateur ham radio operators worldwide, and the ground-based counterpart to the upcoming EZIE mission (see white paper by Gjerloev, Gannon, et al.).

2. Towards a Better Understanding of B to Enable Cutting Edge Heliophysics Research

As seen in Figure 1, multiple factors contribute to **B** and **E** simultaneously: ionospheric electrical conductivity and related spatial gradients, the spatial and temporal scales of the magnetosphere-ionosphere source currents, and the ground conductivity and related spatial gradients. Past theory and modeling work mostly examined these factors independently, but interpretation of **B** that can include multiple factors simultaneously remains challenging and often ambiguous. The superposition of multiple M-I current systems in **B** further increases the complexity of this problem. The purpose of this section is to highlight areas in which progress understanding the source(s) of **B** is needed to address several Heliophysics research objectives.

First, the electrical conductivity of the Earth needs to be accounted for when interpreting **B** in the context of different magnetosphere-ionosphere coupling processes, and when constructing geomagnetic activity indices and GIC forecasts. Though the theory linking **B** to telluric currents is well developed and these currents have a known effect on **B** and related geomagnetic activity indices [Tanskanen et al., 2001; Juusola et al., 2020], the Earth is still usually assumed to be a perfect insulator with negligible telluric currents. This assumption affects all the research areas mentioned in Section 1. In the coming decades, more realistic ground conductivity models need to be obtained from the Magnetotellurics research community and incorporated into all models and analysis of **B** so that telluric currents can be separated from magnetosphere-ionosphere currents. This will lead to geomagnetic activity indices and remote sensing tools that better capture the dynamics of the magnetosphere-ionosphere system. ***These improvements are crucial for***

accurately remote sensing mesoscale current systems; **B** variations on mesoscales (100's km) and time scales <1000s are more likely to contain significant contamination from telluric currents [e.g., Juusola et al., 2020].

Second, fundamental research is needed to understand the sources of **B** from the magnetosphere to the ionosphere and ultimately the ground, along with targeted improvements in the spatial sampling of **B** and **E**. For example, recent work with closely spaced magnetometer stations has revealed intense **B** with remarkably small spatial scales in the auroral zone, suggesting that more closely spaced **B** measurements are needed in the auroral zone to fully characterize and predict events with intense **B**, large time derivatives of **B**, and large **E** [Ngwira et al., 2015, 2018; Engebretson et al., 2019, 2021; Weygand et al., 2021]. Also needed are advanced numerical simulation capabilities that can capture fine spatial scales in the auroral ionosphere and satellite conjunctions to better understand the sources of these events in the magnetosphere/ionosphere.

Third, both fundamental and applied research is needed to improve our understanding of how the multiple spatiotemporal scales of **B** generate GICs, and what fraction of extreme currents in power grids are caused by geomagnetic disturbances related to space weather. Fundamental research is needed to understand what conditions cause the **B** and **E** that drive large GICs (see section 1), including model development and tools for validation of models that predict **B**. Applied research is needed to understand how **B** ultimately generates GICs in power grids. For this, it is crucial that scientists studying **B**, **E**, and the sources of GIC work more closely with power grid utilities to both assess their needs and potentially access direct GIC measurements. A major challenge is the traditionally strained sharing of important data across communities, for example limitations faced by power utilities in opening their data to the public and the diversity of the GIC data themselves, which come from a variety of infrastructure; Open Knowledge Networks (e.g., the ongoing Convergence Hub for the Exploration of Space Science effort) are one method for addressing this challenge. Another challenge is the lack of long-term records of **B** needed for hindcasts, extreme event analysis, and space weather climatology; ground-based magnetometers are often deployed for periods significantly less than one solar cycle.

Fourth, both fundamental and applied research is needed to improve space weather forecasts (including GIC) that rely on **B**. More work is needed to (1) identify and isolate the key observations that can help predict Kp and other indices used in space weather forecasts and (2) move beyond using only global indices to predict local phenomena as our understanding of the geospace system develops and new tools become available (e.g., new observations, machine learning tools). For example, the observations used for the AL index are fixed in geographic latitude, but we know that the auroral electrojets that AL is meant to detect vary in latitude, especially during active conditions. New indices should be designed that target specific areas of interest for forecasts and model validation, such as GICs in specific geographic regions [Dimmock et al., 2020].

