Free Executive Summary

Severe Space Weather Events--Understanding Societal and Economic Impacts Workshop Report

Committee on the Societal and Economic Impacts of Severe Space Weather Events:A Workshop, National Research Council

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*The adverse effects of extreme space weather on modern technology--power grid outages, high-frequency communication blackouts, spacecraft anomalies--are well known and well documented, and the physical processes underlying space weather are also generally well understood. Less well documented and understood, however, are the potential economic and societal impacts of the disruption of critical technological systems by severe space weather. As a first step toward determining the socioeconomic impacts of extreme space weather events and addressing the questions of space weather risk assessment and management, a public workshop was held in May 2008. The workshop brought together representatives of industry, the government, and academia to consider both direct and collateral effects of severe space weather events, the current state of the space weather services infrastructure in the United States, the needs of users of space weather data and services, and the ramifications of future technological developments for contemporary society's vulnerability to space weather. The workshop concluded with a discussion of un- or underexplored topics that would yield the greatest benefits in space weather risk management. *

Summary

SOCIETAL CONTEXT

Modern society depends heavily on a variety of technologies that are susceptible to the extremes of space weather—severe disturbances of the upper atmosphere and of the near-Earth space environment that are driven by the magnetic activity of the Sun. Strong auroral currents can disrupt and damage modern electric power grids and may contribute to the corrosion of oil and gas pipelines. Magnetic storm-driven ionospheric density disturbances interfere with high-frequency (HF) radio communications and navigation signals from Global Positioning System (GPS) satellites, while polar cap absorption (PCA) events can degrade—and, during severe events, completely black out—HF communications along transpolar aviation routes, requiring aircraft flying these routes to be diverted to lower latitudes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers.

The effects of space weather on modern technological systems are well documented in both the technical literature and popular accounts. Most often cited perhaps is the collapse within 90 seconds of northeastern Canada's Hydro-Quebec power grid during the great geomagnetic storm of March 1989, which left millions of people without electricity for up to 9 hours. This event exemplifies the dramatic impact that extreme space weather can have on a technology upon which modern society in all of its manifold and interconnected activities and functions critically depends.

Nearly two decades have passed since the March 1989 event. During that time, awareness of the risks of extreme space weather has increased among the affected industries, mitigation strategies have been developed, new sources of data have become available (e.g., the upstream solar wind measurements from the Advanced Composition Explorer), new models of the space environment have been created, and a national space weather infrastructure has evolved to provide data, alerts, and forecasts to an increasing number of users.

Now, 20 years later and approaching a new interval of increased solar activity, how well equipped are we to manage the effects of space weather? Have recent technological developments made our critical technologies more or less vulnerable? How well do we understand the broader societal and economic impacts of extreme space weather events? Are our institutions prepared to cope with the effects of a "space weather Katrina," a rare, but according to the historical record, not inconceivable eventuality? On May 22 and 23, 2008, a workshop held in Washington, D.C., under the auspices of the National Research Council brought together representatives of industry, the federal government, and the social science community to explore these and related questions. This report was prepared by members of the ad hoc committee that organized the workshop, and it summarizes the key themes, ideas, and insights that emerged during the 1½ days of presentations and discussions.

THE IMPACT OF SPACE WEATHER

Modern technological society is characterized by a complex interweave of dependencies and interdependencies among its critical infrastructures. A complete picture of the socioeconomic impact of severe space weather must include both direct, industry-specific effects (such as power outages and spacecraft anomalies) and the collateral effects of space-weather-driven technology failures on dependent infrastructures and services.

Industry-specific Space Weather Impacts

The main industries whose operations can be adversely affected by extreme space weather are the electric power, spacecraft, aviation, and GPS-based positioning industries. The March 1989 blackout in Quebec and the forced outages of electric power equipment in the northeastern United States remain the classic example of the impact of a severe space weather event on the electric power industry. Several examples of the impact of space weather on the other industries are cited in the report:

- The outage in January 1994 of two Canadian telecommunications satellites during a period of enhanced energetic electron fluxes at geosynchronous orbit, disrupting communications services nationwide. The first satellite recovered in a few hours; recovery of the second satellite took 6 months and cost $50 million to $70 million.
- The diversion of 26 United Airlines flights to non-polar or less-than-optimum polar routes during several days of disturbed space weather in January 2005. The flights were diverted to avoid the risk of HF radio blackouts during PCA events. The increased flight time and extra landings and takeoffs required by such route changes increase fuel consumption and raise cost, while the delays disrupt connections to other flights.
- Disabling of the Federal Aviation Administration's recently implemented GPS-based Wide Area Augmentation System (WAAS) for 30 hours during the severe space weather events of October-November 2003.

