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

ISBN: 0-309-12770-X, 131 pages, 8 1/2 x 11, (2008)

This free PDF was downloaded from:
http://www.nap.edu/catalog/12507.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online, free
- Sign up to be notified when new books are published
- Purchase printed books
- Purchase PDFs
- Explore with our innovative research tools

Thank you for downloading this free PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to comments@nap.edu.

This free book plus thousands more books are available at http://www.nap.edu.

Copyright © National Academy of Sciences. Permission is granted for this material to be shared for noncommercial, educational purposes, provided that this notice appears on the reproduced materials, the Web address of the online, full authoritative version is retained, and copies are not altered. To disseminate otherwise or to republish requires written permission from the National Academies Press.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

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

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study is based on work supported by Contract NNH06CE15B between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

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.

International Standard Book Number 13: 978-0-309-12769-1
International Standard Book Number 10: 0-309-12769-6

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

OTHER REPORTS OF THE SPACE STUDIES BOARD

Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring (2008)
Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity (2008)
Science Opportunities Enabled by NASA's Constellation System: Interim Report (SSB with the Aeronautics and Space Engineering Board [ASEB], 2008)
Space Science and the International Traffic in Arms Regulations: Summary of a Workshop (2008)
United States Civil Space Policy: Summary of a Workshop (SSB with ASEB, 2008)
Workshop Series on Issues in Space Science and Technology: Summary of Space and Earth Science Issues from the Workshop on U.S. Civil Space Policy (2008)

Assessment of the NASA Astrobiology Institute (2007)
An Astrobiology Strategy for the Exploration of Mars (SSB with the Board on Life Sciences [BLS], 2007)
Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration (SSB with ASEB, 2007)
Decadal Science Strategy Surveys: Report of a Workshop (2007)
Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (2007)
Exploring Organic Environments in the Solar System (SSB with the Board on Chemical Sciences and Technology, 2007)
Grading NASA's Solar System Exploration Program: A Midterm Review (2007)
The Limits of Organic Life in Planetary Systems (SSB with BLS, 2007)
NASA's Beyond Einstein Program: An Architecture for Implementation (SSB with the Board on Physics and Astronomy [BPA], 2007)
Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop Report (2007)
A Performance Assessment of NASA's Astrophysics Program (SSB with BPA, 2007)
Portals to the Universe: The NASA Astronomy Science Centers (2007)
The Scientific Context for Exploration of the Moon (2007)

An Assessment of Balance in NASA's Science Programs (2006)
Assessment of NASA's Mars Architecture 2007-2016 (2006)
Assessment of Planetary Protection Requirements for Venus Missions: Letter Report (2006)
Distributed Arrays of Small Instruments for Solar-Terrestrial Research: Report of a Workshop (2006)
Issues Affecting the Future of the U.S. Space Science and Engineering Workforce: Interim Report (SSB with ASEB, 2006)
Review of NASA's 2006 Draft Science Plan: Letter Report (2006)
The Scientific Context for Exploration of the Moon—Interim Report (2006)
Space Radiation Hazards and the Vision for Space Exploration (2006)

Limited copies of these reports are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W., Washington, DC 20001
(202) 334-3477/ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release, which in some cases precedes the year of publication.

COMMITTEE ON THE SOCIETAL AND ECONOMIC IMPACTS OF SEVERE SPACE WEATHER EVENTS: A WORKSHOP

DANIEL N. BAKER, University of Colorado at Boulder, *Chair*
ROBERTA BALSTAD, Center for International Earth Science Information Network, Columbia University
J. MICHAEL BODEAU, Northrop Grumman Space Technology
EUGENE CAMERON, United Airlines, Inc.
JOSEPH F. FENNELL, Aerospace Corporation
GENENE M. FISHER, American Meteorological Society
KEVIN F. FORBES, Catholic University of America
PAUL M. KINTNER, Cornell University
LOUIS G. LEFFLER, North American Electric Reliability Council (retired)
WILLIAM S. LEWIS, Southwest Research Institute
JOSEPH B. REAGAN, Lockheed Missiles and Space Company, Inc. (retired)
ARTHUR A. SMALL III, Pennsylvania State University
THOMAS A. STANSELL, Stansell Consulting
LEONARD STRACHAN, JR., Smithsonian Astrophysical Observatory

Staff

SANDRA J. GRAHAM, Study Director
THERESA M. FISHER, Program Associate
VICTORIA SWISHER, Research Associate
CATHERINE A. GRUBER, Assistant Editor

SPACE STUDIES BOARD

CHARLES F. KENNEL, Scripps Institution of Oceanography, University of California, San Diego, *Chair*
A. THOMAS YOUNG, Lockheed Martin Corporation (retired), *Vice Chair*
DANIEL N. BAKER, University of Colorado
STEVEN J. BATTEL, Battel Engineering
CHARLES L. BENNETT, Johns Hopkins University
YVONNE C. BRILL, Aerospace Consultant
ELIZABETH R. CANTWELL, Oak Ridge National Laboratory
ANDREW B. CHRISTENSEN, Dixie State College and Aerospace Corporation
ALAN DRESSLER, Observatories of the Carnegie Institution
JACK D. FELLOWS, University Corporation for Atmospheric Research
FIONA A. HARRISON, California Institute of Technology
JOAN JOHNSON-FREESE, Naval War College
KLAUS KEIL, University of Hawaii
MOLLY K. MACAULEY, Resources for the Future
BERRIEN MOORE III, University of New Hampshire
ROBERT T. PAPPALARDO, Jet Propulsion Laboratory
JAMES PAWELCZYK, Pennsylvania State University
SOROOSH SOROOSHIAN, University of California, Irvine
JOAN VERNIKOS, Thirdage LLC
JOSEPH F. VEVERKA, Cornell University
WARREN M. WASHINGTON, National Center for Atmospheric Research
CHARLES E. WOODWARD, University of Minnesota
ELLEN G. ZWEIBEL, University of Wisconsin

MARCIA S. SMITH, Director

Copyright © National Academy of Sciences. All rights reserved.

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

---

[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.

Contents

APPENDIXES

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.

1

Introduction

HISTORICAL BACKGROUND

As evidenced in both ancient legend and the historical record, human activities, institutions, and technologies have always been prey to the extremes of weather—to droughts and floods, ice storms and blizzards, hurricanes and tornados. Around the middle of the 19th century, however, society in the developed parts of the world became vulnerable to a different kind of extreme weather as well—to severe disturbances of the upper atmosphere and the near-Earth space environment driven by the magnetic activity of the Sun. Although the nature of the solar-terrestrial connection was not understood at the time, such disturbances were quickly recognized as the culprit behind the widespread disruptions that periodically plagued the newly established and rapidly expanding telegraph networks. During the following century and a half, with the growth of the electric power industry, the development of telephone and radio communications, and a growing dependence on space-based communications and navigation systems, the vulnerability of modern society and its technological infrastructure to "space weather" has increased dramatically.

The adverse effects of extreme space weather on modern technology—power grid outages, high-frequency communication blackouts, interference with Global Positioning System (GPS) navigation signals, spacecraft anomalies—are well known and well documented. The physical processes underlying space weather are also generally well understood, although our ability to forecast extreme events remains in its infancy. Less well documented and understood, however, are the potential economic and societal impacts of the disruption of critical technological systems by severe space weather. Defining and quantifying these impacts presents a number of questions and challenges with respect to the gathering of the necessary data, the methodology for assessing the risks of severe space weather disturbances as low-frequency/high-consequence events, the perception of risk on the part of policy makers and stakeholders, and the development of appropriate risk management strategies.

As a first step toward charting the dimensions of the problem of 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 on May 22-23, 2008, in Washington, D.C., under the auspices of the National Research Council's (NRC's) Space Studies Board. The workshop brought together representatives of industry, the government, and academia (attendees are listed in Appendix B) 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 "the way forward," in which the participants identified un- or underexplored topics relevant to the question of space weather impacts, highlighted various weaknesses in the existing space weather services infrastructure, and suggested improvements that would yield the greatest benefits in space weather risk management.

The key themes, ideas, and insights that emerged during the workshop's 1½ days of informative presentations and lively discussions are summarized in this report, which was prepared by the members of the ad hoc NRC Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop tasked with organizing the workshop (Appendix D). To set the stage for the chapters that follow, we begin with a description of the magnetic superstorms of August-September 1859, by some measures the most severe space weather event on record. Known as the Carrington event, the 1859 storms were referred to throughout the workshop as an example of the kind of extreme space weather event that, if it were to occur today, could have profound societal and economic consequences, with cascading effects throughout the complex and interrelated infrastructures of modern society.

The Great Magnetic Storms of August-September 1859 (the Carrington Event)

Shortly after midnight on September 2, 1859, campers in the Rocky Mountains were awakened by an "auroral light, so bright that one could easily read common print." The campers' account, published in *The Rocky Mountain News*, continues, "Some of the party insisted that it was daylight and began the preparation of breakfast."[1] Eighteen hundred miles to the east, Henry C. Perkins, a respected physician in Newburyport, Massachusetts, observed "a perfect dome of alternate red and green streamers" over New England. To the citizens of Havana, Cuba, the sky that night "appeared stained with blood and in a state of general conflagration" (Figure 1.1). Dramatic auroral displays had been seen five nights before as well, on the night of August 28/29, when (again in the words of Dr. Perkins) "the whole celestial vault was glowing with streamers, crimson, yellow, and white, gathered into waving brilliant folds."[2] In New York City, thousands gathered on sidewalks and rooftops to watch "the heavens . . . arrayed in a drapery more gorgeous than they have been for years." The aurora that New Yorkers witnessed that Sunday night, *The New York Times* assured its readers, "will be referred to hereafter among the events which occur but once or twice in a lifetime."[3]

From August 28 through September 4, auroral displays of extraordinary brilliance were observed throughout North and South America, Europe, Asia, and Australia, and were seen as far south as Hawaii, the Caribbean, and Central America in the Northern Hemisphere and in the Southern Hemisphere as far north as Santiago, Chile (Figure 1.2).[4] Even after daybreak, when the aurora was no longer visible, its presence continued to be felt through the effect of the auroral currents. Magnetic observatories recorded disturbances in Earth's field so extreme that magnetometer traces were driven off scale, and telegraph networks around the world—the "Victorian Internet"[5]—experienced major disruptions and outages. "The electricity which attended this beautiful phenomenon took possession of the magnetic wires throughout the country," the *Philadelphia Evening Bulletin* reported, "and there were numerous side displays in the telegraph offices where fantastical and unreadable messages came through the instruments, and where the atmospheric fireworks assumed shape and substance in brilliant sparks."[6] In several locations, operators disconnected their systems from the batteries and sent messages using only the current induced by the aurora.[7]

The auroras were the visible manifestation of two intense magnetic storms that occurred near the peak of the sunspot cycle. On September 1, the day before the onset of the second storm, Richard Carrington, a British amateur astronomer, observed an outburst of "two patches of intensely bright and white light"[8] from a large and complex group of sunspots near the center of the Sun's disk. The outburst lasted 5 minutes and was also observed, independently, by Richard Hodgson from his home observatory near London. Carrington noted that the solar outburst—a white-light flare—was followed the next day by a magnetic storm, but he cautioned against inferring a causal connection between the two events. "One swallow," he is reported to have said, "does not make a summer."[9]

Space Weather: "The Mysterious Connection Between the Solar Spots and Terrestrial Magnetism"

The dazzling auroral displays, magnetic disturbances, and disruptions of the telegraph network that occurred between August 28 and September 4, 1859, were recognized by contemporary observers—at least the scientifically

FIGURE 1.1 "The red light was so vivid that the roofs of the houses and the leaves of the trees appeared as if covered with blood" (report of the aurora seen in San Salvador, September 2, 1859; see note 2 at the end of this chapter). Low-latitude red auroras, such as those widely reported to have been observed during the Carrington event, are a characteristic feature of major geomagnetic storms. The aurora shown here was photographed over Napa Valley, California, during the magnetic storm of November 5, 2001. Reprinted with permission from D. Obudzinski (www.borealis2000.com). © Dirk Obudzinski 2001.

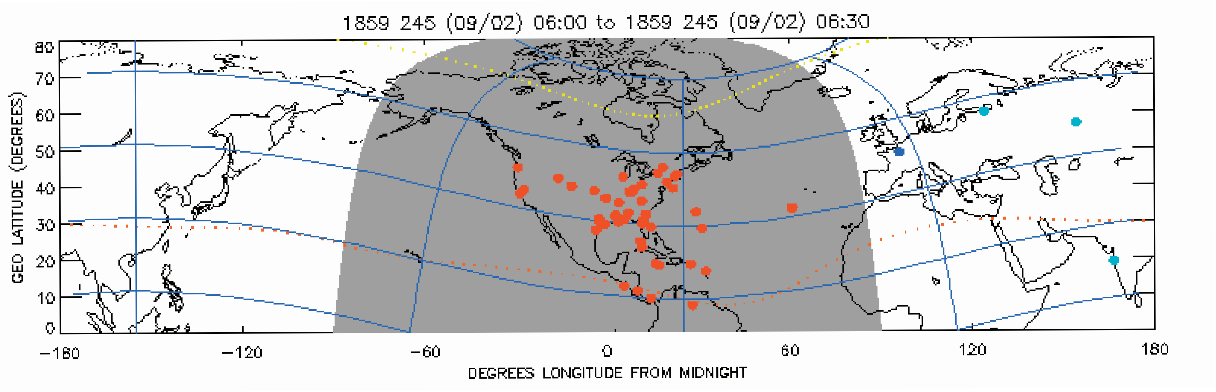


FIGURE 1.2 Locations of reported auroral observations during the first ~1.5 hours of the September 2, 1859, magnetic storm (orange dots). Courtesy J.L. Green, NASA

informed among them—as especially spectacular manifestations of a "mysterious connection between the solar spots and terrestrial magnetism."[10] This connection had been established earlier in the decade on the basis of the regular correspondence observed between changes in Earth's magnetic field and the number of sunspots.[11] Well-established by this time as well was the "intimate and constant connection between the phenomena of the aurora borealis and terrestrial magnetism."[12] And by the mid-1860s, Hermann Fritz in Zürich and Elias Loomis at Yale would furnish convincing evidence of a link between the occurrence of the aurora and the sunspot cycle.[13] "We must therefore conclude," Loomis wrote in *Harper's New Monthly Magazine*, "that these three phenomena—the solar spots, the mean daily range of the magnetic needle, and the frequency of auroras—are somehow dependent the one upon the other, or all are dependent upon a common cause."[14]

Although the existence of the link among solar, geomagnetic, and auroral phenomena was recognized by the time of the 1859 events, the nature of this link was not understood. The white-light flare observations by Carrington and Hodgson furnished a critical clue. But it would not be until the 1930s that the significance of their observations was appreciated, and a full picture of the phenomena that constitute what we now call "space weather" would not emerge until well into the space age.[15]

A major turning point in our understanding of space weather came with the discovery of coronal mass ejections (CMEs) in the 1970s and with the recognition that these, rather than eruptive flares, are the cause of non-recurrent geomagnetic storms.[16] Large-scale eruptions of plasma and magnetic fields from the Sun's corona, CMEs contain as much as 10^{16} grams or more of coronal material and travel at speeds as high as 3000 kilometers/second, with a kinetic energy of up to 10^{32} ergs.[17] Eruptive flares and CMEs occur most often around solar maximum and result from the release of energy stored in the Sun's magnetic field. CMEs and flares can occur independently of one another; however, both are generally observed at the start of a space weather event that leads to a large magnetic storm. To be maximally geoeffective, i.e., to drive a magnetic storm, a CME must (1) be launched from near the center of the Sun onto a trajectory that will cause it to impact Earth's magnetic field; (2) be fast ($\geq$1000 kilometers/second) and massive, thus possessing large kinetic energy; and (3) have a strong magnetic field whose orientation is opposite that of Earth's.[18]

The cause of the magnetic storm that began on September 2, 1859, was thus not the highly energetic flare[19] that Carrington and Hodgson had observed the previous morning. It was a fast CME launched from or near the same giant sunspot region just northwest of the Sun's center that had produced the flare. Had the Solar and Heliospheric Observatory (SOHO) been in operation in 1859, its Large-Angle and Spectrometric Coronagraph (LASCO) would have observed the CME some 20 minutes or so after the flare's peak emission at 11:15 GMT. The CME would have appeared as a bright "halo" of material surrounding the occulted solar disk, indicating that it was headed directly toward Earth (Figure 1.3). Between the time of the flare/CME eruption on September 1 and the onset of the magnetic storm the next morning, 17 hours and 35 minutes elapsed.[20] Dividing the mean distance between Earth and the Sun by the 17.5-hour propagation time yields a speed of approximately 2300 kilometers per second, making the CME of September 1, 1859, the second fastest CME on record.[21]

Moving substantially faster than the surrounding medium, fast CMEs create a shock wave that accelerates coronal and solar wind ions (predominantly protons) and electrons to relativistic and near-relativistic velocities. Particles are accelerated by solar flares as well; and large solar energetic particle (SEP) events, although dominated by shock-accelerated particles, generally include flare-accelerated particles (some of which may be further accelerated by the shock). Traveling near the speed of light, SEPs begin arriving at Earth within less than hour of the CME lift-off/flare eruption and are channeled along geomagnetic field lines into the upper atmosphere above the North and South poles, where they enhance the ionization of the lower ionosphere over the entire polar regions—polar cap absorption (PCA) events—and can initiate ozone-depleting chemistry in the middle atmosphere.[22] SEP events—"solar radiation storms" in NOAA terminology—can last several days.[23]

The mid-19th century lacked the means to detect and measure SEPs, and its most sophisticated technologies were unaffected by them. Thus, in contrast to the widely observed auroral displays and magnetic disturbances, the radiation storm unleashed by the solar eruption on September 1 went unnoticed and undocumented by contemporary observers. There is, however, a natural record of the storm that can be retrieved and interpreted. Nitrates, produced by SEP bombardment of the atmosphere above the poles, settle out of the atmosphere within weeks of a SEP event and are preserved in the polar ice. Analysis of anomalous nitrate concentrations in ice core samples

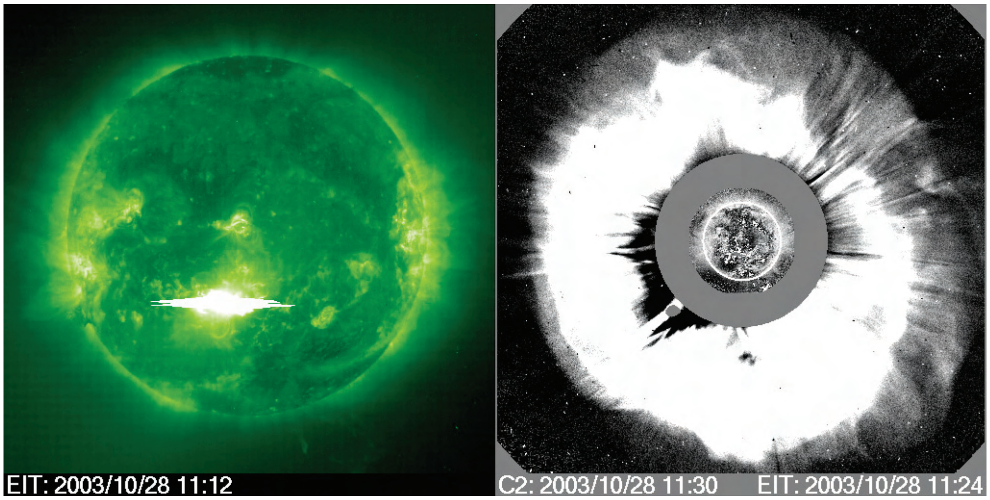


FIGURE 1.3 An X17 flare observed during the 2003 "Halloween" storms with SOHO's Extreme-ultraviolet Imaging Telescope (EIT) (left) and a difference image showing the associated halo CME (right). SOHO is stationed 1.5 million kilometers upstream from Earth, at the Lagrangian point 1. These images suggest what might have been observed on September 1, 1859, if 19th-century technology had been capable of building a SOHO-like space-based solar observatory. Courtesy NASA/ESA.

allows the magnitude of historical—i.e., pre-space-era—SEP events to be estimated.[24] Such an analysis indicates that the 1859 event is the largest SEP event known, with a total fluence of 1.9×10^{10} cm^{-2} for protons with energies greater than 30 MeV, four times that of the August 1972 event.[25]

The shock responsible for the radiation storm hit Earth's magnetosphere[26] at 0450 GMT on September 2. It dramatically compressed the geomagnetic field, producing a steep increase in the magnitude of the field's horizontal (H) component,[27] which marked the onset of the geomagnetic storm. The compression of the field would also have triggered an almost instantaneous brightening of the entire auroral oval (Figure 1.4).

The CME arrived shortly after the passage of the shock and triggered the main phase of the storm, the severity of which can be inferred from contemporary reports of low-latitude auroras and magnetometer data from the Colaba Observatory in Bombay, India.[28] The equatorward boundary of the aurora moves to increasingly lower latitudes (relative to its nominal location at 55°-65° magnetic latitude) with increasing storm intensity.[29] The observations of the aurora as far south as the West Indies, Jamaica, Cuba, and San Salvador are thus evidence that the September storm was extraordinarily intense. A rough quantitative measure of its intensity is provided by the Colaba data, which show a precipitous reduction (1600 nT) in H at the peak of the storm's main phase. Converted to 1-hour averages, these data yield a proxy Dst index of approximately –850 nT.[30] For comparison, the largest Dst index recorded since the International Geophysical Year (1957) is –548 nT for the superstorm of March 14, 1989.[31]

Without upstream solar wind measurements such as are provided today by the Advanced Composition Explorer, researchers can only speculate about the structure of the CME and the magnitude and precise orientation of the associated magnetic fields.[32] What can be inferred with certainty from the intensity and duration of the September storm, however, is that very strong magnetic fields were associated with the CME and that their orientation was opposite that of Earth's. This allowed the two fields to merge and enormous amounts of energy to be transferred into the magnetosphere, producing the magnetospheric and ionospheric phenomena characteristic of a major magnetic storm: (1) increased earthward flow of magnetospheric plasma, creating or intensifying the ring current;[33] (2) the explosive release of stored magnetic energy in multiple magnetospheric substorms; (3) an increase in the energy content of the radiation belts as well as the possible creation of temporary new belts; (4) the

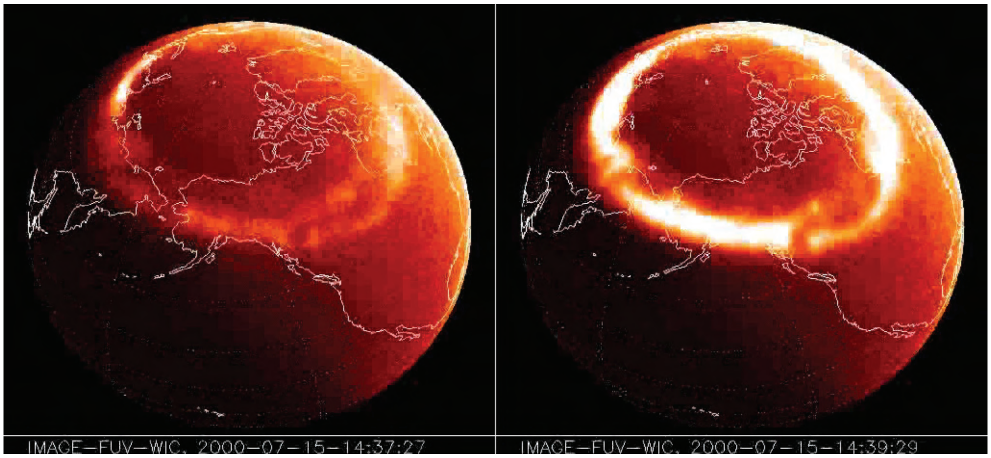


FIGURE 1.4 Far-ultraviolet images of the pre-shock (left) and post-shock (right) aurora obtained with the auroral imager on NASA's IMAGE satellite during the July 14-15, 2000, "Bastille Day" event. Courtesy NASA/IMAGE FUV team.

development of intense auroral currents (electrojets) in the upper atmosphere; and (5) changes in the ionospheric and thermospheric density at midlatitudes.

The storm was at its most intense on September 2, and the geomagnetic field required several days to recover. Balfour Stewart, the director of the Kew Observatory near London, reported that the magnetic elements "remained in a state of considerable disturbance until September 5, and scarcely attained their normal state even on September 7 or 8."[34]

The same chain of events described for the September storm—CME/eruptive flare onset, SEP acceleration (probable), impact of the shock/CME on Earth's magnetic field, the resulting magnetospheric and ionospheric disturbances—will also have occurred in the case of the August 28/29 storm. The occurrence of low-latitude auroras and the dramatic auroral displays witnessed at higher latitudes indicate that this was a severe storm as well, although recently analyzed data from Russian magnetic observatories show that it was less intense and of shorter duration than the September 2 storm.[35] No solar eruptions were reported in association with the August event, and so the transit time or shock/CME speed cannot be determined. It is not known whether the CME was SEP-effective as well as geoeffective.[36] However, it is not unreasonable to speculate that a less intense SEP event was associated with the August 28/29 storm.[37]

SPACE WEATHER EFFECTS AND SOCIOECONOMIC IMPACTS

The August-September auroral and magnetic storms of 1859 were recognized by contemporaries as extraordinary events, and they still rank at or near the top of the lists of particularly severe geomagnetic storms.[38] Given the state of technology in the mid-19th century, their societal impact was limited to the disruptions of telegraph service "at the busy season when the telegraph is more than usually required,"[39] the telegraph companies' associated loss of income, and whatever the attendant effects on commerce and railroad traffic control might have been.[40]

Today the story is quite different. Modern society depends heavily on a variety of technologies that are vulnerable to the effects of intense geomagnetic storms and solar energetic particle events. Strong auroral currents, which wreaked havoc with the telegraph networks during the Carrington event, can disrupt and damage 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), very-high-frequency (VHF), and ultra-high-frequency (UHF) radio communications and navigation signals from GPS satellites. Exposure of spacecraft to energetic particles during SEP events and radiation belt enhancements can cause temporary operational anomalies, damage

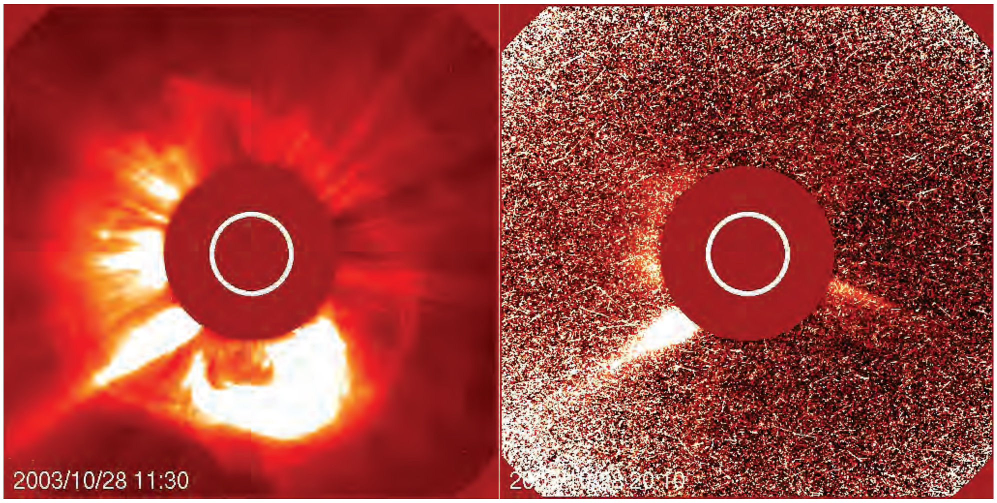


FIGURE 1.5 LASCO images from October 28, 2003, showing the effect of solar energetic particle bombardment on one of the SOHO coronagraphs. The image on the left is of the halo CME. The image on the right was obtained ~8.5 hours later. Courtesy NASA/ESA.

critical electronics,[41] degrade solar arrays, and blind optical systems such as imagers and star trackers (Figure 1.5). Moreover, intense SEP events present a significant radiation hazard for astronauts on the International Space Station during the high-latitude segment of its orbit as well as for future human explorers of the Moon and Mars who will be unprotected by Earth's magnetic field.[42]

In addition to such direct effects as spacecraft anomalies or power grid outages, a complete picture of the impact of severe space weather events on contemporary society, with its complex weave of dependencies and interdependencies, must include the collateral effects of space-weather-driven technology failures. For example, polar cap absorption 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, at a not inconsiderable cost to the airlines[43] and inconvenience to the passengers.

WORKSHOP PLANNING AND REPORT STRUCTURE

This workshop report was prepared by the members of the committee responsible for organizing the May 2008 workshop. In response to its statement of task (Appendix A), the Committee on the Societal and Economic Impacts of Severe Space Weather Events: A Workshop held a planning meeting prior to the workshop at which it gathered information on the issues to be explored. During and following that meeting the committee developed and refined the workshop structure, identified appropriate speaker candidates, and developed targeted questions and other materials for the speakers and sessions. The workshop consisted of eight topical sessions, each with a moderator, a rapporteur, and a panel of speakers representing different stakeholder industries, organizations, and agencies (see the workshop agenda in Appendix B). There were two summary sessions as well, plus a brief introductory talk by Daniel Baker, director of the Laboratory for Atmospheric and Space Physics at the University of Colorado and chair of the committee. Each panelist received a separate set of questions intended to elicit information relevant to the goals outlined in the committee's statement of task. That information is summarized in the succeeding chapters. The structure of the report follows, with one exception, the order of the topical sessions, with each chapter summarizing the key points made during the panelists' presentations and the subsequent discussions and summary sessions. The exception is the session on extreme space weather events, held on the second day of the workshop. That session's presentation by Jim Green (NASA Headquarters) on the Carrington event serves as the starting point for the discussion of 1859 storms in this introductory chapter, while Paul O'Brien's (Aerospace Corporation) presentation on planning for extremes and extreme value analysis is summarized in Chapter 7, "Future Solutions, Vulnerabilities, and Risks." Abstracts were received from most of the workshop speakers, and those are included, as submitted, in Appendix C of this report. The majority of the figures included in this report were taken from the presentations made by the workshop panelists.

NOTES

1. Quoted in Green, J.L., et al., Eyewitness reports of the great auroral storm of 1859, *Adv. Space Res.* 38, 145-153, 2006, p. 149. This is one of a collection of papers published in a special issue of *Advances in Space Research* dedicated to the August-September 1859 geomagnetic storms. Extensive use was made of this collection in the preparation of this introduction, as reflected in the notes that follow. Popular accounts of the Carrington event can be found in Clark, S., *The Sun Kings: The Unexpected Tragedy of Richard Carrington and the Tale of How Modern Astronomy Began*, Princeton University Press, Princeton, N.J., 2007, and Odenwald, S., and J.L. Green, Bracing the satellite infrastructure for a solar storm, *Scientific American*, August 2008.

2. Shea, M.A., and D.F. Smart, Compendium of the eight articles on the "Carrington Event" attributed to or written by Elias Loomis in the American Journal of Science, 1859-1861, *Adv. Space Res.* 38, 313-385, 2006, p. 149. Elias Loomis (1811-1889) was a professor of natural philosophy at Yale University with a particular interest in meteorology. Loomis collected reports of the aurora and magnetic disturbances observed during the 1859 storms and published them in eight installments in the *American Journal of Science*. These were compiled by Shea and Smart and published in the special issue of *Advances in Space Research* referred to in note 1. Henry Perkins' report is contained in Loomis' third article and appears on pp. 332-333 of the *ASR* compendium; the description of the red aurora seen over Havana is from a report published in the first installment; it appears on p. 326 of the *ASR* compendium.

3. *The New York Times*, August 30, 1859.