3. Current State of Ground-based Magnetometer Infrastructure

B measurements are collected by many groups in the US and internationally with a wide range of objectives and funding sources. Considering only the US and only instruments used for Heliophysics-related research, ground-based magnetometers are supported by the NSF Directorate for Geosciences (including the Division of Atmospheric and Geospace Sciences Magnetosphere/Aeronomy/Geospace Facilities Programs, Division of Polar Programs Antarctic

Research Program, and the Division of Earth Sciences), NASA Science Mission Directorate-Heliophysics Division, the Department of Defense (AFOSR), United States Geological Survey, the State of Texas, as well as by the private sector, non-profits, and private citizens. These groups operate magnetometer networks with a wide range of goals and applications (see Section 1), thus use a wide range of magnetometer instrumentation with different sensitivities, sampling rates, etc. (e.g., Engebretson and Zesta, 2017). Their magnetometers operate in all regions of the Earth, from southern/northern polar regions to the geographic equator, requiring further adaptation to different operational environments. Other communities also operate a significant number of ground-based magnetometers. For example, the magnetotelluric community is broadly partitioned into academic and industrial sectors, with the preponderance of industrial work focused on near-surface structure, whereas academic work often generates long-period data most useful to Heliophysics researchers. Nearly all magnetotelluric data are obtained using mobile arrays with relatively short-term deployments of days to months.

Many Heliophysics researchers interact with **B** measurements via a few databases including SuperMAG (Gjerloev, 2012), INTERMAGNET (Love and Chulliat, 2013), THEMIS/SPEDAS (Angelopoulos et al., 2019), NASA CDAWeb, and NOAA/NCEI (https://www.ngdc.noaa.gov/geomag/data.shtml). SuperMAG, supported by the NSF, is an international collaborative effort that processes data from ground-based magnetometers deployed globally, converts all data to the same coordinate system, and makes it possible to generate a range of high-level data products that are widely used by the Heliophysics research community, such as the SML index. Ground-based magnetometer measurements are also publicly available from other repositories not in wide use by the Heliophysics Research Community, including the Incorporated Research Institutions for Seismology (IRIS) Data Management System where the magnetotelluric and seismology communities generally archive data. Some magnetometer datasets that aren't funded by NSF, NASA, etc. are not publicly available.

Chi et al, [2013], the 2016 NSF Geospace Porfolio Review, and Engebretson and Zesta, [2017] all discuss the need for large scale magnetometer projects. As described by Engebretson and Zesta, [2017], "Previous and current practices regarding ground magnetometer deployments in the U.S. have led to a culture of individual arrays having to support both operations and scientific efforts using limited resources. Each team develops their own data recording systems, software, analysis, even data formats. The result has been much duplication of effort and only limited updating of instrumentation and innovation in data products." They further describe how, in contrast to proposals for facilities with comparatively larger budgets such as radars, magnetometer proposals are usually submitted to programs where they compete against research proposals with no equipment or maintenance costs and with durations of 3 years; this places them at a disadvantage and leads to lapses in funding and slow progress in upgrading instrumentation, enabling real-time data transmission from remote sites, and performing basic tasks such as making calibrated data available in a timely manner. In Section 4, we describe several ways to address these issues.

4. Requirements and Recommendations to Proactively Meet the Needs of Heliophysics Researchers and Support Space Weather Operations in the Next 10 Years

NSF Class 2 Magnetometer Facility to Proactively Meet the Needs of Heliophysics Researchers. The 2016 NSF Geospace Portfolio Review recommended that magnetometers be supported as a Class 2 facility with support from the Geospace Facilities program rather than the Magnetosphere base program. This would address many of the issues identified in Section 3, but implementing a single facility for all the ground magnetometers supported by NSF is challenging given their wide range of research objectives, operational environments, deployment requirements, and their split between different programs across NSF GEO. We propose a strategic shift in magnetometer operations via a Class 2 Facility, but its remit should be to (1) track the status of all ground-based magnetometers that provide data publicly (including those on IRIS), (2) ensure NSF-supported data are made available to the Heliophysics research community, (3) identify current or possible future gaps in data coverage due to equipment failures, funding lapses, etc and (4) informed by the Space Weather Advisory Group, SuperMAG advisory board, ground magnetometer advisory board, and other stakeholders, prioritize and fill gaps in coverage through existing and new instrumentation. This facility would use standard data formats, and, wherever possible, standard equipment and datalogging tools.

