Geomagnetism Program Research Plan, 2020–2024

Circular 1469

U.S. Department of the Interior
U.S. Geological Survey

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By Jeffrey J. Love, Anna Kelbert, Benjamin S. Murphy, E. Joshua Rigler, and Kristen A. Lewis

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Preface

This circular presents a research plan for the U.S. Geological Survey Geomagnetism Program. The report was written at the request of the Senior Advisor for Earthquake and Geologic Hazards and the Director of the Geologic Hazards Science Center.

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Abbreviations and Acronyms

AFRL	Air Force Research Laboratory
AGU	American Geophysical Union
CONUS	conterminous United States
DC	direct current
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
Dst	storm-time disturbance
EMAC	Electromagnetic Advisory Committee
EMIW	Electromagnetic Induction Workshops
EMP	electromagnetic pulse
EMPRAD	Electromagnetic Pulse Research and Development working group
EO	Executive Order for Coordinating National Resilience to Electromagnetic Pulses
FERC	Federal Energy Regulatory Commission
GEM	Geospace Environment Modeling program
GIC	geomagnetically induced current
GMT	Greenwich Mean Time
HAO	High Altitude Observatory
IAGA	International Association of Geomagnetism and Aeronomy
IEC	International Electrotechnical Commission
IGY	International Geophysical Year
INTERMAGNET	International Real-time Magnetic Observatory Network
IRIS	Incorporated Research Institutions for Seismology
km	kilometer
LANL	Los Alamos National Laboratory
ModEM	Modular system for ElectroMagnetic inversion software
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NERC	North American Electric Reliability Corporation
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
NRCan	Natural Resources, Canada
NSF	National Science Foundation
NSO	National Solar Observatory

NSTC	National Science and Technology Council
NSWSAP	National Space Weather Strategy and Action Plan
nT	nanotesla
PROSWIFT	Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act
SECS	spherical elementary current system
SWORM	Space Weather Operations, Research, and Mitigation working group
SWPCSpace	Weather Prediction Center
3D	Three-dimensional
U.S.	United States
USGS	U.S. Geological Survey
V	volt

Geomagnetism Program Research Plan, 2020–2024

By Jeffrey J. Love, Anna Kelbert, Benjamin S. Murphy, E. Joshua Rigler, and Kristen A. Lewis

Abstract

The Geomagnetism Program of the U.S. Geological Survey (USGS) monitors geomagnetic field variation through operation of a network of observatories across the United States and its territories, and it pursues scientific research needed to estimate and assess geomagnetic and geoelectric hazards. Over the next five years (2020–2024 inclusive) and in support of national and agency priorities, Geomagnetism Program research scientists plan to pursue an integrated set of research projects broadly encompassing empirical estimation and mapping of geomagnetic disturbance, modeling of solid-Earth conductivity structure and surface impedance, and mapping of magnetic-storm-induced geoelectric fields. Analyses are empirically based, relying on measured time series as well as statistical and numerical modeling of geomagnetic-monitoring data from ground-based observatories and surface-impedance tensors acquired during magnetotelluric surveys. The plan describes augmentation and development of the Geomagnetism Program's existing research portfolio, assuming present funding levels and staffing numbers. Because the projects are interdependent, they cannot be straightforwardly prioritized. They will all be pursued as resources and time permit; additional funding and staffing would enable the projects to be broadened and more rapidly completed. Where appropriate and subject to budgetary constraints and staffing numbers, research on specific projects might be accelerated or even judiciously expanded—some opportunities for expansion are discussed in this plan. Results will provide realistic illumination of the nature of the ground-level expression of space-weather disturbance, a subject of particular importance for projects focused on evaluating the vulnerability of electric-power-grid systems. This plan does not cover Geomagnetism Program operations, which are primarily concerned with the operation of magnetic observatories and, now, magnetotelluric surveys, although the context of such observatories and surveys is discussed. The research element of the program provides guidance for the expansion of program operations and research projects. In addition to the research projects summarized here, program scientists continue to provide leadership to the national and international geomagnetic, magnetotelluric, and space-weather communities.

Directives and Priorities

The National Space Weather Strategy and Action Plan (NSWSAP) of the National Science and Technology Council (NSTC, 2019) directs the U.S. Department of the Interior (DOI), and, by proxy, the Geomagnetism Program of the U.S. Geological Survey (USGS), to work in collaboration with other agencies to enhance national protection by refining space-weather benchmarks (NSTC, 2019, Their Objective 1.1) and modeling the effects of space weather (Objective 1.3), in order to support assessing the vulnerability of critical infrastructure (Objective 1.2) and assessing the cost of space weather (Objective 1.4). The program is directed, in collaboration with other agencies, to contribute to the development of improved space-weather forecasts by supporting fundamental research (Objective 2.3), enhancing modeling techniques and the development of models (Objective 2.5), and releasing historical datasets (Objective 2.6). Furthermore, program research should inform operational priorities within the NSWSAP, including identifying baseline-observation capabilities (Objective 2.1), ensuring the continued operation and possible expansion of observation capabilities (Objective 2.2), identifying new and enhanced measurement methods (Objective 2.4), and enhancing accessibility to operational data (Objective 2.8).

Under the Executive Order for Coordinating National Resilience to Electromagnetic Pulses (White House, March 26, 2019, 13865, Section 5c), the DOI is directed to pursue research, development, deployment, and operational capabilities that enhance understanding of variations of the Earth’s magnetic field associated with electromagnetic pulses (EMPs), both natural and anthropogenic.

The research projects of the USGS Geomagnetism Program are consistent with the DOI (2018) strategic plan for providing science to safeguard communities from natural hazards. The program's work is also consistent with the USGS Natural Hazards Science Strategy for enhancing observations (Holmes and others, 2013, their Goal 1), pursuing fundamental understanding (Goal 2), improving hazard assessments (Goal 3), and providing situational awareness (Goal 4).

Under an act before Congress (as of August 2020, HR 5260) known as Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT), the DOI is noted as being responsible for magnetometer operations and for developing “crustal conductivity models to assess and mitigate risks from space-weather-induced electric ground currents.” Under PROSWIFT, the USGS (along with other agencies) is directed to transition space-weather-research findings, models, and capabilities, as appropriate, to the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DOD).

Background

Magnetic storms are hazardous to the activities and technological infrastructure of modern society. This fact was dramatically demonstrated in March of 1989 when a rare magnetic superstorm (Allen and others, 1989) damaged satellites and interfered with their operation, and disrupted geophysical surveys and over-the-horizon radio communication. This storm caused the collapse of the Hydro-Québec electric power grid in Canada (Bolduc, 2002), damaged a high-voltage transformer at a nuclear-power plant in Salem, New Jersey (Barnes and others, 1991; Rossi, 1990), and, more generally, was responsible for over 200 significant anomalies in North American power-grid transmission networks (North American Electric Reliability Corporation (NERC), 1990). The cost of the March 1989 storm for the Canadian economy has been estimated to have been between $3 and $6 billion (in 1989 Canadian dollars) (Government of Canada, 2002; Riswadkar and Dobbins, 2010). Reflective of the rise of the global economy and an increased reliance on technology, should another Québec-like event occur today, a worldwide economic impact of $2.4 to $3.4 trillion could be expected, equivalent to a global loss in gross domestic product of 3.9 to 5.6 percent (Schulte in den Bäumen and others, 2014).

Longer ago, the great magnetic storm of May 1921 (for example, Hapgood, 2019; Love and others, 2019b) disrupted radio communication and telegraph and telephone systems around the world, and, notably, caused fires in telegraph stations used by New York State and City railroad companies. The Carrington event of 1859 was, by some measures, the most intense magnetic storm ever recorded (for example, Tsurutani and others, 2003; Cliver and Dietrich, 2013); it also disrupted telegraph systems around the world and caused fires at telegraph stations. Should a storm of similar intensity occur today, technological systems around the world might be adversely affected. Under some scenarios, the future occurrence of a rare “perfect magnetic storm” might have a widespread impact, possibly including the widespread collapse of electric-power networks. Such a potential event, sometimes described as being “high-impact, low-frequency,” could have deleterious consequences for the economy and national security (for example, NERC and U.S. Department of Energy (DOE), 2010). While acknowledging that economic impact can be difficult to predict (Eastwood and others 2017), some estimates place the economic cost of such a perfect storm for the United States at $0.6 to 2.6 trillion, with recovery taking years (National Research Council, 2008; Lloyd's, 2013).

Qualitatively, the physical connection between magnetic storms and the interference they can cause to power-grid systems is well understood, and the basic concepts are illustrated in figures 1 and 2. Briefly, geomagnetic disturbance induces geoelectric fields in the Earth's conducting interior. Surface geoelectric fields can drive geomagnetically induced currents (GICs) in power grids through their grounding connections (for example, Molinski, 2002; Piccinelli and Krausmann, 2014). Two factors affect the nature of surface geoelectric fields (Thomson and others, 2009; Love and others, 2014; Kelbert, 2020a). First, storm-induced electric currents in the ionosphere and magnetosphere, driven by the dynamic action of the Sun and its solar wind, generate ground-level geomagnetic disturbances that can be both temporally and spatially complicated. Indeed, predicting storm-time geomagnetic disturbance remains a challenging goal of space-weather modeling projects (for example, National Research Council, 2013; Pulkkinen and others, 2017). Second, the geologic structure of the solid Earth is complicated, and therefore surface electromagnetic impedance is complicated as well. All this means that storm-induced geomagnetic fields are both highly time dependent, and their amplitude and polarization can have a high degree of localized geographic granularity.