With increasing awareness and understanding of space weather effects on their technologies, industries have responded to the threat of extreme space weather through improved operational procedures and technologies. As just noted, airlines re-route flights scheduled for polar routes during intense solar energetic particle events in order to preserve reliable communications. Alerted to an impending geomagnetic storm by NOAA's Space Weather Prediction Center (SWPC) and monitoring ground currents in real-time, power grid operators take defensive measures to protect the grid against geomagnetically induced currents (GICs). Similarly, under adverse space weather conditions, launch personnel may delay a launch, and satellite operators may postpone certain operations (e.g., thruster firings). For the spacecraft industry, however, the primary approach to mitigating the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints. GPS modernization through the addition of two new navigation signals and new codes is expected to help mitigate space weather effects (e.g., ranging errors, fading caused by ionospheric scintillation), although to what degree is not known. These technologies will come on line incrementally over the next 15 years as new GPS satellites become operational. In the meantime, the Federal Aviation Administration will maintain "legacy" non-GPS-based navigation systems as a backup, while other GPS users (e.g., offshore drilling companies) can postpone operations for which precision position knowledge is required until the ionospheric disturbance is over.

The Collateral Impacts of Space Weather

Because of the interconnectedness of critical infrastructures in modern society, the impacts of severe space weather events can go beyond disruption of existing technical systems and lead to short-term as well as to long-term collateral socioeconomic disruptions. Electric power is modern society's cornerstone technology, the technology on which virtually all other infrastructures and services depend. Although the probability of a wide-area electric power blackout resulting from an extreme space weather event is low, the consequences of such an event could be very high, as its effects would cascade through other, dependent systems. Collateral effects of a longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration. The resulting loss of services for a significant period of time in even one region of the country could affect the entire nation and have international impacts as well.

Extreme space weather events are low-frequency/high-consequence (LF/HC) events and as such present—in terms of their potential broader, collateral impacts—a unique set of problems for public (and private) institutions and governance, different from the problems raised by conventional, expected, and frequently experienced events. As a consequence, dealing with the collateral impacts of LF/HC events requires different types of budgeting and management capabilities and consequently challenges the basis for conventional policies and risk management strategies, which assume a universe of constant or reliable conditions. Moreover, because systems can quickly become dependent on new technologies in ways that are unknown and unexpected to both developers and users, vulnerabilities in one part of the broader system have a tendency to spread to other parts of the system. Thus, it is difficult to understand, much less to predict, the consequences of future LF/HC events. Sustaining preparedness and planning for such events in future years is equally difficult.

Future Vulnerabilities

Our knowledge and understanding of the vulnerabilities of modern technological infrastructure to severe space weather and the measures developed to mitigate those vulnerabilities are based largely on experience and knowledge gained during the past 20 or 30 years, during such episodes of severe space weather as the geomagnetic superstorms of March 1989 and October-November 2003. As severe as some of these recent events have been, the historical record reveals that space weather of even greater severity has occurred in the past—e.g., the Carrington event of 1859[1] and the great geomagnetic storm of May 1921—and suggests that such extreme events, though rare, are likely to occur again some time in the future. While the socioeconomic impacts of a future Carrington event are difficult to predict, it is not unreasonable to assume that an event of such magnitude would lead to much deeper and more widespread socioeconomic disruptions than occurred in 1859, when modern electricity-based technology was still in its infancy.

A more quantitative estimate of the potential impact of an unusually large space weather event has been obtained by examining the effects of a storm of the magnitude of the May 1921 superstorm on today's electric power infrastructure. Despite the lessons learned since 1989 and their successful application during the October-November 2003 storms, the nation's electric power grids remain vulnerable to disruption and damage by severe space weather and have become even more so, in terms of both widespread blackouts and permanent equipment damage requiring long restoration times. According to a study by the Metatech Corporation, the occurrence today of an event like the 1921 storm would result in large-scale blackouts affecting more than 130 million people and would expose more than 350 transformers to the risk of permanent damage.

