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# Down to Earth With an Electric Hazard From Space

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**Abstract** In reaching across traditional disciplinary boundaries, solid-Earth geophysicists and space physicists are forging new collaborations to map magnetic-storm hazards for electric-power grids. Future progress in evaluation storm time geoelectric hazards will come primarily through monitoring, surveys, and modeling of related data.

**Plain Language Summary** In reaching across traditional disciplinary boundaries, solid-Earth geophysicists and space physicists are forging new collaborations to map magnetic-storm hazards for electric-power grids.

## Introduction

Magnetic storms bring us beautiful nighttime displays of aurora, but they can also be hazardous for the technological systems of importance to modern society. Of particular concern is the storm time induction of geoelectric fields in the Earth's electrically conducting interior [e.g., *Thomson*, 2007]. During intense magnetic storms, these geoelectric fields can interfere with the operation of electric-power grids, sometimes even damaging high-voltage transformers and causing blackouts [e.g., *Piccinelli and Krausmann*, 2014].

The reality of this hazard was rudely demonstrated in March 1989, when an intense magnetic storm caused the entire Hydro-Québec power-grid system in Canada to collapse. More recently, the Halloween magnetic storm of October 2003 caused operational failures in Swedish systems. Some scenario analyses anticipate the future occurrence of a rare magnetic superstorm, possibly as intense as the "Carrington event" of 1859, which could cause widespread and prolonged loss of electric-power for the United States and other countries, carrying significant economic cost [e.g., *Baker et al.*, 2008]. The importance of the electric power grid is demonstrated by pictures of the nighttime Earth from space (Figure 1).

In 2016, the Federal Energy Regulatory Commission directed the North American Electric Reliability Corporation to develop standards to mitigate the hazardous effects of storm time geoelectric fields for power-grid systems. More generally, the United States Space Weather Strategy of the National Science and Technology Council [*National Science and Technology Council*, 2015], the Decadal Strategy for Solar and Space Physics of the National Research Council [*National Research Council*, 2013], and other allied strategies and plans, both domestic [e.g., *Pulkkinen et al.*, 2017] and international [*Schrijver et al.*, 2015], have identified the estimation and evaluation of geoelectric field hazards as a high-priority pursuit.

## Geomagnetic Monitoring

Around the world, geomagnetic activity is monitored from a network of magnetic observatories [e.g., *Love*, 2008; *Rasson et al.*, 2011]. Their data have contributed to many fundamental scientific discoveries in geomagnetic and space-weather science. Observatory data are used to map electric current patterns in the ionosphere and magnetosphere [e.g., *Kamide et al.*, 1981; *Amm and Viljanen*, 1999] and to validate geospace models [e.g., *Pulkkinen et al.*, 2011]. Real-time observatory data are used to measure the intensity of magnetic storms and perform operational evaluation of space-weather conditions [e.g., *Balch et al.*, 2004; *Menvielle and Marchaudon*, 2007]. Long, historical time series from magnetic observatories reveal the causal relationship between sunspots and magnetic storms, and they are used to analyze the occurrence frequency of extreme-event magnetic storms. Models of this relationship can be used to forecast the future likelihood of magnetic storms across a range of intensities [e.g., *Riley and Love*, 2017], and they contribute to the evaluation of induced geoelectric hazards.

## Magnetotelluric Surveys and Models

Magnetotellurics is a geophysical exploration method for estimating the electrical conductivity structure of the Earth's crust, lithosphere, and mantle from ground-level measurements of the geomagnetic and

**Figure 1.** Nighttime photograph of the United States (credit: NASA).

geoelectric field variation [e.g., *Simpson and Bahr*, 2005; *Unsworth*, 2007]. The relationship between geomagnetic and geoelectric time variation can be distilled down to an “impedance tensor” that is, itself, a function of the subsurface conductivity structure beneath the measurement site. This conductivity structure, in turn, depends upon the myriad of material properties, including mineralogy, partial melt, volatile content, water quality, clay content, aqueous fluids, porosity, and the interconnectivity of cracks and grain boundaries [e.g., *Evans*, 2012].

Magnetotelluric surveys are routinely performed over limited geographic regions for purposes of commercial geothermal and mineral explorations and fundamental research. Since 2006, the National Science Foundation’s EarthScope program [*Williams et al.*, 2010] has supported a national-scale magnetotelluric survey [*Schultz*, 2010] that, so far, has covered about half of the continental United States. The impedance tensors [*Schultz et al.*, 2006–2018] have been inverted for three-dimensional conductivity models that inform fundamental understanding of North American geology and tectonic history [e.g., *Bedrosian and Feucht*, 2014; *Yang et al.*, 2015].