During an intense magnetic storm, geoelectric-field intensities of 1 volt per kilometer (V/km) are common in many places on the Earth's surface; over relatively resistive geologic formations, field intensities can exceed 10 V/km. This might seem rather modest at first, but given that power-grid lines are often more than 100 km in length, integrated voltage can possibly exceed 1000 V. Assuming a line resistance of, for example, 1 ohm, GICs of hundreds of amps over a minute or more can be realized. For a power grid designed for alternating current at a frequency of (typically) 60 Hz, such a GIC is effectively a direct current (DC). This can cause havoc, tripping relays and causing operational instability (for example, Kappenman, 2003; Piccinelli and Krausmann, 2014). Indeed, this is what brought down the Hydro-Québec system in 1989 (for example, Boteler, 2001; Bolduc, 2002). Prolonged periods of DC current can damage high-voltage transformers (Girgis and Vedante, 2012), and if they need to be replaced, restoration of service will be delayed.

An analogous hazard would be an EMP generated by a high-altitude nuclear explosion (for example, Dupont, 2004; Rivera and others, 2016; Gombosi and others, 2017). The low-frequency part of an EMP, referred to as E3, resembles the impulsive disturbance realized during some magnetic storms, although it has a somewhat shorter period band from about 1 to 1,000 seconds. Like storms, an E3 interacts with the Earth's surface impedance to induce geoelectric fields that could interfere with grounded power-grid systems. A hint of the destructive potential of EMP weapons came during the U.S. Starfish Prime test of July 9, 1962, above Johnston

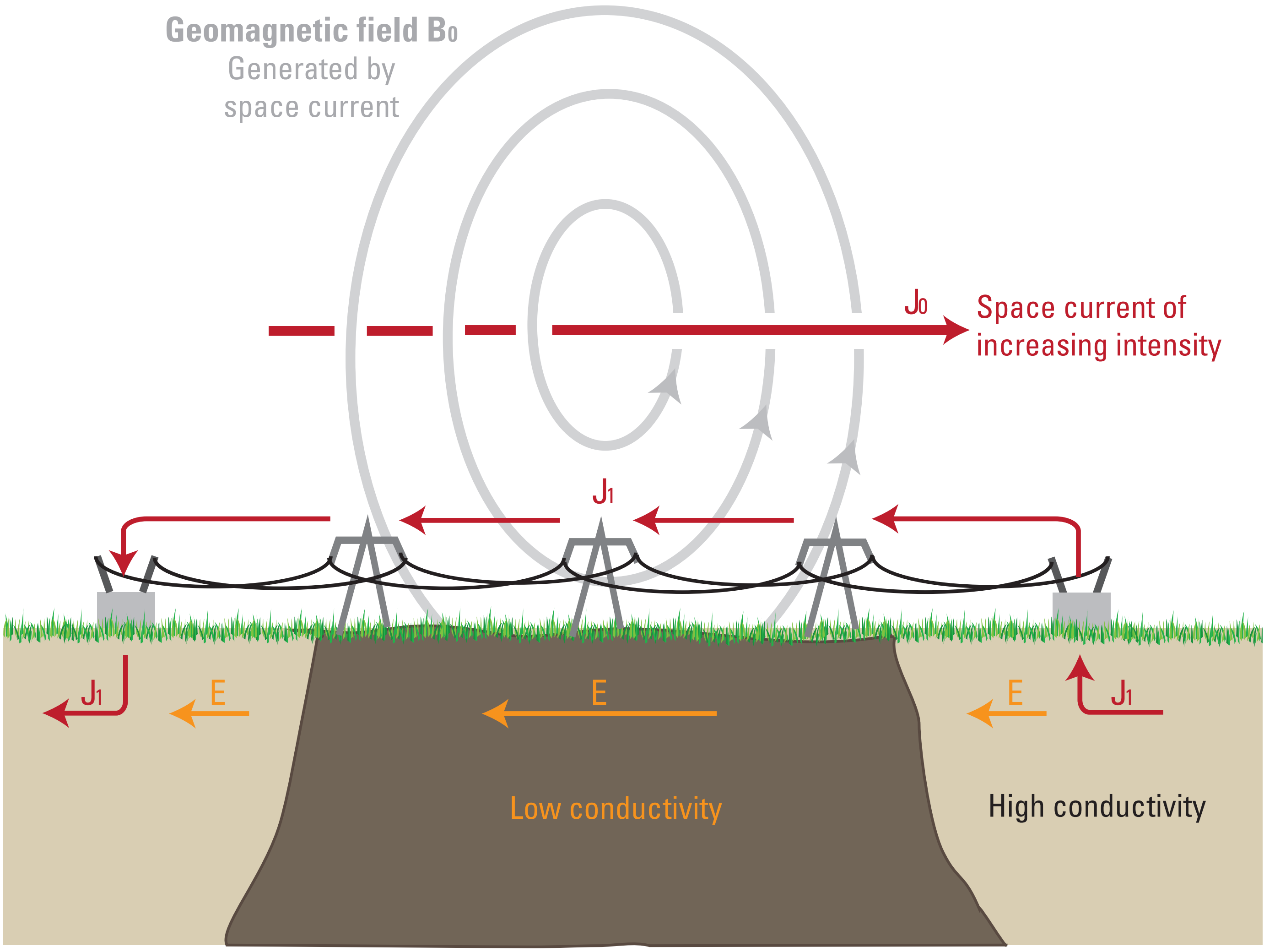


Figure 1. Schematic diagram showing a current (J_0) of increasing intensity over time in the space environment above the Earth's surface. This current generates a geomagnetic field (B_0) that is also increasing in intensity over time. This geomagnetic field, in turn, induces geoelectric fields (E) in the Earth, generally of high (low) amplitude within rock of low conductivity (high conductivity). These geoelectric fields then drive electric currents (J_1) that flow from the Earth through ground connections at transformer substations and across high-voltage transmission lines (for example, Pirjola, 2002).

Island in the Pacific Ocean: 1,350 km away from ground zero, burglar alarms were tripped in Honolulu, Hawaii (Glasstone and Dolan, 1977), and local street lights went black (Vittitoe, 1989). Soviet test 184 (also designated K3) on October 22, 1962, caused fires, destroyed power supplies, and blew fuses on a long communication-cable system beneath ground zero (Greetsai and others, 1998). The proliferation of nuclear weapons and the fundamental dependence of modern society on electricity and electronic technology have motivated recent evaluations of the risk posed by a hostile EMP explosion for national and international security (for example, Graham and others, 2008; Popik and others, 2017).

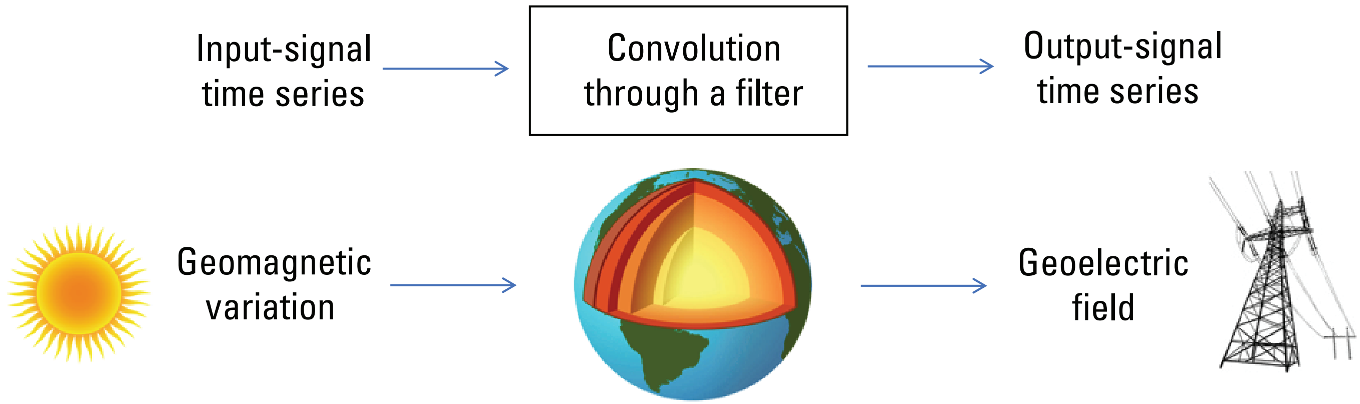


Figure 2. Schematic depiction of physical processes related to estimation of storm-time geoelectric fields. As with formal concepts from time-series analysis, in which an input signal is convolved with a filter function to produce an output signal, geomagnetic disturbance generated by the Sun and solar wind is filtered through an impedance tensor that is itself a function of the conductivity structure of the Earth. The resulting geoelectric field is a geophysical quantity that directly interferes with the operation of electric-power grids.