SPACE WEATHER INFRASTRUCTURE

Space weather services in the United States are provided primarily by NOAA's SWPC and the U.S. Air Force's (USAF's) Weather Agency (AFWA), which work closely together to address the needs of their civilian and military user communities, respectively. The SWPC draws on a variety of data sources, both space- and ground-based, to provide forecasts, watches, warnings, alerts, and summaries as well as operational space weather products to civilian and commercial users. Its primary sources of information about solar activity, upstream solar wind conditions, and the geospace environment are NASA's Advanced Composition Explorer (ACE), NOAA's GOES and POES satellites, magnetometers, and the USAF's solar observing networks. Secondary sources include SOHO and

STEREO as well as a number of ground-based facilities. Despite a small and unstable budget (roughly $6 million to $7 million U.S. dollars annually) that limits capabilities, the SWPC has experienced a steady growth in customer base, even during the solar minimum years, when disturbance activity is lower. The focus of the USAF's space weather effort is on providing situational knowledge of the real-time space weather environment and assessments of the impacts of space weather on different Department of Defense missions. The Air Force uses NOAA data combined with data from its own assets such as the Defense Meteorological Satellites Program satellites, the Communications/Navigation Outage Forecasting System, the Solar Electro-Optical Network, the Digital Ionospheric Sounding System, and the GPS network.

NASA is the third major element in the nation's space weather infrastructure. Although NASA's role is scientific rather than operational, NASA science missions such as ACE provide critical space weather information, and NASA's Living with a Star program targets research and technologies that are relevant to operations. NASA-developed products that are candidates for eventual transfer from research to operations include sensor technology and physics-based space weather models that can be transitioned into operational tools for forecasting and situational awareness.

Other key elements of the nation's space weather infrastructure are the solar and space physics research community and the emerging commercial space weather businesses. Of particular importance are the efforts of these sectors in the area of model development.

Space Weather Forecasting: Capabilities and Limitations

One of the important functions of a nation's space weather infrastructure is to provide reliable long-term forecasts, although the importance of forecasts varies according to industry.[2] With long-term (1- to 3-day) forecasts and minimal false alarms,[3] the various user communities can take actions to mitigate the effects of impending solar disturbances and to minimize their economic impact. Currently, NOAA's SWPC can make probability forecasts of space weather events with varying degrees of success. For example, the SWPC can, with moderate confidence, predict the occurrence probability of a geomagnetic storm or an X-class flare 1 to 3 days in advance, whereas its capability to provide even short-term (less than 1 day) or long-term forecasts of ionospheric disturbances—information important for GPS users—is poor. The SWPC has identified a number of critical steps needed to improve its forecasting capability, enabling it, for example, to provide high-confidence long- and short-term forecasts of geomagnetic storms and ionospheric disturbances. These steps include securing an operational solar wind monitor at L1; transitioning research models (e.g., of coronal mass ejection propagation, the geospace radiation environment, and the coupled magnetosphere/ionosphere/atmosphere system) into operations, and developing precision GPS forecast and correction tools. The requirement for a solar wind monitor at L1 is particularly important because ACE, the SWPC's sole source of real-time upstream solar wind and interplanetary magnetic field data, is well beyond its planned operational life, and provisions to replace it have not been made.

UNDERSTANDING THE SOCIETAL AND ECONOMIC IMPACTS OF SEVERE SPACE WEATHER

The title of the workshop on which this report is based, "The Societal and Economic Impacts of Severe Space Weather," perhaps promised more than this subsequent report can fully deliver. What emerged from the presentations and discussions at the workshop is that the invited experts understand well the effects of at least moderately severe space weather on specific technologies, and in many cases know what is required to mitigate them, whether enhanced forecasting and monitoring capabilities, new technologies (new GPS signals and codes, new-generation radiation-hardened electronics), or improved operational procedures. Limited information was also provided—and captured in this report—on the costs of space weather-induced outages (e.g., $50 million to $70 million to restore the $290 million Anik E2 to operational status) as well as of non-space-weather-related events that can serve as proxies for disruptions caused by severe space storms (e.g., $4 billion to $10 billion for the power blackout of August 2003), and an estimate of $1 trillion to $2 trillion during the first year alone was given for the societal and economic costs of a "severe geomagnetic storm scenario" with recovery times of 4 to 10 years.