Continued Support for Individual Magnetometer Networks with 5-year Projects. Separate from the above facility, individual magnetometer networks should still be proposed to address a variety of science objectives and operational environments. These should be proposed as 5-year projects to maximize the science return from the measurements as this is generally enough time to deploy the systems, test them, and obtain sufficient measurements (baseline magnetic fields) to be usable by the SuperMAG database, thus providing value-added higher-level data products that are widely used by Heliophysics researchers. Upon completion of these projects, the magnetometers should be (1) decommissioned, (2) re-proposed with new science objectives, or (3) temporarily or permanently transfer their operations to the Facility described above. We encourage support for networks involving one or more of these components:

(1) International collaborations that increase operational efficiencies through, for example, joint funding of instrument platforms. Formally allocating funds in each country to support collaborations (e.g., NSF-NERC joint solicitations to support US/UK partnerships) would facilitate these efforts. Mechanisms to support some international partners' efforts – e.g., indigenous communities in Canada, universities in Ethiopia – have rarely been implemented but are needed. This includes support for meetings that facilitate the involvement of these partners early in proposal development (e.g., NSF Dear Colleague Letter 21-077).

(2) Continued support for technology innovations that drive down costs, size, and/or increase instrument sensitivities. This includes open-source code for data logging/communications and build-to-print / off-the-shelf support equipment that make magnetometers more accessible to groups that do not have established programs.

(3) Support for networks that incorporate elements of education, outreach, and/or citizen science. Ground-based magnetometers are ideal tools for these efforts with multiple trends pointing to increased availability/accessibility in future years (Section 1). NSF and NASA can incentivize these projects via support for outreach activities/workshops, working with institutional review boards, and other activities required for education and citizen science projects that aren't included in typical magnetometer project budgets.

(4) NASA and/or NSF support to integrate the ground-based magnetometer community in the planning stages (pre-Phase A) and operations for satellite missions with science objectives requiring or facilitated by **B** measurements, such as NASA's upcoming Geospace Dynamics Constellation mission. This strategy has been shown to yield significant benefits (e.g., THEMIS mission), yet ground-based measurement programs are often done in a more ad hoc fashion shortly before spacecraft launch or afterwards, leaving the possibility that systems will not be deployed in the desired locations or collect data at the desired resolution.

Support for Multi-Instrument Platforms Addressing Multiple Science Objectives and Big Ideas. For example, multi-instrument platforms that incorporate ground magnetometers, ground electrometers, seismometers and GNSS receivers would enable ground-breaking research across multiple divisions within the NSF Geoscience Directorate related to several of NSF's Big Ideas while also increasing efficiencies in deployment/operations. A large-scale effort to study GICs and improve our understanding of telluric currents thus improve remote sensing methods (section 2) could also yield new insights into Earth conductivity and deep-Earth structure [e.g., Kelbert et al., 2020; Egbert et al., 2020], earthquakes, ground-atmosphere-ionosphere coupling, and many other areas. This could be part of the facility listed above or a separate effort supported by multiple divisions within the NSF Geoscience Directorate and/or by other agencies/private sector. It could also be incorporated within existing and future efforts to perform real-time monitoring of **E** and **B** for space weather nowcasts; permanent dense arrays of magnetotelluric instruments, for example, can provide real-time wide area situational awareness of fine scale time- and space variations in **B** and **E**.