4. Green, J.L., and S. Boardsen, Duration and extent of the great auroral storm of 1859, *Adv. Space Res.* 38, 130-135, 2006; 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, 2004. Cliver and Svalgaard (p. 419, Table VII) rank the aurora of September 2 second on the list of the six documented lowest-latitude auroras, after the great aurora of February 1872 (low-latitude extent = 19°); according to Green and Boardsen, however, the September 2 aurora extended to 18° geomagnetic latitude.

5. Standage, Thomas, *The Victorian Internet: The Remarkable Story of the Telegraph and the Nineteenth Century's On-Line Pioneers*, Walker & Co., 1998.

6. The *Philadelphia Evening Bulletin* is quoted in *The New York Times* of August 30, 1859. Sparking started fires in some telegraph offices, and one operator, Frederick Royce of Washington, D.C., received "a very severe electric shock, which stunned me for a moment." A witness saw "a spark of fire jump from [Royce's] forehead to the sounder." Royce's account of his experience was reported in *The New York Times* of September 5, 1859, and reprinted by Loomis (note 2) and G.B. Prescott (note 7).

7. Prescott, G.B., *History, Theory, and Practice of the Electric Telegraph*, Ticknor and Fields, Boston, 1860, p. 320.

8. Carrington, R.C., Description of a singular appearance seen in the Sun on September 1, 1859, *Mon. Not. Roy. Astron. Soc.* 20, 13-14, 1860. Quoted in Bartels, J., Solar eruptions and their ionospheric effects—a classical observation and its new interpretation, *Terr. Mag.* 42, 235-239, 1937.

9. Carrington quoted in E.W. Cliver, The 1859 space weather event: Then and now, *Adv. Space Res.* 38, 119-129, 2006. The quote appears on p. 123.

10. Kirkwood, D., Solar phenomena, *New Englander and Yale Review* 19, 51-63, 1861, p. 62.

11. See Cliver, 2006, pp. 120-121, on the independent discovery in the early 1850s of the connection between geomagnetic activity and the number of sunspots by Edward Sabine, R. Wolf, and A. Gautier.

12. Prescott, G.B., The aurora borealis, *The Atlantic Monthly: A Magazine of Literature, Art, and Politics* 4, 740-751, 1859, p. 748. This article is incorporated almost verbatim in Prescott's 1860 book on the telegraph (note 7).

13. Schröder, W., Herman Fritz and the foundation of auroral research, *Planet. Space Sci.* 46, 461-463, 1998.

14. Loomis, E., The aurora borealis or polar light, *Harper's New Monthly Magazine* 39, 1-21, 1869.

15. See Cliver, 2006, pp. 124-127, on the interpretation of the Carrington event in the 1930s and the development of the modern understanding of solar-terrestrial relations.

16. Gosling, J.T., The solar flare myth, *J. Geophys. Res.* 98, 18937-18949, 1993.

17. Gopalswamy, N., Coronal mass ejections of solar cycle 23, *J. Astrophys. Astron.* 27, 243-254, 2006.

18. Gopalswamy, 2006.

19. According to a conservative estimate of its intensity, "the Carrington flare was a >X10 soft x-ray event, placing it among the top ~100 flares of the last ~150 years." See Cliver and Svalgaard, 2004, p. 410.

20. Bartels, 1937.

21. See Gopalswamy, 2006, p. 251, Figure 6.

22. Jackman, C.H., et al., Satellite measurements of middle atmospheric impacts by solar proton events in solar cycle 23, *Space Sci. Rev.* 125, 381-391, 2006.

23. For example, the largest >10 MeV SEP event of solar cycle 23 lasted $5^1/_2$ days, from 1705 UT on November 4, 2001, until 0715 UT on November 10, 2001. (See *Report of Solar and Geophysical Activity for November 10, 2001*, issued jointly by NOAA and the USAF.)

24. McCracken, K.G., et al., Solar cosmic ray events for the period 1561-1994. 1. Identification in polar ice, 1561-1950, *J. Geophys. Res*. 106, 21585-21598, 2001.

25. McCracken, 2001; Shea, M.A., et al., Solar proton events for 450 years: The Carrington event in perspective, *Adv. Space Res*. 38, 232-238, 2006. Shea et al. give a >30 MeV proton fluence of 5.0×10^9 cm^{-2} for the August 1972 SEP event (Table 1). They state that this was the "first major large solar proton fluence event that was recorded by a spacecraft" and "it is this event against which most comparisons are made" (p. 236). It should be noted that their Table 1 also includes the SEP event of November 12, 1960, for which a fluence twice that of the August event is given (9×10^9 cm^{-2}). However, as Shea and Smart note in an earlier paper, there is considerable uncertainty about the actual value of the >30 MeV proton fluence during this event (Shea, M.A., and D.F. Smart, A summary of major solar proton events, *Solar Physics* 127, 297-320, 1990). For example, Kim et al. note that values as small as 1.3×10^9 cm^{-2} have been estimated for the November 1960 event (Kim, M.-H., X. Hu, and F.A. Cucinotta, Effect of shielding materials from SPEs on the lunar and Mars surface, paper presented at the AIAA Space 2005 Conference, August 30–September 1, 2005, AIAA 2005-6653, 2005).

26. The magnetosphere is the region of space dominated by the geomagnetic field. It is populated by electrically charged particles of varying composition (but mostly protons) originating in the solar wind and the ionosphere. The interaction with the solar wind stretches the magnetosphere on the anti-sunward side into a long, comet-like tail that can extend millions of miles downstream in the solar wind flow.

27. Cf. the magnetometer data from the Kew Observatory outside London, reproduced in Cliver, 2006, p. 123, Figure 4.

28. Tsurutani, B.T., et al., The extreme magnetic storm of 1-2 September 1859, *J. Geophys. Res.* 108(A7), 2003, doi:10.1029/2002JA009504.

29. Yokoyama, N., Y. Kamide, and H. Miyaoka, The size of the aurora belt during magnetic storms, *Ann. Geophys.* 16, 566-583, 1998.

30. Siscoe, G., N.U. Crooker, and C.R. Clauer, Dst of the Carrington storm of 1859, *Adv. Space Res.* 38, 173-179, 2006. The hourly Dst (disturbed storm time) index is the standard measure of magnetic storm intensity. It is derived from measurements made at four low-latitude magnetic observatories of the depression in the magnitude of the horizontal component of the geomagnetic field. The depression in the field is caused by an increase in the energy density of the ring current, a current system encircling Earth at low latitudes. It is the formation of a ring current that constitutes a magnetic storm. Use of the Colaba data for a Dst proxy assumes that the contribution of low-latitude auroral electrojects to the depression in H was insignificant. (For the opposite view, see Green and Boardsen, 2006, p. 134). It should be noted that Dst estimates for the September storm calculated on the basis of assumed solar wind parameters can yield higher values. Tsurutani et al., 2003, predict a Dst of –1760 nT. See also Li, X., et al., Modeling of the September 1-2, 1859, super magnetic storm, *Adv. Space Res.* 38, 273-279, 2006. In contrast, the upper limit Dst that Siscoe et al. derive from solar wind conditions is consistent with the proxy Dst of –850 nT.

31. Cliver and Svalgaard, 2004, p. 416, Table VI; Tsurutani et al., 2003.

32. According to Tsurutani et al., 2003, the storm had a single, brief (1-1.5 hrs) main phase and was caused by a magnetic cloud-type CME with an intense southward magnetic field and no contribution from a draped field in the sheath of shocked solar wind between the CME and the shock. Siscoe et al., 2006, on the other hand, hypothesize that the storm consisted of two main phases separated by a brief recovery. The first main phase was caused by a strongly southward sheath field; the second, by a northward-to-southward rotation of the field within the CME.

33. See note 30.

34. Stewart, B., On the great magnetic disturbance which extended from August 28 to September 7, 1859, as recorded by photography at the Kew Observatory, *Phil. Trans. Royal Soc.* 151, 423-430, 1861.

35. Nevanlinna, H., On geomagnetic variations during the August-September storms of 1859, *Adv. Space Res.* 42, 171-180, 2008.

36. On the properties of SEP-effective shocks, see Gopalswamy, 2006, p. 250, §4.2 and Figure 5.

37. Smart, D.F., M.A. Shea, and K.G. McCracken, The Carrington event: Possible solar proton intensity-time profile, *Adv. Space Res.* 38, 215-225, 2006.

38. Cliver and Svalgaard (note 4) rank the Carrington event against other severe storms in terms of sudden ionospheric disturbance, SEP fluence, CME transit time, storm intensity, and equatorward extent of the aurora. They conclude, "While the 1859 event has close rivals or superiors in each of the above categories of space weather activity, it is the only documented event of the last ~150 years at or near the top of all the lists," p. 407.

39. Walker, C.V., On magnetic storms and currents, *Phil. Trans. Royal Soc.* 151, 89-131, 1861. The quote is from p. 95: "The fact appears to have been that the disturbance was of such magnitude and of so long continuance, and this at the busy season when the telegraph is more than usually required, that our clerks were at their wits' end to clear off the telegrams (which accumulated in their hands) by other less affected but less direct routes."

40. Green et al., 2006, pp. 151-152, estimate a total global loss to the telegraph companies of $300,000 (lost revenue + operator labor loss) but note that there are not enough data to allow an estimate of the collateral impact of the telegraph outages.

41. Damage to Nozomi's communications and power subsystems during a SEP event on April 21, 2002, contributed to the eventual loss of the Japanese Mars mission. The MARIE instrument on NASA's Mars Odyssey is believed to have been irreparably damaged by SEP bombardment during the 2003 Halloween storms (Lee, K.T., et al., MARIE solar quiet time flux measurements of H and He ions below 300 MeV/n, *29th International Cosmic Ray Conference*, 101-104, 2005). Ironically, MARIE was designed to measure the martian space radiation environment.

42. NRC, *Space Radiation Hazards and the Vision for Space Radiation: Report of a Workshop*, The National Academies Press, Washington D.C., 2006; NRC, *Managing Space Radiation Risk in the New Era of Space Exploration*, The National Academies Press, Washington, D.C., 2008.

43. "A typical flight duration for a polar route from a North American destination to Asia is over 15 hours. If the flight must divert for any reason, an additional stop-off is required. This results in considerable time loss, additional fuel, and the added time will require a whole new crew. The average cost of this kind of diversion is approximately $100,000." NOAA, *Intense Space Weather Storms October 19-November 07, 2003*, NOAA National Weather Service, Silver Spring, Md., April 2004, p. 17.

2

Space Weather Impacts in Retrospect

The first session of the workshop offered participants a retrospective look at the impact of some recent space weather events on specific industries. The session was moderated by Peggy Shea (Air Force Research Laboratory and University of Alabama), who opened the session with an overview of the principal kinds of space weather disturbances and illustrated their effects on modern technological systems with examples that included the well-known Quebec blackout during the magnetic superstorm of March 1989 and the disruption of the Anik communications satellites in 1994, as well as some less well known events such as the disruption of Allied radars in 1942 by an intense solar outburst and the brief high-frequency communication outage experienced by Air Force One en route to China during a solar event in 1984. She ended her talk with a comparison of the magnitude of historical solar energetic particle (SEP) events, as determined from ice core samples, with that of more recent events and pointed out that the SEP event associated with the Carrington flare of 1859 was four times larger than the August 1972 SEP event, thought to be the largest SEP event of the space era (see the discussion of the Carrington event in Chapter 1). “We can go back in the past,” she concluded, “but we don’t know what will happen in the future.” Nonetheless, as she noted in the abstract of her talk (see Appendix C), “technological planners should consider the possibility of these extremely large events in the design of their operating systems.”

Shea’s comments set the stage for the four presentations that followed, each of which was devoted to the impact of space weather on a particular technology or industry sector. The speakers were asked to (1) describe the effects of a recent serious space weather event in their areas of expertise, (2) assess in broader terms the monetary or service costs associated with such events, and (3) discuss the measures taken to adjust to or recover from space weather-related disturbances. Frank Koza (PJM Interconnection) and Michael Bodeau (Northup Grumman) represented, respectively, the electrical power and spacecraft industries. Leon Eldredge (Federal Aviation Administration) and Angelyn Moore (Jet Propulsion Laboratory) both addressed, with different emphases, the effects of space weather on navigation systems that rely on signals from Earth-orbiting satellites. Eldredge’s presentation focused specifically on the Wide Area Augmentation System (WAAS) developed by the FAA to augment the Global Positioning System (GPS), while Moore discussed space weather effects on GPS within the context of the International Global Navigation Satellite System Service (IGS).

SPACE WEATHER AND POWER GRIDS

Background

According to the U.S. Energy Information Administration, retail expenditures on electricity were approximately $325 billion in 2006, the most recent year for which data are available, which represents approximately 2.5 percent of that year's GDP. These values, while consequential, significantly understate the economic contribution of this industry since they do not reflect the consumer surplus that buyers receive from their purchases of electricity. This point is illustrated in Figure 2.1, which depicts a hypothetical demand curve for electricity. At price P_1, consumption of electricity equals Q_1. Given this price and quantity, expenditures on electricity can be represented by area A while consumer surplus, the difference between what consumers are willing to pay for electricity in excess of what they actually pay, is represented by area B.[1] Area B represents the net economic benefits to consumer from electricity and thus also represents the economic impact of a supply interruption on consumer net economic welfare.

Because electricity is critical to maintaining modern lifestyles, the consumer surplus from electricity is generally believed to be very large relative to expenditures. As a result, interruptions in electricity supply are believed to be very costly in terms of lost consumer surplus. For example, a recent study by de Nooij, Koopmans, and Bijvoet estimated that for households in the Netherlands, the value of lost load, i.e., the estimated loss in consumer surplus from an electricity market shortage, was €16.4/kWh (equivalent to US$24.47 per kWh as of August 11, 2008).[2] This is about 95 times the 2006 average retail price paid by households in the Netherlands.[3] Consistent with this estimate, the lowest estimate of the economic costs to the United States of the August 2003 blackout in North America is $4 billion.[4] To put this estimate in perspective, wholesale generation revenues in New York

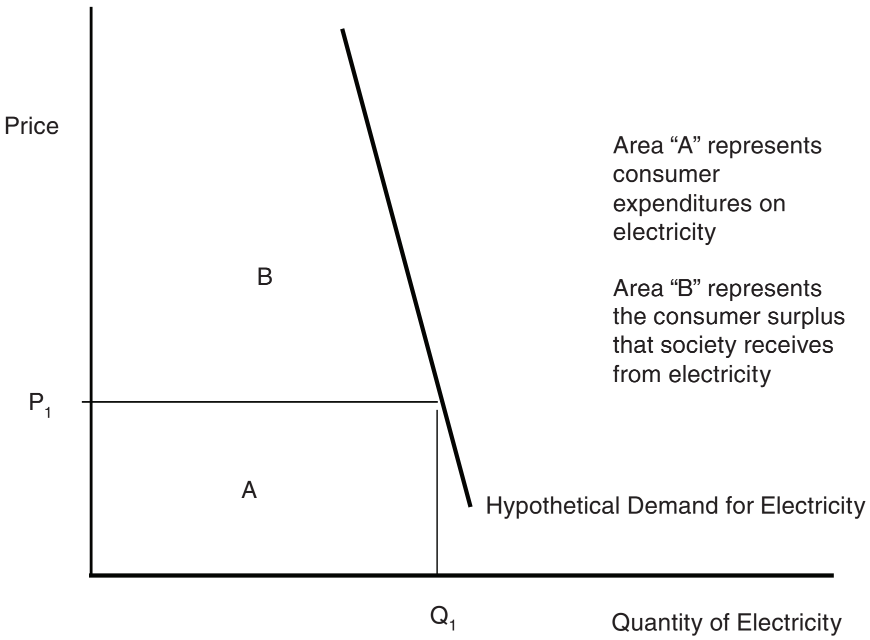


FIGURE 2.1 A hypothetical demand function for electricity, expenditures on electricity, and the consumer surplus from electricity.

state, one of the states most affected by the blackout, were expected to equal approximately $46 million during the blackout period.[5]

The Workshop Presentation

The first speaker at this session was Frank Koza, executive director of Systems Operations at PJM Interconnection. PJM is a regional transmission organization with 164,905 MW of generating capacity that coordinates the movement of wholesale electricity over 56,250 miles of transmission lines in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia. Koza began his presentation by noting that the impacts of space weather on the power system have been well documented. Space weather can give rise to the superposition of extraneous currents onto the normal operational flows on power system equipment. This can create conditions capable of causing damage within seconds. Fortunately, the majority of the events result in relatively minor power system impacts. However, the occasional serious event can have wide-ranging impacts.

One example of a space weather event that had a major impact was the March 1989 superstorm. During this storm, a large solar magnetic impulse caused a voltage depression on the Hydro-Quebec power system in Canada that could not be mitigated by automatic voltage compensation equipment. The failure of the equipment resulted in a voltage collapse. Specifically, five transmission lines from James Bay were tripped, which caused a generation loss of 9,450 MW. With a load of about 21,350 MW, the system was unable to withstand the generation loss and collapsed within seconds. The province of Quebec was blacked out for approximately 9 hours.

Also during this storm, a large step-up transformer failed at the Salem Nuclear Power Plant in New Jersey. That failure was the most severe of approximately 200 separate events that were reported during the storm on the North American power system. Other events ranged from generators tripping out of service, to voltage swings at major substations, to other lesser equipment failures (Figure 2.2).

Koza made the point that operators of the North American power grid constantly review and analyze the potential risks associated with space weather events. Grid operators rely on space weather forecasts such as those produced by NOAA's Space Weather Prediction Center (SWPC; see http://www.swpc.noaa.gov). They also monitor voltages and ground currents in real time and have mitigating procedures in place. PJM, as an example, has monitoring devices in place at key locations on its system, which are monitored in real time. At the onset of significant ground currents at the monitoring stations, PJM will invoke conservative operations practices that will help mitigate the impacts if the solar event becomes more severe. During these operations, flows between low-cost but more distant generating stations and load centers are reduced so as to maintain power grid stability.

What has changed since 1989? On one hand, space weather risks have declined because of increased awareness by system operators and improved forecasts. On the other hand, the evolution of open access on the transmission system has fostered the transport of large amounts of energy across the power system in order to maximize the economic benefit of delivering the lowest-cost energy to demand centers. The magnitude of power transfers has grown, and the risk is that the increased level of transfers, coupled with multiple equipment failures, could aggravate the impacts of a storm. With respect to this trend, the long distance between Hydro-Quebec's hydro-generation stations and load centers is one of the factors that is believed to have contributed to its space weather vulnerability.

Koza also presented his vision of a "perfect storm" space weather event. One might think that an event that occurred at peak load could produce the most severe impacts. However, at peak loads, almost all of the generators are running, and loss of a given amount of generation would have less impact on grid stability than at light load. Loss of multiple facilities at peak load, while of significant concern, can more readily be handled with emergency procedures and other well-established practices.

In Koza's opinion, the power system is more vulnerable to a severe geomagnetic storm during a period of light load with unusually heavy transfer patterns, as is prevalent in the middle of the night during the spring and the fall. Loss of multiple facilities at lighter loads, and high levels of long-distance transfers between low-cost but more distant generating plants and load centers, set up the potential for voltage collapse with minimal ability for mitigation. If several elements were lost at strategic locations, a voltage collapse and associated blackout would be possible.

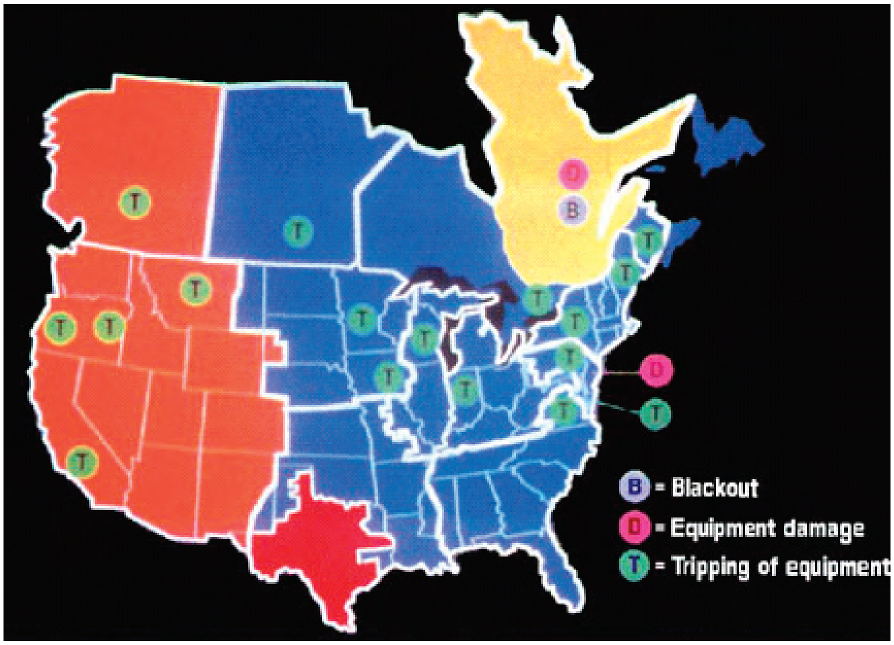


FIGURE 2.2 Power system events due to the March 13, 1989, geomagnetic storm. SOURCE: Electric Power Research Institute, Inc.

There were a number of questions from the audience following the presentation. One individual asked Koza to rank the value of the space weather predictions that PJM receives from the SWPC on a scale of 1 through 10. Koza indicated that the forecasts were invaluable, namely that their value warranted a ranking of 10 out of 10. One of the committee members noted that Koza's assessment of increased power grid vulnerability during the spring and the fall was troubling given the well-documented evidence[6] that major space weather events are more likely during the spring and fall (Figure 2.3).

SPACE WEATHER AND AVIATION NAVIGATION

Background

According to the FAA, enplanement (i.e., the number of passengers boarding airplanes) in the United States, measured in millions of passengers per year, have more than doubled over the period from 1979 to 2006 (Figure 2.4). This growth is not without consequences, as almost any user of the JFK, Atlanta, and O'Hare airports can attest. According to the FAA, nearly 27 percent of flights arrived late in 2007. The Air Transport Association (ATA) estimates that aviation congestion costs the economy $12.5 billion a year. Under the traditional aviation management system, the situation is expected to worsen, given the FAA's projection that enplanements will increase at a faster rate than GDP over the next 20 years. For example, the FAA has estimated that total passenger traffic between the United States and the rest of the world will grow from 141.5 million in 2006 to 422.3 million in 2030.[7]

To accommodate this growth, the FAA has contributed to the development of the Wide Area Augmentation System. WAAS allows GPS to be used as a primary means of navigation. Specifically, the augmentation improves GPS navigation integrity so that near-Category I approaches can be made at a large and increasing number of U.S. airports.[8] Being able to land in poor weather at many more airports effectively increases the robustness of the aviation system. Navigation accuracy is also improved. This capability effectively increases the capacity of the aviation system by allowing for reduced horizontal and vertical separation standards between planes without additional risk.

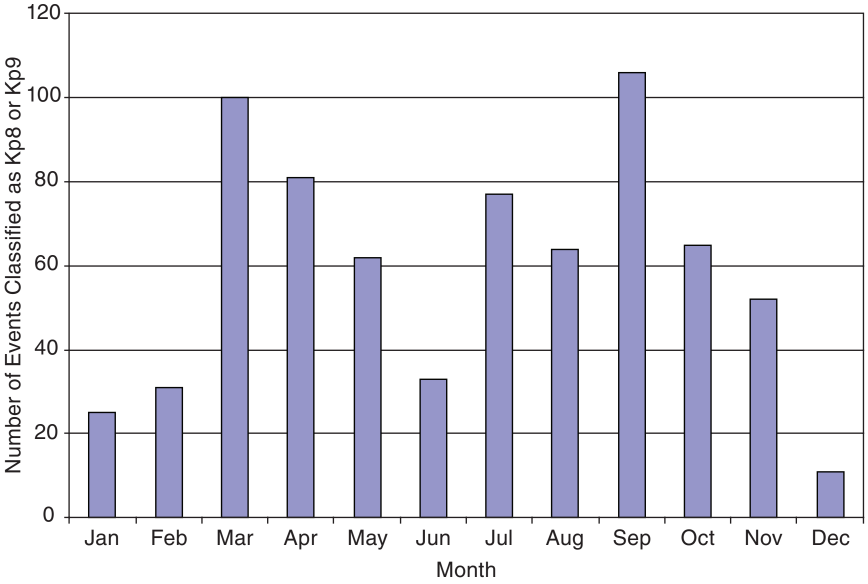


FIGURE 2.3 Incidence of Kp8/Kp9 events by month, 1932-2007, based on an analysis of 222,072 observations. SOURCE: Data from World Data Center for Geomagnetism.

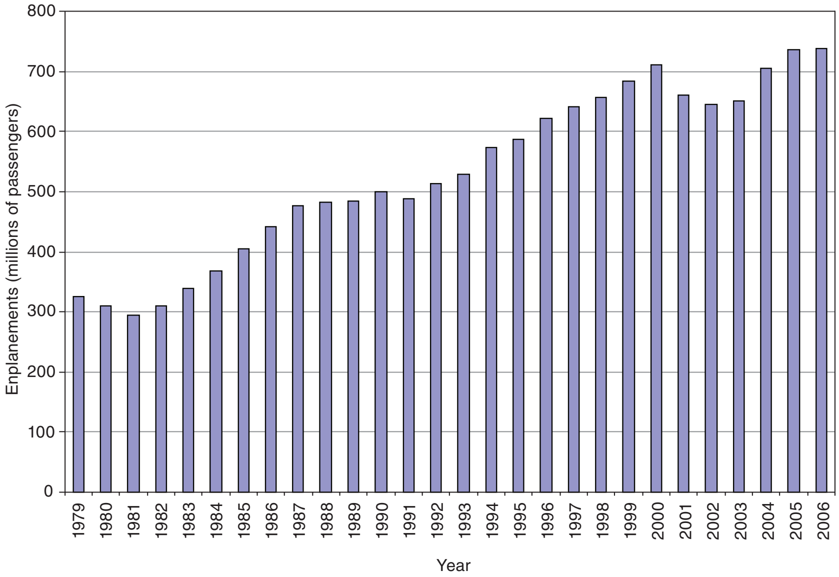


FIGURE 2.4 Historical summary of enplanements in the United States, 1979-2006. SOURCE: FAA enplanement reports, various years.

The Workshop Presentation

Leo Eldredge, program manager of the Global Navigations Satellite Systems Group at the FAA, began his presentation by providing an overview of WAAS. WAAS relies on a network of 38 ground reference stations that collect GPS satellite data. These data are sent through ground communications lines to three master stations that evaluate GPS signal integrity and calculate clock, orbit, and ionospheric corrections to improve accuracy. The integrity messages and augmentation data are distributed to users through two geostationary satellite communications links (Figure 2.5).

Eldredge noted that WAAS provides continent-wide ionospheric corrections for use by single-frequency GPS receivers through use of what is known as a thin shell model. This model takes the three-dimensional ionosphere

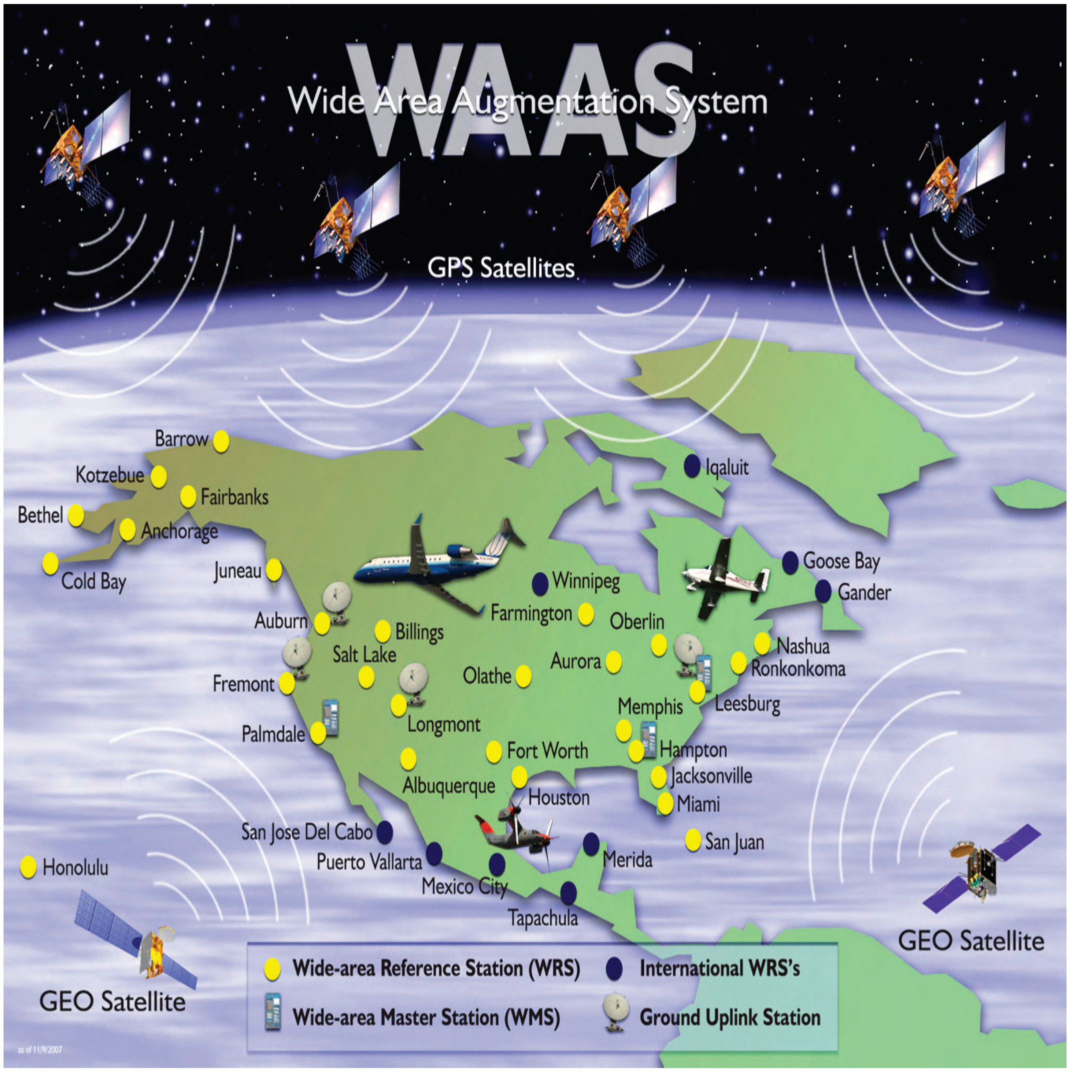


FIGURE 2.5 The WAAS architecture. SOURCE: Leo Eldredge, Federal Aviation Administration, "Space Weather Impacts on the Wide Area Augmentation System (WAAS)," presentation to the space weather workshop, May 22, 2008.

