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Geomagnetic Storms: An Evaluation of Risks and Risk Assessments

By the Office of Risk Management and Analysis

The views expressed in this paper do not necessarily reflect the views of the Department of Homeland Security or any other agency of the Federal government. The Issue Brief program is intended to provoke thoughtful discussion of critical risk management subjects among homeland security enterprise partners.

Summary

Geomagnetic storms — a type of space weather that creates disturbances that affect the planet's magnetic field — have the potential to cause significant damage across the globe with a single event. Severe geomagnetic storms can disrupt the operation of electric power transmission systems and critical infrastructures relying on space-based assets. A geomagnetic storm that degrades the electric power grid would affect not only the energy sector but the transportation, communications, banking, and finance sectors, as well as government services and emergency response capabilities. Despite the potentially serious consequences of a severe geomagnetic storm, a literature review indicates that the state of the art for assessing the security risk from geomagnetic storms is still in development. There are examples of analyses that describe threat, vulnerability, and consequence, but they are not integrated, primarily because of the weakness in the threat analysis. Without a sense of the likelihood of such events or at least a mechanism for relative comparisons, cost-benefit analyses have been unable to demonstrate the utility of investing either in hardening or in testing and maintaining operational procedures. The Federal government lacks comprehensive national-level geomagnetic storm risk management assessments and strategies, and no standing entity exists to coordinate cross-Federal government geomagnetic storm risk analysis. This Issue Brief suggests that the Federal government should consider whether it is appropriate to conduct a formal, comprehensive risk assessment regarding severe geomagnetic storms.

I. Introduction

Over the past decade, natural hazards have caused catastrophic consequences across the globe. Tsunamis, hurricanes, flooding, earthquakes, and volcanic eruptions have led to hundreds of thousands of fatalities and billions of dollars in economic costs. Significant geomagnetic storms — a type of space weather — happen less frequently, but have the potential to cause considerable damage across the globe with a single event. In the past, geomagnetic storms have disrupted space-based assets as well as terrestrial assets such as electric power transmission networks. Extra-high-voltage transformers and transmission lines may be particularly vulnerable to geomagnetically induced currents caused by the disturbance of Earth's geomagnetic field. The simultaneous loss of large numbers of these assets could cause a voltage collapse and lead to cascading power outages, resulting in significant economic costs to the Nation. An extreme geomagnetic storm is a low-probability, high-consequence event that could pose a systemic risk to the Nation.

This Issue Brief:

- Focuses on the risk that geomagnetic storms present
- Examines the state of the art for geomagnetic storm risk assessments

- Outlines lessons and challenges ascertained from an evaluation of geomagnetic storm literature
- Summarizes select Federal government and Department of Homeland Security (DHS) initiatives on geomagnetic storms
- Concludes with several areas for consideration and additional study by DHS. [1]

II. Background on Geomagnetic Storms

Large, violent eruptions of plasma and magnetic fields from the Sun's corona, known as coronal mass ejections, form the origin of geomagnetic storms.[2] Coronal mass ejections shock waves create solar energetic particles — consisting of electrons and coronal and solar wind ions — that when they approach Earth create disturbances that affect the planet's magnetic field. It takes approximately one to three days after a coronal mass ejections launches from the Sun for a geomagnetic storm to reach Earth and to affect the planet's geomagnetic field.[3]

Countries located in northern latitudes, such as Canada, the United States, and Scandinavia, are particularly vulnerable to geomagnetic storms. Power systems in these countries are more likely to experience significant geomagnetically induced currents because of their location in the northern latitudes, the soil type (igneous rock) surrounding electrical infrastructure, and the fact that transmission networks in these countries cover longer distances to the load center.[4] Power systems located in the northern regions of the North American continent are also particularly vulnerable because of their proximity to the Earth's magnetic north pole.[5]

Impact on Infrastructure

Disturbances in the Earth's geomagnetic field can disrupt the operation of critical infrastructures relying on space-based assets. Geomagnetic storms can degrade the strength of and distort signals emitted by Global Positioning System (GPS) satellites. The consequence of such a disruption is that GPS receivers miss a user's exact location. For example, errors in location given by the GPS signal could affect positioning operations of deep-ocean drilling platforms, which could result in the platform changing its position and causing a drill line to break.[6] Geomagnetic storms also have the potential to damage satellites permanently, but signal degradation is a more common consequence of this space weather phenomenon.