Training and Retention of Magnetometer Experts. There are a small number of Heliophysics research groups involved in magnetometer design/operations and, unlike other large-scale research infrastructure (e.g., incoherent scatter radars), there are no summer schools or similar training opportunities for new magnetometer operators. To meet the goals listed above, we recommend support for (1) increased communication between different groups via workshops, (2) support training activities/summer schools, and (3) funding for new PhD students seeking to use magnetometers in their research and/or future career path. We recommend that NSF and NASA encourage collaborative projects between established magnetometer groups and new groups with less experience building, deploying, and operating magnetometers.

Support the exploration and achievement of convergence research via, for example, continued support of SuperMAG. NSF defines convergence as "the merging of innovative ideas, approaches, and technologies from a wide and diverse range of sectors and expertise." In the context of ground-based magnetometers, this includes (1) continued support of SuperMAG to make data accessible via common data formats and high-level data products as it has proven indispensable in this area and is widely used by Heliophysics researchers (see section 3) and increasingly by other research communities, (2) support interdisciplinary collaborations and meetings that include multiple stakeholders who use **B** and **E** to design a framework for making datasets interoperable across communities (e.g., power grid GIC observations), (3) support Observation System Simulation Experiments (OSSE) to intelligently design new coverage and instrumentation requirements (e.g., where to place magnetometers and what type of magnetometer to use).

References:

Angelopoulos, V., Cruce, P., Drozdov, A. et al. The Space Physics Environment Data Analysis System (SPEDAS). Space Sci Rev 215, 9 (2019). https://doi.org/10.1007/s11214-018-0576-4

Beggan, C. D. and Marple, S. R.: Building a Raspberry Pi school magnetometer network in the UK, Geosci. Commun., 1, 25–34, https://doi.org/10.5194/gc-1-25-2018, 2018.

Belakhovsky, V. B., Pilipenko, V. A., Sakharov, Ya. A., & Selivanov, V. N. (2018). Characteristics of the variability of a geomagnetic field for studying the impact of the magnetic storms and substorms on electrical energy systems. Izvestiya, Physics of the Solid Earth, 54(1), 52–65.

Belakhovsky, V., Pilipenko, V., Engebretson, M., Sakharov, Y., & Selivanov, V. (2019). Impulsive disturbances of the geomagnetic field as a cause of induced currents of electric power lines. Journal of Space Weather and Space Climate, 9, A18.

Carrington, R. C. (1860). Description of a singular appearance seen in the Sun on September 1, 1859. Monthly Notices of the Royal Astronomical Society, 20, 13–15.

Carter, B. A., Yizengaw, E., Pradipta, R., Weygand, J. M., Piersanti, M., Pulkkinen, A. A., Zhang, K. (2016). Geomagnetically induced currents around the world during the March 17, 2015 storm. Journal of Geophysical Research: Space Physics,121, 10,496–10,507. https://doi.org/10.1002/2016JA023344.

Chi, P.J., Russell, C.T., Strangeway, R.J., Walker, R.J., Le, G., Rowland, D.E., Gjerloev, J.W., Chun, K.C., McHarg, M.G. (2013), A National Ground Magnetometer Program for Heliophysics Researh, White Paper for the 2013-2022 Solar and Space Physics Decadal Survey.

Chi et al., (2022), Magnetoseismology in a New Era of Magnetospheric Research, White Paper for the 2024-2033 Solar and Space Physics Decadal Survey

Dimmock, A. P., Rosenqvist, L., Hall, J.-O., Viljanen, A., Yordanova, E., Honkonen, I., et al. (2019). The GIC and geomagnetic response over Fennoscandia to the 7–8 September 2017 geomagnetic storm. Space Weather, 17, 989–1010.

Dimmock, A. P., Rosenqvist, L., Welling, D. T., Viljanen, A., Honkonen, I., Boynton, R. J., & Yordanova, E. (2020). On the regional variability of dB/dt and its significance to GIC. Space Weather, 18, e2020SW002497.

G D Egbert, P Alken, A Maute, H Zhang, Modelling diurnal variation magnetic fields due to ionospheric currents, Geophysical Journal International, Volume 225, Issue 2, May 2021, Pages 1086–1109, https://doi.org/10.1093/gji/ggaa533

Engebretson, M., & Zesta, E. (2017). The future of ground magnetometer arrays in support of space weather monitoring and research. Space Weather, 15, 1433–1441.