## Direct Geoelectric Monitoring

Long-term geoelectric field monitoring is performed at only a few places in the world [e.g., *Fujii et al.*, 2015]. Geoelectric time series are useful for validating models and prediction methods, as well as for extending the depth of magnetotelluric investigations of the mantle’s electrical conductivity structure [e.g., *Schultz et al.*, 1987; *Toffelmier and Tyburczy*, 2007]. But due to the complexity of the Earth’s interior structure, storm time geoelectric fields measured at one site can differ significantly from those measured at another just a hundred or so kilometers away [e.g., *Bedrosian and Love*, 2015; *Bonner and Schultz*, 2017]. And this, together with the dedicated attention required to maintain finicky geoelectric monitoring systems over long durations of time, means that it is impractical to operate a permanent geoelectric monitoring network of sufficient density to adequately evaluate geoelectric hazards on a continental scale.

## Geoelectric Hazard Maps

Concerning magnetic storms, it is sometimes said that “if you have seen one storm, you have seen one storm” [*Friedel et al.*, 2002, p. 266]. And, indeed, it is certainly true that each storm has its own unique time-dependency. Recognizing this, one way to characterize geomagnetic activity is in terms of extreme-event variation recorded at ground observatories—this activity can be roughly described in terms of a latitude-dependent function [e.g., *Ngwira et al.*, 2013; *Love et al.*, 2016a; *Woodroffe et al.*, 2016]. The highest levels

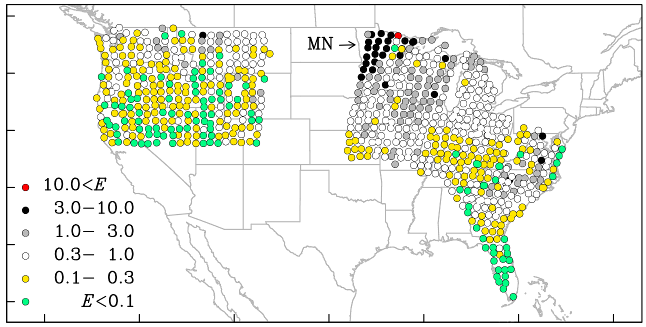


**Figure 2.** Map showing geoelectric amplitudes (V/km) that can be expected to be exceeded once-per-century at EarthScope and USGS magnetotelluric survey sites for north-south geomagnetic variation with a period of 240 s and realized over a duration of 600 s (credit: USGS).

of geomagnetic activity tend to be concentrated underneath the auroral oval and within about 55 to 65° geomagnetic latitude.

By combining extreme-event estimates of geomagnetic activity with the EarthScope magnetotelluric impedance tensors, we can map extreme-event geoelectric amplitude, such as shown in Figure 2 for sinusoidal variation at 240 s realized as a waveform over a duration of 600 s [*Love et al.*, 2016b]. These maps tell us where and how large geoelectric hazards are likely to be in the future. They inform utility company projects for mitigating magnetic storm risk for existing power-grid systems and might even inform plans for "smart grid" systems.

From Figure 2, we see right away that geoelectric hazards can differ significantly from one location to another. Of the parts of the United States that have been surveyed, the greatest geoelectric hazards are in the Northern Midwest, where some sites could experience geoelectric fields greater than 3 V/km during an intense magnetic storm—comparable to the geoelectric amplitudes that brought down the Hydro-Québec power-grid system in 1989 [*Boteler*, 1994]. The generally high amplitudes seen in northern Minnesota can be attributed to old (Archean) geological basement rock [e.g., *Yang et al*., 2015; *Bedrosian*, 2016]; complicated localized differences, here, can be attributed to structures related to continental rifting that convulsed North America 1.1 billion years ago [e.g., *Stein et al*., 2016].

## Looking Forward

Future progress in evaluation storm time geoelectric hazards will come primarily through monitoring, surveys, and modeling of related data. For the United States, completing the national magnetotelluric survey and improving real-time geomagnetic monitoring are high priorities [e.g., *Thomson et al.*, 2009; *Love et al.*, 2014]. Looking beyond statistical hazard maps, ongoing algorithm development [e.g., *Bonner and Schultz*, 2017; *Kelbert et al.*, 2016; *Weigel*, 2017] could enable time-series scenario mapping of individual magnetic storms—convolving a time-dependent map of ground-level geomagnetic disturbance, derived from ground-based magnetometer data [e.g., *Pulkkinen et al.*, 2003; *Rigler et al.*, 2014], with a map of Earth-surface impedance. Such a project could be further developed into a real-time geoelectric mapping service of use for mitigating interference to power-grid operations.

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