Geomagnetic storms can also disrupt terrestrial critical infrastructures, with electric power systems vulnerable to the effects of a geomagnetic storm. As geomagnetic storms reach the Earth they cause the planet's magnetic field to fluctuate, which in turn produces flows of electric currents through conductors

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[1] This Issue Brief contains information included in a report written on behalf of the Office of Risk Management and Analysis for the Organisation for Economic Co-operation and Development's "Future Global Shocks" project.

[2] National Academy of Sciences, *Severe Space Weather Events — Understanding Societal and Economic Impacts Workshop Report***,** National Academies Press, Washington, D.C., 2008.

[3] North American Electric Reliability Corporation, *March 13, 1989 Geomagnetic Disturbance*, NERC, Princeton, NJ, 1990.

[4] Kappenman, John G. and Albertson, Vernon D., "Bracing for the Geomagnetic Storms: As Solar Activity Moves Toward an 11-Year Peak, Utility Engineers Are Girding for the Effects of Massive Magnetic Disturbances," *IEEE Spectrum*, 1990.

[5] Kappenman, John G., et al., "Solar Wind Monitor Satellite Crucial for Geomagnetic Storm Warning," *IEEC Power Engineering Review*, 1990.

[6] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report***,** National Academies Press, Washington, D.C., 2008.

at the Earth's surface. These geomagnetically induced currents can flow through power transmission grids, as well as pipelines and undersea cables, and lead to power system problems.[7]

Electrical power transmission networks face greater vulnerability to geomagnetic storms as they span longer distances to supply demand centers due to the use of high-voltage transmission lines.[8] This is because the longer distances of networks make them better "antennas" to pick up the electrical currents induced by the geomagnetic storms. Geomagnetically induced currents can also overload electrical power grids, causing significant voltage regulation problems and, potentially, widespread power outages. Moreover, geomagnetically induced currents can cause intense internal heating in extra-high-voltage transformers, putting them at risk of failure or even permanent damage. Recent estimates state that 300 large extra-high-voltage transformers in the United States would be vulnerable to geomagnetically induced currents.[9] Damage to an extra-high-voltage transformer from geomagnetically induced currents could take months or even a year to repair and cost in excess of $10 million.[10]

A severe geomagnetic storm that disrupts the electric power grid at a regional, national, or international level affects not only the energy sector but also all the other infrastructure sectors that rely on electricity to carry out their mission. The economic impact of the loss of such critical infrastructure would be high; one estimate of the economic costs to the United States of the August 2003 blackout in North America (not due to an extreme geomagnetic storm) is $6 billion.[11] Once fuel for backup power runs out, resupply of fuel (e.g., through gasoline pumps) is reliant on electricity. A power blackout lasting longer than 72 hours could create longer-term implications for interdependent infrastructures.

Among other sector disruptions, a long-term power outage could disrupt transportation, communication, banking and finance systems, and government services; cause the breakdown of the distribution of potable water owing to pump failure; and cause the loss of perishable foods and medication because of lack of refrigeration.[12] The emergency services sector also would be affected by the prolonged loss of power, through the potential loss of their communications, water supply or even non-working traffic signals, preventing emergency vehicles from quickly responding to an emergency. The water sector requires energy for supply, purification, distribution and treatment of water and wastewater.[13] Leading experts on geomagnetic storms state that potential effects from major geomagnetic storms on the U.S. power grid could persist for multiple years and in turn, "could pose the risk of the largest natural disaster that could affect the United States."[14]

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[7] Kappenman, John G. et al., "Advanced Geomagnetic Storm Forecasting: A Risk Management Tool for Electric Power System Operations," *IEEE Transactions on Plasma Science*, 28:6, 2000.

[8] Kappenman, John G. and Albertson, Vernon D., "Bracing for the Geomagnetic Storms: As Solar Activity Moves Toward an 11-Year Peak, Utility Engineers Are Girding for the Effects of Massive Magnetic Disturbances," *IEEE Spectrum*, 1990.

[9] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report*, 2008.

[10] Barnes, P.R. and Van Dyke, J.W., "Economic Consequences of Geomagnetic Storms (a Summary)," *IEEE Power Engineering Review*, 1990.

[11] US-Canada Power System Outage Task Force, *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*, 2004.

[12] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report*, 2008.

[13] US Department of Energy, "Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water," 2006.

[14] US House of Representatives, Homeland Security Committee, Subcommittee on Emerging Threats, Cybersecurity, and Science and Technology, *Statement Prepared by Dr. William Radasky and Mr. John Kappenman*, 111th Cong., 2nd sess., July 21, 2009.