Engebretson, M. J., Pilipenko, V. A., Ahmed, L. Y., Posch, J. L., Steinmetz, E. S., Moldwin, M. B., Connors, M.G., Weygand, J.M., Boteler, D.H., Russell, C.T., and Vorobev, A.V. (2019). Nighttime magnetic perturbation events observed in Arctic Canada: 1. Survey and statistical analysis. Journal of Geophysical Research: Space Physics, 124, 7442– 7458.

Engebretson, M. J., Pilipenko, V. A., Steinmetz, E. S., Moldwin, M. B., Connors, M. G., Boteler, D. H., et al. (2021). Nighttime magnetic perturbation events observed in Arctic Canada: 3. Occurrence and amplitude as functions of magnetic latitude, local time, and magnetic disturbance indices. Space Weather, 19, e2020SW002526.

Gjerloev, J. W. (2012). The SuperMAG data processing technique. Journal of Geophysical Research: Space Physics, 117(A9).

Hajra, R. (2022). Intense, long-duration geomagnetically induced currents (GICs) caused by intense substorm clusters. Space Weather, 20, e2021SW002937. https://doi.org/10.1029/2021SW002937

Hapgood, M. (2019). The great storm of May 1921: An exemplar of a dangerous space weather event. Space Weather, 17, 950– 975. https://doi.org/10.1029/2019SW002195.

Hayakawa, H., Ebihara, Y., Willis, D. M., Toriumi, S., Iju, T., Hattori, K., et al (2019). Temporal and spatial evolutions of a large sunspot group and great auroral storms around the Carrington event in 1859. Space Weather, 17, 1553– 1569. https://doi.org/10.1029/2019SW002269.

Juusola, L., Vanhamäki, H., Viljanen, A., and Smirnov, M.: Induced currents due to 3D ground conductivity play a major role in the interpretation of geomagnetic variations, Ann. Geophys., 38, 983–998, https://doi.org/10.5194/angeo-38-983-2020, 2020.

Knipp, D. J., Fraser, B. J., Shea, M. A., & Smart, D. F. (2018). On the little-known consequences of the 4 August 1972 ultra-fast coronal mass ejecta: Facts, commentary, and call to action. Space Weather, 16, 1635– 1643. https://doi.org/10.1029/2018SW002024

Kelbert, A. (2020). The Role of Global/Regional Earth Conductivity Models in Natural Geomagnetic Hazard Mitigation. Surveys in Geophysics, 41, 115–166. https://doi.org/10.1007/s10712-019-09579-z

Lester, M., Hughes, W. J., & Singer, H. J. (1984). Longitudinal structure in Pi 2 pulsations and the substorm current wedge. Journal of Geophysical Research: Space Physics, 89(A7), 5489–5494.

Love, J. J., and Chulliat, A. (2013). An International Networkof Magnetic Observatories. EOS, 94, 42, 373-374. https://doi.org/10.1002/2013EO420001

Mayaud, P. N. (1980). Derivation, meaning, and use of geomagnetic indices (Sect. 5.1.3, Chap. 8). Washington, DC: American Geophysical Union.

Menk, F. W., and Waters, C. L. (2013). Magnetoseismology. Weinheim: Wiley VCH. doi:10.1002/9783527652051

Newell, P. T., & Gjerloev, J. W. (2011). Evaluation of SuperMAG auroral electrojet indices as indicators of substorms and auroral power. Journal of Geophysical Research, 116, A12211.

Ngwira, C. M., A. Pulkkinen, F. D. Wilder, and G. Crowley, (2013), Extended study of extreme geoelectric field events for geomagnetically induced current applications, Space Weather, 11, 121-131, doi:10.1002/swe.20021.

Ngwira, C. M., Pulkkinen, A. A., Bernabeu, E., Eichner, J., Viljanen, A., & Crowley, G. (2015). Characteristics of extreme geoelectric fields and their possible causes: Localized peak enhancements. Geophysical Research Letters, 42(17), 6916–6921.