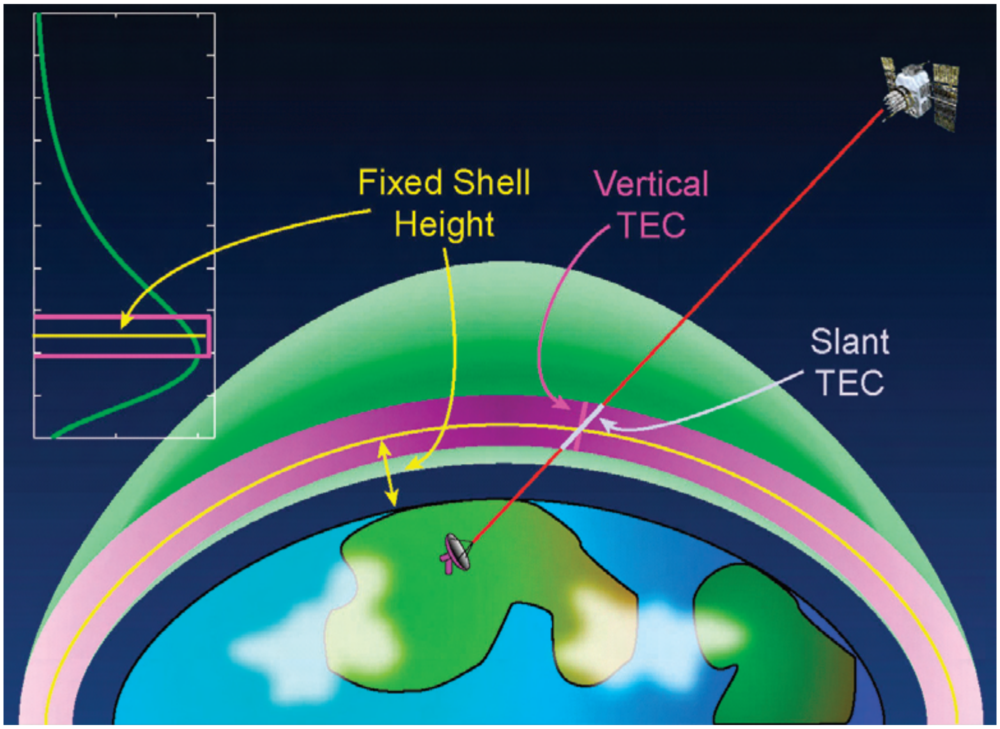


FIGURE 2.6 The thin shell model. SOURCE: Leo Eldredge, Federal Aviation Administration, "Space Weather Impacts on the Wide Area Augmentation System (WAAS)," presentation to the space weather workshop, May 22, 2008.

(shown in green in Figure 2.6) and condenses it to a two-dimensional thin shell (purple). The accuracy of this transformation is dependent on the total electron content in the ionosphere. Most of the time little information is lost and the results are highly accurate. During periods of significant ionospheric disturbance, however, the thin shell model may be inadequate to represent the more complex three-dimensional variations, which causes unacceptable unknown errors. In this situation, integrity, or assured accuracy, is not available in the affected areas, and WAAS can only be used for two-dimensional guidance for a nonprecision approach and landing in these regions throughout the duration of the ionospheric disturbance. Eldredge noted that because of the thin shell model's vulnerability, space weather "presents the largest limitation to vertically guided service." While horizontal navigation guidance was continuously available, vertical navigation guidance was unavailable for approximately 30 hours during the three to four large geomagnetic storms experienced in October 2003.

Figure 2.7 depicts the geographic coverage of the vertical navigation service on a non-disturbed day, while Figure 2.8 depicts the coverage at the height of the geomagnetic storm on October 29, 2003. On the non-disturbed day, vertical navigation service was available throughout North America. On October 29, 2003, vertical navigation service was not available throughout most of the United States. Eldredge noted that while space weather adversely affected the availability of vertical navigation service, lateral navigation service for non-precision approaches and integrity was maintained at all times for all users. In this sense, the system performed exactly as it was supposed to during the October 2003 storms by withholding only the vertical service. Nevertheless, there would be societal and economic consequences (e.g., flight delays) associated with the non-availability of WAAS if the aviation system were dependent on WAAS and a major space storm occurred.

Eldredge concluded his remarks by noting that the movement to a dual-frequency GPS system, relying on L1 and L5, is expected to eliminate the vertical service outages for users that equip with dual-frequency avionics. However, it will be approximately a decade until the transformation to the dual-frequency system is complete.

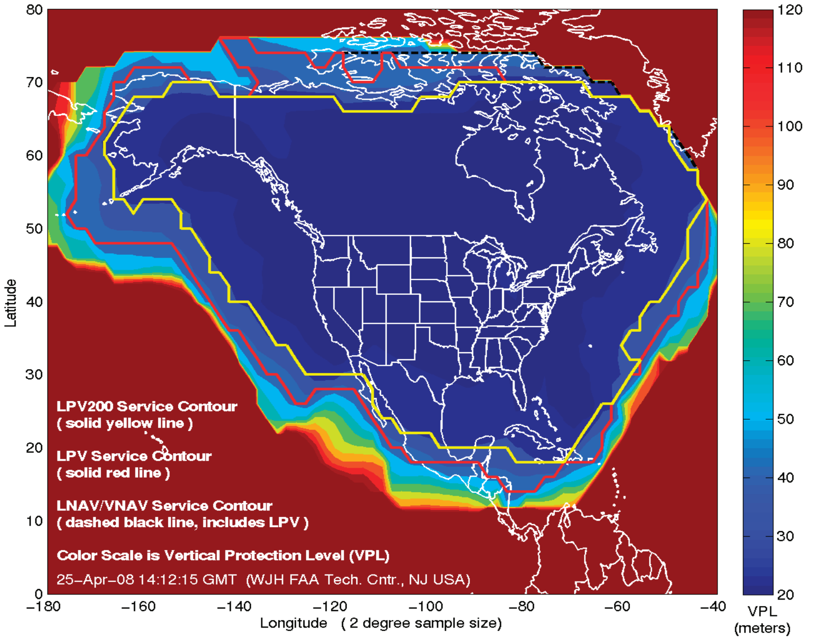


FIGURE 2.7 WAAS vertical service coverage on a non-disturbed day. SOURCE: Leo Eldredge, Federal Aviation Administration, "Space Weather Impacts on the Wide Area Augmentation System (WAAS)," presentation to the space weather workshop, May 22, 2008.

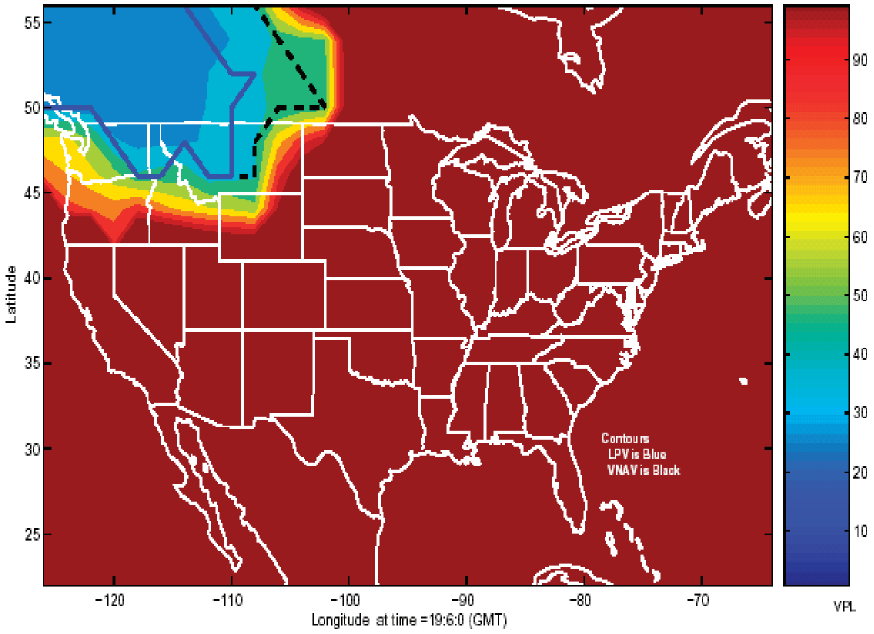


FIGURE 2.8 WAAS vertical service non-availability at the height of the storm on October 29, 2003. SOURCE: Leo Eldredge, Federal Aviation Administration, "Space Weather Impacts on the Wide Area Augmentation System (WAAS)," presentation to the space weather workshop, May 22, 2008.

SPACE WEATHER AND SATELLITES

In his presentation, Michael Bodeau of Northrop Grumman Space Technology gave an overview of the economic services provided by commercial communications satellites and how the provision of those services can be threatened by adverse space weather conditions.

The current fleet of approximately 250 satellites represents an approximately $75 billion investment with a revenue stream in excess of $25 billion per year, or greater than $250 billion over the life of these satellites. As in the case of both electric power and aviation, the latter figure understates the true economic value of commercial communications satellites, given that the value to society equals expenditures by consumers plus the consumer surplus (see Figure 2.1).

Some of the specific services that commercial communications satellites provide include:

- Communication services that provide remote populations with news, education, and entertainment (e.g., global cell phones, satellite-to-home TV and radio, and distance learning);
- A cost-effective means for interconnecting geographically distributed business offices (e.g., satellite links of store registers to regional distribution centers provide automatic inventory control and pricing feedback at a major retailer, and a major auto maker utilizes a satellite-based private communication network to update its entire system of dealer sales staff on new model features and service crews on new repair procedures);
- A cost-effective means of connecting businesses with their customers (e.g., facilitating point-of-sale retail purchases made with credit or debit cards at gas stations and convenience stores); and
- Critical backup to terrestrial cable systems vital to restoring services during catastrophic events (earthquakes, hurricanes) that damage ground-based communications systems.

The central thesis of Bodeau's presentation was that satellites are critical infrastructure and that space weather has posed a constant challenge to designers and operators of satellites, and indirectly to their customers. The impacts of space weather have ranged from momentary interruptions of service to a total loss of capabilities when a satellite fails. Bodeau stressed that access to space weather data is critical to finding the cause of anomalies and failures, which is the first step in making satellites more resistant to space weather events.

Bodeau indicated that there have been numerous studies correlating satellite anomalies with space weather. The data he presented indicate that more than half the anomalies experienced in 2003 occurred during the October 2003 storms (Figure 2.9).

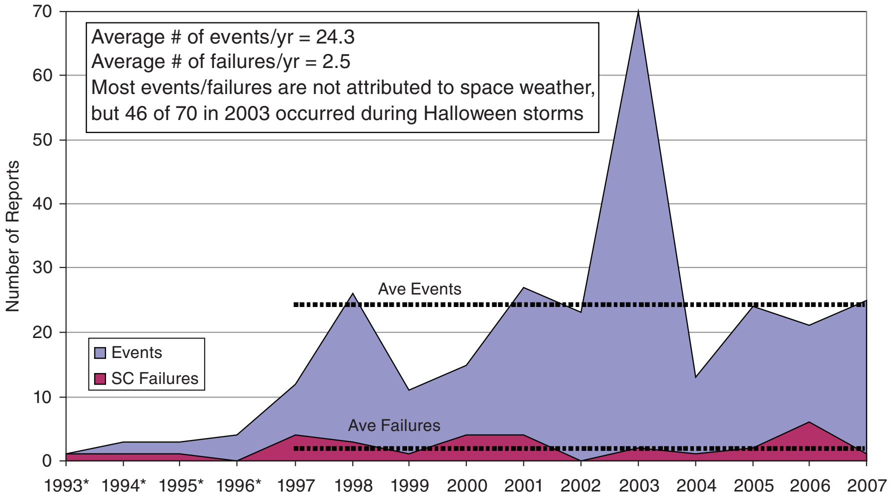


FIGURE 2.9 Space weather and satellite anomalies/failures. SOURCE: Michael Bodeau, Northrop Grumman, "Impacts of Space Weather on Satellite Operators and Their Customers," presentation to the space weather workshop, May 22, 2008.

One example of space weather's impact on satellites was Telesat's Anik experience in 1994.[9] On January 20, 1994, Telesat's Anik E1 was disabled for about 7 hours as a result of space weather-induced static-electricity-discharge damage to its control electronics. This satellite provides communication services in Canada. During this period, the Canadian press was unable to deliver news to 100 newspapers and 450 radio stations. In addition, telephone service to 40 communities was interrupted.

One hour after E1 recovered, Telesat's Anik E2 went off-air. As a result, TV and data services were lost to more than 1,600 remote communities. Backup systems were also damaged, making the US$290 million satellite useless. Approximately 100,000 home satellite dish owners were required to manually re-point their dishes to E1 and other satellites. The satellite was restored following a US$50 million-C$70 million 6-month recovery effort. The costs of interrupted services across Canada (i.e., the loss in consumer surplus to Canadians) are unknown.

The Anik failures illustrate an important point that may be overlooked, given the understandable tendency to focus on dramatic "big" space weather events such as the "Halloween" storms of 2003, the March 1989 storm, and the Carrington event. Namely, the impact of space weather on spacecraft systems is not limited to anomalies or failures that occur during the CME-driven geomagnetic storms (such as those just mentioned) that occur episodically around solar maximum. Of major concern to the spacecraft industry are the periodic enhancements of the magnetospheric energetic electron environment associated with high-speed solar wind streams emanating from coronal holes during the declining phase of the solar cycle (see Figure 5.13).[10] The Anik anomalies occurred during just such an energetic electron storm, which had begun a week earlier as a high-speed solar wind stream swept past Earth.

It should be noted as well that space weather-related spacecraft anomalies can occur even when there is no CME-driven storm or high-speed stream. Energy transferred from the solar wind to the magnetosphere through the merging of the interplanetary and terrestrial magnetic fields builds up in the magnetotail until it is explosively released in episodic events known as magnetospheric substorms. Substorms, which occur during non-storm times as well as storm times, inject energetic plasma into the inner magnetosphere and can cause electrical charge to build up on spacecraft surfaces. The electrostatic discharge that occurs subsequently is one of the major causes of spacecraft anomalies.

During the subsequent question-and-answer session, Bodeau was asked about the value of space weather forecasts. His initial response was that communications satellites are supposed to operate 24/7 and that a forecast in that sense is not useful. He then went on to indicate that behind-the-scenes repositioning and controlling of a satellite could be delayed if it were known that adverse space weather conditions were expected. On the other hand, if an anomaly that had occurred in the past had revealed a weakness in a satellite design, and if satellite operators could do something to mitigate such a weakness by changing operations, then they would like to know when adverse conditions were going to recur so that they could take preventive action.

Bodeau noted that the value of forecasts is more apparent with respect to science satellites, whose instruments tend to be far more sensitive to the space environment than those of communication satellites. For science satellites, there are substantial risks and few benefits from operating under adverse space weather conditions, and thus it would make sense to put their instruments and even the whole satellite into a safe mode when adverse space weather conditions are projected.

SPACE WEATHER AND GPS SERVICES

Background

It would be difficult to overstate the societal contribution of GPS. As discussed in the first workshop session, GPS is in the process of revolutionalizing aviation navigation. Other applications include the following:[11]

- GPS receivers enable users to determine the time to within 100 billionths of a second, without the cost of owning and operating atomic clocks. This capability can be of enormous value to firms that need to synchronize their network computers or instruments.

- GPS technology is revolutionizing transport logistics by making it possible to track and forecast the movement of freight.
- GPS may one day result in a significant reduction in highway fatalities by warning drivers when their car is about to leave the roadway.
- GPS-based applications enable farmers to adopt precision agricultural methods of planning, field mapping, soil sampling, tractor guidance, crop scouting, and yield mapping. For example, GPS allows more precise application of pesticides, herbicides, and fertilizers, thereby increasing output at lower cost.
- GPS provides the fastest and most accurate method for mariners to determine their location. This is a significant benefit, given the nation's reliance on imported oil carried by tankers and the environmental consequences of oil spills.

The Workshop Presentation

Angelyn Moore of the Jet Propulsion Laboratory presented evidence on how space weather has impacted GPS services. Her talk made use of data from the International Global Navigation Satellite System (GNSS) Service (IGS; formerly the International GPS Service), a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GNSS station data to generate precise GNSS products.[12] Participants include, among others, mapping agencies, space agencies, research agencies, and universities. Currently the IGS supports two GNSSs: GPS and the Russian GLONASS (GLONASS, a navigation system comparable to the U.S. GPS, was developed by the former Soviet Union and is now operated by the Russian Space Forces). Over 350 permanent, geodetic GNSS stations operated by more than 100 worldwide agencies constitute the IGS network. These civilian, dual-frequency stations contribute data to multiple data centers on at least a daily basis at a 30-second sampling rate; subsets contribute hourly and four times hourly, and an IGS real-time pilot project is getting under way. The IGS maintains a vendor-neutral stance and specifies only functional requirements; the network is therefore very heterogeneous in instrumentation.

In her talk Moore noted that a representative station suffered intermittent loss of tracking on some or all channels during periods of the October 2003 geomagnetic storms. The effect of such a loss of data will vary according to how many stations in the area are available and whether all of them are affected, and on the application under consideration. The IGS Ultrarapid orbits are a key IGS product that in 2003 were generated twice daily. Through the final week of October 2003, some degradation of the Ultrarapid accuracy could be discerned: not all IGS analysis centers were able to contribute orbit products, and accuracies slipped a few centimeters. Nevertheless, the combined IGS Ultrarapid product achieved better than 10-cm accuracy for most satellites throughout the week. The slight loss in accuracy would generally not have much of an impact on some types of geodetic processing, such as long-term monitoring of plate motion. However, high-rate and real-time GPS analysis is rapidly improving in detecting seismic surface waves and co-seismic displacement,[13,14,15] and brief or partial loss of tracking because of space weather during a critical event could certainly degrade applications with societal and economic impacts, such as tsunami warning systems.

During the subsequent question-and-answer session, Moore was asked about the value of space weather forecasts. Her response was that she would probably attach a low value to a forecast, probably 2 on a scale of 1 to 10. Her only caveat was that there might be users that would take alternative courses of action if a forecast of adverse conditions were available. Moore also was asked if the affected receiver or receivers were semi-codeless and therefore more sensitive to losing lock on the L2 signal than would be the case when L2 or L5 GPS coded signals were available. She confirmed that this was the case.

SUMMARY

The starting point of this workshop session was the observation that the most severe events over the past few solar cycles should not be viewed as an indicator of what could be expected in the future. For example, the Carrington event in 1859 was approximately four times larger than anything seen in the past 50 years. Nevertheless, there is evidence that space weather over the past two solar cycles has challenged the integrity of the electric power system, a key infrastructure in which interruptions in supply can have major economic consequences. Specifically, the March 1989 geomagnetic space storm resulted in a major blackout in the Hydro-Quebec power grid and also contributed to power grid anomalies throughout North America. In the opinion of Frank Koza of PJM Interconnection, power grids such as PJM are most vulnerable to space weather during periods of light load with unusually heavy electricity flows from generating plants to load centers, as is prevalent in the middle of the night during the spring and the fall. This assessment of increased power grid vulnerability during the spring and the fall was found to be troubling given the well-documented evidence that major space weather events are more likely during the spring and fall. Given this coincidence between power grid vulnerability and the incidence of major space weather events, it was not surprising that Koza indicated that PJM places a high value on space weather forecasts.

Evidence was also presented that space weather has impaired the provision of GPS. One notable example was the FAA's inability to provide its GPS-augmented vertical aviation navigation guidance for approximately 30 hours during the large geomagnetic storms in late October 2003. This vulnerability is expected to persist over the next decade. The value of improved space weather forecasting may be less significant in this case than with respect to electric power, since aviation safety can be maintained by increasing vertical separation standards. However, there may be considerable interest by airlines and passengers in forecasts of severe space weather events because of the impact of these events on the capacity of the aviation navigation system. Among the important societal applications of GPS, Angelyn Moore noted that high-rate and real-time GPS analysis is rapidly improving in detecting seismic activity, which in turn can have applications for tsunami warnings.

This workshop session also provided an overview of the economic value of services provided by satellites and how the provision of those services can be threatened by adverse space weather conditions. Michael Bodeau of Northrop Grumman indicated that numerous studies have correlated satellite anomalies with space weather. Specifically, more than half the anomalies experienced in 2003 occurred during the large geomagnetic storms in late October 2003. The economic impacts of these anomalies have ranged from minor to highly significant depending on the nature of the impact and whether substitute services were available. The value of improved space weather forecasts is dependent on the nature of the satellite service and the extent to which operators can mitigate the potential damage to a satellite by changing operations.

NOTES

1. For more information about the concept of consumer surplus, see N.G. Mankiw, *Principles of Microeconomics,* Fourth Edition, 2007, pp. 138-142.

2. de Nooij, M., C.C. Koopmans, and C.C. Bijvoet, The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks, *Energy Economic*s 29(2), 277-295, 2007.

3. See http://www.eia.doe.gov/emeu/international.

4. Electricity Consumers Resource Council, The economic impacts of the August 2003 blackout, 2004, available at http://www.elcon.org/Documents/EconomicImpactsOfAugust2003Blackout.pdf.

5. This estimate is based on forecasted load and day-ahead reference prices.

6. For example, C.T. Russell and R.L. McPherron, Semiannual variation of geomagnetic activity, *J. Geophys. Res.* 78, 92-108, 1973.

7. Office of Aviation Policy and Plans, *FAA Long-Range Aerospace Forecasts: Fiscal Years 2020, 2025, and 2030,* September 2007, p. 10.

8. The glide path of a descending airplane passes through a "decision height" at which the pilot must decide to abort or complete the landing. Category I precision conditions exist when the decision height is 200 feet or above and the runway visual range is 2400 feet or greater.

9. Bedingfield, K.L., R.D. Leach, and M.B. Alexander, *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment,* NASA Reference Publication 1390, August 2006, pp. 1 and 5.

10. Encounters with high-speed streams recur approximately every 27 days during the declining phase of the solar cycle, corresponding to the rotation period of the Sun. The geomagnetic disturbances associated with them are referred to as "recurrent" geomagnetic storms, which differ from CME-driven storms in both their cause and phenomenology. See J.E. Borovsky and M.H. Denton, Differences between CME-driven storms and CIR-driven storms, *J. Geophys. Res.* 111, A07S08, 2006, doi:10.1029/2005JA011447. Instruments in space and on the ground monitor the substorm and energetic electron environments,

which can provide some warning to satellite operators of hazardous conditions. These instruments are distinct from those used to detect large solar flares and CMEs.

11. These examples are drawn from the National Executive Committee for Space-Based Positioning, Navigation, and Timing, available at http://www.navcen.uscg.gov/gps/default.htm.

12. Dow, J.M., R.E. Neilan, and G. Gendt, The International GPS Service (IGS): Celebrating the 10th anniversary and looking to the next decade, *Adv. Space Res.* 36(3), 320-326, 2005, doi:10.1016/j.asr.2005.05.125.

13. Larson, K.M., P. Boudin, and J. Gomberg, Using 1-Hz GPS data to measure deformations caused by the Denali fault earthquake, *Science* 300, 1421, 2003, doi:10.1126/science.1084531.

14. Choi, K., A. Bilich, K. Larson, and P. Axelrad, Modified sidereal filtering: Implications for high-rate GPS positioning, *Geophys. Res. Lett.* 31, L22608, 2004, doi:10.1029/2004GL021621.

15. Bock, Y., L. Prawirodirdjo, and T. Melborne, Detection of arbitrarily large dynamic ground motion with a dense high-rate GPS network, *Geophys. Res. Lett.* 31, L06604, 2004, doi:10.1029/2003GL019150.

3

Space Weather and Society

The impacts of severe space weather events go beyond disruption of existing technical systems and can lead to short- and long-term, collateral socioeconomic disruptions and problems. Both public and private sector organizations need to understand how severe space weather can influence society and how it can be managed so as to mitigate negative effects. The workshop's second session considered past events and potential impacts now and in the future, with consideration given to next-generation systems. The presentations were made by R. James Caverly of the Department of Homeland Security and Todd La Porte, Jr., of George Mason University.

The presenters were asked to respond to these questions:

- What is your assessment of probable or reasonably possible societal impacts (economic and physical) resulting from a significant space weather event?
- What different impacts can you envision in the future with new and expanded technologies, assuming no additional space weather protection?
- What are the key factors in managing socioeconomic impacts of space weather events?

For each of the questions, consider both short- and long-term critical infrastructure outages caused by space weather.

SPACE WEATHER, INFRASTRUCTURE AND SOCIETY

Much of the discussion focused on various types of infrastructure—such as those for communications, electric power, water, banking and finance, and transportation—and the effects on the nation following their disruption for extended periods. Of significant note is the increasing interconnectedness and complexity of most infrastructure, together with ever expanding services dependent on infrastructure.

It was clear from the presentations and discussions in this workshop session that society faces different types of risks due to space weather events now than it did during the Carrington event in 1859. Notable for both its scientific and its technological impact, the Carrington event was probably the most important space weather event of the past 200 years. It initially attracted scientific attention because it disrupted telegraphic communication for as long as 8 hours, presented a visual panoply of nighttime lights to observers, and was widely reported in newspapers. Caverly reasoned that a contemporary Carrington event would lead to much deeper and more widespread social disruptions than those of 1859. Basic to his contention are the enormous changes to the nation's infrastructure over the past century and a half and the virtual certainty of additional changes in the future.

Today scientists have a better understanding of the technical causes and implications of space weather, and even of appropriate technical responses to it, than they did in the past. Knowledge of the social, institutional, and policy implications of space weather is growing but is still rudimentary. The disruption of the telegraph system in 1859 caused problems in communication, but because modern society is so dependent on large, complex, and interconnected technical systems—and because these systems not only are vital for the functioning of the economy but also are vulnerable to electromagnetic events—a contemporary repetition of the Carrington event would cause significantly more extensive (and possibly catastrophic) social and economic disruptions. La Porte said that understanding the consequences resulting from interdependencies of infrastructure disrupted during significant space weather is essential. Caverly stated that although systems may be well designed themselves, there is a need to consider the "system of systems" concept and to examine the associated dependencies in detail. He added that today there is growing awareness among planners, managers, and designers of this necessity.

In a parallel example, Caverly compared the effects of the 1906 San Francisco earthquake to its potential effects today. To better understand this analysis, consider three terms of art: *direct impact* of an event on an infrastructure, *dependency* of one infrastructure on another, and the *interdependency* of an infrastructure on the one it impacts. The 1906 earthquake had enormous direct influence on virtually all the infrastructures of San Francisco. Today such an earthquake would have direct local consequences but the disruptions would also be felt across the country because of the interconnectedness of the national infrastructures (Figure 3.1).

Caverly discussed how a space weather event could have an impact on delivery of electric power. For example, following a power outage, electrified transportation ceases for the duration of the outage. When there is a short-term power outage with rapid restoration, the impacts may be minimal. However, with a long-term outage (say,

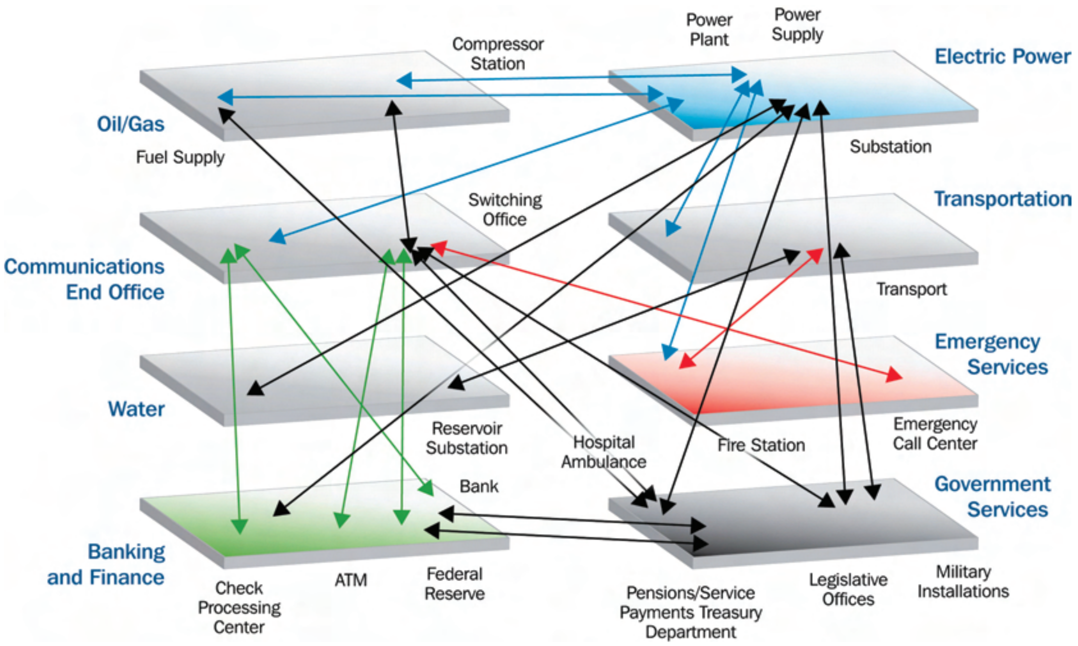


FIGURE 3.1 Connections and interdependencies across the economy. Schematic showing the interconnected infrastructures and their qualitative dependencies and interdependencies. SOURCE: Department of Homeland Security, National Infrastructure Protection Plan, available at http://www.dhs.gov/xprevprot/programs/editorial_0827.shtm.

several days, or perhaps, because of severe equipment damage, even considerably longer), then the loss of power after backup power supplies are exhausted could affect water, communication, banking and finance, and just about every critical infrastructure including government services. Loss of these systems for a significant period of time in even one region of the country could affect the entire nation and have international impacts. For example, financial institutions could be shut down, freight transportation stopped, and communications interrupted, as suggested in Figure 3.1. The concept of interdependency is evident (for example) in the unavailability of water due to long-term outage of electric power and the inability to restart an electric generator without water on-site, supplies of which have been exhausted.

In the discussion following Caverly's presentation, a focus was electric power because of the dependencies of virtually all other infrastructures and services on it and the fact that electric power can be seriously affected by space weather events. Electricity is not storable in form; conversion from other energy sources (e.g., hydro, fossil fuel, nuclear) is required, and the production of electrical energy must be instantaneously matched to the current demand. It is transported via the electric power grids of the United States and Canada, requiring constant attention to many details to assure safe, reliable, secure operations.

As the nation's infrastructures and services increase in complexity and interdependence over time, a major outage of any one infrastructure will have an increasingly widespread impact. For example, the dependence of nearly all critical services on information technology is ever increasing, and the flow of information is itself dependent on communications infrastructure and a reliable supply of electric power. Backup power supplies do exist, but in most cases only for limited periods. Service reliability includes provisioning of backup facilities, which must be sufficiently isolated from each other that a single and perhaps even multiple events would not simultaneously shut down both locations.

Other examples of key infrastructure dependencies discussed by Caverly included the following:

- Loss of key infrastructure for extended periods due to the cascading effects from a space weather event (or other disturbance) could lead to a lack of food, given low inventories and reliance on just-in-time delivery, loss of basic transportation, inability to pump fuel, and loss of refrigeration.
- Emergency services would be strained, and command and control might be lost.
- Medical care systems would be seriously challenged.
- Home dependency on electrically operated medical devices would be jeopardized.

RISK EVALUATION

As infrastructure designers plan ahead for next-generation systems, recognizing the likelihood of greater interconnectedness and complexity, a key design parameter will be resiliency of the systems to both natural and human-induced perturbations. As the systems transition to these newer designs, risk will be evaluated. The NIPP (National Infrastructure Protection Plan) defines "risk" as a function of threat, vulnerability, and consequence: $R = f(T,V,C)$.

Workshop participants discussed broad conceptual approaches to making public infrastructure more resilient to space weather events. These approaches are similar to those identified for ensuring national security and apply to threats of many kinds, including natural and human-induced:

- *Detect.* Identify potential attacks and validate and/or communicate the information, as appropriate.
- *Defend.* Protect assets by preventing or delaying the actual attack, or reducing an attack's effect on an asset, system, or network.
- *Mitigate.* Lessen the potential impacts of an attack, natural disaster, or accident by introducing system redundancy and resiliency, reducing asset dependency, or isolating downstream assets;
- *Respond.* Engage in activities designed to enable rapid reaction and emergency response to an incident, such as conducting exercises and having adequate crisis response plans, training, and equipment; and
- *Recover.* Allow businesses and government organizations to resume operations quickly and efficiently,

such as by using comprehensive mission and business continuity plans that have been developed through prior planning.