Historical Examples

To illustrate the vulnerability of various types of infrastructure to geomagnetic storms, it is worth presenting three historical examples: the October-November 2003 "Halloween" event; the Quebec Power Outage of 1989; and the Carrington Event of 1859.

From late October to early November 2003, large geomagnetic storms, which peaked at a severity of -410nanoTeslas,[15] affected the power system infrastructure, the aviation industry, and satellite communications in Europe and North America. In Sweden, a large power utility experienced transformer problems, which led to a system failure and a subsequent power outage.[16] During the 2003 Halloween event, the international airline industry experienced communication problems on a daily basis, with significantly degraded communications at high-latitudes. The Federal Aviation Administration (FAA) could not provide GPS navigational guidance for approximately 30 hours.[17]

On March 13, 1989, a geomagnetic storm that registered -640 nanoTeslas affected Canadian and U.S. power systems, resulting in a major power outage for nine hours for the majority of the Quebec region and for parts of the northeastern United States.[18] Geomagnetically induced currents flowing through the power system severely damaged seven static compensators in the Hydro-Quebec grid, causing them to trip or shut down automatically before preventive measures were possible.[19] The unavailability of new equipment to replace damaged equipment prevented power restoration to the transmission network. After nine hours, 83 percent of full power was restored, but one million customers were still without electrical power.[20]

The most severe space weather event recorded in history is the Carrington Event of 1859, measured at -850 nanoTeslas.[21] From August 28 to September 4, 1859, auroral displays, often called the northern or southern lights, spanned several continents and were observed around the world. According to modern experts, the auroras witnessed were actually two intense geomagnetic storms. Across the world, telegraph networks experienced disruptions and outages as a result of the currents generated by the geomagnetic storms.[22] The economic costs associated with a catastrophic geomagnetic storm similar to that of the Carrington Event could measure in the range of several trillion dollars.[23]

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[15] A severe geomagnetic storm is defined as any event with a disturbance storm time of less than -500 nanoTeslas. No recorded geomagnetic storm since 1932 has exceeded -760 nT; Cliver, E.W. and L. Svalgaard, "The 1859 Solar-Terrestrial Disturbance and the Current Limits of Extreme Space Weather Activity," *Solar Physics* 224:407-422, 2005.

[16] National Oceanic and Atmospheric Administration, *Intense Space Weather Storms October 19–November 7, 2003*, Government Printing Office, Washington, D.C., 2004.

[17] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report*, 2008.

[18] Molinski, Tom S., et al., "Shielding Grids from Solar Storms," *IEEE Spectrum*, November 2000.

[19] North American Electric Reliability Corporation, *March 13, 1989 Geomagnetic Disturbance*, NERC, Princeton, NJ, 1990.

[20] Ibid.

[21] Earlier surveys estimated that the Carrington Event registered at -1760 nanoTeslas, but more recent studies have determined the severity of the storm was -850 nanoTeslas.

[22] Green, James L., et al., "Eyewitness Reports of the Great Auroral Storm of 1859," *Advances in Space Research* 38: 145–154, 2006.

[23] US House of Representatives, Homeland Security Committee, Subcommittee on Emerging Threats, Cybersecurity, and Science and Technology, Statement Prepared by Dr. William Radasky and Mr. John Kappenman, 111th Cong., 2nd sess., 21 July 2009.

III. GEOMAGNETIC STORM RISK ASSESSMENT: STATE OF THE ART

Awareness of geomagnetic storms and their potential effects has grown in the past two decades, but a comprehensive understanding of the risks has proved elusive. A literature review of geomagnetic storm risk assessments indicates that the state of the art for assessing the security risk from this type of event is still embryonic. There are examples of analyses that describe threat, vulnerability, and consequence, but they are not integrated, primarily because of the weakness in the threat analysis. The lack of valid risk assessments has limited risk mitigation efforts in many critical infrastructure sectors, as it is difficult to demonstrate the utility of investing in either hardening or operational mitigation efforts, especially if these investments reduce time and money spent in preparing for more common risks.

Consequence Assessment

The existing literature primarily refers to economic consequences when discussing geomagnetic storms. One of the simplest ways to assess consequence is to aggregate insured losses. The insurance industry tends to evaluate natural hazards from this perspective, including estimates of past incidents that involved the loss of an insured asset, such as communication satellites.[24] A similar approach typifies the first step of economic cost estimates of effects on the energy sector. These begin by assigning monetary values to assets that require replacement due to a geomagnetic storm and the "replacement energy cost" to a region given that it cannot produce electric power for a short period and must purchase it from other providers.