Such cost information is interesting and useful—but as the outcome of the workshop and this report make clear, it is at best only a starting point for the challenge of answering the question implicit in the title: What are the societal and economic impacts of severe space weather? To answer this question quantitatively, multiple variables must be taken into account, including the magnitude, duration, and timing of the event; the nature, severity, and extent of the collateral effects cascading through a society characterized by strong dependencies and interdependencies; the robustness and resilience of the affected infrastructures; the risk management strategies and policies that the public and private sectors have in place; and the capability of the responsible federal, state, and local government agencies to respond to the effects of an extreme space weather event. While this workshop, along with its report, has gathered in one place much of what is currently known or suspected about societal and economic impacts, it has perhaps been most successful in illuminating the scope of the myriad issues involved, and the gaps in knowledge that remain to be explored in greater depth than can be accomplished in a workshop. A quantitative and comprehensive assessment of the societal and economic impacts of severe space weather will be a truly daunting task, and will involve questions that go well beyond the scope of the present report.

NOTES

1. The Carrington event is by several measures the most severe space weather event on record. It produced several days of spectacular auroral displays, even at unusually low latitudes, and significantly disrupted telegraph services around the world. It is named after the British astronomer Richard Carrington, who observed the intense white-light flare associated with the subsequent geomagnetic storm.
2. For the spacecraft industry, for example, space weather predictions are less important than knowledge of climatology and especially of the extremes within a climate record.
3. False alarms are disruptive and expensive. Accurate forecasts of a severe magnetic storm would allow power companies to mitigate risk by canceling planned maintenance work, providing additional personnel to deal with adverse effects, and reducing the amount of power transfers between adjacent systems in the grid. However, as was pointed out during the workshop, if the warning proved to be a false alarm and planned maintenance was canceled, the cost of large cranes, huge equipment, and a great deal of material and manpower sitting idle would be very high.

SEVERE SPACE WEATHER EVENTS—

UNDERSTANDING SOCIETAL AND ECONOMIC IMPACTS

A WORKSHOP REPORT

Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop

Space Studies Board

Division on Engineering and Physical Sciences

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Cover: (Upper left) A looping eruptive prominence blasted out from a powerful active region on July 29, 2005, and within an hour had broken away from the Sun. Active regions are areas of strong magnetic forces. Image courtesy of SOHO, a project of international cooperation between the European Space Agency and NASA.

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Preface

On October 30, 2003, the House Committee on Science, Subcommittee on Environment, Technology, and Standards held a hearing on space weather and on the roles and responsibilities of the various agencies involved in the collection, dissemination, and use of space weather data. Testimony was given by representatives from NOAA, NASA, and the USAF as well as by representatives from different industries. Questions included, What is the proper level of funding for agencies involved in space environmental predictions? and, What is the importance of such predictions to industry and commerce?

Coincidentally, and rather remarkably, at that very time the Sun exhibited some of its strongest eruptive activity in the last three decades. Enormous outbursts of energy from the Sun during late October and early November 2003 produced intense solar energetic particle events and triggered severe geomagnetic storms, the wide ranging effects of which were described as follows:

> The Sydkraft utility group in Sweden reported that strong geomagnetically induced currents (GIC) over Northern Europe caused transformer problems and even a system failure and subsequent blackout. Radiation storm levels were high enough to prompt NASA officials to issue a flight directive to the ISS astronauts to take precautionary shelter. Airlines took unprecedented actions in their high latitude routes to avoid the high radiation levels and communication blackout areas. Rerouted flights cost airlines $10,000 to $100,000 per flight. Numerous anomalies were reported by deep space missions and by satellites at all orbits. GSFC Space Science Mission Operations Team indicated that approximately 59% of the Earth and Space science missions were impacted. The storms are suspected to have caused the loss of the $640 million ADEOS-2 spacecraft. On board the ADEOS-2 was the $150 million NASA SeaWinds instrument. Due to the variety and intensity of this solar activity outbreak, most industries vulnerable to space weather experienced some degree of impact to their operations.[1]

These events reminded scientists and policy makers alike how significantly the space environment can affect human society and its various space- and ground-based technologies.

Motivated by the October-November 2003 events (popularly known as the Halloween storms of 2003), the Committee on Solar and Space Physics (CSSP) of the National Research Council (NRC) began to consider the need to assess systematically the societal and economic impacts of what is now known widely as "space weather."

[1]NOAA, *Intense Space Weather Storms October 19-November 07, 2003*, NOAA National Weather Service, Silver Spring, Md., April 2004, p. 1.