As discussed by workshop participants and presenters, all risks cannot be totally eliminated. The goal is to quantify risks and protect against or provide recovery as best possible, recognizing the value of early warnings. Caverly emphasized that meeting these challenges successfully will be greatly enhanced with continued effective partnerships between the infrastructure sectors and federal, state, tribal, and local governments, with international coordination. He concluded with the caution, “We are good at what we know; we are not good at what we don’t know. Planning and preparedness is obviously the key.”

LOW-FREQUENCY/HIGH-CONSEQUENCE EVENTS

La Porte addressed the issue of how well equipped society is to deal with the potential disruptions caused by space weather events and what the institutional implications of such impacts could be. He argued that space weather events are a classical example of what social scientists call a low-frequency/high-consequence (LF/HC) event, that is, an event that has the potential to have a significant social impact, but one that does not occur with the frequency or discernable regularity that forces society to develop plans for coping with the event.[1] The concept of LF/HC events was helpful in giving participants in the workshop a way to think about the social problems associated with and responses to space weather events. La Porte emphasized that this type of event raises a unique set of problems for public (and private) institutions and governance. It requires different types of budgeting and management capability and consequently challenges the basis for conventional policies and risk management. Equally important, he emphasized, is that institutional and social responses to space weather events require a totally different approach than do technical system responses.

La Porte pointed out that most social and political institutions are managed on the assumption that they operate within a universe of constant or reliable conditions. Translated to the realm of space weather, this means that social institutions operate under the assumption that they exist in an environment of consistent geomagnetic conditions. The ability of managers to address long-term problems is dependent on their having the time, leadership, and necessary resources to develop robust solutions. When confronted with a LF/HC solar event, however, the leaders of conventional social and political institutions find that management policies based on assumptions of constancy do not work well. Moreover, because of the interrelatedness of the economic and technical systems in modern society, risks to one part of the broader system tend to affect other parts of the system. Consequently, it is difficult to understand, much less to calculate, the risks of future LF/HC events. Sustaining preparedness and planning for such low-frequency events in future years is equally difficult.

La Porte emphasized that high-reliability systems are dependent on both technical and organizational phenomena. Each requires highly reliable operations, and each involves a wide range of institutions, technologies, and stakeholders, exhibiting the functional differentiation that is characteristic of a complex, interdependent society. In this context, the issues that are of particular importance for management are sustaining policy attention to the issue, developing appropriate regulatory responses, and obtaining technical design options that can minimize or eliminate disruptions due to rare extreme events, such as space weather events.

RESEARCH ON COMPLEX, ADAPTIVE SYSTEMS

La Porte acknowledged that the first response to the prospect of such technical and organizational disruptions is to try to learn to predict anomalies and extreme events, in short, to study space weather. But he argued that to stop there would be shortsighted. He emphasized the critical need to conduct research that enables understanding of how to create and sustain high-reliability organizations or systems that can deal successfully with low-probability issues in a socioeconomic and institutional context. Examples of such organizations include air traffic controller operations, management of electric power grids, and aircraft carriers. Among the research questions that need to be asked is how such organizations come to be dynamic in ways that allow them to absorb changes and challenges from both the technical side and the economic or social environments within which these technical systems operate. These organizations are rare and expensive to maintain, and it is important to understand better how they operate. Institutional learning is generally done through trial and error and in small-scale settings before being expanded to larger-scale settings. But La Porte stressed that a different kind of research is needed to understand integrated technical and socioeconomic systems, including communications, electric power, transportation, logistics, computation, and technical components operating in situations where the totality of the system cannot be modeled. This limitation in modeling complex, interdependent technical and social systems, combined with the fact that scientists can only model the implications of future geomagnetic events and cannot test the systems, raises significant research problems. An additional and critical question for understanding potential socioeconomic consequences of space weather events is how managers and organizations can learn to deal with severe geomagnetic events without directly experiencing them.

Despite these difficulties, there are ways in which organizations can think about adaptation to and management of extreme space weather events. Research on complex adaptive systems has done a great deal to enhance understanding of certain situations, despite the fact that understanding how to deal with unknown and not-yet-experienced situations is still extremely difficult. Auto-adaptive systems in which technical competence is high, organizational capacity is high, and openness to new ideas is high should be studied, although it is extraordinarily difficult to find these three qualities in a single organization. La Porte cited the states of California and Florida as providing good examples of public sector learning in response to unexpected, high-consequence events because of their capacity to respond to earthquakes and hurricanes. He emphasized the roles of political leadership, support from the business community, and the existence of a knowledgeable public in bringing this about.

The second consideration La Porte emphasized is what he and colleagues have written about as the efficiency-vulnerability trade-off. This trade-off operates where technical systems and capitalist market systems intersect. Economic matters tend toward efficiency, and efficiency means that business decision makers and policy makers inevitably have to make budgetary choices among actions with various costs. Rare or uncommon situations that have not occurred in the recent past are viewed as ripe for elimination of “unneeded” costs. Although this approach improves the immediate bottom line, it can significantly hamper robust operations in the future, when the rare event or uncommon situation may actually take place. When these rare events have negative impacts on systems with complex dependencies and interdependencies, businesses, institutions, and governments could find that their capacity to respond effectively has been compromised. Managers might discover too late that the seemingly slack resources that were reprogrammed have been quickly consumed by other uses and lost. Under these conditions, the social response to unexpected space weather events could be inadequate and could lead to other significant socioeconomic problems.

In conclusion, La Porte emphasized the need for more research on issues related to dependency creep and the efficiency-vulnerability trade-off. This is especially important, he argued, for institutions with relative long time horizons. Dependency creep can occur when systems that were developed for one purpose are used by other people for new purposes. That is, existing systems are extended to deal with evolving problems. As a result, new constituents place new demands on the systems and expand them to respond to other issues. Over time, dependency creep can be a significant challenge to both effective policy making and efficient management and operations.

SUMMARY

Severe space weather can induce abnormalities in and can damage modern systems, including economic systems, that constitute the nation’s critical infrastructure. Service disruptions of relatively short or conceivably very long duration may spread from a directly affected system to many other systems due to dependencies and interdependencies among, for example, electric power supply, transportation and communications, information technology, and government services. As systems become more complex and adaptive over time, the social and economic impacts of space weather are likely to increase.

Space weather events may be characterized as low-frequency, high-consequence events. Institutions have developed relatively good ways to prepare for and defend against damaging events that are well understood and likely to occur relatively often. However, low-frequency events, even if the potential damage is great, are typically less well understood and are not given the attention needed to develop complex, costly protection. Speakers in this workshop session emphasized the importance of devoting greater attention to technological, institutional, and management responses to these events, given what is known about space weather events and their potential to have increasingly broader impacts on both technical and socioeconomic systems.

NOTE

1. Perrow, C., *Normal Accidents: Living with High-risk Technologies,* Princeton University Press, Princeton, N.J., 1999.

4

Current Space Weather Services Infrastructure

The goal for the workshop's third session was to identify the space weather products (data, services, and forecasts) that are available, the organizations that provide these products, and the means by which these products are made available to a wide variety of customers. To begin, five panel members, representing various government sectors of the U.S. and European space weather community, were invited to provide their perspectives. The panel included O. Chris St. Cyr and Charles Holmes, both from NASA; William Murtagh of the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA); Major Herbert Keyser from the U.S. Air Force (USAF) Director of Weather's office; and Michael Hapgood of the Science and Technology Facilities Council's Rutherford Appleton Laboratory. These speakers were asked to provide a review of current space weather resources and services along with their understanding of which elements are most important and which may be missing or require substantial effort to meet customers' expressed needs and expectations. To aid in the preparation for the workshop, each of the speakers was asked to answer the following questions:

1. What current data sources and services infrastructure are used or provided by your organization(s)?
2. What space weather services (including data) are provided? Identify which are situational awareness (nowcasting) services and which are forecasting services.
3. What models and tools do you use to provide your services? Identify which are physics based, expert system based, neural network based, empirically based, and so on.
4. Who are your primary customers?
5. What is the latency of the services relative to real time? For the forecasting services, what is the prediction window?

Two additional questions were specifically addressed to the NASA representatives:

6. Will NASA provide its own space weather monitoring for the exploration missions or will it also rely on support from others such as NOAA?
7. Does NASA plan to help with the transfer to operations of the results from the theory and modeling programs it supports?

These questions, and the answers and comments presented in this chapter, helped to clarify the existing status of space weather resources, how they can be accessed, and what is needed to maintain them. At times, the questions and comments from the audience extended somewhat beyond the session's main purpose to address, for example, the issue of how new forecasters can be attracted and educated to maintain the staffing of the infrastructure.

SPACE WEATHER DATA, INFRASTRUCTURE, AND SERVICES PROVIDED FOR SPACE WEATHER SITUATIONAL AWARENESS AND FORECASTING

NASA and NOAA Roles

Space weather data are currently provided by assets controlled by government organizations in both the civilian (primarily NASA and NOAA) and the defense sectors (primarily the USAF). NASA relies on a fleet of spacecraft in Earth orbit as well as in orbits around the Sun at 1 AU. See Figure 4.1. Although the NASA missions are all primarily for scientific research, they provide much of the space weather data used by both civilian and military customers. NASA space missions track solar disturbances from their sources on the Sun, follow their propagation through the heliosphere (i.e., interplanetary space), and measure their impacts at Earth. The satellites use a combination of remote sensing observations of the Sun and direct in situ measurements of the solar wind.

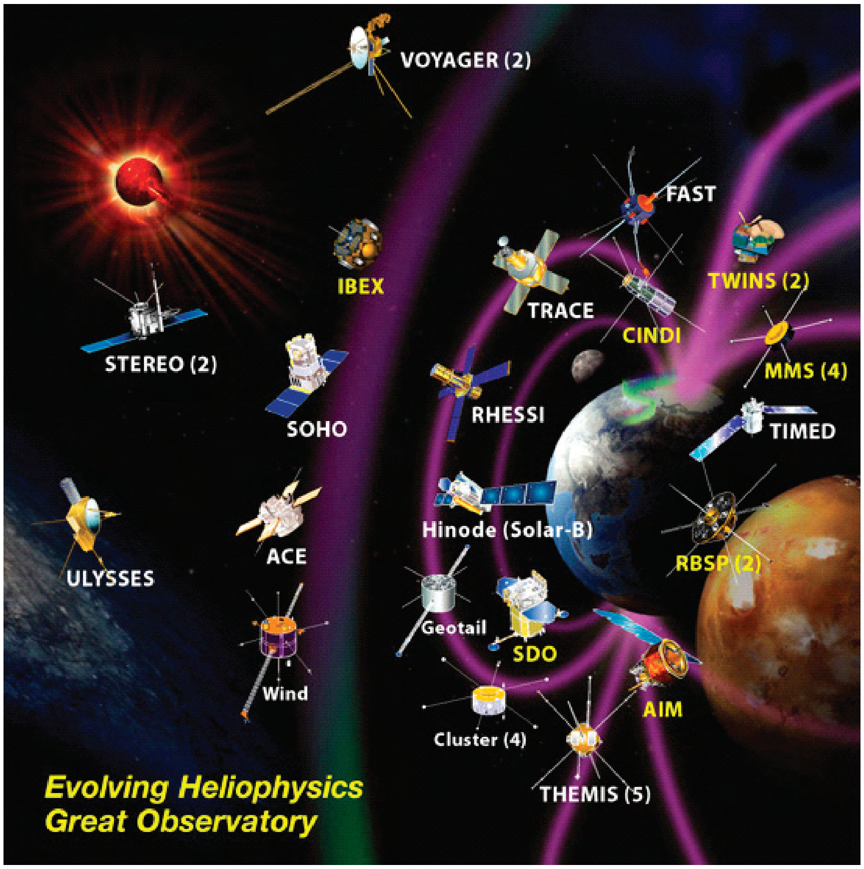


FIGURE 4.1 Missions collecting heliophysics data. SOURCE: O.C. St. Cyr, NASA-GSFC, "Current Space Weather Services," presentation to the space weather workshop, May 22, 2008.

The Earth-orbiting spacecraft take critical measurements of space weather effects in Earth's magnetosphere and ionosphere. In addition, numerous ground-based observatories provide data for characterizing space weather conditions and effects.

NASA's role in space weather was discussed by St. Cyr (NASA/Goddard) and Holmes (NASA Headquarters). St. Cyr noted that although NASA missions are driven by scientific priorities, these missions can and do supply substantial and critical space weather information. However, NASA does not provide space weather situational awareness (SA)[1] and forecasting services. NASA does have strong theory and modeling programs that are attempting to produce physics-based models that can be used in the development of forecasting and SA tools. As such, at NASA, heliophysics is the science behind space weather. St. Cyr emphasized NASA's research-to-operations challenge that foresees the adoption of a distributed sensor network coupled to future large-scale data-assimilation space environment models. He pointed to NASA's support for the development of space-based sensors that make many of the measurements needed for space weather applications and noted that many are developed for the first time at NASA and then transitioned to operations with other agencies. In many cases, the data returned from NASA's near-Earth and interplanetary missions, especially ACE and SOHO (in cooperation with the European Space Agency) are used for space weather analysis. Providing a data beacon on ACE so that its summary data could be made available to organizations, like NOAA SWPC, created the ability to generate new forecasting and SA services. Holmes noted that NASA has deployed beacons on the currently operating Solar-Terrestrial Relations Observatory (STEREO) spacecraft. NASA would like to provide beacons, wherever feasible, on its future satellite missions such as the Radiation Belt Storm Probe (RBSP) and the Magnetosphere Multi-Scale (MMS) mission. He also noted that NASA, which operates a large fleet of spacecraft affected by space weather, is developing requirements in an ongoing study that is examining the current status of SA services and forecasting and is looking at how these activities can be improved using today's knowledge. One of the primary questions the study will address is what is needed from the space weather perspective if NASA sends humans back to the Moon and to Mars.

Holmes described the linkages between the existing Heliophysics Great Observatory, the data it provides, and the science being developed by using these data. This science provides the necessary basis for space weather SA and forecasting. He pointed out a relatively recent development from SOHO that improves the ability to predict solar radiation storms. A new data analysis technique allows electron particle flux measurements from the COSTEP sensor to be used to predict the arrival times of MeV protons from solar events. This science result has now been turned into a near-real-time capability to forecast the arrival of solar protons in near-Earth space where these protons can harm satellites and humans. He also emphasized that in time, as the STEREO Behind spacecraft gets farther away from the Earth-Sun line, as shown in Figure 4.2, it will provide a view of solar disk features about a week or more in advance of when they will be visible from Earth. Combining the STEREO Ahead and Behind views with the SOHO view (on the Earth-Sun line) currently provides NOAA and Air Force Weather Agency (AFWA) forecasters with a nearly 360° view of the solar surface. These data can be used to forecast when active regions on the Sun will be in a position to affect Earth, should they erupt. He then noted that when launched the Solar Dynamics Observatory (SDO) will provide continuous space weather data with only a 15-minute delay. Thus data from solar eruptions and their evolution will be available to forecasting models in near-real time. The SDO project has been working with the forecast community to identify the useful data content, and to show how the SDO data can be accessed.

As mentioned above, NASA spacecraft provide sources of raw data that are used directly by customers to access space weather SA. However, these data are also used by the NOAA National Weather Service (NWS) SWPC, the USAF, and European organizations to produce more refined, long-term forecasting products.

The NOAA SWPC has primary responsibility for the civilian communities' operational space weather products and forecasting services. Murtagh noted that NOAA SWPC provides multiple watches, warnings, alerts, and summaries to inform the user communities. These notices are often automatic responses to expected disturbances that are forecast based on past experience and current data. These may be general, such as expectations that there may be a solar event based on structures observed on the solar disk. In such cases, the notice identifies which data generated the concern and provides some limited information on the basis for the forecast. Watches are used for making long-lead predictions of geomagnetic activity. Warnings are used to raise customers' level of alertness based on an expectation that a space weather event is imminent. Alerts indicate that the observed conditions,

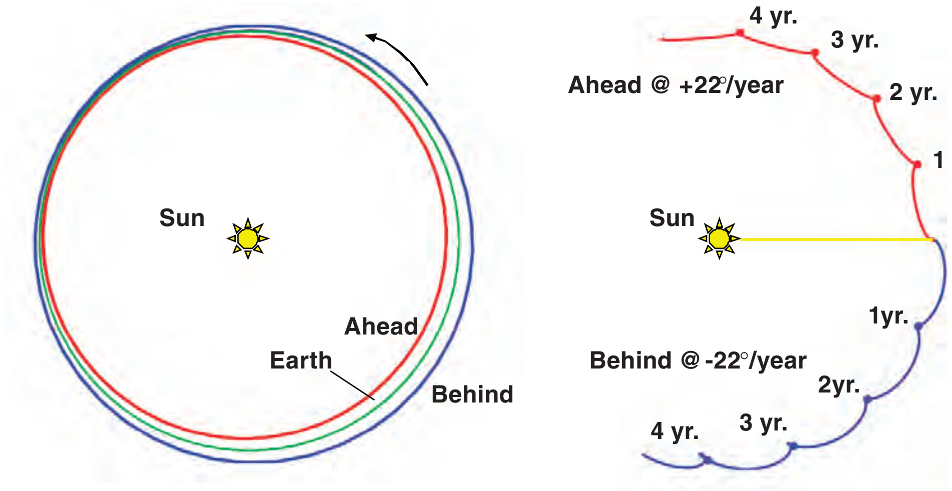


FIGURE 4.2 STEREO orbits. *Left:* Heliocentric inertial coordinates (ecliptic plane projection). *Right:* Geocentric solar ecliptic coordinates, fixed Earth-Sun line (ecliptic plane projection). SOURCE: Charles P. Holmes, NASA Heliophysics Division, Science Mission Directorate, "NASA's Heliophysics Great Observatory," presentation to the space weather workshop, May 22, 2008.

highlighted by the warnings, have crossed a preset threshold or that a space weather event has already started. Finally, summaries are issued to keep customers informed about the progress of the event and to characterize the event once it has ended.

NOAA SWPC also provides 39 types of event-driven space weather operational products—50 percent from GOES; 38 percent from ground-based magnetometer measurements; 7 percent from the USAF's ground-based Solar Electro-Optical Network (SEON), which comprises the Solar Optical Observing Network (SOON) and the Radio Solar Telescope Network (RSTN); and 2 percent from NASA's ACE spacecraft, as shown in Figure 4.3. NOAA requires that primary data sources be real time and continuous, and that they have redundancy. This requirement is not met for most of the NASA research missions with the exception of ACE. ACE provides data to NOAA from its position at the L1 Lagrangian point between the Sun and Earth. It is a primary data source for measurements of solar particles and magnetic fields. ACE provides a critical ~45-minute advance warning before a coronal mass ejection (CME) strikes Earth. The lack of a primary source of continuous coronagraphic observations like those provided by SOHO/LASCO puts NOAA in a vulnerable situation. Without a solar coronagraph it would be difficult to predict the properties and trajectories of CMEs that are responsible for large geomagnetic storms.

NOAA forecasters use different scales and categories to characterize the magnitude and impact of space weather events in much the same way as meteorologists use intensity scales for hurricanes and tornados. For example, NOAA uses the R-scale, for radio blackouts based on solar x-ray flux from GOES, to characterize the level of interruption of communication in frequency ranges affected by the solar radio flux. NOAA also characterizes the magnitude of solar proton events and magnetic storms using the S-scale and the G-scale. These space weather scales are described in detail on NOAA's website (see http://www.swpc.noaa.gov/Data/) and are summarized in Table 4.1.

NOAA's team of space weather forecasters uses more than 1,400 different types of data from NOAA, NASA, the USAF, and the USGS and other space- and ground-based platforms around the world, providing a variety of products and services for the worldwide space weather community via the NOAA website, by anonymous FTP server, and, for subscribers, as e-mail messages. The products are presented to the customer both graphically and textually. Twenty-four space weather alerts and 12 selected products are also available via the NOAA Weather Wire, the NWS direct broadcast system. The products and alerts available via Weather Wire are described on an

Primary	Secondary
GOES	SOHO/LASCO
POES	SOHO/EIT
Boulder/Fredericksburg magnetometers	STEREO
ACE	Ground- and space-based observatories (research focus)
SEON (SOON and RSTN)	Ground-based magnetometers
	Neutron monitors and riometers

Total Event-Driven Products = 39

• Boulder magnetometer	15
• GOES	20
• SEON	03
• ACE	01

FIGURE 4.3 Space weather data sources. Primary data sources, which are required for driving operational products, must be real-time and continuous. Secondary data sources are used to enhance products. SOURCE: William Murtagh, NOAA Space Weather Prediction Center, "Current Space Weather Services Infrastructure," presentation to the space weather workshop, May 22, 2008.

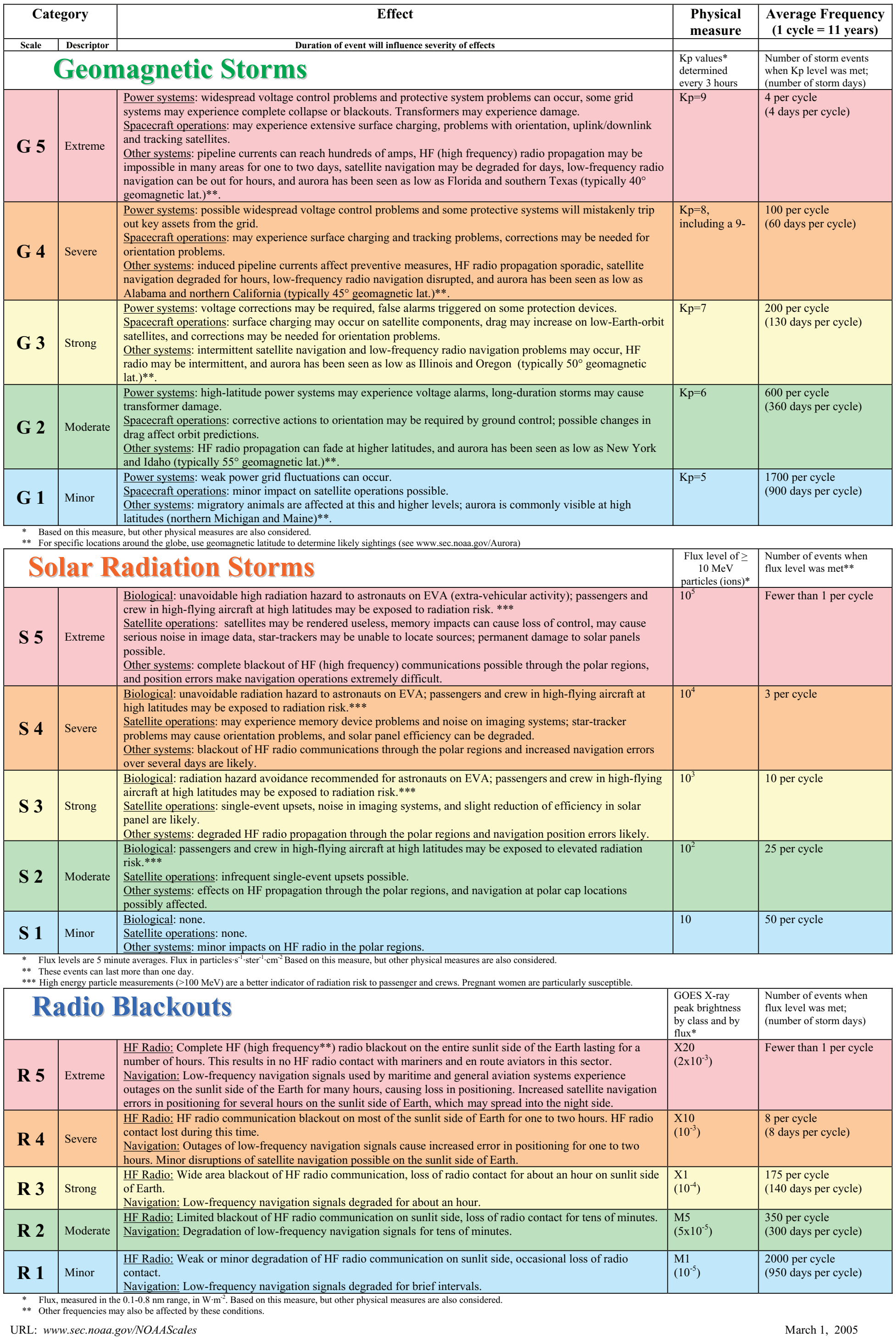
associated website (see http://www.swpc.noaa.gov/wwire.html). In addition to giving a view of the current situation, or now-casting, NOAA's products also provide near-term (hours to days) and long-term (months to years) forecasts and trends. An example of the latter is the forecast that attempts to project the duration of space weather events and, for solar events, provide some guidance relative to delayed effects like magnetic storms that are often generated by the resultant disturbed and enhanced solar wind. Another example is the use of GOES measurements to make 24- to 48-hour advance predictions of trapped radiation fluxes at geosynchronous orbits.

Department of Defense Efforts

The Department of Defense (DOD) is both a user and a supplier of space weather information. Herbert Keyser noted that presidential policy makes the DOD responsible for protecting U.S. space-based activities. This makes it of utmost importance for the DOD to elevate the capabilities of its space weather systems and improve the quality of its products. Within DOD, the USAF is the lead organization for space weather activities. The Air Force uses space-based observations from satellites operated by the Defense Meteorological Satellites Program (DMSP), the Defense Support Program (DSP), and the Communications/Navigation Outage Forecast System (C/NOFS), to name a few. The Global Positioning System (GPS) network is used to provide data on the total electron content (TEC) of the ionosphere. Ground-based measurements provided by the USAF currently include those made by the Solar Optical Observing Network (SOON), Radio Solar Telescope Network (RSTN), and Digital Ionospheric Sounding System (DISS). In the near future, the Improved SOON (ISOON) will replace the SOON, and the Next Generation Ionosonde (NEXION) sensors will replace the DISS. Most of these facilities operate 24 hours per day or, in the case of the solar observatories, from sunrise to sunset.

To meet its DOD customers' needs for space weather data and products, the Air Force combines NOAA's data with data from its own sources. For example, the NOAA data products are used by the specialists at AFWA to provide assessments of the impacts of space weather on many different DOD "missions," a mission being a task that needs to be performed to support DOD activities. Keyser described five example mission areas that are affected by space weather: geolocation, communications, satellite operations, space tracking, and navigation. To perform these missions with high reliability requires knowledge of the ionospheric electron content, ionospheric disturbance levels, energetic particles, radiation disturbances, and magnetic disturbances, respectively. Ionospheric

TABLE 4.1 NOAA Space Weather Scales



Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.sec.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·ster^{-1}·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in W·m^{-2}. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

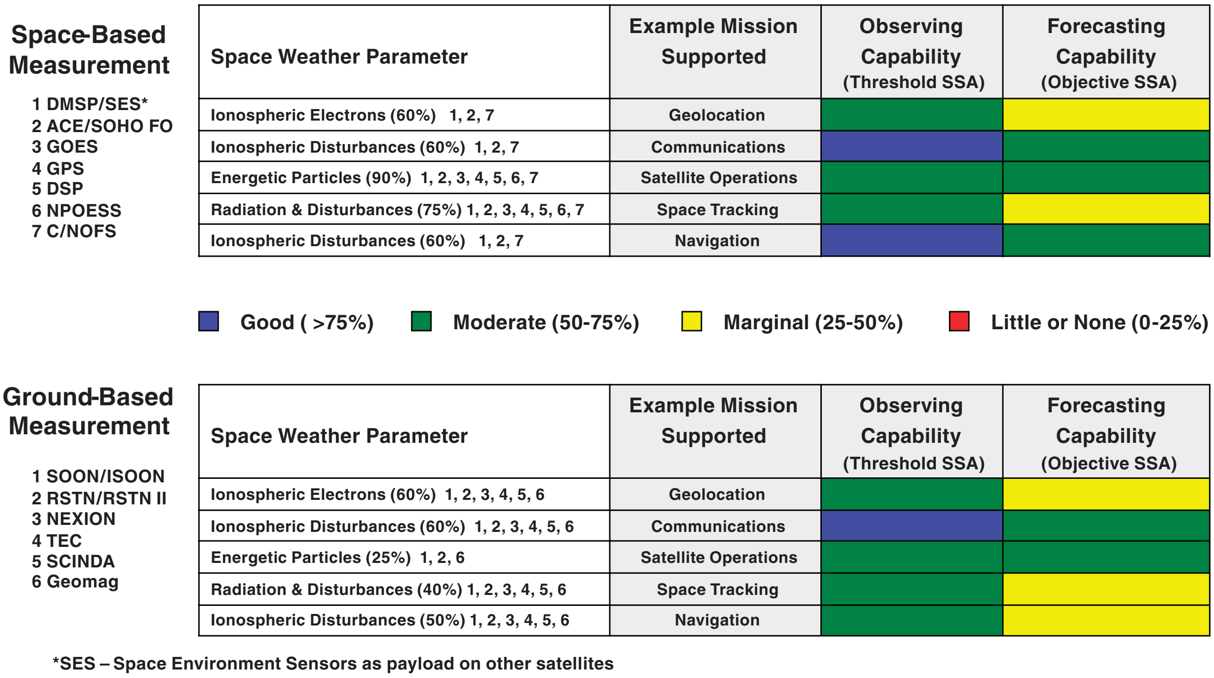
URL: *www.sec.noaa.gov/NOAAScales* March 1, 2005

SOURCE: NOAA Space Weather Prediction Center; see http://www.swpc.noaa.gov/NOAAscales/.

disturbances affect both communications (because of signal fade, degradation, and loss) and navigation (GPS signal degradation) in much the same way. Figure 4.4 summarizes the sources and types of space weather measurements that are needed to support each of those five military mission areas.

Keyser indicated that, in addition to the missions and products shown in Figure 4.4, the overarching mission is to be able to distinguish between natural and man-made problems with U.S. technologies and systems—i.e., are the "bad guys trying to prevent us from doing what we want to do." The Air Force has to be able to attribute problems with systems to one of three categories: hardware and software failures, space weather effects, or any direct attacks on the systems. For example, was a solar radio burst or a thunderstorm the cause of a communication problem, or was it caused by someone trying to deny the use of the communication band? He noted, "If we can get to the point where we can plan and forecast space weather, . . . then we can mitigate these problems and possibly even exploit the advantage that we would have."