Program Roles and Capabilities

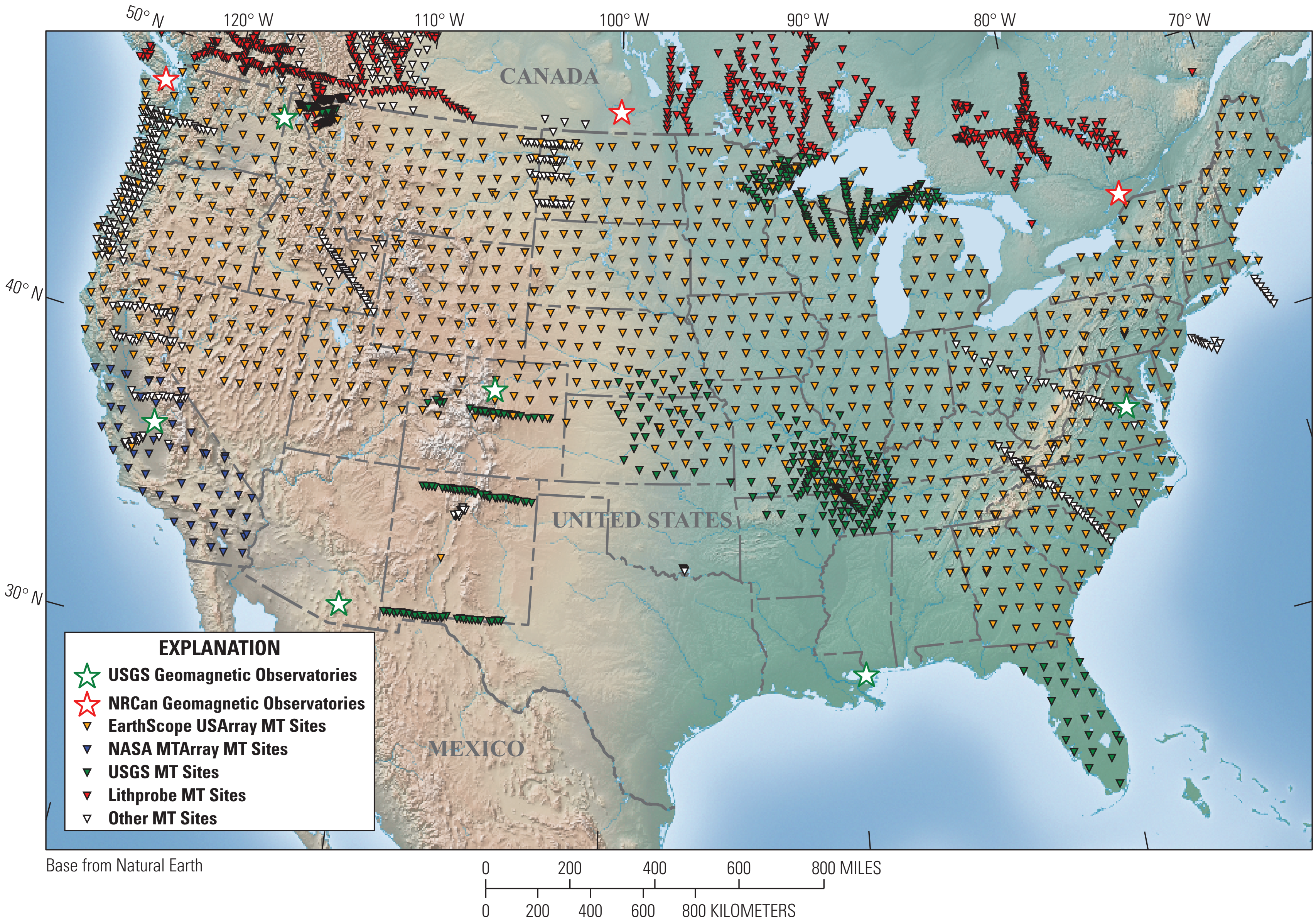
In support of national priorities for developing and providing information and services in the National interest, the USGS Geomagnetism Program monitors geomagnetic-field variation through the operation of a network of observatories across the U.S. and its territories (Love and Finn, 2011), and it pursues scientific research needed to estimate and assess geomagnetic and geoelectric hazards. Recent omnibus appropriations legislation has expanded Geomagnetism Program responsibilities to ensure the completion of a magnetotelluric survey across the conterminous U.S. (CONUS). The program's research element is small: two scientists are assigned full-time research, and one scientist is categorized as equipment development grade, and, as such, he concentrates on operational product development; in addition, the program benefits from occasional 2-year-term, postdoctoral fellows. The program is headquartered in the Geologic Hazards Science Center in Golden, Colorado, along with national and international earthquake programs and the national landslides program. Program scientists collaborate with the USGS Geology, Geophysics, and Geochemistry Science Center located nearby at the Denver Federal Center. Program scientists collaborate with colleagues from allied government agencies and academia and increasingly from the commercial sector.

USGS Geomagnetism Program scientists have a diverse mix of expertise in geology, solid-Earth geophysics, space physics, and data science. In recent years, this expertise has been utilized in the pursuit of an influential portfolio of research projects: analysis of historical magnetic superstorms, empirical mapping of storm-caused geomagnetic disturbance, inverse modeling of solid-Earth electrical-conductivity structure, analysis of its surface expression as impedance, and empirical mapping of storm-induced and EMP geoelectric fields. In the coming years, the program's research portfolio is expected to expand slightly to include analysis of the ground response to EMP. Program research results inform utility companies in vulnerability evaluations of electric-power grid systems mandated by regulatory agencies, and, more generally, they provide realistic illumination on the nature of the ground effects of space-weather disturbance.

Data Context

USGS Geomagnetism Program research scientists rely on time series acquired by magnetometers at ground-based stations (fig. 3). Program research complements program operational responsibilities for its network of 14 magnetic observatories, 6 of which are in CONUS (Love and Finn, 2011). Additionally, and of relevance to the emphasis of this research plan, geoelectric time series are being acquired at the Boulder magnetic observatory (Blum and others, 2017). Program observatories provide a baseline observation capability (NSTC, 2019, Objective 2.1) that needs to be sustained (Objective 2.2) and even enhanced (Holmes and others, 2013, Goal 1).

Some Geomagnetism Program observatories have been in operation for over a century, providing long time-series recordings of magnetic storms, quasi-diurnal solar-quiet tides, and slow secular geomagnetic variation generated in the Earth's core. The program's oldest data, time series acquired by analog variometers, are of high accuracy (a few nTs; nT, nanotesla) and useful for identifying general features of magnetic storms, but these data have a resolution of only 1 hour. Electronic fluxgate magnetometers, a standard instrument for measuring magnetic field variation over time (for example, Primdahl 1979), and digital acquisition systems have been operated at the observatories since the 1980s, and since then the program's basic data product has been 1-minute



Base from Natural Earth

Figure 3. Map of USGS and NRCan (Natural Resources, Canada) geomagnetic-observatory locations and U.S. and Canadian magnetotelluric (MT) survey sites. Many of the magnetotelluric impedance tensors are available through IRIS; additional data (also shown here) are in the process of being archived. Omnibus appropriations legislation for fiscal year 2020 has provided funds to the USGS for continuation of EarthScope-protocol magnetotelluric-data acquisition in the southwestern and south-central United States.

time series; 1-second resolution data have been acquired at the observatories since the early 2010s. The program's 1-minute and 1-second data are transmitted from all the observatories to program headquarters in Golden, Colorado, within minutes of acquisition, they are then made available to users, both in-house and to external partner agencies. The program's observatory operations are coordinated with those in other countries through the International Real-time Magnetic Observatory Network (INTERMAGNET, https://www.intermagnet.org), a global consortium of magnetic observatory institutes (for example, Love and Chulliat, 2013).

Geomagnetism Program research scientists also use magnetotelluric impedance tensors constructed from data acquired during surveys across North America and especially CONUS. In summary, (for example, Chave and Jones, 2012; Unsworth, 2007) at a given geographic site, simultaneous time-series measurements are made of natural-geomagnetic and geoelectric-field variation. The empirical relationship between these measurements is a transfer function equivalent to an impedance tensor divided by permeability. Magnetotelluric impedance tensors, constructed from data across a distribution of sites as part of a survey (for example, Egbert, 2007a), can be inverted for models of the internal conductivity structure of the Earth (for example, Kelbert and others, 2019). For purposes of geoelectric-hazard analysis, the combination of impedance tensors and time series (from observatories or models) can be used to estimate geoelectric-field variation (for example, Kelbert and others, 2017). Across CONUS, many impedance tensors (Schultz and others, 2006–2018; Schultz, 2010) used by the program were acquired by the EarthScope project of the National Science Foundation (NSF) (Williams and others, 2010); these tensors have a site spacing of about 70 km and a useful acquisition-period band from about 10 seconds to 10,000 seconds. Other tensors, such as from Florida and northern Arkansas, are derived from data collected by the U.S. Geological Survey in accordance with EarthScope protocol; still other tensors are collected as parts of other projects and often under different protocols.

In support of priorities for releasing new datasets (NSTC, 2019, Objective 2.6), enhancing the accessibility and sharing of observational data (Objective 2.8), and enhancing observations (Holmes and others, 2013, Goal 1), the USGS Geomagnetism Program is leading a project for compiling new and historical magnetotelluric impedance tensors (Kelbert and others, 2018; Kelbert, 2020b). These tensors are archived in a database (http://ds.iris.edu/spud/emtf) hosted by the Incorporated Research Institutions for Seismology (IRIS). The work includes checking and, in some cases, repairing historical functions. Compilation of historical impedance tensors, such as those acquired by the Lithoprobe Program of the Canadian Natural Sciences and Engineering Research Council, is a high priority. Work on this project has involved, and will continue to involve, collaboration with Oregon State University and IRIS. Results will provide input to the national impedance map (Project 4. National Impedance Map) and the project on EMP (Project 7. Electromagnetic-Pulse Hazard Analysis). Fiscal Year 2020 appropriated funds will support continuation of the magnetotelluric survey across the southern CONUS sector not completed by EarthScope.