Ngwira, C. M., D. Sibeck, M. V. D. Silveria, M. Georgiou, J. M. Weygand, Y. Nishimura, and D. Hampton (2018), A study of intense local dB/dt variations during two geomagnetic storms, Space Weather, 16, doi:10.1029/2018SW001911.

Ohtani, S. (2022). New Insights from the 2003 Halloween Storm into the Colaba 1600 nT Magnetic Depression during the 1859 Carrington Storm. Journal of Geophysical Research: Space Physics, 127, e2022JA030596. https://doi.org/10.1029/2022JA030596

Peticolas, L.M., Craig, N., Odenwald, S.F. et al. The Time History of Events and Macroscale Interactions during Substorms (THEMIS) Education and Outreach (E/PO) Program. Space Sci Rev 141, 557–583 (2008). https://doi.org/10.1007/s11214-008-9458-5

Pulkkinen, A., et al. (2013), Community-wide validation of geospace model ground magnetic field perturbation predictions to support model transition to operations, SpaceWeather, 11, 369–385, doi:10.1002/swe.20056.

Pulkkinen, A., et al. (2017), Geomagnetically induced currents: Science, engineering, and applications readiness, Space Weather, 15, 828– 856, doi:10.1002/2016SW001501.

Reiter K, Guillon S, Connors M & Jackel B 2021. Statistics of large impulsive magnetic events in the auroral zone. J. Space Weather Space Clim. 11, 44. https://doi.org/10.1051/swsc/2021029.

Russell, C.T., Chi, P.J., Dearborn, D.J. et al. THEMIS Ground-Based Magnetometers. Space Sci Rev 141, 389–412 (2008). https://doi.org/10.1007/s11214-008-9337-0.

Shen, X.-C., Shi, Q., Wang, B., Zhang, H., Hudson, M. K., Nishimura, Y., Hartinger, M. D., Tian, A., Zong, Q.-G., Rae, I. J., & Degeling, A. W. (2018). Dayside Magnetospheric and Ionospheric Responses to a Foreshock Transient on 25 June 2008: 1. FLR Observed by Satellite and Ground-Based Magnetometers. Journal of Geophysical Research: Space Physics, 123(8), 6335–6346.

Sugiura, M., & Chapman, S. (1960). The average morphology of geomagnetic storms with sudden commencement. Abhandlungen der Akademie der Wissenschaften zu Göttingen, 1–53. Göttingen: Göttingen Math. Phys. Kl., Sondernheft Nr.4.

Tanskanen, E. I., Viljanen, A., Pulkkinen, T. I., Pirjola, R., Häkkinen, L., Pulkkinen, A., and Amm, O. (2001), At substorm onset, 40% of AL comes from underground, J. Geophys. Res., 106(A7), 13119– 13134.

Turner, D. L., Shprits, Y., Hartinger, M., & Angelopoulos, V. (2012). Explaining sudden losses of outer radiation belt electrons during geomagnetic storms. Nature Physics, 8(3), 208–212.

Welling, D. (2019). Magnetohydrodynamic Models of B and Their Use in GIC Estimates. In Geomagnetically Induced Currents from the Sun to the Power Grid (eds J.L. Gannon, A. Swidinsky and Z. Xu). https://doi.org/10.1002/9781119434412.ch3

Weygand, J. M., Engebretson, M. J., Pilipenko, V. A., Steinmetz, E. S., Moldwin, M. B., Connors, M. G., et al. (2021). SECS analysis of nighttime magnetic perturbation events observed in Arctic Canada. Journal of Geophysical Research: Space Physics, 126, e2021JA029839. https://doi.org/10.1029/2021JA029839.

Zhang, H., Zong, Q., Connor, H., Delamere, P., Facskó, G., Han, D., Hasegawa, H., Kallio, E., Kis, Á., Le, G., Lembège, B., Lin, Y., Liu, T., Oksavik, K., Omidi, N., Otto, A., Ren, J., Shi, Q., Sibeck, D., & Yao, S. (2022). Dayside Transient Phenomena and Their Impact on the Magnetosphere and Ionosphere. Space Science Reviews, 218(5), 40.