An alternate method to assessing the consequences of a geomagnetic storm is to avoid cost estimation and focus on the effect within a sector of infrastructure. There are three clear examples of approaches to take. The first approach details all the potential effects on the types of components within an electric system, including production, transmission, and distribution.[25] A second approach goes a step further to describe the anticipated effects of a geomagnetic storm on the components of a system. Such an analysis could provide information on the reactive reserve power requirements for a power system, but not forecast whether the system can or cannot sustain such an event and maintain service.[26] The third approach is to forecast whether an electric grid can sustain continuity of service.[27]

Vulnerability Assessment

The March 1989 geomagnetic storm led to new interest in the vulnerability of the electric power infrastructure to space weather in general and geomagnetically induced currents more specifically. A 1991 study prepared by Oak Ridge National Laboratory noted that storm severity by itself was a poor indicator of whether a geomagnetic storm would have an effect on electric utility systems. Ground conductivity played an important role, as did the direction of extra-high-voltage lines because magnetic

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[24] Jansen, Frank, et al. "Space Weather: Hazard to the Earth?," *Swiss Reinsurance Company,* 2000.

[25] For example, a 1991 study prepared by Oak Ridge National Laboratory used this approach to document past problems encountered in various types of equipment; Barnes, P.R. et al, *Electric Utility Industry Experience with Geomagnetic Disturbances,* Oak Ridge National Laboratory. 1991.

[26] For a 2002 assessment of the electric power transmission system of the United Kingdom, the consequences for multiple scenarios that varied by storm severity were expressed as estimates for reactive power losses; Erinmez, Arslan I., et al , "Management of the geomagnetically Induced Current Risks on the National Grid Company's Electric Power Transmission System," *Journal of Atmospheric and Solar-Terrestrial Physics 64* (2002).

[27] The North American Electricity Reliability Corporation stated that a severe storm "could entail the potential for widespread damage to extra-high-voltage transformers," which could lead to "prolonged restoration and long-term chronic shortages of electricity supply capability; North American Electric Reliability Corporation, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System*, NERC, Princeton, New Jersey, U.S.A., 2010. Also see Kappenman, J.G. "Geomagnetic Disturbances and Impacts Upon Power System Operations," in *The Electric Power Engineering Handbook*, 2nd Edition, ed. Leonard L. Grigsby, Boca Raton, Florida, CRC Press/IEEE Press, 2007 and.

field fluctuations generally flow in an east–west direction.[28] Similarly, researchers concluded that longer extra-high-voltage lines are exposed to larger geomagnetically induced currents, and that equipment in more northern latitudes was most likely to be affected. Vulnerability factors differ for other industries, but latitude is a common consideration. The aviation industry is concerned primarily with risks during high-latitude (above 50 degrees) and polar operations (above 78 degrees). For satellite systems, the equatorial region has the highest potential for ionospheric irregularities.[29] For satellite communications, latitude is an important factor in total electron count density (along with altitude and time of day), which in turn is a major component of vulnerability to interference and delays of signals.[30]

Threat Assessment

The previously mentioned Oak Ridge National Laboratory study acknowledges the lack of insight into threat information for geomagnetic storms.[31] Without a quantitative or qualitative approach to comparing the potential threat of geomagnetic storms to other phenomena, it is exceedingly difficult for any organization or nation to assess the risks to meaningfully inform strategic policy and planning decisions. The Oak Ridge National Laboratory study describes the 11-year cycle of geomagnetic disturbances that gives some insight into when to expect peak solar activity, but cautions that "no accurate method is presently available to predict either the onset or the magnitude of a geomagnetic disturbance." Tom Molinski and colleagues [see Figure 1] attempted to put a frequency on severe geomagnetic events based on latitude.[32] But Molinski's definition of "severe," is below the level of the March 1989 Quebec geomagnetic storm, so his paper may provide little insight into the probability of more extreme and consequential storms. Another study modeled data from 1958 to 2007 to develop estimated frequencies for geomagnetic storms of different magnitudes [see Table 1]. This study notes, however, that "[w]ithout the compilation of disturbance storm time (Dst) statistics from a longer time span, it is difficult to say" whether these estimates are reasonable.[33]

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[28] Barnes, P.R. et al, *Electric Utility Industry Experience with Geomagnetic Disturbances*, Oak Ridge National Laboratory. 1991.

[29] American Meteorological Society Policy Program and SolarMetrics, *Integrating Space Weather Observations & Forecasts into Aviation Operations*, American Meteorological Society & SolarMetrics Policy Workshop Report, Washington, D.C, 2007.