The nation's vulnerability to space weather effects is an issue of increasing concern.[2] For example, long-line power networks connecting widely separated geographic areas may absorb damaging electrical currents induced by geomagnetic storms. Similarly, the miniaturization of electronic components used in spacecraft systems makes them potentially more susceptible to damage by energetic particles produced during space weather disturbances. The United States also has a continuous human presence in space on the International Space Station, and the president and NASA have put into place a program to expand the activities of the United States as a space-faring nation with a future permanent settlement on the Moon and eventually a mission to Mars. However, despite all of these potential vulnerabilities to the effects of space weather, relatively few detailed studies of the socioeconomic impacts of severe space weather events have been carried out.

In 2007 the Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop, operating under the auspices of the Space Studies Board (SSB) of the National Academies, was charged to convene a public workshop that would feature invited presentations and discussion to assess the nation's current and future ability to manage the effects of space weather events and their societal and economic impacts. Although cost-benefit analyses of terrestrial weather observing systems and mitigation strategies have a long history, similar studies for space weather are lacking. Workshop sessions were intended to look at the effects of historical space weather events; in particular, an examination of the record solar storms of October-November 2003 was intended to focus the presentations and provide data to project future vulnerabilities. The inclusion of historic events and intervals was important in order to capture the breadth of space weather impacts (which can be different from event to event). A goal was also to understand impacts that occur during nonstorm times. The workshop was also to include sessions on how space weather impacts might change with time as technologies evolve and new technologies appear.

To meet the goals established within the NRC guidelines, the committee invited a wide range of attendees for a 1½-day public workshop in Washington, D.C., on May 22-23, 2008. Participants were drawn from a broad cross section of those interested in or directly affected by severe space weather events, including government agencies and industry as well as private vendors of space weather services. The workshop provided an initial forum for gathering information on specific space weather effects and on the status and unmet challenges of forecasting. Copies of the presentations made at the workshop can be viewed online at http://www7.nationalacademies.org/ssb/spaceweather08_presentations.html.

Because of the original multiagency flavor of the planning for the workshop, there were elements of the study statement of task (given in Appendix A) that raised questions about how certain ground-based (National Science Foundation (NSF)-sponsored) facilities might be used to forecast or mitigate space weather effects. However, as the planning progressed and the scope of the required work grew clearer, it became obvious that in order to address the task's primary theme of socioeconomic impacts within the time and resources available, the effort needed to hew to the principal issues of civilian, military, and commercial impacts of space weather and mitigation strategies based on operational capabilities. The workshop and its goals reflect this more focused approach. This approach did elicit discussion of a number of flight instruments such as the solar wind monitor on NASA's ACE (Advanced Composition Explorer) spacecraft, but little or no discussion of instrument(s) such as DASI (Distributed Arrays of Small Instruments), FASR (Frequency-Agile Solar Radiotelescope), and AMISR (Advanced Modular Incoherent Scatter Radar), which were still at the concept stage, under development, or under construction, respectively, at the time of the workshop. The scientific bases for DASI, FASR, and AMISR have been addressed in previous NRC reports,[3,4,5] and their utilization for space weather purposes remains an active goal of the NSF as the facilities come fully online.

This report of the workshop was prepared by the organizing committee. The report summarizes the workshop

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[2]Office of the Federal Coordinator for Meteorology (OFCM), *Report of the Assessment Committee for the National Space Weather Program,* FCM-R24-2006, OFCM, Silver Spring, Md., 2006, p. 1, available at http://www.ofcm.gov/r24/fcm-r24.htm.

[3]National Research Council, *Distributed Arrays of Small Instruments for Solar-Terrestrial Research: A Workshop Report,* The National Academies Press, Washington, D.C., 2006

[4]National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* The National Academies Press, Washington, D.C., 2003.

[5]National Research Council, *Ground-Based Solar Research: An Assessment and Strategy for the Future,* National Academy Press, Washington, D.C., 1998.

proceedings but does not offer any recommendations. Instead, the workshop was intended to help gather information and identify issues for analysis in a possible follow-on study that could provide recommendations on future space weather programs, resource needs, and interagency coordination to improve services and knowledge for those affected by space weather.

The organizing committee is deeply appreciative of the time and effort contributed by people from industry, government, and academia. It is the committee's hope that the present report will provide policy makers and the general public with a better understanding of the importance of space weather to a wide range of economic and societal activities and light the way to future analyses and assessments.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Elizabeth Cantwell, Oak Ridge National Laboratory,
Jack R. Jokipii, University of Arizona,
Todd M. La Porte, Jr., George Mason University,
Louis J. Lanzerotti, New Jersey Institute of Technology, and
William Murtagh, NOAA/National Weather Service.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George A. Paulikas, The Aerospace Corporation. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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