Project 1. Historical Magnetic Superstorms

In support of priorities for developing space-weather benchmarks (NSTC, 2019, Objective 1.1), releasing new datasets (NSTC, 2019, Objective 2.6), and pursuing fundamental understanding (Holmes and others, 2013, Goal 2), the USGS Geomagnetism Program is leading projects to estimate the intensity of historical magnetic superstorms (for example, Love and others, 2019a, 2019b; Love, 2020) and the probability of their occurrence in the future (for example, Love and others, 2015); an example of the former is shown in figure 4. Estimating the intensity of storms that occurred after 1957 is relatively straightforward—during the International Geophysical Year (IGY, 1957–1958), standard measures of storm intensity, such as Dst (storm-time disturbance), were developed, and observatory operations were improved, resulting in data of improved accuracy and continuity. Prior to the IGY, when there were fewer observatories, and operational continuity was sometimes poor, the situation is more challenging. A recent reconnaissance of historical records by program scientists suggests that useful records exist for the most intense storm for each solar cycle since about 1900. With such a compilation and physically justified statistical models, scientists anticipate that improved estimates can be made of the occurrence frequency of intense storms together with estimates of statistical variance (uncertainty). This project will augment historical datasets (NSTC, 2019, Objective 2.6) and inform a subproject on the evaluation of historical magnetic-storm effects.

Project 2. Geomagnetic Field Mapping

In support of priorities for developing space-weather models (NSTC, 2019, Objective 2.5) and improving hazard assessments (Holmes and others, 2013, Goal 3), the USGS Geomagnetism Program is leading a project for developing capabilities for real-time and retrospective mapping of geomagnetic-field disturbance over North America (Rigler and others, 2019); an example of such a map is shown in figure 5. This project uses data from the USGS Geomagnetism Program's observatory network (and that of Natural Resources, Canada (NRCan); Newitt and Coles, 2007). Geospatial interpolation is required to estimate geomagnetic-field disturbances at locations far from the observatories. For various reasons, and especially because they are physically realistic and interpretable, the program has identified spherical elementary current systems (SECS) (for example, Amm, 1997; Amm and Viljanen, 1999) as suitable for this interpolation—the fields below the ionosphere and above the Earth's surface are assumed to be potential (free of currents). A robust

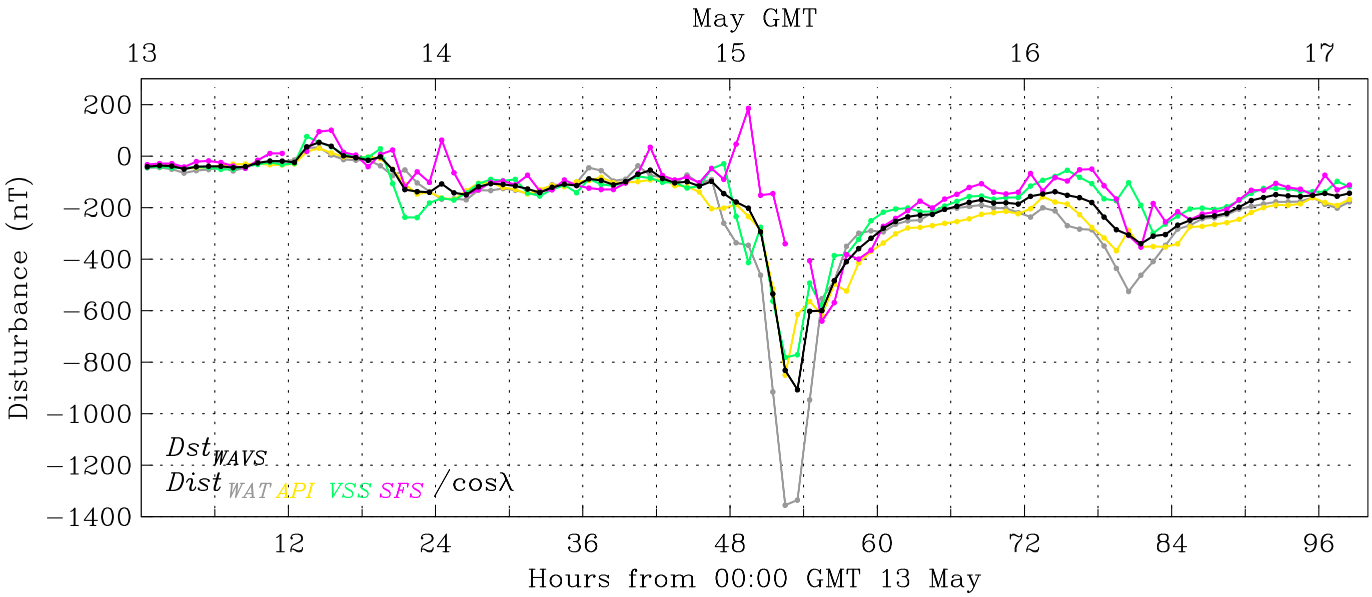


Figure 4. Latitude-weighted disturbance time series from the Watheroo, Australia (WAT, gray), Apia, Samoa (API, yellow), Vassouras, Brazil (VSS, green), and San Fernando, Spain (SFS, pink) observatories, and the Dst_{WAVS} (WAT, API, VSS, SFS) time series (black) from 00:30 (GMT, Greenwich Mean Time) May 13 to 02:30 May 17, 1921 (Love and others, 2019a). nT, nanotesla.

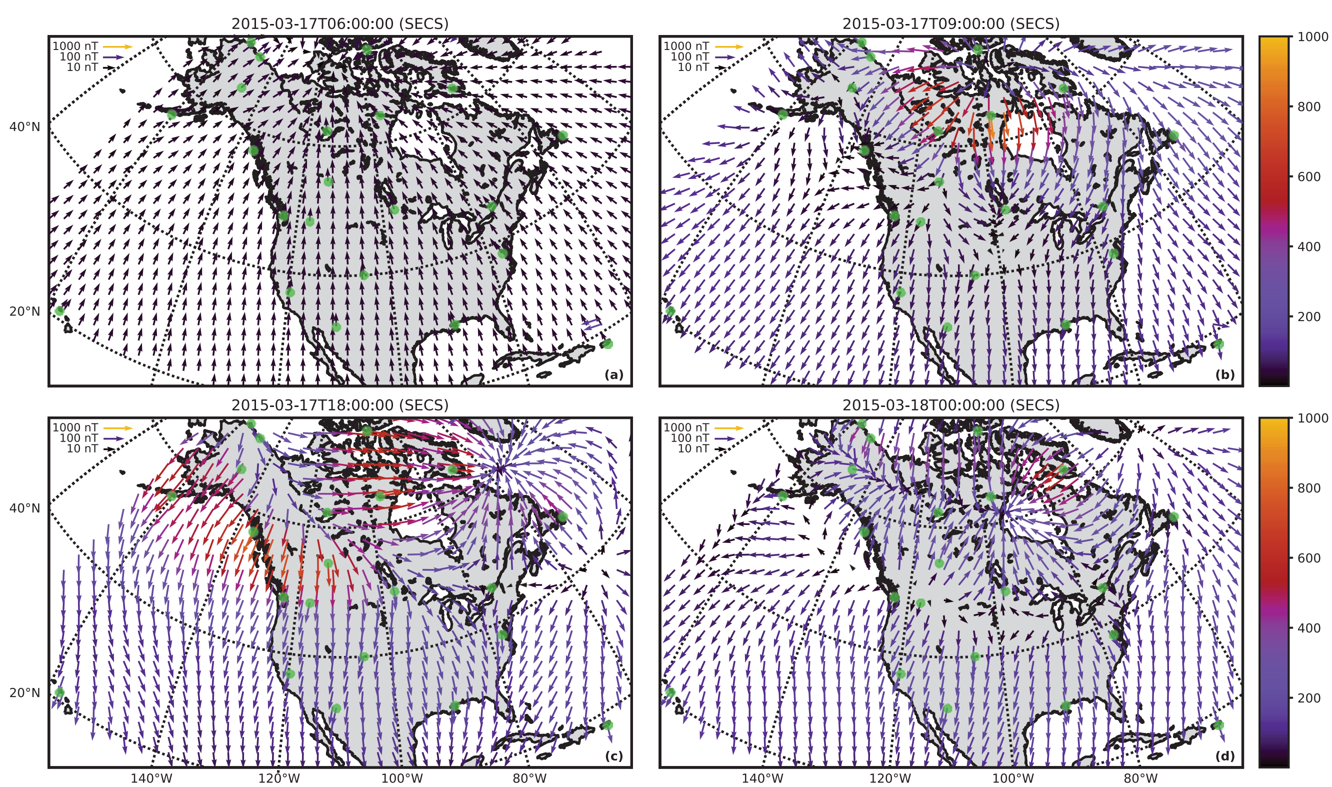


Figure 5. Snapshots of the North American distribution of spherical elementary current-system-interpolated horizontal magnetic-field vectors during the 2015 St. Patrick's Day magnetic storm (Rigler and others, 2019). nT, nanotesla.

optimal-estimation algorithm enables the SECS functions to be fitted to observatory data, and these fits can, in turn, be expressed as a map of geomagnetic-field disturbance at the Earth's surface.