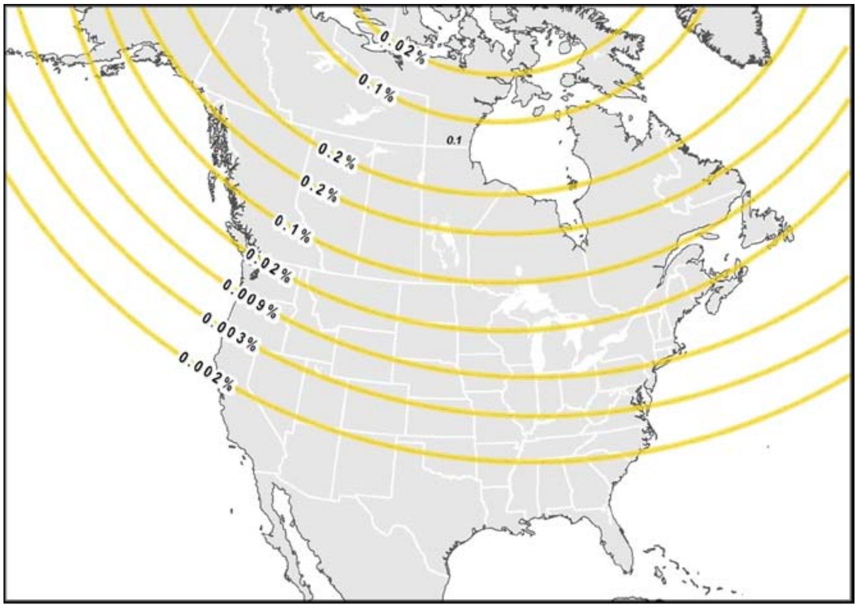
[30] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report*, 2008.

[31] Barnes, P.R. et al, *Electric Utility Industry Experience with Geomagnetic Disturbances*, Oak Ridge National Laboratory, 1991.

[32] Molinski, Tom S., et al., "Shielding Grids from Solar Storms," *IEEE Spectrum*, November 2000.

[33] Love, J.J. and J.L. Gannon, "Revised Dst and the Epicycles of Magnetic Disturbance: 1958-2007," *Annales Geophysicae 27* (2009).

Figure 1. Probability of a North American Event >300nanoTesla/min



Source: Molinski, Tom S., et al., "Shielding Grids from Solar Storms," IEEE Spectrum, November 2000

Table 1. Estimated Frequencies for Geomagnetic Storms of Different Magnitudes

Strength of the Storm (nanoTesla)	Frequency
> 100	4.6 per year
> 200	9.4 per 10 years
> 400	9.73 per 100 years
> 800	2.86 per 1,000 years
> 1,600	7.41 per 1,000,000

Source: Love, J.J. and J.L. Gannon, "Revised Dst and the Epicycles of Magnetic Disturbance: 1958-2007," Annales Geophysicae 27 (2009).

Risk Assessment

This literature review finds that the lack of a valid threat assessment precludes a comprehensive risk assessment. There are, however, some valuable analytic reports that allow decision makers to examine the issue of geomagnetic storm risk. One of the first was the aforementioned Oak Ridge National Laboratory study that documented past problems encountered in various types of equipment.[34] The general conclusions are that the vulnerability of U.S. electric grid connections likely will rise due to the trends in industry and increasing use of extra-high-voltage equipment that is essential in modern electric power transmission.

Molinski and colleagues examined the risk to U.S. and Canadian electrical grid connections and provided valuable contributions to the field.[35] By displaying probability and vulnerability geographically, the analysis provided one way for urban areas to consider the likelihood of an event. The study also

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[34] Barnes, P.R. et al, *Electric Utility Industry Experience with Geomagnetic Disturbances*, Oak Ridge National Laboratory, 1991.

[35] Molinski, Tom S., et al., "Shielding Grids from Solar Storms," *IEEE Spectrum*, November 2000.

compares this likelihood to other natural hazards, such as wind and ice storms, which are much more common. Like the Oak Ridge report, it does not attempt to combine the risk factors, but it does discuss them sequentially, providing a general framework for discussing the issue.

Finally, the 2002 assessment of the U.K. grid by Arslan Erinmez followed a similar pattern but provided much more insight into operational risks.[36] This assessment built on the vulnerability components that the strategic assessments identified by determining regional ground conductivity and then mapping the electric transmission system to identify susceptible equipment. The result was a scenario-by-scenario estimate of the reactive power reserve requirements for various storm scenarios. Unfortunately, this lacked any differentiation by likelihood of the scenarios, but the results were useful in that they provided decision makers with the potential severities of the consequences given an occurrence and the assessed vulnerability of the system.