Given the Air Force's desire for products to enable the above missions, Keyser outlined current capability levels using a color-coded scale, as shown in Figure 4.4. In addition, he discussed different space weather effects in relation to impacts and indicated how AFWA forecasters generated their products, some of which include the following: ionospheric analyses, 24-hour forecasts, HF communications and geolocation error analyses, and auroral impacts on operations. It was immediately clear that much of the forecasters' output was based on "rules of thumb" and statistical relationships. It was also clear from Keyser's presentation that many of the products were useful for now-casting, rather than forecasting, space weather events. To date, physical models are not routinely used, but AFWA is making progress on space environment models (see the section titled "Space Weather Models and Tools" below). AFRL R&D work is progressing but needs more funding to transition these elements to operations. For example, AFWA incorporated the GAIM (Global Assimilation of Ionospheric Measurements) model into its operations a year and a half ago. Such tools can make a great difference for the DOD. Keyser noted that



Space-Based Measurement

1 DMSP/SES*
2 ACE/SOHO FO
3 GOES
4 GPS
5 DSP
6 NPOESS
7 C/NOFS

Space Weather Parameter	Example Mission Supported	Observing Capability (Threshold SSA)	Forecasting Capability (Objective SSA)
Ionospheric Electrons (60%) 1, 2, 7	Geolocation	🟩	🟨
Ionospheric Disturbances (60%) 1, 2, 7	Communications	🟦	🟩
Energetic Particles (90%) 1, 2, 3, 4, 5, 6, 7	Satellite Operations	🟩	🟩
Radiation & Disturbances (75%) 1, 2, 3, 4, 5, 6, 7	Space Tracking	🟩	🟨
Ionospheric Disturbances (60%) 1, 2, 7	Navigation	🟦	🟩

🟦 Good (>75%) 🟩 Moderate (50-75%) 🟨 Marginal (25-50%) 🟥 Little or None (0-25%)

Ground-Based Measurement

1 SOON/ISOON
2 RSTN/RSTN II
3 NEXION
4 TEC
5 SCINDA
6 Geomag

Space Weather Parameter	Example Mission Supported	Observing Capability (Threshold SSA)	Forecasting Capability (Objective SSA)
Ionospheric Electrons (60%) 1, 2, 3, 4, 5, 6	Geolocation	🟩	🟨
Ionospheric Disturbances (60%) 1, 2, 3, 4, 5, 6	Communications	🟦	🟩
Energetic Particles (25%) 1, 2, 6	Satellite Operations	🟩	🟩
Radiation & Disturbances (40%) 1, 2, 3, 4, 5, 6	Space Tracking	🟩	🟨
Ionospheric Disturbances (50%) 1, 2, 3, 4, 5, 6	Navigation	🟩	🟨

*SES – Space Environment Sensors as payload on other satellites

FIGURE 4.4 Space weather capability needs. SOURCE: Herbert Keyser, USAF, "Space and Intel Weather Exploitation," presentation to the space weather workshop, May 22, 2008.

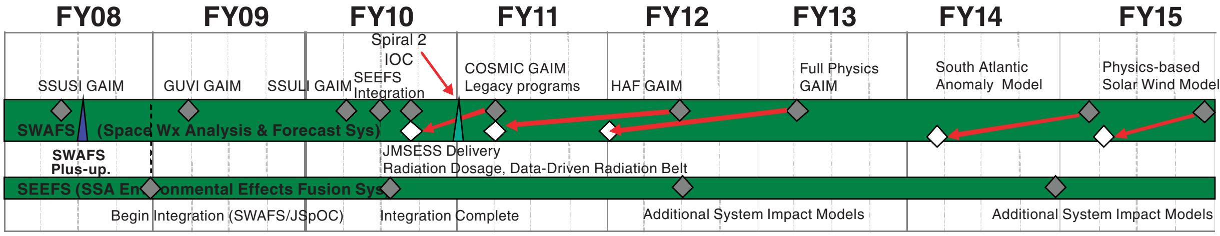


FIGURE 4.5 Current and planned space weather tools and models. SOURCE: Herbert Keyser, USAF, "Space and Intel Weather Exploitation," presentation to the space weather workshop, May 22, 2008.

the output of such tools could be used to tell an HF or special operations user that conditions are going to require a backup system, for example.

The DOD is striving to increase the sampling of the space weather environment for the coming solar maximum (in 2011-2012) and beyond. NPOESS was supposed to do this by gradually replacing the role now performed by the DMSP satellites. However, the loss of all but one of its space weather sensors due to the Nunn-McCurdy Act means that there will be a gap in the space weather coverage starting at about 2016 if the loss of NPOESS sensors is not addressed. Keyser suggested that the best way to fix this situation is to invest more in partnerships with other agencies. He noted, for example, that "NSF has some great capabilities in their solar observatories. They have their science mission, and we don't want to impinge on that. However, at the same time we could both benefit from a little bit of investment on our part to get an operational use at the end of the day."[2] In addition, the Air Force's plan to enhance its capabilities to observe ionospheric weather includes leveraging "additional ionosondes fielded by the National Science Foundation, NOAA, and international partners." Finally, Keyser presented a schedule (Figure 4.5) showing the current status of USAF-developed tools and models, and their near-term products. Also identified were the tools and models that are expected to be implemented or available in the period from FY 2009 through FY 2015.

European Programs

Space weather, a global phenomenon that spans national boundaries, is a challenge best met by international cooperation. In this regard the committee sought to obtain information on the experiences of European colleagues. Hapgood presented a summary of the space weather programs in Europe, a mix of activities funded at national and European levels. The European-level activities are divided mainly between the European Union (EU) and the European Space Agency (ESA). The programs are a mix of research and operational activities from 25 countries in the EU and 17 countries involved in ESA. Hapgood described the space weather landscape in Europe as "complicated" and "very fragmented." In addition, there is a large overlap of activities since many of the newest EU members are not a part of ESA. It should be noted that Canada, while not in Europe, is an associate member of ESA. In many ways, ESA is an analog to NASA with overtones of the National Science Foundation. ESA is funded by the member countries. When it comes to providing space weather services there is a cross-national perspective. In general the cross-national activities focus on the front-end services, i.e., the services that take data from sensors and deliver products, according to Hapgood. He provided a chart (reproduced as Figure 4.6) that showed many of the elements of the European space weather landscape. He noted that most of the communication occurs at the level of the boxes in Figure 4.6 marked DIAS, COST 296, and so on. (The COST designation is an acronym for Cooperation in Science and Technology.) The COST 724 (Space Weather Prediction Team) shown near the center of Figure 4.6 is being reformed, and Hapgood, the head of the SWWT (Space Weather Working Team) in the area of space weather prediction services, thinks that it will receive a new approval to go forward.

The most important element in Figure 4.6, according to Hapgood, is the SWENET (Space Weather European Network), originally funded by ESA and still being provided some support by ESA as an R&D activity. SWENET

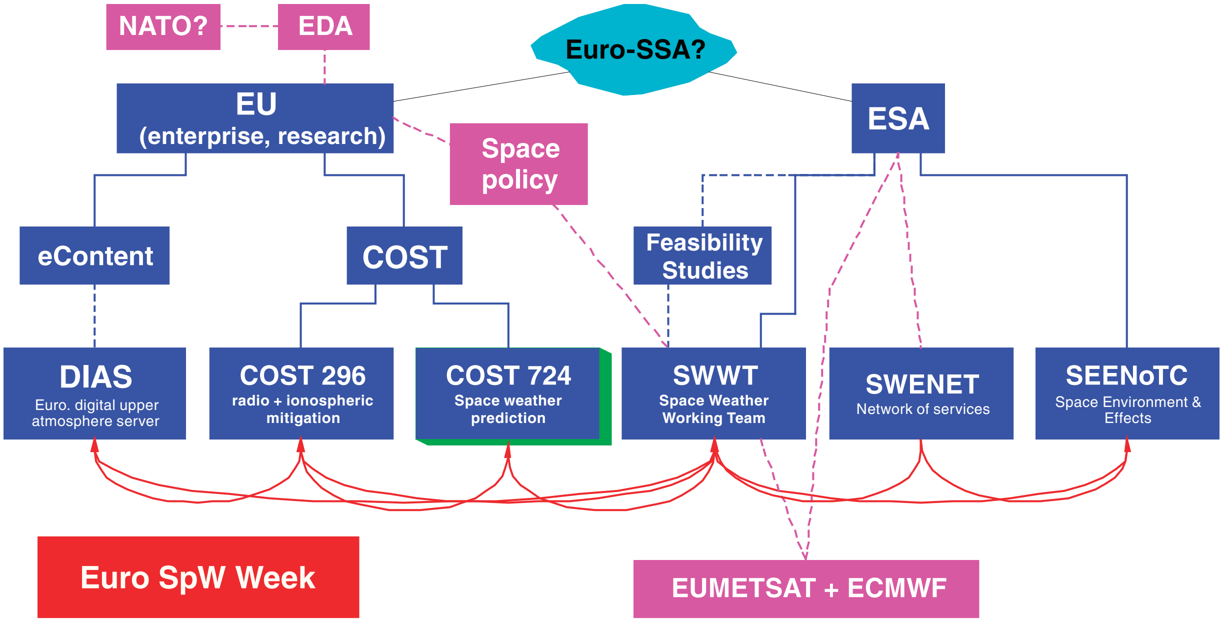
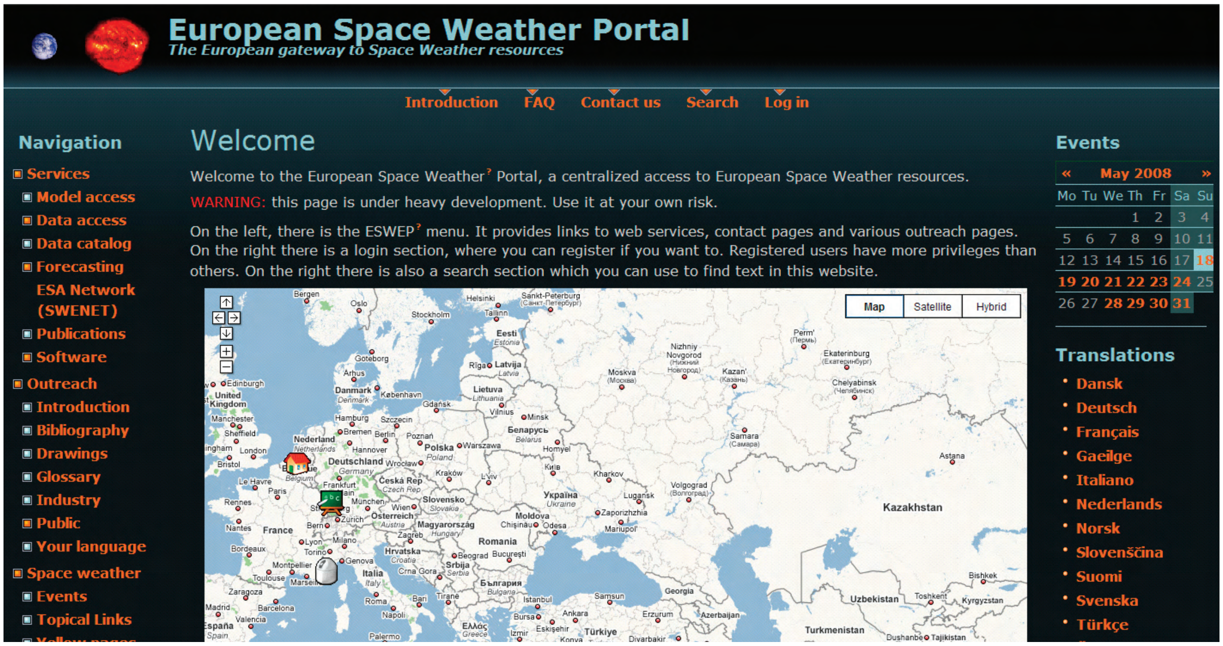


FIGURE 4.6 Some elements of European space weather infrastructure. SOURCE: Michael Hapgood, STFC Rutherford Appleton Laboratory, "Current Space Weather Services Infrastructure in Europe," presentation to the space weather workshop, May 22, 2008.

offers a way of federating a significant number of space weather services around Europe, between 25 and 30 at the moment. Its website (http://esa-spaceweather.net/swenet/ index.html) provides space weather data and data analysis with links to the NOAA SWPC website. SWENET services are organized into three categories: ground effects, ionospheric effects, and spacecraft effects. Under each category are multiple elements such as nowcasts, forecasts, and simulation outputs. Each is listed under a shorthand acronym that is often not self-explanatory. However, clicking on the elements takes the user to the site that developed the tool and identifies which institute hosts the content. The tools are generally developed by different research institutes within Europe. For example, the GIC (ground induced current) forecast was developed by the Swedish Institute of Space Physics (IRF) and is a prototype service that forecasts the rate of change of the local geomagnetic field, the ground electrical field, and GICs every 10 minutes. Since ESA is an R&D agency, the SWENET will ultimately reside outside ESA. There are also plans for a European space situational awareness (SAA) program being developed at ESA. That program could be a possible home for SWENET. The SAA activity will be federating existing assets, and so all the smaller national programs could be put into a larger context. A meeting is planned for November 2008 at which the ministries of 25 to 30 nations will vote on the legal framework for SSA.

European data sources for space weather measurements are fairly limited. Most of the space-based measurements are by-products of science research programs supported by ESA and the national space agencies. Two examples of instruments that can provide space weather data are (1) the Sun Watcher with AP-sensors and image processing (SWAP) on the Proba-2 mission and (2) the Heliospheric Imagers (HI) on the twin STEREO spacecraft. These instruments can provide warnings of flares and coronal mass ejections from the Sun. ESA is also interested in placing low-cost space radiation monitors on as many spacecraft as possible. In addition, there are many ground-based measurement systems located in Europe. These include magnetometers, neutron monitors, GPS receivers (for TEC and scintillation measurements), and ionosondes (for density and drift velocity measurements). A 2001



Welcome to the European Space Weather^2 Portal, a centralized access to European Space Weather resources.

WARNING: this page is under heavy development. Use it at your own risk.

On the left, there is the ESWEP^2 menu. It provides links to web services, contact pages and various outreach pages. On the right there is a login section, where you can register if you want to. Registered users have more privileges than others. On the right there is also a search section which you can use to find text in this website.

FIGURE 4.7 Space Weather Portal web page. SOURCE: Cost 724, ESA and BIRA-IASB. Reprinted with permission.

survey found ground-based space weather measurements provided by 20 countries, with France, Germany, Italy, and the U.K. providing the most measurements.

Hapgood discussed in some detail a Web facility known as the European Space Weather Portal (http://www.spaceweather.eu/), the entry Web page to which is shown in Figure 4.7. He noted, “This is a bottom-up initiative from the community to create a website that links into all kinds of space weather services across Europe.” It came out of the COST 724 initiative shown in Figure 4.6 and is currently in development. Examples of the types of models being developed are the exospheric solar wind model and a plasmapause location model. Both of these models provide proxies for observables that would be used by higher-level models that generate specific space weather products.

Hapgood’s analysis of the infrastructure for the European space weather community indicated that it has strengths in terms of the skills provided by the space science and engineering community, but also some major weaknesses, including the following: (1) the programs are fragmented, (2) there is limited awareness among the decision makers (who ultimately control the budgets), (3) many of the products are of poor quality, and (4) space weather is still seen as being a part of astronomy. Three threats were also identified: (1) the fragmented nature of the programs leads to piecemeal funding cuts, (2) there is competition with other areas of astronomy, and (3) many still view the space between the planets as empty and therefore harmless. Finally, several opportunities were suggested by Hapgood: (1) there is a strong case to be made for organizing in a global context, (2) better services can be provided through networking, and (3) the quality of space weather products should be improved.

SPACE WEATHER MODELS AND TOOLS

Speakers for this workshop session were asked about which models and tools are in use by the space weather forecasting community and whether these are empirical or physics-based. Speakers from NOAA and the USAF stated that the majority of their models are empirically based. Such models are inexpensive to operate, are easy to use, and have shorter computer run-times compared to the more theoretical models. However, efforts are under way by NOAA SWPC, AFWA, and other organizations to replace some of these models with physics-based models, which ultimately will be preferred because they represent a deeper understanding of cause-and-effect relationships. Physics-based models also have the potential to reduce the uncertainty in space weather forecasts. One program involved in this endeavor is operated by the Community Coordinated Modeling Center (CCMC), a multiagency partnership tasked with supporting the development, testing, and evaluation of advanced space weather models. The state-of-the-art CCMC models are used by both the science community and the space weather forecasting community, mainly for research purposes. One challenge is to identify the most useful models, simplify them, and make them more operationally friendly.

NOAA uses its own models and tools to obtain additional lead time or to improve the accuracy of its space weather warnings and watches. Some examples of the space weather models used at SWPC are highlighted below.[3]

- The *D-region Absorption Prediction model* predicts the impact of solar x-ray flares on the radio propagation characteristics of the ionosphere. This empirically based model is used extensively by the airlines in monitoring high frequency (HF) radio communications blackouts.
- The *Storm-time Ionospheric Correction model* provides information on departures from the normal F-region critical frequency in 20° latitude bands starting from +/− 20° geomagnetic latitude and increasing to the poles. The model provides a convenient tool for estimating the response of the ionosphere to geomagnetic activity.
- The *U.S. Total Electron Content tool* is a model for deriving the vertical and slant TEC over the continental United States in near-real time. This empirical tool is used to estimate the delays in GPS signals due to the changes in the electron content of the ionospheric path between the GPS satellite and the receiver.
- The *Wang-Sheeley-Arge (WSA) model* is used to predict the solar wind speed and the polarity of the interplanetary magnetic field (IMF) at Earth. These are two important quantities for determining the severity of geomagnetic disturbances caused by solar wind and CME events. The model uses data from solar magnetograms, the solar wind speed observed by the ACE spacecraft, and a potential field model to estimate the divergence of the solar magnetic field. Predictions of the solar wind speed and IMF polarity from 1 to 7 days in advance are routinely made with the WSA model.

DOD space weather models are supported by NASA Headquarters, the USAF Weather Agency, and the Air Force Space Command (AFSPC). AFWA supports the Space Weather Analysis and Forecast System (SWAFS) that uses data and models from a variety of space weather sources. The current models used for SWAFS are empirical models, but ultimately SWAFS will use physics-based models for the global ionosphere, South Atlantic Anomaly, and the solar wind. The SWAFS models are currently being integrated into the AFSPC's Space Situational Awareness Environmental Effects Fusion System (SEEFS). SEEFS provides more than near-real-time space weather conditions to operational users; it also provides system impact assessments so that operators can know when they have to switch to backup systems. Planned DOD investments in models, applications, graphics, data fusion, and decision aids will improve operational space weather support.

In Europe, space weather services are being coordinated and made available through the community-wide European Space Weather Portal noted above (see Figure 4.7 and its associated website address). Most of the models appear to be empirically based models, with physics-based models being developed.

CUSTOMERS FOR CURRENT SPACE WEATHER SERVICES

Workshop panel members indicated that their space weather customers are incredibly varied, ranging from those that want very specific and tailored products to those that are unsure about what they want or need. In all cases, speakers indicated that they are prepared to meet their customers' needs or to learn what is missing and what can be done to better define the needs. In some cases the service providers have customers within their own organization—for example, NASA needs space weather services to support its high-altitude aircraft and spaceflight missions. In many cases the necessary data services are being provided from other NASA missions. Ultimately, the workshop panelists from NASA's Heliophysics Division felt that their primary customers were the heliospheric science community. However, they also indicated that NASA missions from other directorates, such as those that support human and robotic explorers, those that provide launch activities, and those that support and operate NASA's fleet of spacecraft, are also users of space weather data provided by the Heliospheric Division. As noted above, St. Cyr discussed the fact that within NASA a study is in progress to understand and define the requirements for all such mission support.

Murtagh presented a list of SWPC's primary customers. Figure 4.8 shows a range of impact areas with examples of specific customers from those areas, as well as types of actions that customers take in response to SWPC alerts and examples of the possible costs incurred by not taking such action. Figure 4.8 illustrates a need being fulfilled and the importance of the SWPC's products to a very wide community. However, Murtagh also indicated (during the question-and-answer period) that more sophisticated services were being left up to commercial industry. Space weather data are gathered, reduced, and presented by NOAA SWPC along with some general products. However, it is up to private industry to develop the specialized products that target specific needs for specific customers. These products and services often use products that are generated by NOAA SWPC. However, NOAA SWPC does not compete with private industry in this activity.

Hapgood provided examples of users for the three types of services available from the SWENET website discussed above. For the ionospheric services, he identified users from the GPS, HF radio systems (aviation, military, amateurs), and science communities. For geomagnetically induced currents and ground effects services, he identified the power grids of Scandinavia and Scotland, oil and mineral surveyors, and pipeline operators as users.

EACH MONTH AT SWPC

- **400,000 Unique Customers**
- **50,000,000 File Transfers**
- **120 Countries Represented by Users**
- **67,500,000 Web Hits**
- **0.3 TBytes of Data Downloaded**

Impact Area	Customer (examples)	Action (examples)	Cost (examples)
Spacecraft (Individual systems to complete spacecraft failure; communications and radiation effects)	• Lockheed Martin • Orbital • Boeing • Space Systems Loral • NASA, DoD	• Postpone launch • In orbit - Reboot systems • Turn off/safe instruments and/or spacecraft	• Loss of spacecraft ~$500M • Commercial loss exceeds $1B • Worst case storm - $100B
Electric Power (Equipment damage to electrical grid failure and blackout conditions)	• U.S. Nuclear Regulatory Commission • N. America Electric Reliability Corp. • Allegheny Power • New York Power Authority	• Adjust/reduce system load • Disconnect components • Postpone maintenance	• Estimated loss ~$400M from unexpected geomagnetic storms • $3-6B loss in GDP (blackout)
Airlines (Communications) (Loss of flight HF radio communications) (Radiation dose to crew and passengers)	• United Airlines • Lufthansa • Continental Airlines • Korean Airlines • NavCanada (Air Traffic Control)	• Divert polar flights • Change flight plans • Change altitude • Select alternate communications	• Cost ~ $100k per diverted flight • $10-50k for re-routes • Health risks
Surveying and Navigation (Use of magnetic field or GPS could be impacted)	• FAA-WAAS • Dept. of Transportation • BP Alaska and Schlumberger	• Postpone activities • Redo survey • Use backup systems	• From $50k to $1M daily for single company

FIGURE 4.8 Examples of customers and impact areas for space weather data. SOURCE: William Murtagh, NOAA Space Weather Prediction Center, "Current Space Weather Services Infrastructure," presentation to the space weather workshop, May 22, 2008.

Finally, for the spacecraft effects services, he identified satellite operators, like the European Satellite Operations Centre, as users.

Keyser indicated that the entire DOD was his user and did not make distinctions between the different parts. In that sense, the DOD is its own customer and the AFWA is the primary source of its space weather services. He did note that the Air Force was given the responsibility for protecting all U.S. space assets. The primary DOD customers are organizations that provide or use geolocation, communications, navigation, space operations, and space object tracking services.

LATENCY OF SERVICES AND FORECAST WINDOWS

The workshop panel speakers did not explicitly answer the question about the latency of their services relative to real time, but some information can be gained from the websites they supplied. Typically, data from NASA research missions are available in near-real time with delays from minutes to hours. Users can obtain these data directly from the mission project pages. NASA has provided beacon broadcast capability on some of its spacecraft (e.g., ACE, STEREO, and in the future SDO) to further decrease the time between the collection of data and their availability to users. NOAA SWPC also provides near-real-time space weather data and products from its website (http://www.swpc.noaa.gov/ Data/index.html#alerts). For example, the NOAA SWPC solar and geomagnetic indices are updated frequently, with delays of 1 minute to a few hours, at worst. Data from the space weather sensors operated by the DOD and the model outputs produced from ingesting these data have latency periods similar to those of NOAA. Nearly all of the workshop speakers indicated that their data are available to users 24 hours per day on their websites. Users can also make requests to have data products and alerts sent via e-mail.

Likewise, the prediction windows for the forecast services provided were not explicitly mentioned by all of the panel speakers. For the operational services (NOAA and DOD), assimilative models are in use to provide now-cast and forecast capabilities for space weather events and their impacts on operational systems. Using data from the ACE spacecraft, NOAA SWPC modelers can provide a warning time of approximately 1 hour for CME-related geomagnetic storms. These forecasts have a high level of confidence. NOAA provides daily forecasts of solar and geophysical activities for the next 24-72 hours in its Daily Space Weather Summary and Forecast reports. Less reliable long-term 7-day forecasts from NOAA are made in the Space Weather Advisory Outlooks that are issued each week. These are typically short descriptive statements indicating the likelihood of future space weather events. Three-day and 27-day advance forecasts of quantitative solar and geophysical indices (e.g., x-ray flare probability, 10.7-cm radio flux, Ap and Kp) are also produced by NOAA SWPC. The 3-day forecasts are issued daily, and the 27-day forecasts are issued weekly.

The DOD uses similar forecasts. An important point emphasized by Keyser is that the military is interested not so much in forecasting the space weather environment as in forecasting and mitigating space weather impacts on their operational systems.

During the question-and-answer period, a speaker remarked that it would be immensely useful to be able to predict CME arrival times at Earth to within a couple of hours. Right now, using data from instruments like those on STEREO, predictions to within a half a day are not possible. This is a challenge for the physics-based models that describe the propagation of space weather disturbances from the Sun to Earth.

SPACE WEATHER MONITORING FOR THE NASA EXPLORATION MISSIONS

As indicated in the combined presentations by St. Cyr and Holmes, NASA is currently conducting a self-assessment of the requirements for its human exploration mandate. St. Cyr noted that the Space Radiation Analysis Group at Johnson Space Center in Houston has the lead at NASA in the area of space weather impacts on human exploration. It was noted that the Houston group also works closely with NOAA SWPC. It was not clear which element of NASA had responsibility for monitoring space weather impacts affecting its purely robotic missions. However, it was stated that NASA would provide some of its own space weather investigations (such as through the Lunar Reconnaissance Orbiter) to satisfy both its science mission and its need for space weather monitoring.

The NASA participants in the workshop noted that NASA would be working closely with NOAA SWPC and others on future exploration missions.

TRANSFER OF THE RESULTS OF NASA'S THEORY AND MODELING PROGRAMS TO OPERATIONS

Both St. Cyr and Holmes indicated that NASA is currently working to transfer the results of its theory and modeling programs to agencies involved in operations. NASA participates in the multiagency CCMC, a partnership among NASA, NSF, NOAA, the Office of Naval Research, and several USAF organizations. Holmes summarized the activities of the CCMC, which he called the 15th mission of NASA's Heliophysics Great Observatory, in his presentation. The CCMC is housed at Goddard and provides the opportunity for the developers of state-of-the-art physics models to load their models onto Goddard's supercomputers and make the results of their runs available to the research and forecasting communities. It is, he believes, a great success story that shows what the community has put together to support the modeling of space weather. A related topic that was mentioned was the transfer of space weather sensor technology initially developed for NASA science missions. Once the sensors have been proven and their data have been tested by the forecasting community, the sensors will be transitioned to the operational agencies.

QUESTIONS AND DISCUSSION

The question-and-answer session included a discussion of several issues related to space weather situational awareness and forecasting services. Some of the themes are presented in the examples given here. A two-part question asked, "What is the current status of radiation belt modeling and models . . . and who is responsible for the work in this area?" Joseph Fennell, a workshop attendee, noted that an ISO (International Organization for Standardization) activity to develop next-generation radiation models was being led by CNES in France, the Air Force Research Laboratory (AFRL), Los Alamos National Laboratory (LANL), the Aerospace Corporation, and others. Hapgood noted that one of the challenges faced in radiation belt modeling was obtaining good magnetic field models that underpin the radiation models.

As in the panel presentations, there was much discussion of data that could be interpreted to get some idea of the space weather situation, but Daniel Baker noted that many users do not want data as much as they want results that they can readily apply. He asked the panel, "How much are you thinking about not providing . . . close to raw data but [instead] much more integrated [products] that readily provide the answers that operators and users really need?" Murtagh answered that from the NOAA SWPC perspective there are a couple of things to consider. NOAA and the National Weather Service have a responsibility to provide data and a baseline product suite. But, he noted, SWPC has to be very careful that it does not cross into the area where commercial service providers take the opportunity to fine-tune some of the data and products provided by SPWC, an example being space weather services tailored for the power grid industry: even though SWPC can specify the space weather environment, an outside commercial service provider will provide information on the likelihood of a geomagnetically induced current. Keyser noted that for some time the DOD has been creating impact-based products for customers like the Space Command, adding that it is the impacts that the operator flying the satellite or reading the radar screens cares about. St. Cyr reiterated that NASA's Living With a Star (LWS) program targets research and technologies and tries to bridge the "valley of death," the gap between research and operational tools. He noted that during the Space Weather Week meeting in Boulder (April 2008) a new model had been unveiled that had LWS support. The presentations made it clear that while there is much space weather data available, the number of tailored products that meet known user needs is limited but also is rapidly evolving.

Another question that generated considerable interest dealt with whether a formal educational program existed for prospective space weather forecasters and budding service providers. Fennell noted that the Air Force tries to develop such people within its organization by offering extended education at Air Force expense. Keyser acknowledged that the Air Force production of space weather experts had declined. He remarked that he was probably one of youngest people in the room, noting at the same time that the audience, which included many of those interested in space weather, is a national resource that is quickly disappearing and that this, in his opinion, is an issue that needs to be addressed. Murtagh noted that NOAA SWPC is trying to address the problem and has had five to seven students per year in various summer programs.

One audience member noted the large number of various types of programs discussed and wondered what they cost. He questioned what he felt was a lack of cooperation among the various agencies and also asked why the people using the services were not paying for them. He asked, "Why does it seem like everything is so frayed?" Workshop participant Louis Lanzerotti pointed out that there is a U.S. National Space Weather Program and that several of the agencies involved in it were represented on the panel.

SUMMARY

Space weather services in the United States are provided primarily by government organizations such as NASA, NOAA's SWPC, and elements of the DOD. NASA has the largest number of civilian space satellites that provide the raw data used by other organizations in creating tailored products to meet customers' needs. It is also the primary organization for providing the scientific research for understanding space weather phenomena. NOAA provides more refined space weather data, forecasts, and warning products that are most relevant to the public and industry. The U.S. Air Force is the lead agency designated with the responsibility for providing space weather assessments for the military. Its emphasis is on providing situational awareness (real-time conditions) of the space weather environment and assessments of impacts on military operations and systems.

The space weather infrastructure cannot function without the continual stream of space weather data collected by various assets on the ground and in space. Although NASA currently provides much of the raw data from its research satellites, William Murtagh and Herbert Keyser said that they foresee potential gaps in space weather coverage because of inadequate plans for deploying new and dedicated systems. Other problems are caused by hardware development programs going over their budgets, such as NPOESS, which has led to cuts in future data collection capabilities.

Several speakers mentioned the challenges of improving the cooperation among the various organizations that provide space weather services. In particular, Michael Hapgood highlighted the difficulties by describing the current European space weather infrastructure as "complicated and fragmented." Essentially all speakers suggested that a strong case could be made for better networking with national and international partners. An example of a success story for cooperation is the multiagency CCMC, which has been tasked with transitioning research-based space weather models and making them more useful to the operational community. This is a major undertaking that is required to make the leap from now-casting to having the ability to predict severe storms days in advance.

NOTES

1. Situational awareness involves the perception and understanding of current space events, threats, activities, and conditions, including natural environmental conditions and space systems status, capabilities, constraints, and use, and an ability to assess potential near-term outcomes.

2. Keyser referred specifically to the NSF's Global Oscillation Network Group (GONG) and Synoptic Optical Long-term Investigation of the Sun (SOLIS) initiatives.

3. The complete list of space weather models used at SWPC can be found at http://www.swpc.noaa.gov/Data/index.html#models.

5

User Perspectives on Space Weather Products

In the workshop session titled "User Perspectives on Space Weather Products," the panel reviewed how various sectors and services are currently utilizing space weather forecasting and climatology products. Of particular interest was the impact that access to space weather products (data and derived information) has on their operations and customers and on society at large. The panel members were (1) Michael Stills, manager of International Operations Flight Dispatch, United Airlines, representing transportation for people and cargo; (2) James McGovern, Reliability Coordination Services, ISO New England, Inc. (an independent system operator), representing the electric power industry; (3) Lee Ott, chief scientist at OmniSTAR, which provides precision geo-location services to oil and gas exploration companies and to agriculture; (4) David Chenette, director, Space Sciences and Instrumentation, Lockheed Martin Advanced Technology Center, representing both space weather instrument providers and satellite operators and manufacturing; and (5) Kelly Hand, senior program engineer, Space Situational Awareness, Aerospace Corporation, representing the U.S. Air Force (USAF).

The panelists were asked to consider the following questions in their presentations:

- Please provide examples of the types of space weather products used in your industry or organization, and how they are used. What sources of data do you use? Do you use long-term forecasts, short-term forecasts, real-time data, or historical data?
- How often does space weather cause a change from "normal" operations? What data do you use to decide when it is safe to resume normal operations?
- What kinds of impacts does space weather have on your companies and services and on their customers?
- How would you judge the quality of the current data; i.e., how often do you get false warnings and missed warnings?