Errors associated with the geomagnetic-field maps need to be reduced. Most fundamentally, these errors could be substantially reduced with data from additional magnetic observatories and variometer stations across CONUS. Indeed, this project can help justify additional monitoring stations (Project 8. Gap Analyses and Operational Support). Geomagnetism Program scientists are working to combine the SECS mapping models with physics-based models of the ionospheric-magnetospheric system by using machine-learning techniques and data assimilation. Work on this project involves collaboration with the NOAA Space Weather Prediction Center (SWPC), the National Aeronautics and Space Administration (NASA), the U.S. Air Force Research Laboratory (AFRL), and the High Altitude Observatory (HAO) at the National Center for Atmospheric Research (NCAR). When combined with work on the national impedance map (Project 4. National Impedance Map), results will provide input for real-time geoelectric-field mapping (Project 5. Geoelectric-Field Mapping).

In support of priorities for developing space-weather models (NSTC, 2019, Objective 2.5), for pursuing fundamental understanding (Holmes and others, 2013, Goal 2), improving hazard assessments (Goal 3), and providing situational awareness (Goal 4), the USGS Geomagnetism Program is developing statistical methods for separating geomagnetic-disturbance signals from solar-quiet and secular signals in observatory data (Rigler, 2017) that can be used for the calculation of magnetic indexes (scalar measures of disturbance) that are widely used in the space-weather and terrestrial-geomagnetism communities. The program has developed statistical maps of geomagnetic disturbance (Love and others, 2016a) that, in combination with surface impedance values (Project 4. National Impedance Map), can be used for (simple) statistical estimations of geoelectric hazards (Love and others, 2016b). These projects could be further developed, for example, by characterizing the statistics of storm-time magnetic declination, which would be a product of potential interest for navigation and directional drilling for oil and gas.

Project 3. Earth-Conductivity Modeling

In support of priorities for pursuing fundamental understanding (Holmes and others, 2013, Goal 2), and as a basis for developing space-weather models (NSTC, 2019, Objective 2.5) and improving hazard assessments (Holmes and others, 2013, Goal 3), the USGS Geomagnetism Program is developing models of CONUS subsurface electrical-conductivity structure. Heretofore, three-dimensional (3D) conductivity models have been obtained on a regional basis (for example, Meqbel and others, 2014; Yang and others, 2015; Murphy and Egbert, 2017) or globally at a substantially lower spatial resolution (for example, Sun and others, 2015). Initial work has involved the compilation of regional and global 3D conductivity models obtained at different resolutions; these have been combined into one continuous model (Kelbert and others, 2019) (fig. 6). Incremental updates and improvements are expected as new data become available. In the long term, consistent modeling for all of CONUS will be accomplished by the simultaneous modeling of thousands of magnetotelluric impedance tensors through the use of inverse theoretical methods (for example, Egbert, 2007b) and the Modular system for ElectroMagnetic inversion (ModEM) software (Kelbert and others, 2014), modified to accommodate supercomputer-memory needs and the spherical geometry of the Earth.

Modeling 3D CONUS electrical conductivity is an important steppingstone for several of the other projects outlined here. It supports the National Impedance Map (Project 4. National Impedance Map) by enabling geophysically based interpolation between the magnetotelluric survey sites to yield high-resolution, gridded impedances in CONUS. The framework of this project will further facilitate the investigation of anomalous, non-plane-wave response to short-spatial-scale geomagnetic-field disturbance realized during storms. Exploration of the limitations of the plane-wave approximation, inherent to magnetotelluric modeling, are planned by using realistic ionospheric-current sources (Projects 2. Geomagnetic Field Mapping and 5. Geoelectric-Field Mapping). Outside of the Geomagnetism Program, insights from the geological structure that the models reveal (for example, Hermance, 2011) inform projects undertaken by the USGS Geology, Geophysics, and Geochemistry Science Center for the evaluation of mineral resources (for example, Bedrosian, 2016; Murphy and others, 2019) and projects undertaken by the Earthquake Program for the evaluation of tectonic structures in areas prone to earthquake hazards. An important plausible extension of this project is consistent modeling of the conductivity structure of CONUS and Canada. Collaboration will be with Oregon State University.

Project 4. National Impedance Map

In support of priorities for developing space-weather models (NSTC, 2019, Objective 2.5) and improving hazard assessments (Holmes and others, 2013, Goal 3), the USGS Geomagnetism Program is mapping the surface impedance of CONUS—an important and high-profile product needed for retrospective, real-time, and prospective scenario estimation of geoelectric fields induced by magnetic storms and for the prospective estimation of geoelectric fields induced by EMP (White House, 2019). Synthetic analyses have already shown that the amplitude and polarization of induced geoelectric

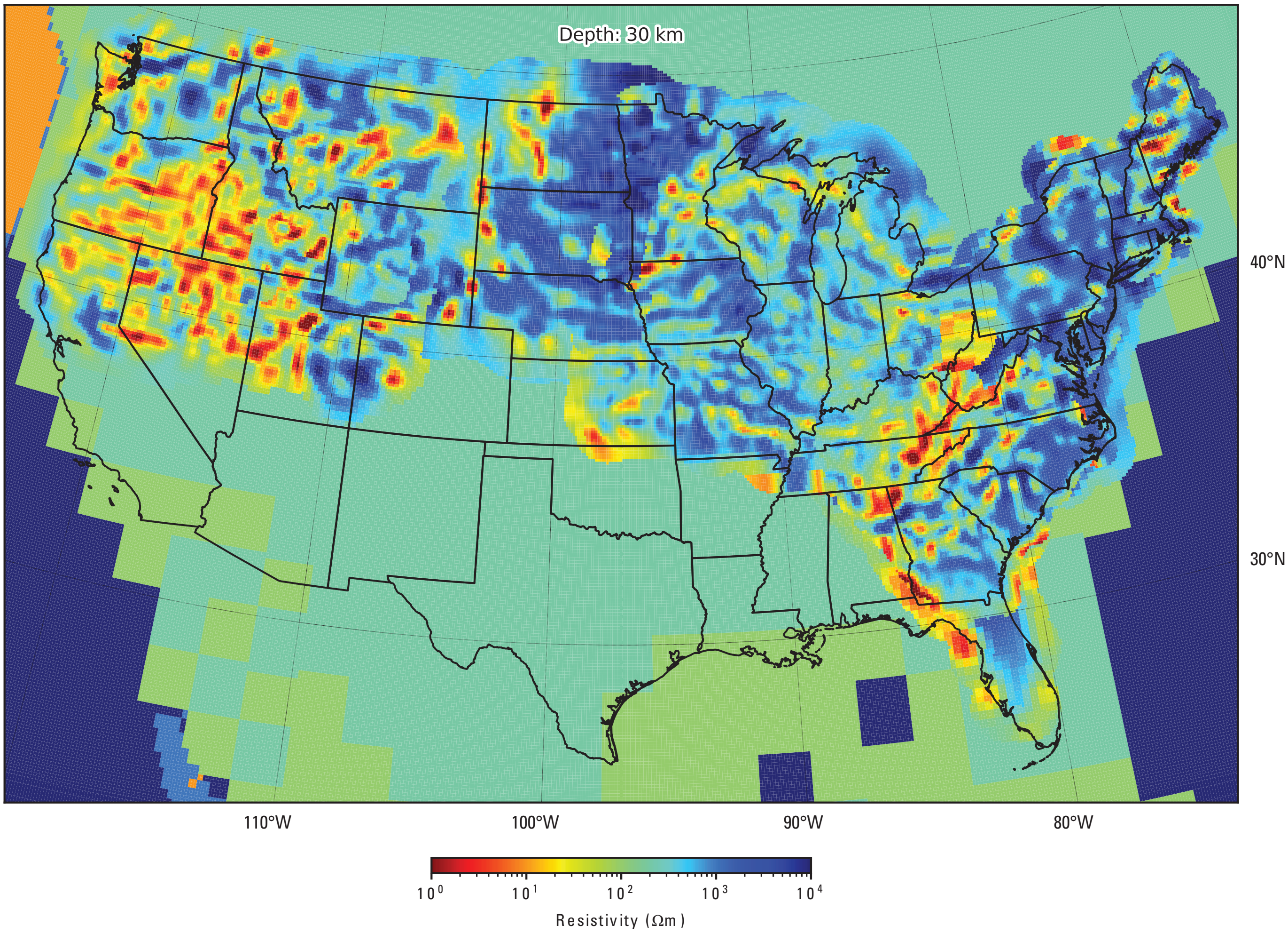


Figure 6. A synthesized CONUS electrical-conductivity model at a depth of 30 kilometers obtained from the inversion of EarthScope impedance tensors (Kelbert and others, 2019). Depth-dependent models of conductivity structure inform fundamental understanding of geologic structures. Integration of conductivity models can provide physically realistic and geographically continuous maps of surface impedance. Lack of structure in the south-central and southwest areas is a result of the lack of magnetotelluric data.

fields are strongly affected by the Earth's surface impedance (for example, McKay and Whaler, 2006; Bedrosian and Love, 2015).

Several variants of the National Impedance Map are being developed and maintained, and their utility for real-time geoelectric-field mapping (Project 5. Geoelectric-Field Mapping) and statistical-hazard mapping (Project 6. Statistical Maps of Geoelectric Hazards) is being evaluated and explored. Most straightforwardly, impedance can be mapped by plotting integrated quantities derived from the magnetotelluric tensors—for example, amplitude-polarization ovals (as shown in figure 7*A* and *B*), an empirical impedance map), apparent resistivity, or phase. Geographically dense estimates of surface impedance can be obtained by sampling impedances derived from a conductivity model (Project 3. Earth-Conductivity Modeling). Finally, these impedance maps can be interpolated on the power grids themselves to facilitate the calculation of line voltages and GICs. An important plausible extension of this project is modeling of CONUS-Canadian surface impedance.