Risk Mitigation

The literature on mitigating risk of geomagnetic storm effects on electric power systems focuses on two basic methods of reducing either the vulnerability or the consequence. The first risk mitigation method is hardening; the second is bolstering operational procedures. The literature review demonstrated that hardening is most effective for critical transformers that play a major role in power transmission. For example, electric power utilities can harden their systems against geomagnetically induced currents through passive devices or circuit modifications that can reduce or prevent the flow of geomagnetically induced currents. However, hardening measures are very expensive, and power systems are difficult to replace.

Operational mitigations are actions taken to minimize potential exposure to geomagnetically induced currents, such as taking assets off-line, maintaining real-time situational awareness, and reacting aggressively to developments to avoid voltage collapse. The literature review found that operational mitigations tend to cost far less than hardening but rely on warnings, alerts, monitoring devices, and proper execution of plans and procedures. A key operational mitigation approach taken by the Federal government is space weather monitoring and prediction. As will be discussed in more detail later in the paper, the Federal government has invested significantly in means for providing warning and alerts about space weather, including geomagnetic storms. This is also an area where the United States cooperates extensively with international partners.

Summary of the State of the Art

As noted above, the literature indicates that the state of the art for assessing the security risk from geomagnetic storms is still in development. Some elements of these strategic assessments — specifically the use of probability to describe the threat of geomagnetic storms — hold promise, and the scenario-based assessment used by Arslan Erinmez and colleagues provides a solid foundation for addressing risks to the electric infrastructure, as well as cascading effects. The literature does not reveal similar efforts for other sectors of infrastructure, which tend to rely on ad hoc consequence assessments to provide insight into the potential risks from geomagnetic storms. The lack of valid risk assessments has limited risk mitigation efforts. Without a sense of the likelihood of such events or at least a mechanism for relative comparisons, cost-benefit analyses have been unable to demonstrate the utility of investing either in hardening or in testing and maintaining operational procedures, especially if these investments reduce investments in preparing for more common risk, such as ice storms. The lack of scenario-based analyses in sectors other than electric power has limited the ability to perform multi-sector analysis and obtain a more thorough understanding of the operational constraints that the Nation or region may encounter in

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[36] Erinmez, Arslan I., et al., "Management of the geomagnetically Induced Current Risks on the National Grid Company's Electric Power Transmission System," *Journal of Atmospheric and Solar-Terrestrial Physics,* 64, 2002.

response to a major geomagnetic storm, and therefore represents a severe impediment to response planning.

IV. Risk Lessons and Challenges from Geomagnetic Storms Evaluation

The literature review and analysis of geomagnetic storms encountered and revealed several challenges and lessons that are commonplace in homeland security risk analysis and management. Three are highlighted in the following section. First, measures taken by the electric power industry to reduce risk from terrestrial storms has increased risk from space weather — a classic example of a trade-off among risks. Second, relying on worst-case scenarios for assessments can be problematic if there is great uncertainty surrounding the frequency of the worst-case scenario. Finally, when available data on a subject is limited, assessments sometimes depend on a small number of analyses, which can result in circular reporting.

Trade-offs Among Risks

In many ways, the Nation's level of vulnerability to extreme geomagnetic storms is due to strategies and treatments employed to manage other, more frequent risks. Over the years, the electric power industry has built extra-high-voltage transformers to increase the reliability of electric power systems in cases of more commonly encountered natural hazards and events. As mentioned earlier, the use of long transmission lines has enabled the electric energy sector to transmit power to distant supply demand centers. However, long distance transmission lines are more susceptible to geomagnetically induced currents, which could result in the overloading of electrical power grids and subsequent damage to extra-high-voltage transformers. This increases the risk of disruption to electric power grids to this rarer natural hazard, which could cause comparably much more damage. Therefore, it can be argued that industry (consciously or unconsciously) transferred the risk from terrestrial storms to space weather. The question is whether the balance is appropriate. Any discussion with industry must take into account the different risks that it faces and the trade-offs among the risks.