Because of the varying histories of their use of space weather data, the panelists differed in their ability to respond to all of these questions.

AIRLINE INDUSTRY PERSPECTIVE

Michael Stills described how in 1999 United Airlines began using routes over the North Pole to fly from Chicago to Hong Kong, with 12 demonstration flights. In 2007, United operated more than 1800 flights over the pole and made its 8,000th polar flight in April 2008, demonstrating the dramatic rise of air traffic over the North Pole. United is not alone. Thirteen carriers flew polar routes for a combined total of almost 7300 polar flights in 2007, an increase of nearly 2000 flights from the prior year.

Why polar routes? As Stills indicated, aircraft can cost hundreds of dollars per minute to operate. Polar routes reduce the time in flight. As an example, United Flight 829 on a polar route took 14 hours and 32 minutes to fly from Chicago to Hong Kong in March 2006. It carried 316 passengers and 5000 pounds of additional cargo. If the same plane had flown the best available non-polar route to Hong Kong, due to the greater headwinds it would have required 15 hours and 41 minutes, reducing the passengers to 246 and removing all 5000 pounds of extra cargo. So the polar routes allow United Airlines to avoid the strong wintertime headwinds and decrease travel time, and therefore transport more passengers and cargo, thus offering a more economical and convenient service to its customers.

Federal regulations require flights to maintain communications with Air Traffic Control and their company over the entire route of flight. United relies on SATCOM, which is communication via satellites in geosynchronous orbit (located about 22,000 miles above the equator). Aircraft lose the ability to communicate with these satellites when they go above 82 degrees north latitude (within the circle shown toward the center of Figure 5.1). In this region, aircraft communications are reliant on HF (high-frequency) radio links.

Strong solar activity causes HF radio blackouts in the polar region. Occasionally the Sun emits a shower of high-energy protons and other ions (called a solar energetic particle (SEP) event). When the protons hit Earth's outermost atmosphere (called the ionosphere), they increase the density of ionized gas, which in turn affects the ability of radio waves to propagate.[1] HF radio frequencies in the polar regions are particularly affected because the solar protons can directly reach the ionosphere in the polar cusp of Earth's magnetic field. The radio blackouts over the poles are called polar cap absorption (PCA) events. When a solar event causes severe HF degradation in the polar region, aircraft that are dependent on SATCOM have to be diverted to latitudes below 82 degrees north so that SATCOM satellite communication links can be used. United Airlines currently utilizes the NOAA Space Weather Prediction Center (SWPC) space weather scales and alerts to plan upcoming flights and to instruct planes in transit to divert from polar routes.

PCA blackouts can last up to several days, depending on the size and location of the disturbance on the Sun that triggers them. For example, between January 15 and 19, 2005, five separate x-ray solar flares occurred that produced radio blackouts of R3 intensity. (The radio blackout scales are shown in Figure 5.2.) One of the alerts, shown in Figure 5.3, tied the expected intensity of the blackout to the X1.2 strength of the solar x-ray flare.[2] For 4 consecutive days, flights from Chicago to Hong Kong could not operate on polar routes. The longer non-polar routes required an extra refueling stop in Anchorage, Alaska, which added delays ranging from 3 to 3½ hours. In total, 26 flights operated on less than optimal polar routes or non-polar routes. Increased flight time and extra landings and takeoffs increase fuel consumption and cost, and the delays disrupted connections to other flights.

Stills noted, "Ten years ago United had no reason to take space weather into consideration, but now it is something that United Airlines actively monitors, and we change and enhance our policies and procedures as more information and data become available."

Stills indicated that United Airlines already considers in its flight planning the information and data it receives from SWPC, such as D region absorption and polar cap absorption that affects HF communications. United is also interested in K index geomagnetic status and x-ray intensity, and has just mandated that its meteorological team monitor proton flux with energy levels of 10 MEV and greater and 100 MEV and greater.

The availability of real-time solar flare monitoring and radio blackout alert services allows the airline industry to use polar routes safely. In response to an audience question, Stills indicated that accurate, high-confidence forecasts would also be useful: "Typically . . . the planning . . . for international flights . . . is done 2 to 3 hours in advance of the actual operation. But the infrastructure and support for an airline operation, typically things like which aircraft is assigned to, say, the Chicago-Hong Kong flight tomorrow, . . . is done a day in advance. The crews are assigned well in advance. They have duty time limits. All of those things come into play."

"So it is extremely important to have an accurate prediction," Stills emphasized. "It is very important to have it in a timely fashion and as far in advance as possible. Clearly we realize there are limitations, but to have from an infrastructure standpoint a forecast, say, 6 to 10 hours in advance would be wonderful, but from an operational

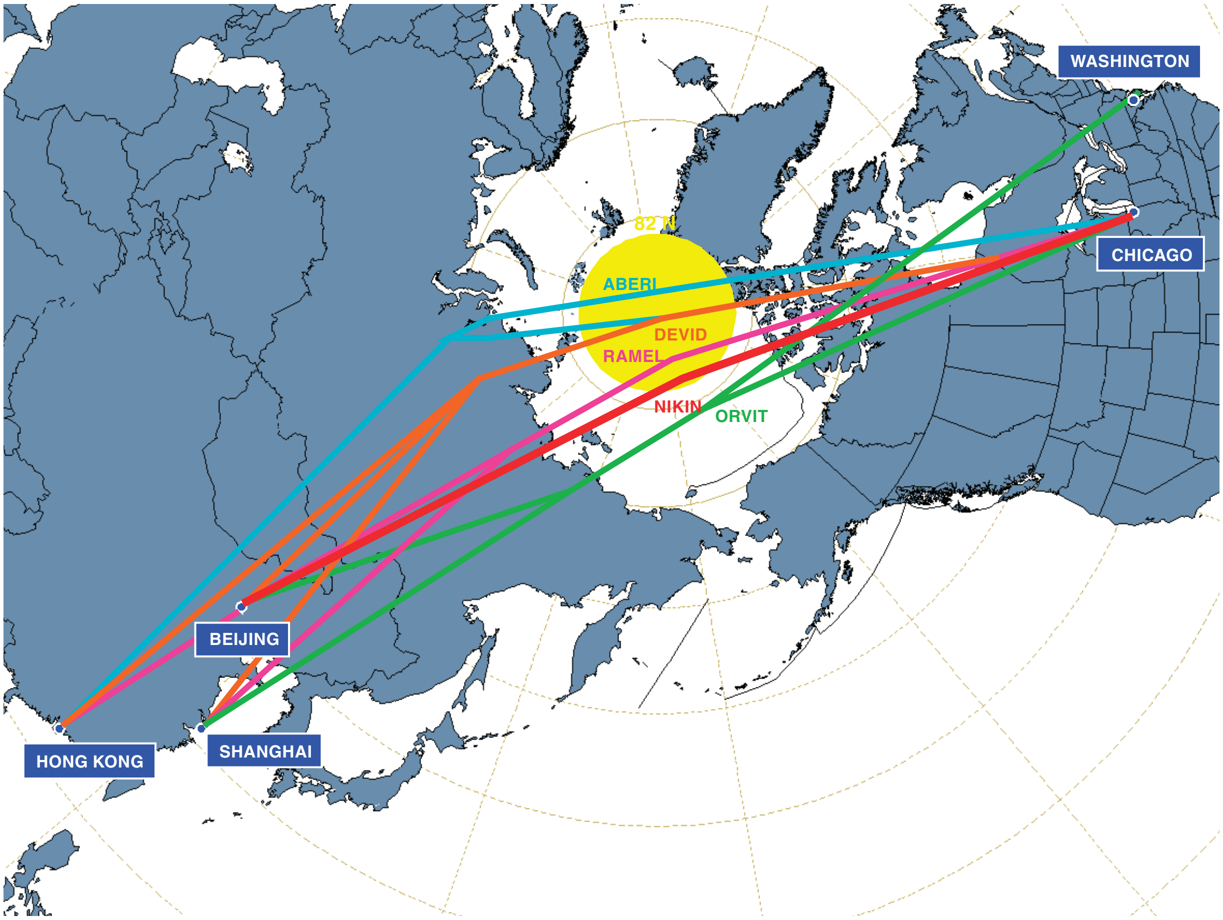


FIGURE 5.1 Using polar routes for air traffic necessitates high-frequency radio communications at high latitudes (circular area toward center of figure), which can be disrupted by solar activity. SOURCE: Michael Stills, United Airlines, "Polar Operations and Space Weather," presentation to the space weather workshop, May 22, 2008.

and planning standpoint, we are probably looking at a minimum of, say, 3 to 4 hours in advance, where we can make a tactical decision and still feel confident in the operation."

ELECTRIC POWER INDUSTRY PERSPECTIVE

A geomagnetic storm that occurred in 1989 caused a blackout in the Quebec province of Canada (Figure 5.4). A transient disturbance of Earth's magnetic field, a geomagnetic storm is caused by energetic streams of particles and fields that originate from the Sun and impact and distort Earth's magnetic field. The transient changes in Earth's magnetic field interact with the long wires of the power grid, causing electrical currents to flow in the grid. The grid is designed to handle AC currents effectively, but not the DC currents induced by a geomagnetic storm. These currents, called geomagnetically induced currents (GICs; also known as ground-induced currents), cause imbalances in electrical equipment, reducing its performance and leading to dangerous overheating. A major electrical transformer was damaged in the 1989 Quebec event (see Figure 5.4), resulting in significant direct financial loss to the utility in addition to other indirect losses to the northeastern U.S. and Canadian economies from the blackout. Procedures were adopted, and are currently in place, that inform electric grid operators to take actions that will prevent a blackout and to protect equipment.

Category		Effect	Physical Measure	Average Frequency (1 cycle=11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met/ (number of storm days)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide-area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

FIGURE 5.2 Radio blackout severity scales from NOAA SWPC are used by United Airlines to re-route aircraft on polar routes in response to expected radio communication blackouts. SOURCE: NOAA Space Weather Prediction Center.

In his presentation James McGovern also provided an example from October 2003 when a significant solar flare and coronal mass ejection (CME) occurred (Figure 5.5). NOAA's SWPC issued a series of alerts, warnings, and predictions, giving power grid operators advance warning that severe space weather conditions were imminent that would put the power grid at risk. From past experience, the grid operators knew that the intensity of the DC current induced in their systems (which they monitor with their own instrumentation) scaled with the intensity of the geomagnetic storm. The intensity of the geomagnetic storm in turn is given by the K index (Table 5.1).

The power grid operators responded to warnings and to real-time space weather data provided by the NOAA SWPC (formerly the SEC, or Space Environment Center, as shown in Box 5.1) by modifying the way the power grid was operated in order to maintain adequate power quality for customers and reserve capacity to counteract the effects of space weather. Despite severe GICs, the power transmission equipment was protected and the grid maintained continuous operation. In the workshop discussion, though, McGovern pointed out that the alerts and real-time data could be improved. As an example, the K index data provided by the SWPC seemed to lag the effects on the northeastern power grid: the induced-current monitors had already reached level 2 at 01:31 on Wednesday,

Space Weather Message Code: SUMX01
Serial Number: 45
Issue Time: 2005 Jan 15 0108 UTC

SUMMARY: X-ray Event exceeded X1
Begin Time: 2005 Jan 15 0022 UTC
Maximum Time: 2005 Jan 15 0043 UTC
End Time: 2005 Jan 15 0102 UTC
X-ray Class: X1.2
Optical Class: 1b
Location: N14E07
NOAA Scale: R3 – Strong

FIGURE 5.3 Example of an x-ray event alert. SOURCE: NOAA Space Weather Prediction Center, available at http://www.swpc.noaa.gov/alerts/archive/archive_01Jan2005.html.

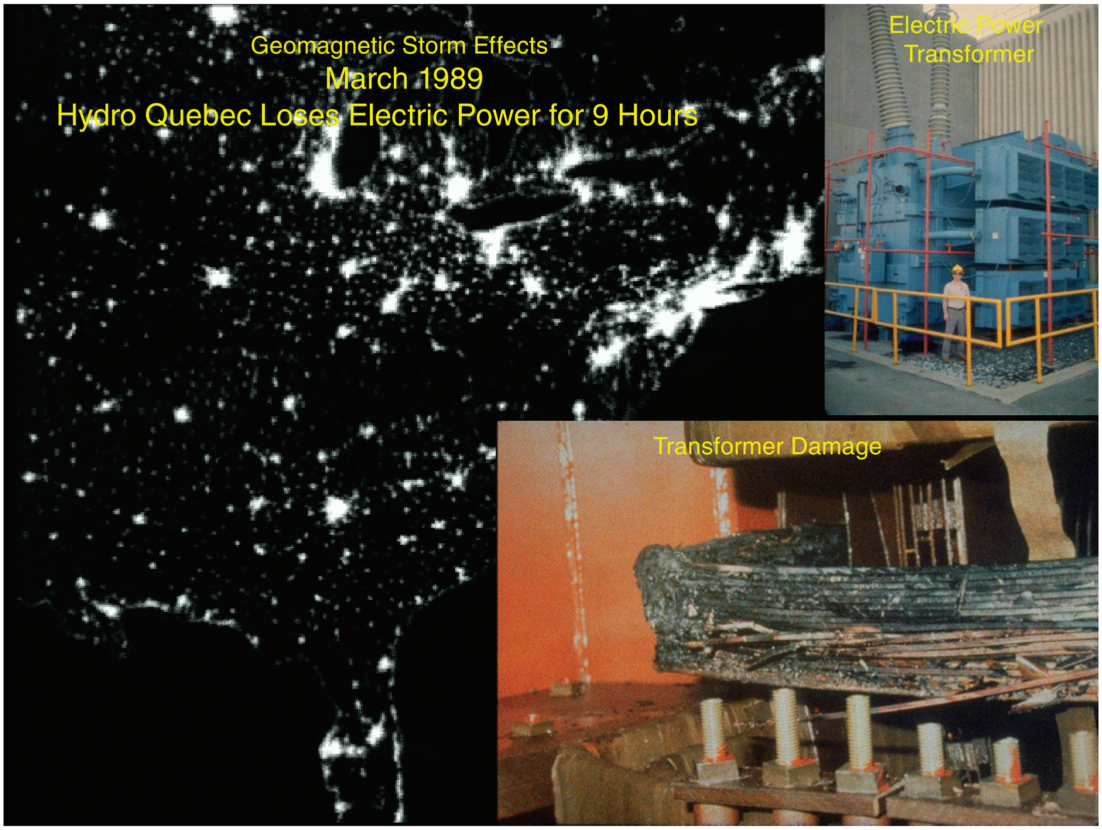


FIGURE 5.4 A 1989 geomagnetic storm caused a blackout in the Quebec region and damaged a high-voltage transformer. SOURCE: Rodney Viereck, NOAA Space Environment Center, "Space Weather: What Is It? How Will It Affect You?," available at lasp.colorado.edu/~reu/summer-2007/presentations/SW_Intro_Viereck.ppt.

which corresponds to K = 7, whereas the SWPC warned of K = 6 at 02:09, 38 minutes later. The SWPC uses ground magnetometer stations located in Boulder, Colorado, and Fredericksburg, Virginia, which are at geomagnetic mid-latitudes. A 4-hour delay in collecting and averaging ground magnetometer sampling (Boulder and Fredericksburg), with a consequent 4-hour lag in issuing K index alerts, requires system operators to rely on their own instrumentation, which may not be as accurate. Further, the northeastern U.S. power grids and particularly the Canadian power

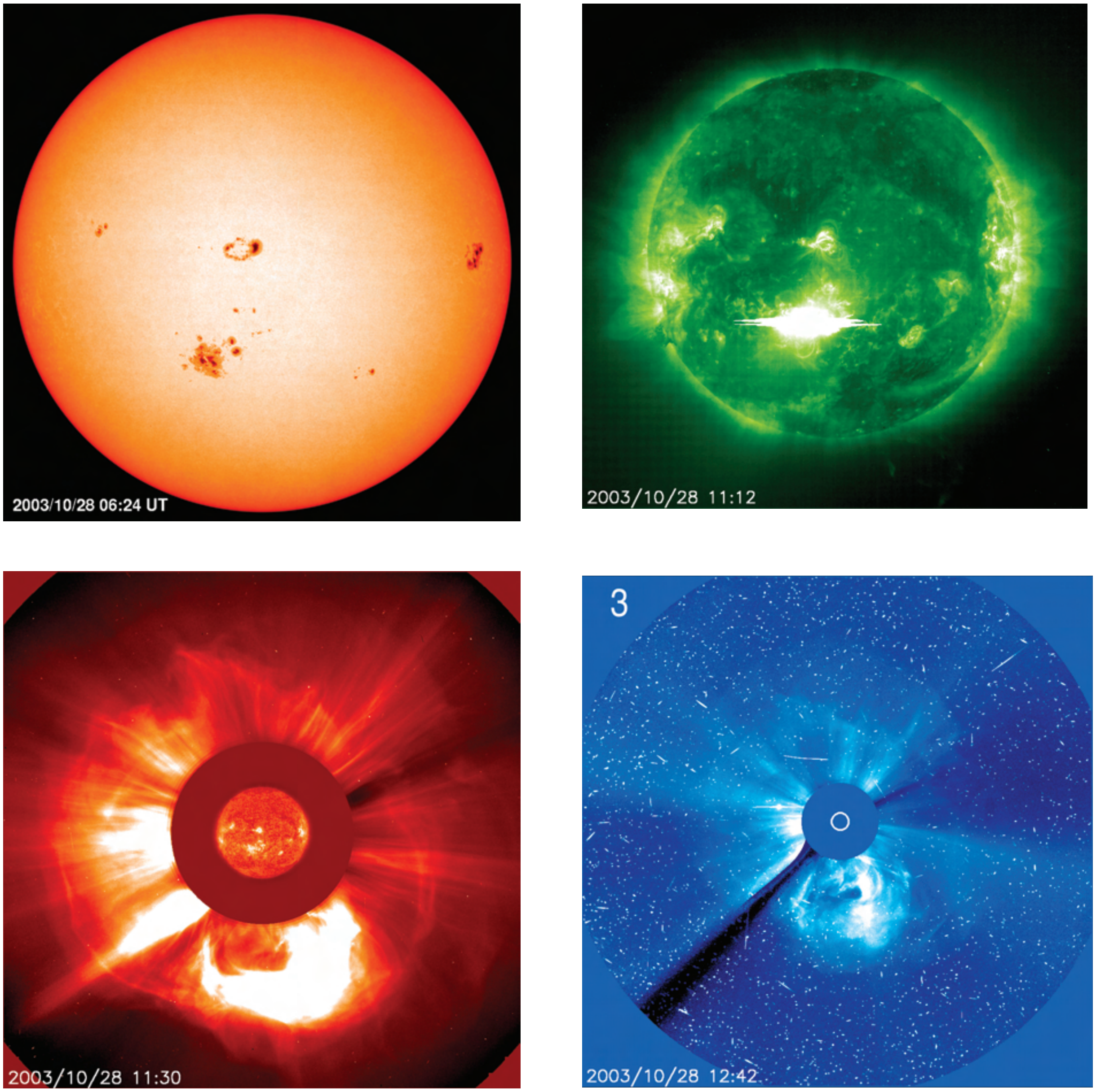


FIGURE 5.5 October 28, 2003, evolution of a solar storm. A large sunspot (brownish black spot seen in the lower half of the solar disk in the upper-left-hand image) erupted with a strong x-ray flare (bright white spot in lower half of the false-green color EIT image of the Sun, upper-right-hand image). Within minutes, LASCO detected a halo coronal mass ejection (CME) emerging from the Sun (which is blocked by the central occulting disks in the lower-left-hand image). An hour and a half after the flare, a shower of energetic protons and ions reached the SOHO spacecraft, creating the "snow" in the lower right LASCO image, confirming that the CME was headed toward Earth. When it impacted Earth's magnetic field, this CME triggered powerful geomagnetic storms that caused problems for the electric grid in Northern Europe, polar cap absorption events, and in-orbit satellite anomalies and failures. SOURCE: NASA; see http://sohowww.nascom.nasa.gov/hotshots/2003_10_28/.

TABLE 5.1 Geomagnetic Storm Intensity and K Index Value

GIC Severity Level	XFMR[a] Neutral DC Current	Corresponding Geomagnetic Storm Index
1 Minor	5-14 amps	
2 Moderate	15-29 amps	K7
3 Major	30-59 amps	K8
4 Severe	>60 amps	K0

[a] XFMR, transformer. Shown in Figure 5.4 is an example of a high-voltage electrical power transformer damaged by GICs.

grids are located at higher geomagnetic latitudes, which are more strongly affected by geomagnetic storms. As a consequence, the magnetic disturbances at higher latitudes reach higher K levels before those at the lower-latitude stations. A general feature of geomagnetic storms is that their timing and intensity are a local phenomenon, and the best real-time data come from geomagnetic field monitoring equipment located closest to the end user of the data. As a result, system operators at higher latitudes utilize higher-latitude sources of magnetic disturbance data in addition to the NOAA SWPC and combine those data with real-time ground-current monitoring throughout their grid. These other third-party (often commercial) sources of geomagnetic data also add to the real-time data some interpretation and forecasting that are of value to electric power system operators.

In addition to real-time space weather monitoring, high-reliability near-term forecasts are critical to power system operators. Advance warning about the arrival of an earthward-directed CME is of critical importance for grid operators, allowing them time to take the measures needed to protect the grid. “The most important device that I know of out there to give us a heads-up is ACE,” McGovern noted. “ACE gives our operators about a 45-minute warning.” As Frank Koza said earlier, “We can reposition our system in probably up to 15 minutes. With 15 minutes’ advance notice we can quick-start units, reducing generation in the northern areas, picking up generation in the southern areas, offloading our tie lines, offloading our transformers, even manning key facilities so that we have operators there to switch off a transformer if they see the temperature on that transformer overloading.” And, “for the real-time operator, 45 minutes to an hour is very important. I would give it a 10 (on a scale of 1 to 10). That would be the same for the day-ahead market, which is at least 24 hours out.”

PRECISION GEO-LOCATION SERVICES INDUSTRY PERSPECTIVE

Precision geo-location services based on GPS signals arose almost simultaneously with the birth of the GPS system more than 20 years ago (see Box 5.2). Precision geo-location is critical to many users (see Figure 5.6) including,

- Oil and gas companies,
- Agriculture,
- Mining,
- Construction contractors, and
- Government agencies,

as part of their operations performing,

- Seismic navigation,
- Dynamic and static rig positioning,
- Dredging control,
- Vessel and vehicle tracking,
- Photogrammetry and geographic registration, and
- Position confirmation and attitude monitoring using GPS kinematic solutions.

BOX 5.1
Sequence of Events During October 2003 Storm Illustrating Power Grid Operators' Response to Evolving Geomagnetic Storm and Space Weather Warnings

Tuesday October 28, 2003

- 07:37 hrs (EST) - SEC reports – X-ray event exceeded X10
- 12:08 hrs (EST) - SEC reports – Extended Warning: Geomagnetic K index of 4 expected
- 13:04 hrs (EST) - SEC reports – Extended Warning: Geomagnetic K index of 4 expected
- 16:39 hrs (EST) - SEC reports – Watch: Geomagnetic A index of 100 or greater predicted
- 22:55 hrs (EST) - SEC reports – Warning: Geomagnetic K index of 5 expected

Wednesday October 29, 2003

- 01:31 hrs - Maine, Chester SVC reports Level 2 ground-induced-current alarms
- 02:09 hrs - SEC reports – Warning: Geomagnetic K index 6 expected (3rd party forecaster predicted K8)
- 02:15 hrs - Maine, Chester SVC reports Level 3 ground-induced-current alarms
- 02:15 hrs - ISO New England
  - —*Implemented M/S # 2 Abnormal Conditions Operating Procedure for all New England effective for next 24 hours due to SMD activity. (Implementation of this Operating Procedure authorizes the New England system operator to assume an emergency condition defensive posture to protect the reliability of power system)*
  - —*Cancelled scheduled 345-kV circuit breaker maintenance at nuclear plants in Vermont and Connecticut.*
- 02:17 hrs - Quebec limiting exports to New England due to SMD activity in the Nicolet area of Montreal. (System operator had already begun to add generators to network.)
- *Both New England HVDC converter station imports limited to >40% to <90% of normal rating*
- *New Brunswick imports are limited to 600 MW maximum.*
- *ISO re-dispatching New England area generation to cover load demand*
- 02:23 hrs - SEC reports – Alert: Geomagnetic K index 7 or greater expected
- 02:49 hrs - SEC reports – Alert: Geomagnetic K index 7
- 03:45 hrs - SEC reports – Alert: Geomagnetic K index 8
- 03:55 hrs - Maine, SVC reports Level 4 ground-induced-current alarms
- 04:41 hrs - SEC reports Alert: Geomagnetic K index of 9
- 07:28 hrs - SEC reports Alert: Geomagnetic K index of 7
- 09:26 hrs - Maine, SVC reports Level 3 ground-induced-current alarms locked with chattering, Level 4-induced current alarm spikes
- 09:54 hrs - Vermont HVDC imports from Quebec being reduced to below 185 MW due to increased SMD activity
- 09:58 hrs - Maine, SVC reports Level 4 ground-induced-current alarms
- 10:07 hrs - Ontario – reports voltage and MW swings observed at the Bruce Nuclear Units on Lake Huron and Pembrooke region
- 10:07 hrs - Ontario – reports Mountain Chute Unit #2 tripped (Pembrooke region)
- 10:07 hrs - Ontario – reports Bruce Nuclear Units reducing VAR output to stabilize
- 10:14 hrs - Maine, SVC reports Level 2 ground-induced-current alarms

BOX 5.2
Precision Geo-location Services Evolved with GPS System

1984	First GPS receiver purchased by Chance, only 5 operational GPS satellites
1986	Fugro launches only world's only commercial, satellite based, positioning system
1987	Fugro introduces DGPS services as GPS satellites gradually become operational
1991	S/A turned on
1992	GPS system 24 hr most locations
1993	GPS IOC
1993	Fugro fully transitions to DGPS
1993	Fugro develops OTF kinematic positioning for USACOE
1994	A/S turned on (loss of access to L2 directly)
1995	GPS FOC
1997	Fugro introduces first integrated VBS products with GPS manufacturers
1998	Problems in South America
1999	StarfixPlus dual frequency service
2000	S/A turned off
2001	Fugro launches HP service in USA
2002	Fugro introduces integrated HP products
2003	WAAS IOC
2003	Halloween Event
2004	Fugro launches integrated XP products
2006	Dec Radio Burst Event

SOURCE: Lee Ott, OmniSTAR, Inc., "Meeting the Challenges of Nature: The Impact of Space Weather on Positioning Services: Solar Cycle Progression and the Maturing of GPS," presentation to the space weather workshop, May 22, 2008.

As an example, OmniSTAR provides differential GPS corrections to users that buy their own GPS receivers. As Lee Ott noted, "Our strategy is to give enough information to the user so that the user at his current location can make the appropriate decision about whether or not his positioning is accurate. He can make that decision himself." This approach is important because in the diverse community of GPS users the needed level of accuracy varies.

GPS signals originate from satellites that are at about 12,000 miles altitude, and these signals have to pass through the ionosphere in order to reach GPS receivers on the ground (see Figure 5.7). The GPS signals are degraded in several ways by severe space weather. When the density of electrons and ions in the ionosphere increases in response to solar flares, the propagation delays (time delays) change, the paths that the GPS signals follow are slightly distorted (bent like light is when it passes from air to water), and the strength of the GPS radio signal is weakened. The consequence of the distortion is that the GPS receivers miss a user's exact location. Such errors in location can have very significant effects on the operation of deep-ocean drilling platforms, for example, because if the errors are too large, the platform could move off its intended position, causing a drill line to break. And if the signal weakens sufficiently, the GPS receiver might not be able to provide the necessary location. An example of the signal fade that occurred during a significant solar flare event in December 2006 is shown in Figure 5.8. As noted by Ott, "Once [deep-ocean drilling platforms] are on station and sitting in maybe a thousand feet of water and drilling a hole, the cost of that rig is about a million dollars a day. If they are drilling a hole and something eventful happens and they lose their positioning, they have to do an immediate disconnect. The only way they can do it [is to use] blowout preventers, which basically are big scissors that just cut the pipe off. So

FIGURE 5.6 A diverse range of businesses use precision geo-location. SOURCE: Lee Ott, OmniSTAR, Inc., "Meeting the Challenges of Nature: The Impact of Space Weather on Positioning Services: Solar Cycle Progression and the Maturing of GPS," presentation to the space weather workshop, May 22, 2008.

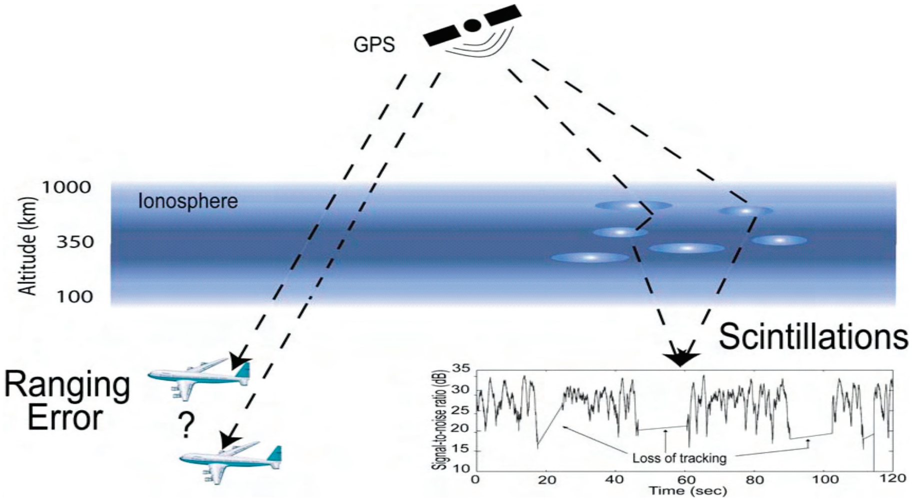


FIGURE 5.7 Ionosphere-induced GPS errors. Ionospheric range delay results from normal signal propagation through the ionosphere. Scintillations result from severe ionospheric signal scattering. Amplitude fading or signal-to-noise degradation is caused by solar radio bursts. SOURCE: Paul M. Kintner, Jr., Cornell University, "A Beginner's Guide to Space Weather and GPS," February 21, 2008, available at http://gps.ece.cornell.edu/SpaceWeatherIntro_update_2-20-08_ed.pdf.