Impedance maps inform needed evaluations of the quality of data acquired by ongoing magnetotelluric surveys, such as that for completing the national survey under EarthScope protocols. By illustrating the geographic complexity of impedance, the project informs gap analyses needed to justify additional magnetotelluric surveying (Project 8. Gap Analyses and Operational Support). As new magnetotelluric surveys are performed and new impedance tensors become available, the impedance map are planned to be periodically updated. To facilitate checking and reproducibility by outside investigators, version numbers, digital object identifiers, and metadata are planned to be used for reference data, models, and algorithms.

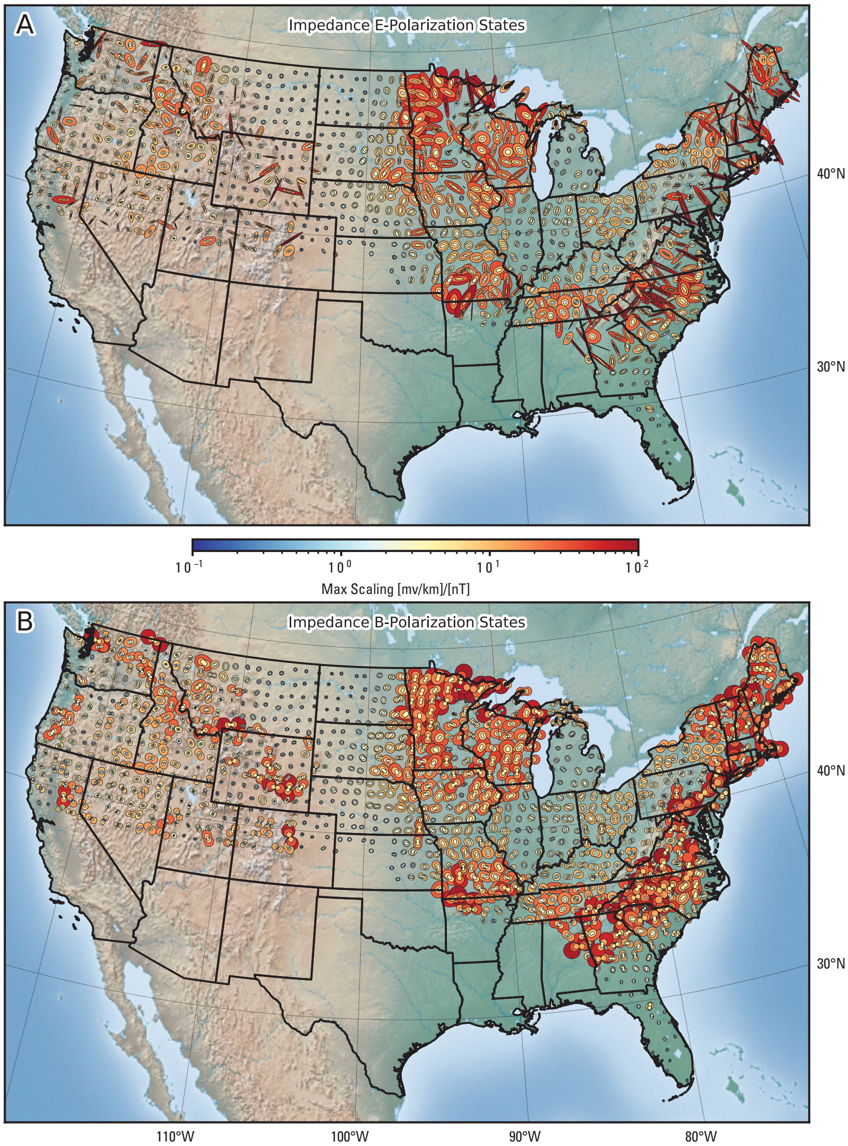


Figure 7. Maps showing the amplitude and polarization imparted by magnetotelluric impedances to the induced geoelectric field for a given geomagnetic field *A*, as a function of the azimuthal direction (declination) of the geomagnetic field, and *B*, as a function of the azimuthal direction of the induced geoelectric field, each for variational periods of 10, 100, and 1,000 seconds (smallest to largest ovals). Generally, due to resistive rock structures, impedance is high over parts of the Midwest and the area of the Piedmont east of the Appalachians; conversely, impedance is low over sedimentary basins, such as over the state of Michigan.

Project 5. Geoelectric-Field Mapping

In support of priorities for developing space-weather models (NSTC, 2019, Objective 2.5), transitioning capabilities from research to operations (Objective 2.7), and providing situational awareness (Holmes and others, 2013, Goal 4), the USGS Geomagnetism Program is collaborating with NOAA SWPC and the University of Colorado to provide real-time and retrospective CONUS maps of geoelectric-field variation (Love and others, 2018; see fig. 8). This project is the result of several years of concentrated effort, which involves time-domain convolution of magnetic-field maps (Project 2. Geomagnetic Field Mapping) with the national impedance map (Project 4. National Impedance Map) (for example, Kelbert and others, 2017, 2019). The current real-time map product uses only one-dimensional, depth-dependent models of surface impedance. Program scientists are working with NOAA to implement more realistic models of surface impedance, including geographically dense sampling of CONUS surface impedance derived from conductivity models.

Checks on the accuracy of the estimated geoelectric fields will be made by comparing them directly against measured data, such as those now being acquired at the USGS Boulder magnetic observatory (Blum and others, 2017) or those acquired during magnetotelluric surveys. A critical validation analysis will include Geomagnetism Program collaboration with NOAA and the power-grid industry for examination and comparison of modeled geoelectric-field maps as inputs to GIC calculations compared to real GIC measurements in the power grids (for example, Pulkkinen and others, 2017; Sun and Balch, 2019). The outcome of such validation exercises will, in turn, inform needed refinements of USGS magnetic-field and national impedance-mapping projects and possibly even motivate denser magnetotelluric surveys and the installation of additional magnetic observatories.

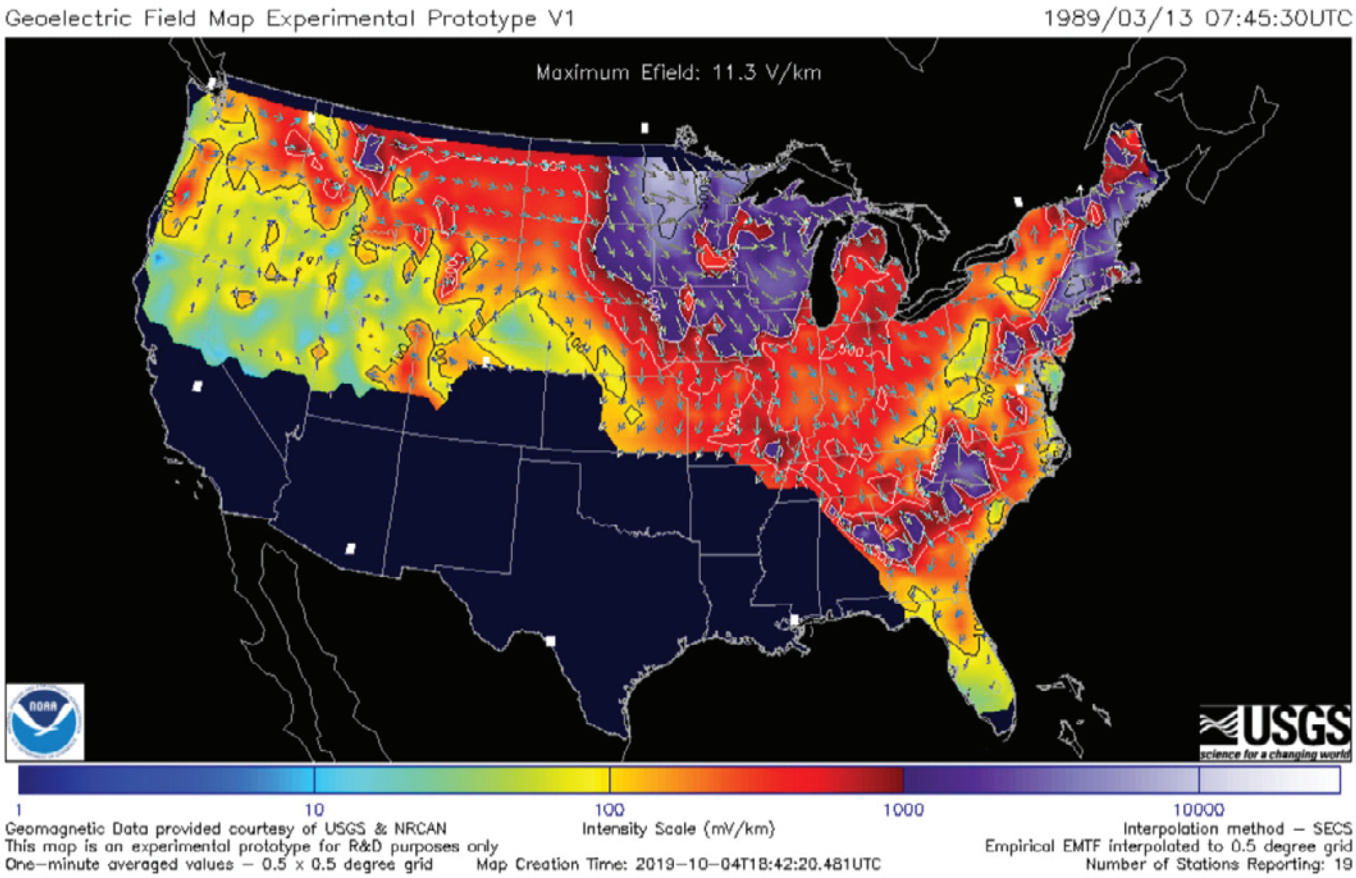


Figure 8. Snapshot from the NOAA-USGS time-dependent mapping project, which is similar to the map presented by NOAA in real time. Shown here is an instance during the March 1989 magnetic superstorm. NOAA, National Oceanic and Atmospheric Administration; USGS, U.S. Geological Survey; EMTF, electromagnetic transfer function; NRCan, Natural Resources Canada; UTC, coordinated universal time.