Similarly, there are also trade-offs among risks associated with satellites and reliance on GPS. Federal agencies, along with international firms based in the construction, agriculture, and energy sectors, rely on space-based assets such as GPS to conduct surveying and drilling operations. The use of GPS has enabled international firms to reduce their labor costs, ensure time savings during a project, and to perform precise operations. For example, in the energy sector, oil and gas companies are dependent on GPS signals to aid drilling platforms. The reliance on GPS has allowed international firms to become more efficient and to reduce overall costs but has led to unintended consequences for several industries dependent on space-based assets. Geomagnetic storms can cause GPS satellites to either lose their signal or to become degraded. This short-term signal degradation causes GPS receivers to relay inaccurate positioning information that would disrupt surveying and drilling operations. International firms and U.S. government agencies would have to incur high costs to protect their GPS systems from geomagnetic storms. However, these entities are willing to accept the risk posed by low-frequency/high consequence geomagnetic storms, and can employ back-up alternatives to keep operations running at a limited capacity during a storm.

Utility of Worst-Case Scenarios

The geomagnetic storms literature review also revealed the limited utility of relying on a worst-case scenario for policy making or planning purposes. If the probability of a worst-case scenario is unknown, then depending on such a scenario to drive policy, resource allocation, and strategic planning decisions is generally problematic. Homeland security leaders might fall prey to probability bias if they focus solely on the consequences of a worst-case scenario without taking into account the likely frequency. The result could be unsound or ill-informed decision making. For example, one of the most prominent and prolific geomagnetic storm authors chose to base his risk assessments on the Carrington Event of 1859, which was the most severe space weather event recorded in history. The Carrington storm was approximately three times as intense as the most severe geomagnetic storm of the past three decades and a storm of equal magnitude would have extreme consequences on modern infrastructure. Because of the historical precedent, it is not outlandish to use the magnitude of the Carrington Event as the worst case. But great uncertainty exists about the frequency of such events. One of the major limitations of worst-case scenarios is that only the damage potential is considered, and not the probability of the scenario. In addition to the extraordinarily low probability of such a worst case, the extreme consequences also make any policy guidance difficult. As an example, the loss of power along the entire eastern seaboard of the United States for months exceeds any existing planning, and introduces significant uncertainties about how the government, industry, and the population might react.

Data Concerns

Security risk assessments sometimes face the challenge of limited data availability. When historical records and information on an event or scenario is sparse, risk assessments often depend on a small number of existing analyses or even a single underlying reference. This often results in a form of circular reporting, where multiple reports or assessments are based on a few sources or even a single source. Homeland security leaders must trust that this source provides accurate measures of probability, threat, consequence, and vulnerability. Three of the recent, high-profile analyses used in this Issue Brief's literature review all relied on a single source — John Kappenman — for estimates of consequence that tended to be more extreme than other perspectives.[37] As an example, Kappenman testified before Congress that a severe geomagnetic storm would have catastrophic effects with infrastructure and economic impacts that could persist for multiple years and cost several trillion dollars per year; yet it was unclear what kind of analysis and methodology led to those impact assessments.[38]

V. Federal Government and DHS Geomagnetic Storms Activity

The Federal government lacks comprehensive, national-level geomagnetic storm risk management assessments and strategies. Additionally, no standing entity exists to coordinate cross-Federal government geomagnetic storm risk analysis, despite the clear threat to critical infrastructure. However, the U.S. government has dedicated resources that help manage geomagnetic risk, specifically in assisting industry with support to operational mitigations by providing space weather warnings systems.

Considering the dependence of operational risk mitigation strategies on geomagnetic storm threat notification, it should not be surprising that there is significant Federal government focus on space weather monitoring and prediction. The NOAA National Weather Service's Space Weather Prediction Center (SWPC) maintains partnerships with twelve institutions that contribute space-based and ground-based data related to space weather. This provides the foundation for SWPC forecasts, warnings, and alerts for its civilian government and commercial users. The U.S. Air Force's Weather Agency (AFWA) performs similar services for military customers. The Federal government provides much of the actual assets and manpower for the International Space Environment Service. For example, the NASA Advanced Composition Explorer satellite provides real-time solar wind data that, when combined with

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[37] National Academy of Sciences, *Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report***,** National Academies Press, Washington, D.C., 2008; National Aeronautics and Space Administration, "Severe Space Weather--Social and Economic Impacts," *NASA Science News, 2009;* North American Electric Reliability Corporation, *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System*, NERC, Princeton, New Jersey, U.S.A., 2010.

[38] U.S. House of Representatives, Homeland Security Committee, Subcommittee on Emerging Threats, Cybersecurity, and Science and Technology, *Statement Prepared by Dr. William Radasky and Mr. John Kappenman*, 111th Cong., 2nd sess., 21 July 2009.

other information, can yield real-time geomagnetically induced currents forecasts.[39] Additionally, NASA's Solar Terrestrial Relations Observatory plays a critical role, along with National Oceanic and Atmospheric Administration (NOAA)'s Geostationary Operational Environmental Satellite and Polar Operational Environmental Satellite satellites. Furthermore, NOAA cooperates with the United States Air Force to provide space weather information.