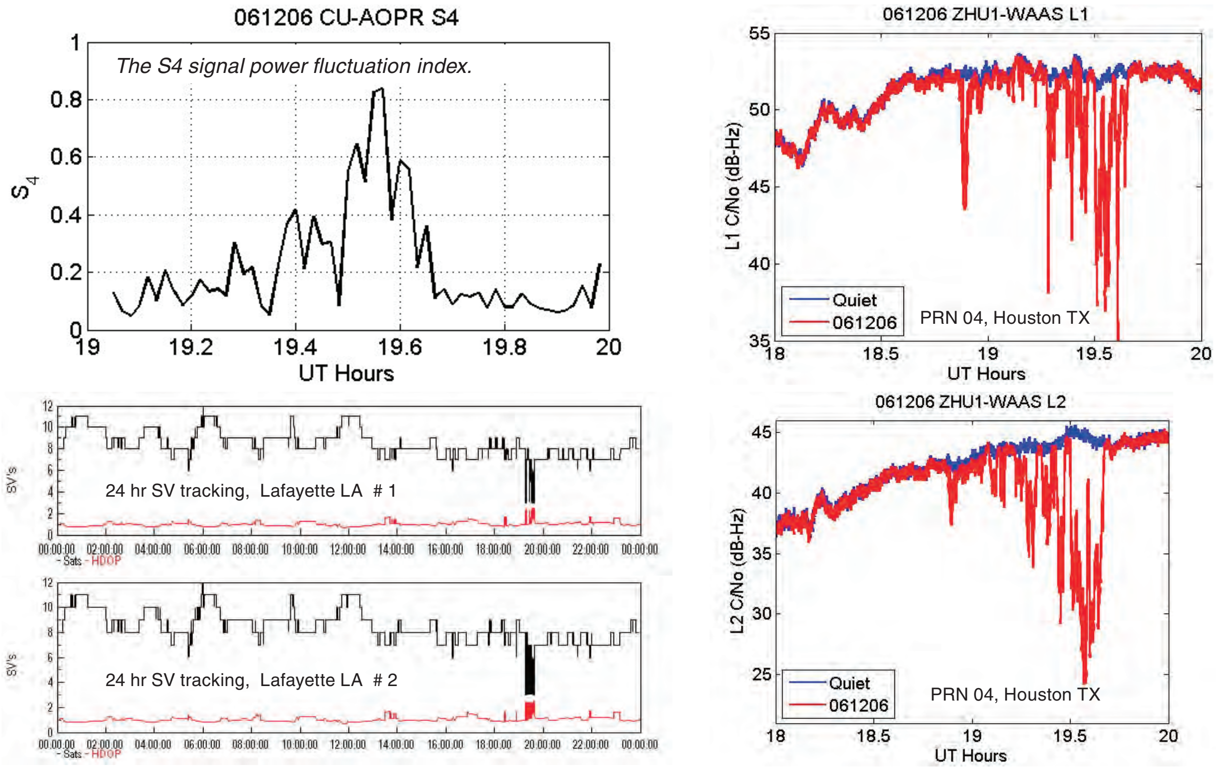


FIGURE 5.8 Example of GPS signal degradation caused by a solar storm. SOURCE: Courtesy of Alessandro Cerruti, Cornell University.

you . . . have lost a little bit of production time, but now you have got to spend 2 days to go fish that pipe out of the hole and get back into production."

Accurate real-time knowledge of the GPS error is critical to knowing when operations have to be interrupted and when it is safe to resume. Ott pointed out that "what we really want is . . . the rate of change of the ionospheric delay . . . because that is what kills the tracking loops in the GPS receivers, and that is what causes the errors." He noted that current GPS monitoring systems cannot transmit data fast enough to keep up with the movement of the ionosphere. Consequently, for some uses, such as marine applications, multiple overlapping systems are employed and the results independently compared to validate positioning. When one or more systems drop out, positioning information quality control is lost. Future GPS spacecraft transmitting at higher power will mitigate some of the problems. OmniSTAR is transitioning its monitoring network to dual-frequency stations and will add Global Navigation Satellite System (GLONASS)[3] services to GPS in the future, which will further improve the reliability of the error estimates.

An accurate forecast of imminent GPS outages and an accurate look ahead to when it will be safe to resume operation are essential because many GPS users need time to suspend operations and then to recover and resume operations. The current ability to forecast ionospheric disturbances is poor. Alerts based on indices of activity, such as NOAA's K index and the X-flux index, result in many false alarms. As Ott pointed out: "It doesn't work very well, because every time the numbers get high we alert our customers and nothing happens. This has been going on for the last several years." Missed alarms are also an issue: "We got an . . . alert [last fall] from the NOAA prediction center that there was a coronal mass event that happened. They said it is not going to hit Earth, and lo and behold, it wiped us out in the Southern Pacific. It actually got as far north as the San Diego area. So prediction is obviously lacking, and we need some kind of better prediction scheme and so on that is more reliable, that at least the customers will pay attention to and believe us." Since most end users of geo-location information plan their operations in advance, this industry ranks having a highly reliable and accurate 24-hour prediction at a 9 out of 10.

SATELLITE MANUFACTURING AND OPERATIONS INDUSTRY PERSPECTIVE

Satellites operate within Earth's magnetosphere and radiation belts. David Chenette stated that ". . . living with space weather is a fact of life. The space radiation environment is the most significant limitation on the lifetime of the system. The [degradation of] electronics is what limits the performance of the system, and a lot of the cost of GEO communication satellites is driven by the need for 10- or 15-year missions to be able to withstand 100 kilorads [total dose]." Satellite designers need access to accurate long-term models of the radiation environment. Figure 5.9 shows the radiation belts as defined by models currently available from NASA that are used for design.

Chenette stated that unfortunately, the radiation belt models are overly pessimistic about the amount of degradation that will occur and have led to costly overdesign of many satellites in some orbits. (For instance, in GEO, new models[4] show that the degradation due to radiation belt electrons can be as much as a factor of 4 to 7 lower than predicted by the old NASA AE8 model.) Less degradation implies that smaller and less expensive solar arrays can be used and will still provide sufficient power at the end of a 15-year mission and that electronics need lower-weight shielding. Since it costs roughly $40,000 to put a pound of mass into GEO, saving weight reduces cost. Yet some of the early science satellites that flew in other regions of the radiation belts collected only a few months' worth of data, which, for lack of more complete data, are being used to represent a complete solar cycle. Long-term variability in the radiation environment has been seen when satellites have measured radiation over a solar cycle (about 11 years) or longer. This produces significant uncertainty and risk for satellites being designed

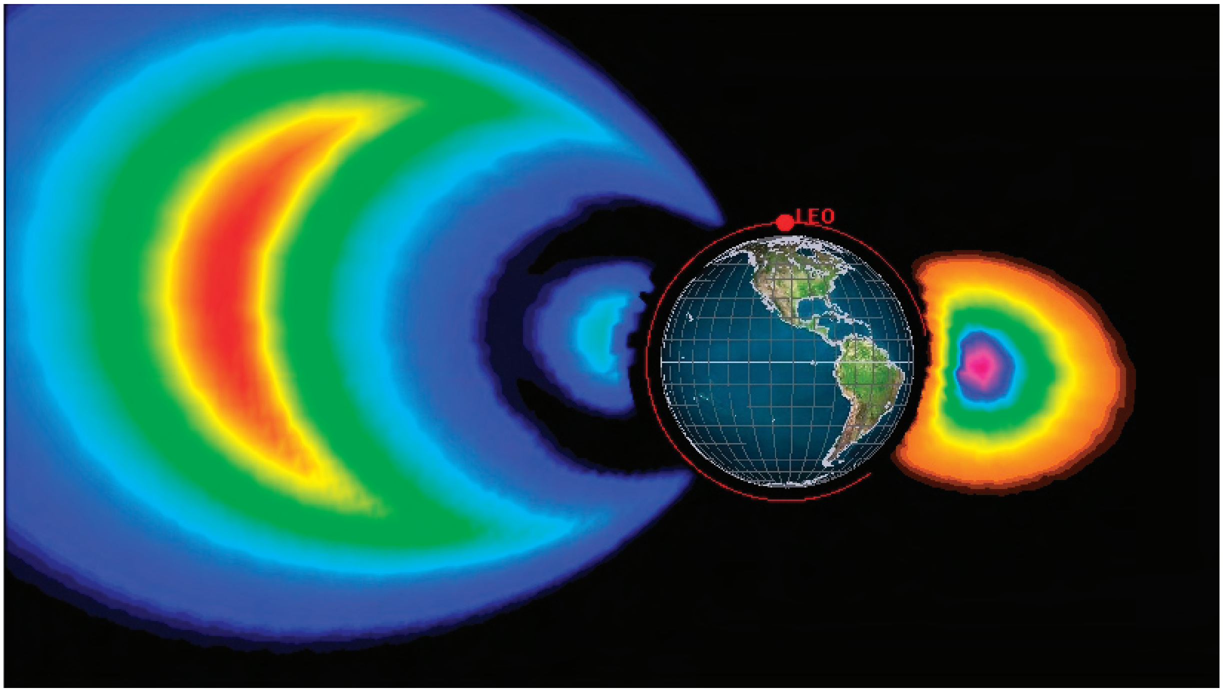


FIGURE 5.9 Satellites operate in the harsh environment of Earth's electron belts (shown on left side only) and proton belt (shown only on the right side). SOURCE: David Chenette, Lockheed Martin Space Systems Company, "Aerospace Industry User Perspectives on Space Weather Data Products (and Models)," presentation to the space weather workshop, May 22, 2008.

and operated in non-traditional orbits where only a snippet of a solar cycle's worth of data has been collected. Several subsequent spacecraft missions, such as CRRES,[5] have mapped portions of the radiation belts, but the data have not been assimilated into the NASA radiation belt models used by satellite designers and mission planners. There is tremendous interest in these communities for an update of the NASA radiation belt models and planned radiation belt probe missions to fill out the remaining gaps in those models.

The Sun also has a significant effect on peak environments that satellites must endure. As an example, Chenette pointed to high-energy proton data from the science satellite IMP-8 (see Figure 5.10). The rate at which high-energy particles impact spacecraft shows spikes above a slowly varying background rate (heavy line at the bottom of the peaks in Figure 5.10). "These are daily averages so that the total flux you measure over a day can be easily a thousand times the background. That is the distribution. It goes from just above the background on small little spikes to factors of 1000 or more. This is not believed to be a bounded distribution. It is like hurricanes or earthquakes. The worst ones probably have yet to be found. What we really need for designing . . . is the probability distribution of these intensities, because we need to be able to respond to customer requirements for being able to survive an event or being able to operate through an event. That can place very different design requirements on your system."

Satellite designers use historical space weather data captured in climatological models to define long-term average exposures and statistical distributions of peak events. Real-time space weather and short-term forecasts (called now-casts) are also used to support launch decisions (Figure 5.11). Launch vehicles are not designed to operate in all possible weather conditions. Chenette remarked, "You don't launch rockets in hurricanes, and you don't launch rockets into worst-case space weather either. You can save a lot of money by not needing to do that, and just like the [ground] weather example, you can afford to wait. Given that limitation, you are not going to place a billion-dollar bet on a launch. It is absolutely essential that you understand the environment into which it

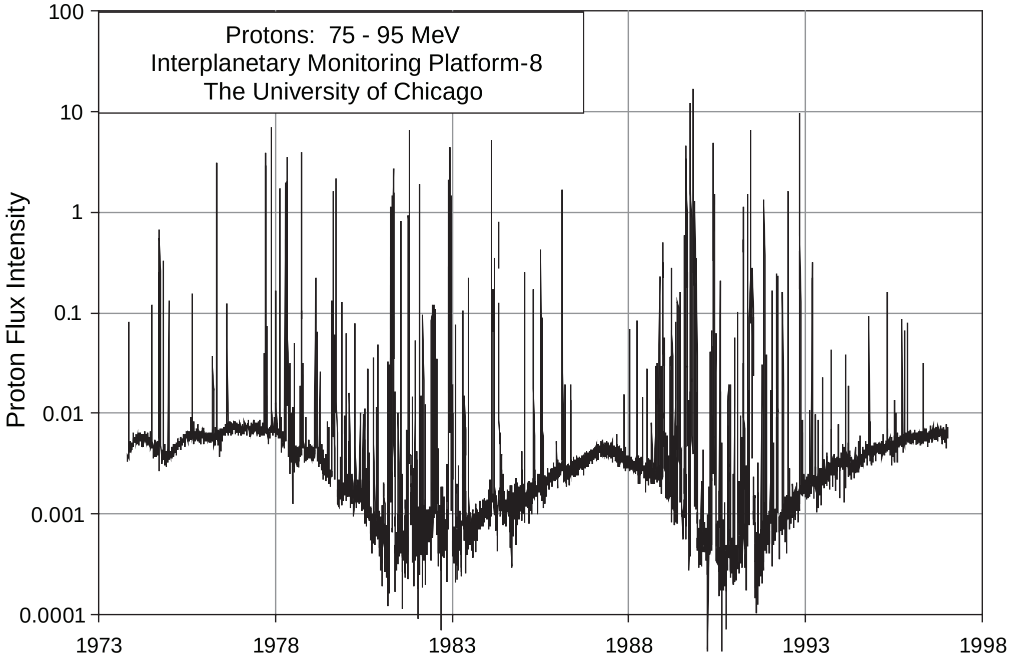


FIGURE 5.10 High-energy proton environment shows dramatic short-term spikes and slow background variability. SOURCE: David Chenette, Lockheed Martin Space Systems Company, "Aerospace Industry User Perspectives on Space Weather Data Products (and Models)," presentation to the space weather workshop, May 22, 2008.

FIGURE 5.11 Launch vehicle lifting from pad. Launches are postponed if ground weather or space weather makes a launch too risky. SOURCE: U.S. Air Force.

goes, and that that environment is safe enough. What we really need in this case is the ability to anticipate enough in advance so that we know that the more susceptible launch vehicle—because it only has to work properly for a little while—will be flying through a safe environment."

Once a satellite is launched and is on orbit, the satellite operators will continue to monitor the space environment. Most of the equipment on a satellite has to operate 24 hours a day, every day, for the entire 10- to 15-year life of the satellite regardless of space weather. But other equipment is used only intermittently, behind the scenes. Examples are thrusters that are used to counteract the naturally occurring drift of satellites away from their desired orbits. As with launches, satellites operators will review current space weather conditions, such as high-energy electron environments, to determine if the environment is calm or disturbed. If the environment is disturbed, the thruster operation is postponed, reducing the risk to the satellite and its customers.

Making this operational judgment call requires that current weather data, such as the GOES[6] energetic electron data (Figure 5.12), be obtained from the NOAA SWPC. The plot in Figure 5.12 shows that the environment (and the solar conditions that drive it) has some limited repeatability, which allows making forecasts with some confidence. But other phenomena, such as solar flares (see the GOES 13 image of a solar flare in Figure 5.13) and CMEs, are not accurately forecast, and real-time monitoring is essential to reducing risk for satellite operators. "We really need to be able look at the Sun and know not only that there is an active region that [might] create a major storm, but also what the signatures are of the precursors [that forecast] these major events. I think there is

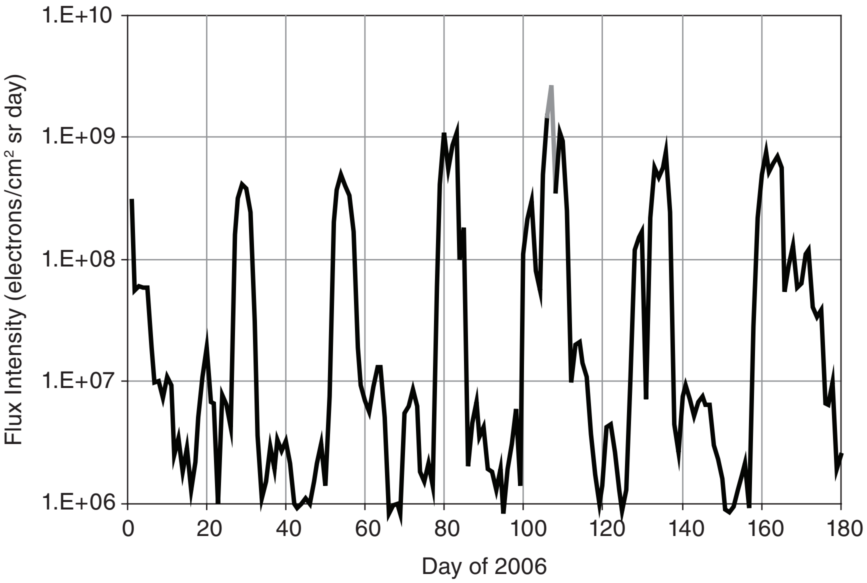


FIGURE 5.12 High-energy electron flux history shows some repeatability, suggesting that short-term forecasts with some confidence might be made. SOURCE: David Chenette, Lockheed Martin Space Systems Company, "Aerospace Industry User Perspectives on Space Weather Data Products (and Models)," presentation to the Space weather workshop, May 22, 2008.

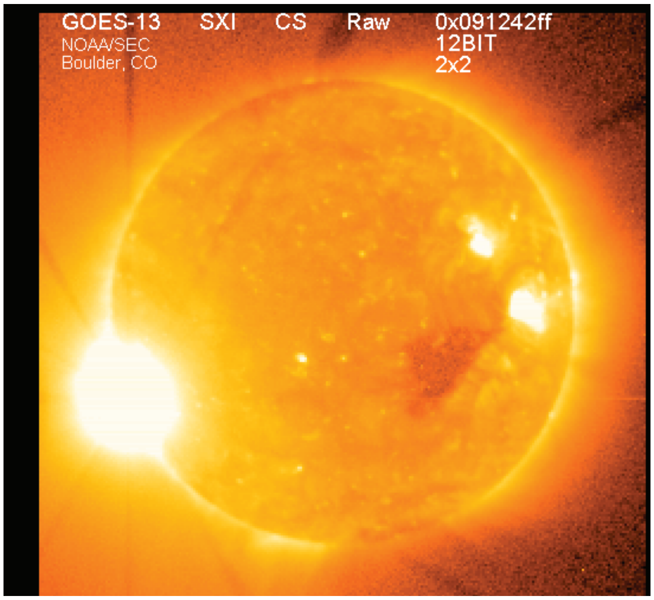


FIGURE 5.13 Solar flare image. Forecasting these solar flares and the adverse space weather they create requires more data and models than are currently available. SOURCE: NASA.

every reason to believe that with the much higher resolution information that is coming to us from the SDO,[7] we will have the science necessary to support those [forecasts].”

Despite the best efforts of satellite design engineers, anomalies due to unexpected interactions between satellites and space weather continue to occur. Having the ability to re-create the environment around the satellite at the time leading up to the anomaly is critical to determining if space weather caused the anomaly or not. Since most satellites do not carry environment monitors, anomaly investigators rely on data from other satellites and on models that extrapolate the environment from where it was observed to the location of the satellite that had the anomaly. So the ability to collect historical real-time data and extrapolate to other locations is also vital to satellite operators. On a scale of 1 to 10, with 10 being highly desirable, Chenette stated that “without long-term [climatology] predictions we would be dead—that is a 10. Being able to have a few days’ advance notice of higher activity would be an 8 or 9 [for launch vehicles and space operations, including manned operation on the Moon and in transit to Mars].”

U.S. AIR FORCE PERSPECTIVE

U.S. presidential policy assigns the responsibility to protect the space assets of the military, the intelligence community, the civil space assets, and the assets of allies to the U.S. Strategic Command, which is the operator of the U.S. Department of Defense (DOD) space systems and services. To fulfill that responsibility requires that the USAF maintain space situational awareness. That awareness includes monitoring the space environment.

Space weather has effects on the performance of DOD space assets that are similar to those it has on the civil and commercial assets discussed by other presenters in this session (Figure 5.14). Communication and navigation services used by DOD are affected by ionospheric disturbances that cause fading and scintillation of RF signals in equatorial regions and HF blackout in the polar regions. Potential loss of signal affects communication and

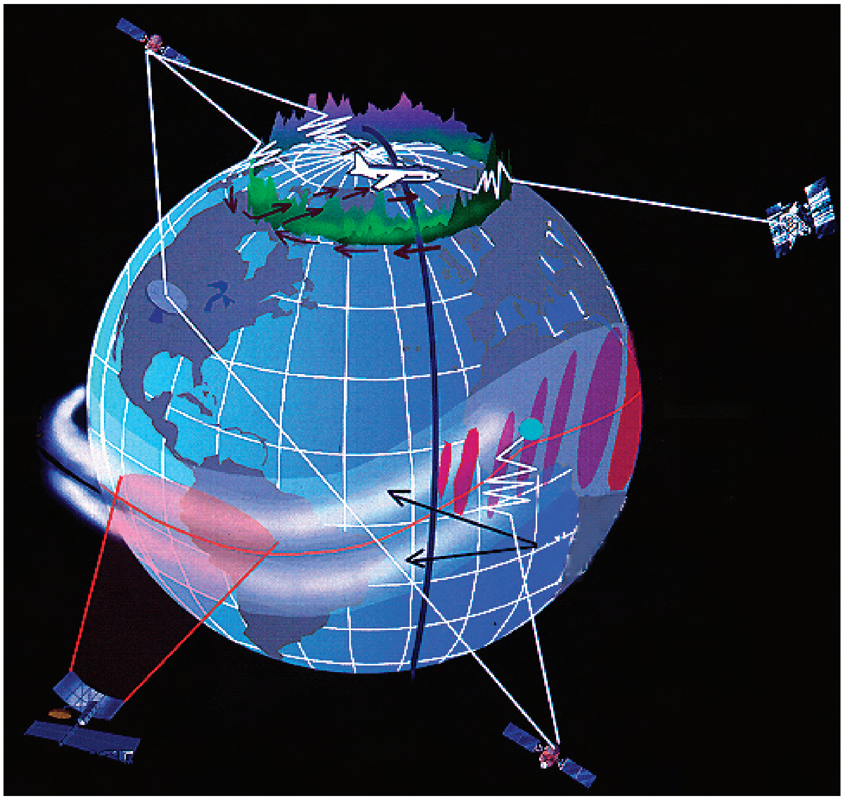


FIGURE 5.14 Military systems are affected by diverse space weather conditions. SOURCE: Kelly J. Hand, U.S. Air Force, “Space Weather—A DOD User Perspective,” presentation to the space weather workshop, May 22, 2008.

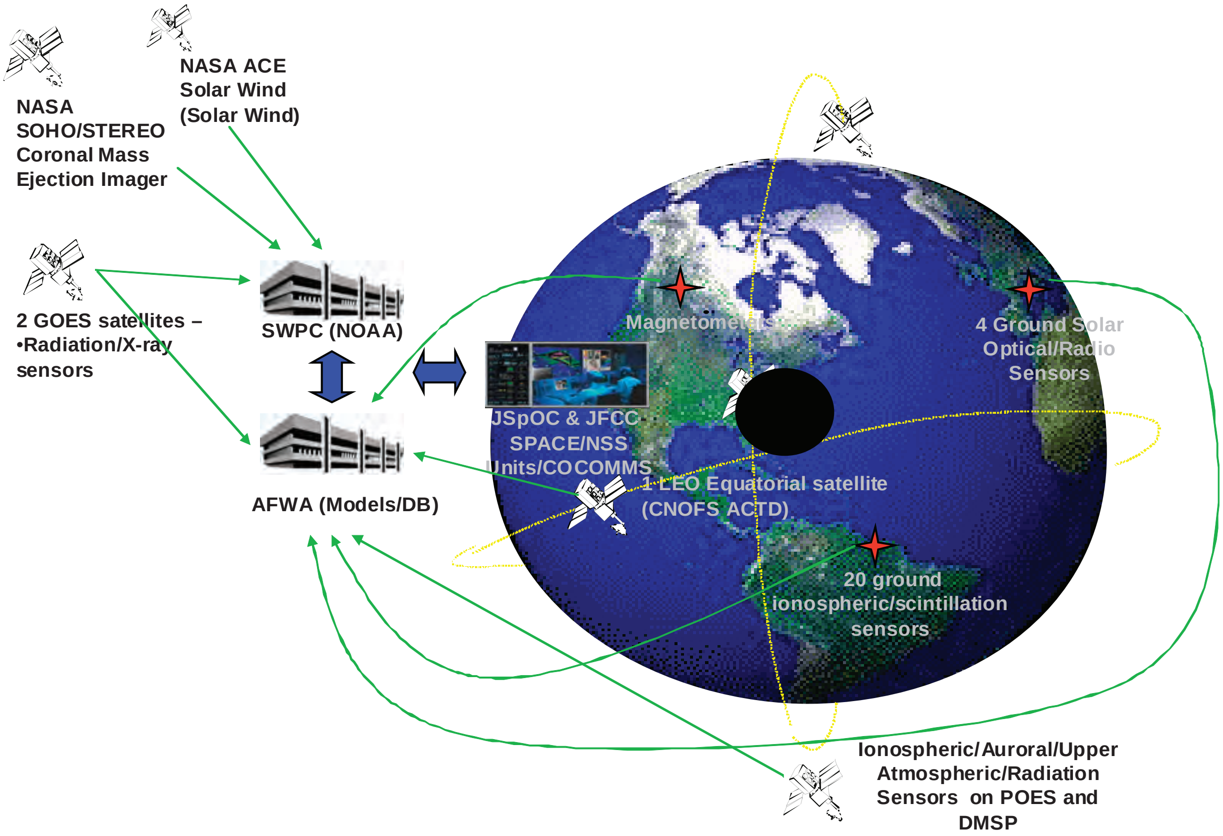


FIGURE 5.15 A wide range of space- and ground-based systems are utilized to create situational awareness of space weather and its impacts. SOURCE: Kelly J. Hand, U.S. Air Force, "Space Weather—A DOD User Perspective," presentation to the space weather workshop, May 22, 2008.

associated command and control of troops. GPS-aided systems used by military operations can also be affected. Increased atmospheric drag resulting from geomagnetic storms affects orbits of satellites and orbital debris. The Air Force Space Command has to update models of the orbits of debris with the latest sensor data in order to forecast potential collisions with satellites and the International Space Station (ISS). The ISS has made collision avoidance maneuvers in response to forecasts that show that debris will get too close for comfort.

The example of space station debris avoidance shows that space situational awareness is more than just observing space weather. Kelly Hand summarized the actions necessary to address the space weather aspect of situational awareness: (1) *observe* environmental conditions, using space- and ground-based sensors; (2) *process* sensor data, using environmental models to form complete pictures of the actual and forecast environment; (3) *determine effects* of the actual or forecast environment on systems and mission operations; (4) *integrate effects* into situational awareness, planning to mitigate those effects. The USAF relies on collaborative partnerships with other agencies in order to obtain and use the data it needs to develop situational awareness (Figure 5.15). Hand noted that "from a space operational perspective . . . we need to have an understanding of what is happening in the natural space environment in more detail and more rapidly than we are currently experiencing today. Also, information concerning its [space weather's] effects needs to be effectively integrated. . . . Our bottom-line concern with space weather is to determine how badly, when, and where space weather impacts our space systems and services and what we can do with that information to better protect and deliver those space services."

SUMMARY

Space weather clearly affects our technological systems and society. This workshop session presented four diverse examples of industries that manage or support technological systems that are directly affected by space weather: electrical power grid operators; precision geo-locations services; satellite manufacturing, launching, and operations, and the U.S. Air Force. In an effort to mitigate the impacts of space weather, each has responded by monitoring and reacting to current conditions, utilizing existing space weather data sources and services, and adding its own industry-unique assessment.

Space weather data are collected by satellites or ground-based observatories (e.g., ground-based magnetometer stations that study geomagnetic fields or riometers that monitor the state of the ionosphere). Some government services, such as NOAA's SWPC, have been established that provide some data collection, interpretation, and dissemination services that are utilized by industry (e.g., solar proton event intensity is used by spacecraft operators when making launch decisions, and by airlines in deciding on polar route diversion). Some rudimentary forecasting and alerts have been established and are utilized by industry to prevent imminent problems (e.g., power grid operators use ACE satellite data to secure the grid against an imminent geomagnetic storm). These services have allowed industries to minimize the disruptions caused by space weather, to the benefit of their millions of customers and society as a whole. The existing systems in place were deemed extremely beneficial (10 on a scale of 1 to 10) by the session's speakers.

The session's speakers indicated, however, that more could be done. First, a plan is needed to transition from scientific research platforms to continuously operating platforms in order to maintain the current data streams and alerts with continuous and redundant systems. Some of the research assets that industry currently depends on (e.g., ACE) are nearing the end of their life, and no plan is in place for a replacement. Second, each industry representative indicated that a reliable 24-hour forecast would be of significant value to reducing risks and disruptions, typically ranking it between 8 and 10 on a scale of 1 to 10. Currently available warnings are of little value to some industries, such as precision geo-location, because of the large number of false alarms and missed alarms.

In short, workshop participants learned that many industries have found a use for space weather data and have come to depend on current sources for that data to safeguard their technological systems and the services they provide to society. The industries represented in this session want to continue to have access to the near-real-time data they currently get, and they would eagerly adopt credible 24-hour forecasts when available.

NOTES

1. A description of polar cap absorption triggered by solar proton events can be found at http://www.windows.ucar.edu/spaceweather/polar_com.html. A more technical source is J.D. Patterson, T.P. Armstrong, C.M. Laird, D.L. Detrick, and A.T. Weatherwax, Correlation of solar energetic protons and polar cap absorption, *J. Geophys. Res.* 106(A1), 149-163, 2001.

2. The high-frequency (HF) radio blackouts covered by the R scales occur on the sunlit side of Earth, primarily at lower latitudes, and are a type of disturbance different from than the polar cap absorption (PCA) events affecting polar aircraft HF communications. PCAs are caused by solar protons and not by x-rays. The SWPC monitors the solar energetic particle flux in real time and issues alerts when the proton flux exceeds a specified threshold. The solar proton flux is categorized by a different set of levels, called the S scale (see http://www.swpc.noaa.gov/NOAAscales/index.html#SolarRadiation Storms). So the S scale, and not the x-ray intensity categorized by the R scale, is the proper scale to describe the intensity of the solar radiation storm and associated PCA. However, the coronal mass ejection (CME) that causes the PCA, if it is Earth directed, is often associated with a strong solar x-ray flare. The x-rays reach Earth in minutes, while the slower protons typically require many tens of minutes to hours to reach Earth, so x-rays provide an early warning that is not provided by the real-time proton monitors. Alerts tied to x-ray flares and described by the R scales are therefore useful to airlines, even though the x-rays have no direct connection to PCAs. Confirmation that a CME has occurred, is Earth directed, and will trigger solar energetic particle and PCA events can be given by satellites. This was done using IMP8 and is now being done by the Advanced Composition Explorer (ACE) and Solar and Heliospheric Observatory (SOHO).

IMP8, launched in 1973 and operated for 28 years, was the last of the Interplanetary Monitoring Platform spacecraft. It carried 12 instruments designed to monitor the interplanetary plasma, electric and magnetic fields, and high-energy cosmic-ray environments near Earth. See http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-078A and J.D. Patterson, T.P.

Armstrong, C.M. Laird, D.L. Detrick, and A.T. Weatherwax, Correlation of solar energetic protons and polar cap absorption, *J. Geophys. Res.* 106(A1), 149-163, 2001.

From its location at the Lagrangian point L1 about 1.5 million km from Earth and 148.5 million km from the Sun, ACE has a prime view of the solar wind, interplanetary magnetic field and higher-energy particles accelerated by the Sun, as well as particles accelerated in the heliosphere and the galactic regions beyond. ACE also provides near-real-time 24/7 continuous coverage of solar wind parameters and solar energetic particle intensities (space weather). When reporting space weather ACE provides an advance warning (about 1 hour) of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts. see http://www.srl.caltech.edu/ACE/ace_mission.html). More detail can be found in Stone et al., The Advanced Composition Explorer, *Space Science Reviews* 86, 1, 1998.

SOHO also obits at the L1 Lagrangian point, where it continuously monitors the Sun with 12 different instruments. Of particular use for space weather warnings are EIT (Extreme Ultraviolet Imaging Telescope), which can detect eruptive solar flares, and LASCO (Large Angle and Spectrometric Coronagraph), which can detect coronal mass ejections that may impact Earth's magnetosphere. See http://sohowww.nascom.nasa.gov/about/docs/SOHO_Fact_Sheet.pdf. Sample EIT and LASCO images are shown in Figure 5.5.

3. GLONASS is based on a constellation of active satellites that continuously transmit coded signals in two frequency bands, which can be received by users anywhere on Earth's surface to identify their position and velocity in real time based on ranging measurements. The system is a counterpart to the U.S. GPS, and both systems share the same principles in their data transmission and positioning methods. GLONASS is operated by the Coordination Scientific Information Center (KNITs) of the Ministry of Defense of the Russian Federation. See http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml.