Scenario mapping of storm-induced geoelectric fields that incorporate whole-Earth, physics-based modeling of the magnetosphere, ionosphere, and solid Earth (Projects 2. Geomagnetic Field Mapping, 3. Earth-Conductivity Modeling, and 4. National Impedance Map), will likely show that some places exhibit localized complexity resulting from a combination of geomagnetic disturbance and impedance, both of which are spatially complicated. Scenario mapping constrained by data will enable and inform the analyses of errors associated with the plane-wave approximation of magnetotellurics (Project 4. National Impedance Map), and it will help users to identify needs for additional and higher density magnetotelluric surveys (Project 8. Gap Analyses and Operational Support).

Results from this project will inform the electricity utility industry in their projects for evaluating the vulnerability of power-grid systems. Additional Geomagnetism Program projects could include real-time and retrospective estimation of time-varying voltages on CONUS power grids, similar to that done in the mid-Atlantic U.S. before the March 1989 storm (Lucas and others, 2018), although an ongoing challenge is the sparsity of observatories used for geomagnetic-field mapping (Project 2. Geomagnetic Field Mapping). An important and plausible extension of this project is the consistent, joint mapping of CONUS and Canadian geoelectric fields.

Project 6. Statistical Maps of Geoelectric Hazards

In support of priorities for facilitating vulnerability assessments of critical infrastructure (NSTC, 2019, Objective 1.2), developing space-weather models (Objective 2.5), and improving hazard assessments (Holmes and others, 2013, Goal 3), the USGS Geomagnetism Program is leading a project for developing statistical maps of geoelectric hazard across CONUS (Lucas and others, 2018; Love and others, 2019c; Lucas and others, 2020). This project uses interpolations of magnetic observatory data and magnetotelluric impedance tensors. In the future, the latter could be improved by using a geographically dense sampling of surface impedance (Project 4. National Impedance Map) derived from conductivity models (Project 3.

Earth-Conductivity Modeling). Importantly, the geographic sparsity of observatories is a lesser challenge for statistical analyses than for time-continuous mapping (Project 5. Geoelectric-Field Mapping).

Hazard maps, such as shown in figure 9 as voltages on the national power grid, can inform vulnerability-evaluation projects of the NERC mandated by the Federal Energy Regulatory Commission (FERC) (2013). Once extreme-value voltage is estimated, GICs can be estimated by using Kirchhoff's laws, line resistances, and grid interconnectivity; in turn, the stress a grid would experience during a rare magnetic superstorm can be estimated. Recently initiated work includes the parameterization of maximum geoelectric-field intensity in terms of global indexes of geomagnetic disturbance, permitting retrospective estimation of the geoelectric hazards realized during great magnetic storms of the past. An important plausible extension of this project is consistent mapping of CONUS and Canadian geoelectric hazards needed to evaluate the exposure and vulnerability of the integrated North American power-grid systems. Collaboration is with the USGS Geology, Geophysics, and Geochemistry Science Center and the University of Colorado.

Project 7. Electromagnetic-Pulse Hazard Analysis

In support of priorities motivated by the EMP Executive Order 13865 (White House, 2019), the USGS Geomagnetism Program is examining the effects of realistic surface impedance on E3-induced geoelectric fields. Towards that end, the program uses some of the methods developed in its analysis of storm-induced geoelectric fields (Lucas and others, 2018, 2020). An idealized but standard model is being used for estimating bomb-induced geomagnetic disturbance (Legro and others, 1985; International Electrotechnical Commission (IEC), 1996). This model is convolved with surface impedance (Project 4. National Impedance Map) to obtain maps of the E3 geoelectric field. Both time-dependent-scenario and hazard maps can be developed in this way.

This project will illuminate the effects of the Earth's 3D conductivity structure on the E3-induced geoelectric fields—until now, E3induction was typically considered for idealized one-dimensional Earth models (Commission to Assess the Threat to the United States (U.S.) from Electromagnetic Pulse (EMP) Attack, 2017). As for magnetic storms, investigation is needed of the non-plane-wave response to short-spatial-scale geomagnetic-field disturbance.

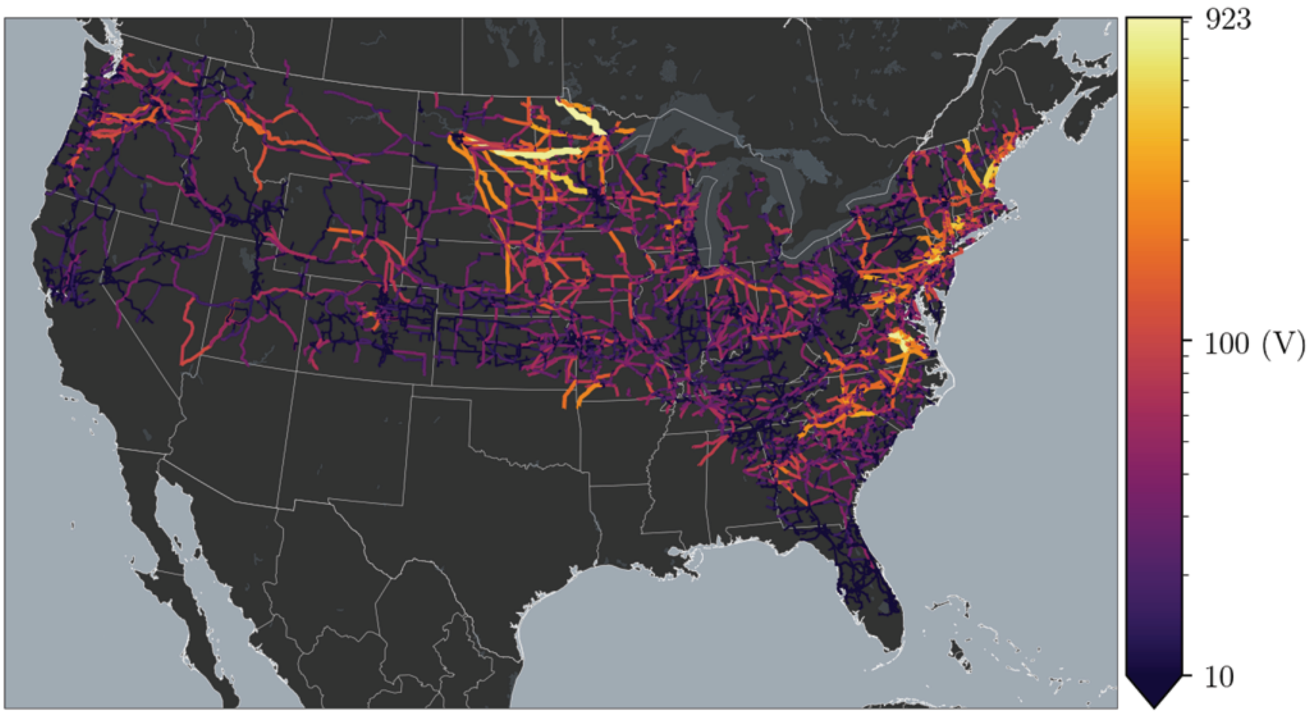


Figure 9. Once-per-century extreme magnetic-storm-event predictions of transmission-line voltage (Lucas and others, 2020): high and low hazards are yellow and purple, respectively. That the highest hazards are in the northern Midwest and the Piedmont east of the Appalachians demonstrates the important role that surface impedance plays in determining localized geoelectric hazards.

This project might benefit from reconnaissance deployments of high-frequency magnetotelluric sensors with a variety of spacings and orientations in a variety of geological settings across CONUS. Collaboration is needed among diverse agencies—possibly including the Los Alamos National Laboratory (for example, Rivera and others, 2016)—to enable realistic modeling. Results are likely to be influential for the EMP-assessment projects of the FERC (2013), Electric Power Research Institute (EPRI) (Horton, 2017), DOE (2017), and the DOD (Siebert and Witt, 2019).

Project 8. Gap Analyses and Operational Support

In support of priorities for ensuring baseline operational space-weather-observation platforms, capabilities, and networks (NSTC, 2019, Objective 2.2); identifying, developing, and testing innovative approaches to enable enhanced, more informative, robust, and cost-effective measurements (Objective 2.4) and observations (Holmes and others, 2013, Goal 1); the USGS Geomagnetism Program is examining the temporal and spatial complexity of storm-time geomagnetic and geoelectric disturbance. As illustrated in figure 10, the difference in geomagnetic disturbance recorded at distant but neighboring observatories can be significant. Work on this project can exploit the geomagnetic-disturbance maps (Project 2. Geomagnetic Field Mapping) and include analyses of geomagnetic data from the relatively dense observatory network in Europe. Geoelectric hazard maps (Project 6. Statistical Maps of Geoelectric Hazards) can also be used to identify potential locations for additional observatories or variometer stations—new stations might, for example, be installed in areas where geoelectric hazards are known to be high and far removed from existing observatory locations. The program plans to also examine the spatial resolution of the National Impedance Map (Project 4. National Impedance Map) derived from available magnetotelluric- survey tensors; the 70-kilometer survey-station spacing under EarthScope protocols might need to be augmented with surveys of finer scale in areas of spatially complex impedance. All of this will, in turn, help scientists to address the challenges of mapping geomagnetic (Project 2.