While geomagnetic storm risk activities primarily take the form of space weather monitoring and prediction services, rather than full-scope risk analysis or management, the Department of Homeland Security is involved in several geomagnetic storm initiatives: The Federal Emergency Management Agency partnered with various European groups and NOAA to hold a geomagnetic storm workshop in February 2010. The National Communications System has commissioned studies on geomagnetic storm preparedness. DHS offices are also involved in activities that deal with potential consequences of geomagnetic storms, even if they are not specifically focused on the geomagnetic risks themselves. For example, the Office of Policy has completed a risk assessment on the loss of the GPS timing signal to critical infrastructure, the results of which indicated the GPS timing signal was "essential" to 11 critical infrastructure sectors. The Science & Technology Directorate is a member of the GIC Interagency Working Group, formed in May 2010 and driven by the White House Office of Science and Technology Policy and the National Security Staff.

Finally, DHS' Homeland Infrastructure Threat and Risk Analysis Center is developing a National Risk Estimate (NRE) for civil uses of GPS to inform executive-level decisions. This NRE, which responds to a request from the National Executive Committee for Space-based Positioning, Navigation and Timing (PNT), will provide a baseline estimate of risks to U.S. critical infrastructure sectors that use GPS-derived PNT and assess how those risks are estimated to evolve over the next two decades. In particular, the assessment will focus on GPS disruptions stemming from intentional disruptions, unintentional disruptions, and naturally occurring events such as geomagnetic storms. The assessment will highlight impacts on critical infrastructure in five sectors: banking and finance, communications, emergency services, energy, and transportation systems. While geomagnetic storms will be only one of many disruption sources analyzed, the effort should produce valuable and credible insight into the potential consequences of geomagnetic storms for critical infrastructure relying on GPS.

VI. Considerations

One of the difficulties in risk analysis is identifying the relative risks across a spectrum of unwanted events. With so little known about the frequency of geomagnetic storms and the uncertainties of first- and second-order consequences, it is exceedingly difficult to compare this to other major natural hazards and man-made effects. Regardless, in terms of expected loss, it is possible to say that extreme geomagnetic storms are not high-risk natural hazards to the Nation, given that these are very low-frequency events. The combination of the existing space weather alert system with operational mitigation strategies in the electricity, aviation, and satellites industries means most geomagnetic storms will not result in long-term damage to critical infrastructures or disruption of related services for more than a few hours. Yet the potential consequences of an extreme or severe geomagnetic storm warrant additional attention. Relying on measures developed to mitigate other risks in the absence of full geomagnetic storm risk management is not necessarily a sound strategy.

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[39] Lundstedt, H. (2006), "The Sun, Space Weather and GIC Effects in Sweden," *Advances in Space Research* 37:6.

The potential for cascading effects on critical infrastructure stemming from an extreme geomagnetic storm means the Federal government should consider whether it is appropriate to conduct a formal, comprehensive risk assessment regarding severe geomagnetic storms. Such an effort could be spearheaded by the National Academy of Sciences or could be driven by an interagency effort, led perhaps by DHS' Science & Technology Directorate. DHS and other sector-specific agencies could contribute by bringing together critical infrastructure operators, government continuity of operations managers, national and local authorities, and member of the public to discuss potential cascading effects from the widespread loss of electric power and space-based assets. Just as important, discussions would focus on how critical decisions would be made in the event of a severe geomagnetic storm, when they would need to be made, and what information would be vital for making the identified decisions.

An assessment could be done through a combination of methods. To start, analysts could examine studies and after-action reports of past events, including non-geomagnetic storm electricity outages. Next, conducting a series of discussion-based exercises would provide insight into how key players would react during a severe geomagnetic storm, as well as identify challenges and information gaps. The outcomes of these studies and discussion-based exercises could be used to design a basic fault tree model for the progression from a geomagnetic storm event through its consequences, with assumptions about the time available for, and likely effectiveness of, different interventions made explicit. The exercise participants could be brought back to discuss the progression of a geomagnetic storm in this model, and discuss adjustments that might realistically achieve better outcomes. While the results of the exercises and modeling discussions would not produce greater certainty about the likelihood of a severe geomagnetic storm, they would feed into a formal risk assessment that would provide insight into the consequences of severe geomagnetic storms and the preparedness level of the Federal government and private sector partners. Such an analysis would also be beneficial to agencies studying other hazards that could interrupt electricity supplies and space-based assets.