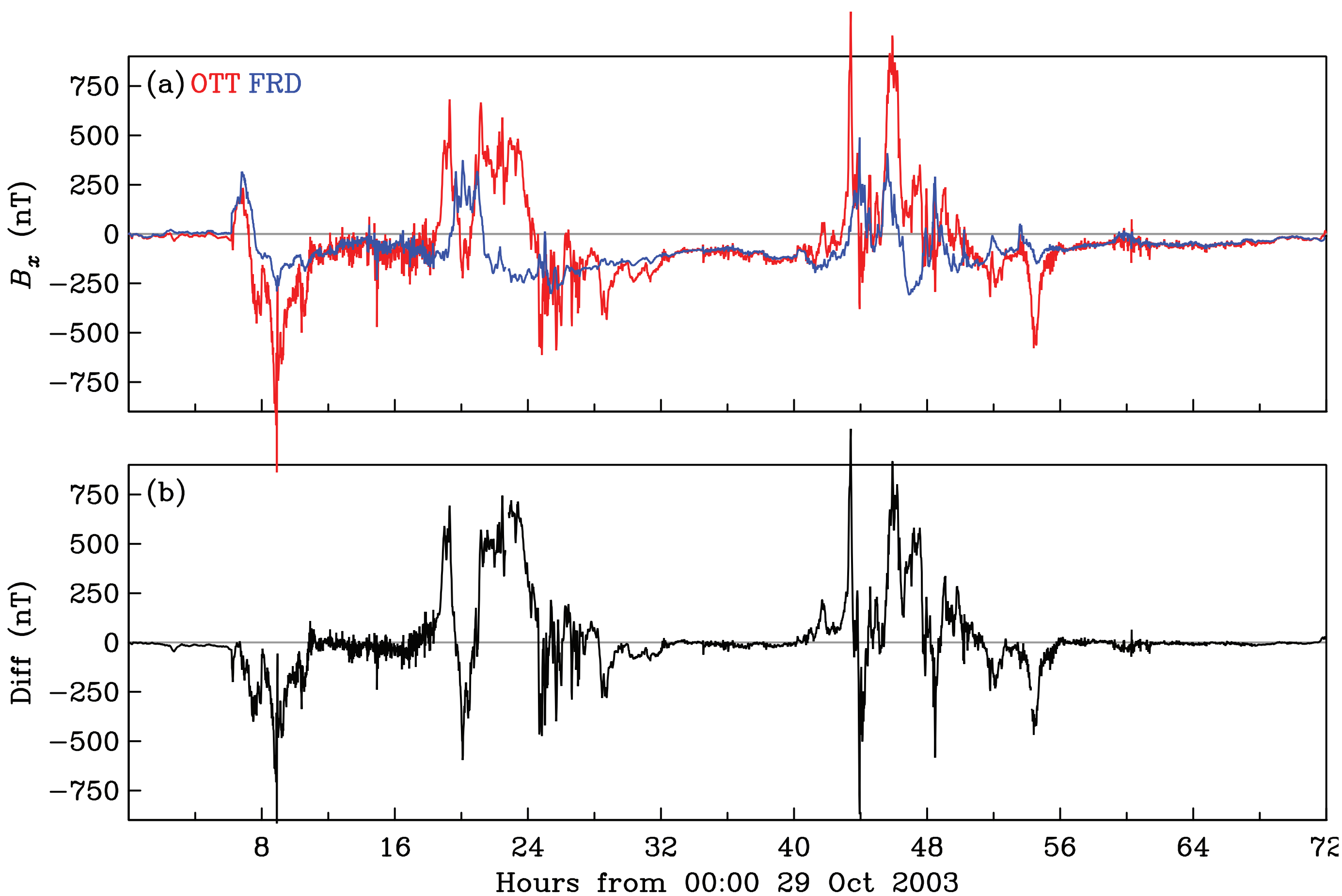


Figure 10. Comparison of *A*, 1-minute north-south B_x geomagnetic-disturbance time series recorded at the Ottawa, Canada (red, OTT) and Fredericksburg, Virginia (blue, FRD) observatories during the Halloween storm of October 29–31, 2003 (Balch and others 2004), and *B*, the difference between the OTT and FRD time series. These observatories are separated by 814 kilometers.

Geomagnetic Field Mapping) and geoelectric disturbances (Projects 5. Geoelectric-Field Mapping and 6. Statistical Maps of Geoelectric Hazards).

External Collaborative Projects

USGS Geomagnetism Program scientists collaborate with several research groups on their projects. For example, as part of an ongoing collaboration with NCAR on physics-based modeling of the magnetospheric-ionospheric system, staff are developing (as of August 2020) a Biot-Savart algorithm that can be used to estimate ground geomagnetic-field disturbance. On another front, program scientists are collaborating with (1) the University of Texas at Arlington on numerical simulations of the most extreme sudden geomagnetic impulse theoretically possible; (2) the National Solar Observatory on analysis of historical records of an intense solar flare and solar-proton event; and (3) the USGS Geology, Geophysics, and Geochemistry Science Center on several projects related to geoelectric hazards and the modeling of solid-Earth conductivity structure by using magnetotelluric-survey data.

Community Leadership

The scientists of the USGS Geomagnetism Program play important roles in the terrestrial geomagnetic, magnetotelluric, and space-weather communities. They serve the Nation through the NSTC's Space Weather Operations, Research, and Mitigation (SWORM) working group and the Electromagnetic Pulse Research and Development (EMPRAD) working group, providing expertise in the ground effects of natural and anthropogenic electromagnetic-field disturbance. They advise FERC and NERC on storm-induced geoelectric hazards. They advise the National Geospatial-Intelligence Agency (NGA) on their World Magnetic Model project. They provide a liaison to NSF's Geospace Environment Modeling (GEM) steering group, and they serve on GEM's metrics-and-validation resource group. They serve on an advisory panel for university magnetometer programs and on IRIS's Electromagnetic Advisory Committee (EMAC). They advised NSF's EarthScope program on its magnetotelluric survey, and they played essential roles in the processing of EarthScope magnetotelluric data and in archiving related impedance tensors (Kelbert and others, 2018). They have served on the Leadership Council of NSF's EarthCube (Kelbert, 2014; Aronson and others, 2015), as well as on its committees for science, technology and architecture, and nominations. They have organized conference sessions for the American Geophysical Union (AGU) and the International Union of Geology and Geophysics (IUGG). They have advised the domestic oil-and-gas industry on the use of geomagnetic data for directional drilling (Buchanan and others, 2013).

Internationally, USGS Geomagnetism Program research scientists and leadership support geomagnetic monitoring (Love and Finn, 2017) by providing guidance for INTERMAGNET. They serve on the Executive Committee of the International Association of Geomagnetism and Aeronomy (IAGA) and on the program committee of IAGA's Electromagnetic Induction Workshops (EMIW). Program scientists have a strong publication record, and notably, their research results have been reported in the popular press.

Some Conditional Aspirations

The preceding plan (with its eight integrated projects) is ambitious, and aspects of each project are currently being pursued (as of August 2020). Even with the present level of funding and staffing numbers, given the demonstrated productivity of USGS Geomagnetism Program scientists, good progress on all eight projects can be anticipated, as program scientists are fully occupied with their individual responsibilities. Given this, we can then imagine what the program might be able to do should increased funding and higher staffing numbers be realized. Most directly, progress on the projects might be accelerated and judiciously expanded. This would certainly benefit electric-utility companies with their projects for evaluating the vulnerability of power-grid systems to the deleterious effects of natural and anthropogenic geoelectric disturbance.

In more detail, the capability for mapping geoelectric fields (Project 5. Geoelectric-Field Mapping) could enable retrospective analyses of historical magnetic storms (Project 1. Historical Magnetic Superstorms) and prospective analyses of physics-based models (Project 2. Geomagnetic Field Mapping) of a potential superstorm. Scenario results would help put the statistical geoelectric-hazard maps (Project 6. Statistical Maps of Geoelectric Hazards) and the time-dependent geoelectric maps (Project 5. Geoelectric-Field Mapping) into perspective. Similarly, building on the proposed EMP analysis (Project 7. Electromagnetic-Pulse Hazard Analysis), physics-based models of source geomagnetic disturbance would help to put idealized EMP geoelectric maps into perspective. Any of these projects would benefit from additional support for Geomagnetism Program research, including work done through postdoctoral appointments.

If funding were sufficient to support new and additional Geomagnetism Program observatories (or simpler variometer stations) across CONUS and (or) new and additional regional magnetotelluric surveys in areas that the national-scale survey shows are likely to have high and spatially complicated geoelectric hazards, then scientific analyses of the new resulting data would provide more detailed time-dependent geoelectric maps (Project 5. Geoelectric-Field Mapping) and more detailed regional geoelectric-hazard maps (Project 6. Statistical Maps of Geoelectric Hazards). Additional support could also enable the analysis of geoelectric hazards that can affect pipelines, railroads, and transoceanic telecommunication cables, each of which would be qualitatively different from hazard analyses for power grids.

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