4. Boscher, D.M., S.A. Bourdarie, R.H.W. Friedel, and R.D. Belian, Model for the geostationary electron environment: POLE, *IEEE Trans. Nucl. Sci.* 50(6), 2278-2283, 2003.

5. CRRES, Combined Release and Radiation Effects Satellite. See http://nasascience.nasa.gov/missions/crres.

6. GOES, Geostationary Operational Environment Satellite. GOES 13 is the most recent addition to the in orbit fleet of GOES satellites and carries the primary solar x-ray imager. These satellites provide continuous terrestrial weather monitoring (http://www.goes.noaa.gov/) and monitoring of solar activity and space weather (http://www.swpc.noaa.gov/).

7. SDO, Solar Dynamics Observatory. SDO is designed to improve understanding of the Sun's influence on Earth and near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. See http://sdo.gsfc.nasa.gov/.

6

Satisfying Space Weather User Needs

The workshop session on satisfying space weather user needs was a continuation of the preceding session on user perspectives on space weather products and included the same panelists (Michael Stills from United Airlines, James McGovern from ISO New England, Inc., Lee Ott from OmniSTAR, Inc., David Chenette from Lockheed Martin Advanced Technology Center, and Kelly Hand from the U.S. Air Force). These panelists represented aviation, electric power, GPS services, spacecraft development and launch, and military interests, respectively. The focus of this session was on satisfying the ongoing needs of the space weather community. In the previous session the audience heard how various communities use the currently available space weather information. This session looked at plans for providing space weather prediction data over the next several years based on the needs of the various user communities and the resources available. The panel members from the previous session discussed, along with audience participants, whether these plans for the future will satisfy their needs and if not, what additional information is needed.

The single presentation in this session was given by NOAA's Thomas J. Bogdan, space weather program manager and director of the Space Weather Prediction Center (SWPC). Bogdan as space weather program manager is responsible for space weather planning, understanding user needs and requirements, and putting into the budget cycle initiatives to satisfy those needs at appropriate future times. As director of the SWPC, the operational arm of NOAA and the single point of responsibility in the U.S. government for space weather forecasting and prediction for the civil and commercial communities, he works closely with the U.S. Air Force Weather Agency (AFWA), which has the same responsibility for the military community of the United States.

In 2005, the space weather activities at NOAA were moved from the Office of Oceanic and Atmospheric Research, which is in NOAA's research arm, into the National Weather Service, NOAA's operational arm. With that move, space weather activities at NOAA were no longer a line item in the presidential budget but instead became part of the local warnings and forecast line item that is funded at about $850 million annually and includes support for all of the National Weather Service. In 2008 the name of the space weather operation center was changed from Space Environment Center to the Space Weather Prediction Center to emphasize user needs for prediction capability in the space environment. Bogdan noted that the positive side of these moves is that NOAA has incorporated the SWPC within the overall NOAA Weather and Water Goal organization, showing recognition that "weather" includes not only traditional terrestrial weather parameters but also the effects of solar activity (x-rays, coronal mass ejections (CMEs), radio noise, proton and electron fluxes, plasma streams). However, the space weather prediction and reporting efforts continue to be supported by a very small and unpredictable annual budget (roughly US$5 million to $6 million) that is more reflective of a research and development (R&D) enterprise than an operational enterprise with real-time national space weather prediction responsibility. Despite the small and unstable funding that limits capabilities, the SWPC has experienced a steady growth in its customer base, even during the years of solar minimum when disturbance activity is lower.

ORGANIZATION OF THE NATIONAL SPACE WEATHER PROGRAM

Bogdan pointed out that the U.S. federal government has chosen to coordinate space weather activities through the National Space Weather Program (NSWP), participated in by eight agencies including NASA, the Department of Commerce (NOAA), the Department of Defense, the National Science Foundation, the Department of the Interior, the Department of Energy, the Department of State, and the Department of Transportation. The NSWP operates under the auspices of the Office of the Federal Coordinator for Meteorology. The federal government has designated the SWPC as the single point of responsibility for space weather forecasting and prediction for the civil and commercial communities.

As background, a search shows that a strategic plan for the NSWP was developed in 1995 by the National Space Weather Program Council (FCM-P30-1995, August 1995) and was followed in 1997 by an implementation plan (FCM-P31-1997, January 1997) that identified specific objectives and recommended activities necessary for improving space weather predictive capabilities. The 2000 Implementation Plan (FCM-P31-2000, July 2000) identified some 70 targeted space weather research proposals funded by the agencies involved in the NSWP to improve understanding of the space weather environment. Despite the progress made up to that time, the 2000 Implementation Plan reported that capabilities fell short of the requirements for warning, now-casting, forecasting, and post-event analysis, and that in many areas significant shortfalls remained and much work needed to be done. One reason is that agencies involved in the NSWP fund their own activities but do not contribute funding directly to the SWPC for meeting identified user needs.

NASA funds at several hundreds of million dollars annually the development of science satellites and provides extensive and essential real-time data on space weather to the SWPC that are used in its predictions and forecasts. NASA also funds extensive efforts to model the space environment but is not responsible for funding or contributing to the SWPC's data preparation and alert-reporting capabilities. The National Science Foundation funds the development of models of the space environment but does not provide funding support for SWPC data analysis or operations. The USAF funds the development and operations of space weather sensors in the Defense Meteorological Satellites Program and provides the data to the SWPC. It supplies rather modest funding for data preparation and reporting capabilities through the AFWA and also does provide some modest support to the SWPC for selected operations of interest involving the ACE satellite. NOAA funds at an annual level of US$45 million to $65 million the development of space weather instrumentation flown on weather satellites, such as those in the GOES series, and those data are provided as part of SWPC forecasts. The other agencies in the NSWP, the Department of Energy and the Department of the Interior, do not provide any funding to the SWPC toward satisfying direct user needs.

CORE MISSION AND CURRENT CAPABILITIES OF THE SPACE WEATHER PREDICTION CENTER

The core mission of the SWPC as stated by Bogdan is to:

- Assess, survey, analyze, and evaluate the best available data on solar weather;
- Evaluate what the needs are, what the research community can bring forward in the way of models and theory, and what real-time data NASA, the European Space Agency (ESA), and Russian satellites can provide now and in the future on the solar wind, solar particles, and x-rays;
- Design, fabricate, test, validate, and install new products and services that meet the needs of the user community; and

- Provide critical, actionable information at the right time to the right people including forecasts of upcoming events and impact.

The SWPC critically depends on data received primarily from science satellites funded and operated by NASA and its international partners. These currently include STEREO, SOHO, and ACE.[1] Bogdan stated that there are no backups or replacements for these satellites, and in the event of their failure the ability of the SWPC to provide essential data, forecasts, and predictions would be severely affected.

Bogdan indicated that the modest SWPC budget is currently allocated to (1) processing and quality control of space weather data obtained from the NOAA-funded GOES 10, 11, and 12 satellites; (2) postlaunch testing for the GOES 13 satellite; and (3) risk reduction and algorithm development on data from the GOES-R satellite. As a result of these priorities, planned R&D activities are not possible within the current budget. Activities are focused on the core mission "to provide space weather products and services that meet the evolving needs of the nation," Bogdan stated. Included in this core mission is the duty to organize critical space weather data in a format that users can readily access and to archive the data for future use and analysis. Without this data management effort, studies of past solar events by users and long-term studies of solar weather climatology by users would not be possible. Observational problems that sometimes arise with the NOAA instruments on the GOES satellites must be resolved within the very limited SWPC budget with the result, Bogdan reported, that "almost no R&D efforts can be supported."

Bogdan emphasized that "to fulfill this mission with such limited resources it is vital that data from the assets of many other national and international organizations continue to be available." As stated above, the SWPC currently acquires real-time data from the NASA-funded STEREO, SOHO, and ACE satellites and will need similar real-time data from the Radiation Belt Storm Probe satellites under development by NASA and expected to be launched in 2011, as reported on NASA websites.

Bogdan indicated that a number of DOD groups are interested in space weather and that "the SWPC is partnering with them in every way possible." As reported on its website, the Joint Space Operations Center (JSpOC), a part of the U.S. Strategic Command, is charged with protecting U.S. space systems. An aspect of producing such protection is maintaining situational awareness, the ability to know everything in the environment that can affect the operations of U.S. military and surveillance satellites, which in turn requires a continual, real-time awareness of space weather. The JSpOC relies on the AFWA, which partners with the SWPC in providing predictions, forecasts, alerts, and archived data to military users to satisfy this situational awareness responsibility but does not fund the SWPC in this endeavor.

Bogdan mentioned an international component to the partnering in that there are some 12 regional space weather centers around the globe, in Australia, Canada, Russia, Poland, India, and elsewhere. The SWPC must also leverage results from the research community and fledging commercial businesses since they cannot satisfy all user needs with the current very modest budgets. For example, the SWPC analyzes and selects the best space environment models developed by many scientists in the research community. Another example is the modeling of Earth's crust in North America around key electrical power transformer locations including the currents induced by past major solar storms. John Kappenman of Metatech Corporation reported from the audience that his company will soon offer this capability as a service. The SWPC welcomes these commercial services, although it must be especially diligent in evaluating and adopting new models and services to ensure applicability, reliability, and durability for the users.

Bogdan outlined the FY 2008 capability levels of the SWPC in providing long-term forecasts (1 to 3 days), short-term forecasts and warnings (less than 1 day), and now-casts and alerts (Figure 6.1). Only 1 of the 14 capabilities shown in Figure 6.1—that of providing now-casts and alerts of global and regional solar x-ray flux—is considered satisfactory (color-coded green). Three prediction capabilities are considered poor (color-coded red). In the critical area of long-term forecasts (1 to 3 days), the ability to predict ionospheric disturbance probabilities is regarded as poor (color-coded red). Capabilities for long-term forecasts of M-flare and X-flare probabilities, solar energetic particle probabilities, geomagnetic storm probabilities, and solar-irradiance flux levels are considered less than satisfactory, with much more work needed (color-coded yellow). As discussed in the "Panel and Audience Feedback" section below, reliable long-term forecasts were identified by the panel members as the most important need of the user communities. With reliable (minimal false alarms) long-term forecasts of a day or more, the various user communities could take actions to mitigate the effects of impending solar disturbances and minimize the resulting economic impact. Even in the short-term forecasts and warnings category, two areas—M-flare and X-flare probabilities and global and regional ionospheric disturbance probabilities—are coded red. No capabilities in the short-term forecasts and warnings category are considered satisfactory. Given that users at this workshop identified reliable, long-term forecasts as their most important need, the current absence of satisfactory short-term and long-term forecast capabilities is a serious shortfall in the National Space Weather Program.

FUTURE DIRECTIONS OF THE SPACE WEATHER PREDICTION CENTER

Bogdan indicated that new directions for the SWPC would include the following if the available budgets permit:

- Secure an operational L1 solar wind monitor.
- Transition a numerical CME/solar wind model into operations.
- Secure backup capability for GOES-10 XRS (X Ray Spectrometer) data stream.
- Complete compliance measures necessary for the SWPC to become a partner in the National Climate Service to help guide future solar observations, research, modeling, and forecast development activities.
- Transition the whole-atmosphere model into operations.
- Develop forecast capabilities based on STEREO data streams.
- Revamp the concept of operations of the Space Weather Forecast Office.
- Transition a coupled magnetosphere/whole-atmosphere model into operations.
- Develop precision GPS forecast and correction tools.
- Develop operational radiation environment models.

With these objectives in mind and if funding issues can be resolved, Bogdan indicated that the capabilities of the SWPC in FY 2014 could be improved as indicated in Figure 6.2. If these capabilities are achieved, the SWPC in 2014 could provide high-confidence 1- to 3-day forecasts of geomagnetic storms and ionospheric disturbances, whereas such forecasts do not exist today. This capability would go a long way toward satisfying user needs for space weather forecasting.

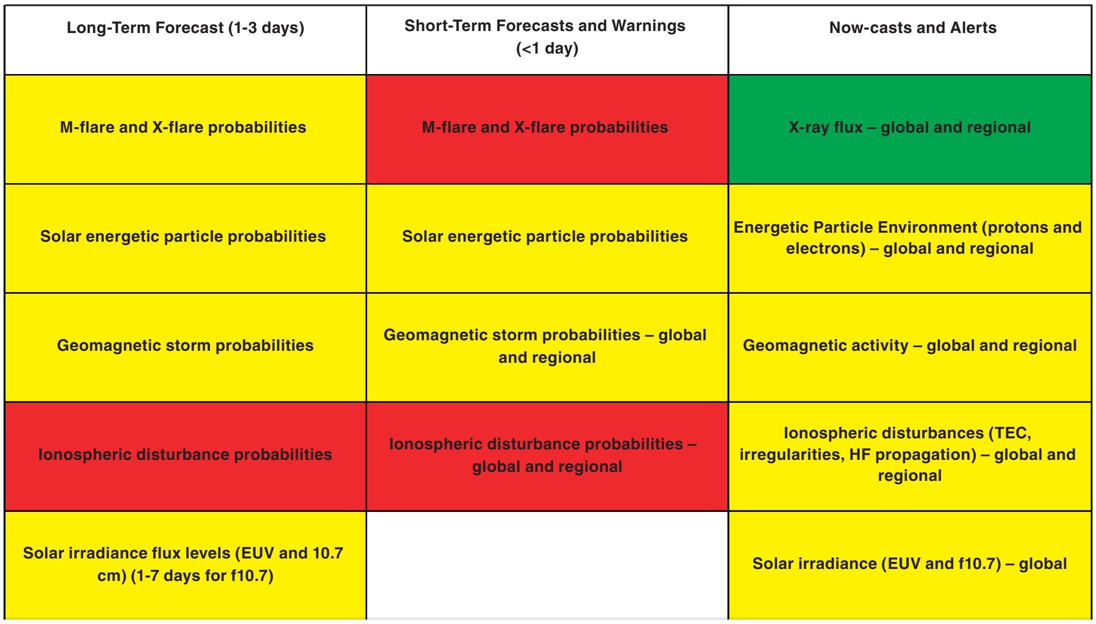
PANEL AND AUDIENCE FEEDBACK

Following Bogdan's presentation, Daniel Baker of the University of Colorado asked the panelists to define quantitatively the benefits of receiving high-quality forecasts several hours to 1 day to several days in advance and conversely the cost of receiving less than accurate or inaccurate (false-alarm) space weather alerts. The audience was also invited to participate with questions for the speaker and panel members.

Stills of United Airlines noted that polar flights are vulnerable to space weather effects on communications. Although space weather events are infrequent, the number of polar flights is increasing rapidly and these flights are critical for a number of reasons, including the large aircraft and passenger loads affected, the long (approximately 15-hour) flight duration, and the small margin for error in terms of fuel for such long flights. A 24-hour alert would allow time to plan a different route that would require a refueling stop along the way. A much shorter alert time also would be useful, but operational costs increase when there is less advance warning. It is evident that false alarms are disruptive and expensive.

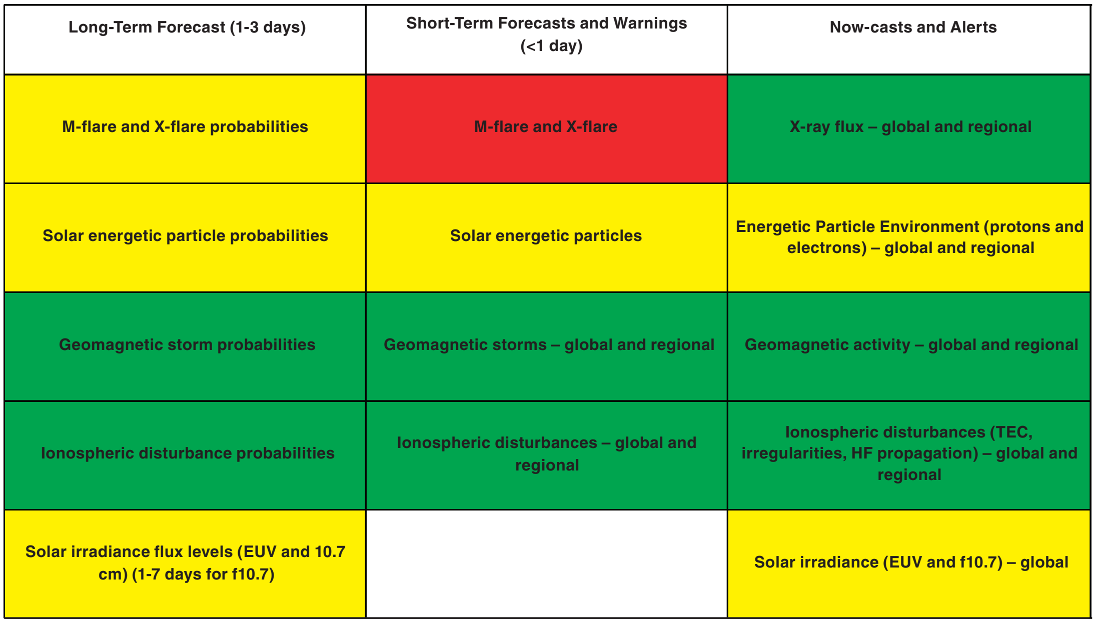
McGovern of ISO New England, Inc., said that a space weather warning would allow power companies to prepare by canceling planned maintenance work, providing additional personnel to deal with adverse effects, and reducing power transfers between adjacent systems in the grid. If false alarms occurred and planned maintenance was canceled, the cost of large cranes, huge equipment, and a lot of material and manpower sitting idle would be very high.

Bogdan stated in response, "If phenomena are not observed, they can't be predicted. The SWPC ability to



Long-Term Forecast (1-3 days)	Short-Term Forecasts and Warnings (<1 day)	Now-casts and Alerts
M-flare and X-flare probabilities	M-flare and X-flare probabilities	X-ray flux – global and regional
Solar energetic particle probabilities	Solar energetic particle probabilities	Energetic Particle Environment (protons and electrons) – global and regional
Geomagnetic storm probabilities	Geomagnetic storm probabilities – global and regional	Geomagnetic activity – global and regional
Ionospheric disturbance probabilities	Ionospheric disturbance probabilities – global and regional	Ionospheric disturbances (TEC, irregularities, HF propagation) – global and regional
Solar irradiance flux levels (EUV and 10.7 cm) (1-7 days for f10.7)		Solar irradiance (EUV and f10.7) – global

FIGURE 6.1 Fiscal year 2008 capability levels of the NOAA Space Weather Prediction Center. Green, satisfactory; yellow, less than satisfactory; red, poor. SOURCE: Thomas J. Bogdan, Space Weather Prediction Center, NOAA, presentation to the space weather workshop, May 22, 2008.



Long-Term Forecast (1-3 days)	Short-Term Forecasts and Warnings (<1 day)	Now-casts and Alerts
M-flare and X-flare probabilities	M-flare and X-flare	X-ray flux – global and regional
Solar energetic particle probabilities	Solar energetic particles	Energetic Particle Environment (protons and electrons) – global and regional
Geomagnetic storm probabilities	Geomagnetic storms – global and regional	Geomagnetic activity – global and regional
Ionospheric disturbance probabilities	Ionospheric disturbances – global and regional	Ionospheric disturbances (TEC, irregularities, HF propagation) – global and regional
Solar irradiance flux levels (EUV and 10.7 cm) (1-7 days for f10.7)		Solar irradiance (EUV and f10.7) – global

FIGURE 6.2 Potential capability levels of the NOAA Space Weather Prediction Center in FY 2014. Green, satisfactory; yellow, less than satisfactory; red, poor. SOURCE: Thomas J. Bogdan, Space Weather Prediction Center, NOAA, presentation to the space weather workshop, May 22, 2008.

observe is going to make the difference between what we can predict and what we can't." He further stated that "prediction is the key to the future and is the answer to helping customers make good business decisions and maintain their continuity of operations." He was hopeful that modeling of CMEs from the Sun to Earth would be the most beneficial in this regard since the transit time ranges from 20 hours to 3 days. He further stated that the capability of modeling CMEs is very mature and could be implemented in the near future. From an economic and societal perspective, the benefits could be substantial, given that CMEs have a demonstrated potential to cause large adverse impacts. Bogdan was not hopeful about modeling of solar flares in the near future.

St. Cyr of NASA asked where in each of the panel member organizations space weather data would be used and whether it would be used in terrestrial weather offices. Stills said that space weather was handled by United's terrestrial weather desk in order to have a single point of contact. McGovern described his organization's reliance on an industry group known as NERC, the North American Electric Reliability Corporation, which was established to ensure the reliability of the bulk power system in North America. NERC receives its space weather data from the NOAA SWPC. Ott said that space weather warnings are handled separately at OmniSTAR since terrestrial weather does not affect differential GPS corrections. He raised a further question about ionospheric storms and "bubbles" in the ionosphere that affect GPS signals and asked how we know when such bubbles have dissipated. Bogdan responded that ionospheric modeling is sophisticated and could, he believed, be used to predict when such dissipation would occur. Joseph Fennel of the Aerospace Corporation pointed out that half of the anomalies observed on spacecraft occur when there is no large storm activity on the Sun, but rather when energy is transferred within the magnetosphere, a process defined as a substorm, and that modeling of these events will be much more difficult.

Ott also said that for about 10,000 subscribers in the United States and double that worldwide, in applications ranging from agriculture to offshore oil exploration, engineering, and production, if GPS or the OmniSTAR correction service becomes unavailable long enough to disrupt an operation, it can cost up to "tens of millions of dollars." For example, a seismic survey costs about $60,000 per day, and it takes hours to repeat a lost survey line. If positioning control for offshore drill rigs is lost, it can take 2 days to re-position the rig and re-fit the pipe, with an operating cost of about $2 million per day. Loss of the positioning reference also could risk dragging a 50-ton anchor over an oil pipeline. Tom Stansell of Stansell Consulting said that whereas these interruptions can be and have been caused by the effects of a highly disturbed ionosphere on dual-frequency GPS measurements with "semi-codeless" receivers, such problems will be all but eliminated (with rare exceptions) as the GPS constellation becomes fully populated by "modernized" satellites carrying the second civil signal, L2C, and beyond that the third civil signal, L5. OmniSTAR uses NOAA SWPC products to warn users of potential space weather effects, but Ott noted that so many warnings have been false alarms that customers stop paying attention and are upset when a loss of service does occur. New signals to be provided by the GPS III satellites are expected to greatly mitigate these problems by about 2014.

Louis Leffler, retired from NERC, pointed out that, historically, space weather has affected new technologies differently from previously used technologies. He cited the shift from the telegraph to the radio for long-range communications and the unexpected effects that solar weather had on the ionosphere and on radio signal propagation. As technologies become more sophisticated, the sophistication of the underlying physics and chemistry needs to improve, because we are going to be surprised in the future, just as we have been in the past. Todd La Porte of George Mason Univesity supported these points and reminded the audience that even though the nuclear power industry had operated highly reliably for some time and still does, the single Three Mile Island incident in March 1979 was followed by essentially a 100 percent cessation of new nuclear reactor construction in the United States because of a loss of confidence by the public. He posited that it is a fact that we will experience large solar weather storms in the future, albeit infrequently, and we should be open-minded to the fact that surprises will occur. But the public does not necessarily respond to such surprises in a rational manner, and there are often unintended consequences.

SUMMARY

The U.S. federal government has chosen to coordinate space weather responsibilities through the NSWP, which includes NASA, the Department of Commerce (NOAA), the Department of Defense, the National Science Foundation, the Department of the Interior, the Department of Energy, the Department of State, and the Department of Transportation. The NSWP operates under the auspices of the Office of the Federal Coordinator for Meteorology. The SWPC, an operational arm of NOAA and the single point of responsibility in the government for space weather forecasting and prediction for the civil and commercial communities, operates on a very small and unpredictable annual budget (roughly US$5 million to $6 million) that limits capabilities. Nevertheless, the SWPC's customer base has grown steadily, even during the years of solar minimum when solar disturbance activity is lower.

Thomas Bogdan showed the FY 2008 capability levels of the SWPC to provide long-term forecasts (1 to 3 days), short-term forecasts and warnings (less than 1 day), and now-casts and alerts. In only 1 of 14 areas was the capability considered satisfactory (see Figure 6.1). In three areas the prediction capability was shown as poor, including in the critical area of long-term forecasts (1 to 3 days) of ionospheric disturbance probabilities. The FY 2008 capabilities for long-term forecasts of M-flare and X-flare probabilities, solar energetic particle probabilities, geomagnetic storm probabilities, and solar-irradiance flux levels were shown as less than satisfactory, with much more work to be done. Bogdan also showed projected future capabilities for the SWPC if funding issues can be resolved (see Figure 6.2). If several new objectives are achieved, Bogdan stated that the SWPC in FY 2014 would have the capability of high-confidence 1- to 3-day forecasts of geomagnetic storms and ionospheric disturbances, forecasts that do not exist today.

Following Bogdan's presentation on the NOAA SWPC, panelists discussed the benefits of receiving high-quality space weather forecasts, as well as the cost of receiving less than accurate or inaccurate (false-alarms) alerts, for operations such as airline polar flights, power company maintenance work and transfers of power between adjacent systems in the grid, and seismic surveys for offshore oil exploration, engineering, and production. Panelists, along with members of the audience, clearly indicated the economic and societal benefits of having, at a minimum, a reliable 24-hour alert of impending severe space weather and were concerned that such a capability does not exist today.

NOTE

1. The two STEREO (Solar-Terrestrial Relations Observatory) satellites were launched by NASA in 2006 into Earth's orbit around the Sun to obtain stereo pictures of the Sun's surface and to measure the magnetic fields and ion fluxes associated with solar explosions. The STEREO satellites trace the flow of energy and matter from the Sun to Earth. The Solar and Heliospheric Observatory (SOHO), launched on December 2, 1995, is an international collaboration between ESA and NASA to study the Sun from its deep core to the outer corona and the solar wind. The Advanced Composition Explorer (ACE), launched by NASA on August 25, 1997, orbits the L1 Lagrangian point where the gravitational pull of Earth and the Sun and centripetal force balance in such a way as to give an orbit of exactly 1 Earth year. For more information on ACE and SOHO, see note 2 in Chapter 5.

7

Future Solutions, Vulnerabilities, and Risks

The workshop session titled “The Future: Solutions or Vulnerabilities?” was intended to look into the future and evaluate how technical systems and their utilization are expected to evolve, and how this evolution affects their vulnerability to space weather. The technical infrastructure, enabling technologies, and space-based assets of the country are constantly changing. New electronic devices, new navigation systems, and new power grid systems are all evolving in response to improved technologies and increased requirements for efficiency and capability. Within this environment of innovation, designers will need to trade engineering solutions to mitigating space weather impacts against operational needs and space weather forecasting. This chapter addresses the evolution of current technologies and systems and their vulnerability to space weather, anticipated new technologies that may be more, or less, vulnerable to space weather than currently, and the estimation of future risks. Session panelists were asked to examine their industry with the understanding that we do not know the full range of possible space weather as demonstrated by the Carrington event of 1859, whose effects on Earth’s magnetic field were far greater[1] than those of any magnetic storm in the space era, and by the solar radio burst on December 6, 2006, which was 10 times more intense than any previous solar radio burst recorded over the past 50 years.

The session’s speakers each received questions, tailored to their particular expertise, that can be generally summarized as follows: (1) How will current technologies and systems evolve and what will be their vulnerability to space weather? (2) Can new technologies be expected that will be vulnerable to space weather? and (3) Will engineering solutions that mitigate space weather effects be possible and practical in the future?

The limitations of a workshop format allowed for a sampling of three technology infrastructure areas in this session. An analysis of electrical power systems was presented by John Kappenman of Metatech Corporation. Presentations on GPS and aviation systems were given by Thomas McHugh of the FAA and Christopher Hegarty of the MITRE Corporation. An analysis of satellite systems was presented by Ronald Polidan of Northrop Grumman Corporation. In addition, a presentation on estimating future extremes of space weather by T. Paul O’Brien from the Aerospace Corporation was presented by Joseph Fennell and is covered in this section. These presentations and the related workshop discussions are summarized below. In some cases the summarized material draws substantially from the abstracts of the presentations included in Appendix C.

POWER GRIDS

Future Vulnerability

Severe space weather has the potential to pose serious threats to the future North American electric power grid.[2] Recently, Metatech Corporation carried out a study under the auspices of the Electromagnetic Pulse Commission and also for the Federal Emergency Management Agency (FEMA) to examine the potential impacts of severe geomagnetic storm events on the U.S. electric power grid. These assessments indicate that severe geomagnetic storms pose a risk for long-term outages to major portions of the North American grid. John Kappenman remarked that the analysis shows "not only the potential for large-scale blackouts but, more troubling, . . . the potential for permanent damage that could lead to extraordinarily long restoration times." While a severe storm is a low-frequency-of-occurrence event, it has the potential for long-duration catastrophic impacts to the power grid and its users. Impacts would be felt on interdependent infrastructures, with, for example, potable water distribution affected within several hours; perishable foods and medications lost in about 12-24 hours; and immediate or eventual loss of heating/air conditioning, sewage disposal, phone service, transportation, fuel resupply, and so on. Kappenman stated that the effects on these interdependent infrastructures could persist for multiple years, with a potential for significant societal impacts and with economic costs that could be measurable in the several-trillion-dollars-per-year range.

Electric power grids, a national critical infrastructure, continue to become more vulnerable to disruption from geomagnetic storms. For example, the evolution of open access on the transmission system has fostered the transport of large amounts of energy across the power system in order to maximize the economic benefit of delivering the lowest-cost energy to areas of demand. The magnitude of power transfers has grown, and the risk is that the increased level of transfers, coupled with multiple equipment failures, could worsen the impacts of a storm event.

Kappenman stated that "many of the things that we have done to increase operational efficiency and haul power long distances have inadvertently and unknowingly escalated the risks from geomagnetic storms." This trend suggests that even more severe impacts can occur in the future from large storms. Kappenman noted that, at the same time, no design codes have been adopted to reduce geomagnetically induced current (GIC) flows in the power grid during a storm. Operational procedures used now by U.S. power grid operators have been developed largely from experiences with recent storms, including the March 1989 event. These procedures are generally designed to boost operational reserves and do not prevent or reduce GIC flows in the network. For large storms (or increasing dB/dt levels) both observations and simulations indicate that as the intensity of the disturbance increases, the relative levels of GICs and related power system impacts will also increase proportionately. Under these scenarios, the scale and speed of problems that could occur on exposed power grids have the potential to impact power system operators in ways they have not previously experienced. Therefore, as storm environments reach higher intensity levels, it becomes more likely that these events will precipitate widespread blackouts in exposed power grid infrastructures. The possible extent of a power system collapse from a 4800 nT/min geomagnetic storm (centered at 50° geomagnetic latitude) is shown in Figure 7.1. Such dB/dt levels—10 times those experienced during the March 1989 storm—were reached during the great magnetic storm of May 14-15, 1921.

The least understood aspect of this threat is the permanent damage to power grid assets and how that will impede the restoration process. Transformer damage is the most likely outcome, although other key assets on the grid are also at risk. In particular, transformers experience excessive levels of internal heating brought on by stray flux when GICs cause a transformer's magnetic core to saturate and to spill flux outside the normal core steel magnetic circuit. Kappenman stated that previous well-documented cases have involved heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers. These multi-ton apparatus generally cannot be repaired in the field, and if damaged in this manner, they need to be replaced with new units, which have manufacture lead times of 12 months or more. In addition, each transformer design can contain numerous subtle design variations that complicate the calculation of how and at what density the stray flux can impinge on internal structures in the transformer. Therefore the ability to assess existing transformer vulnerability or even to design new transformers that can tolerate saturated operation is not readily achievable.

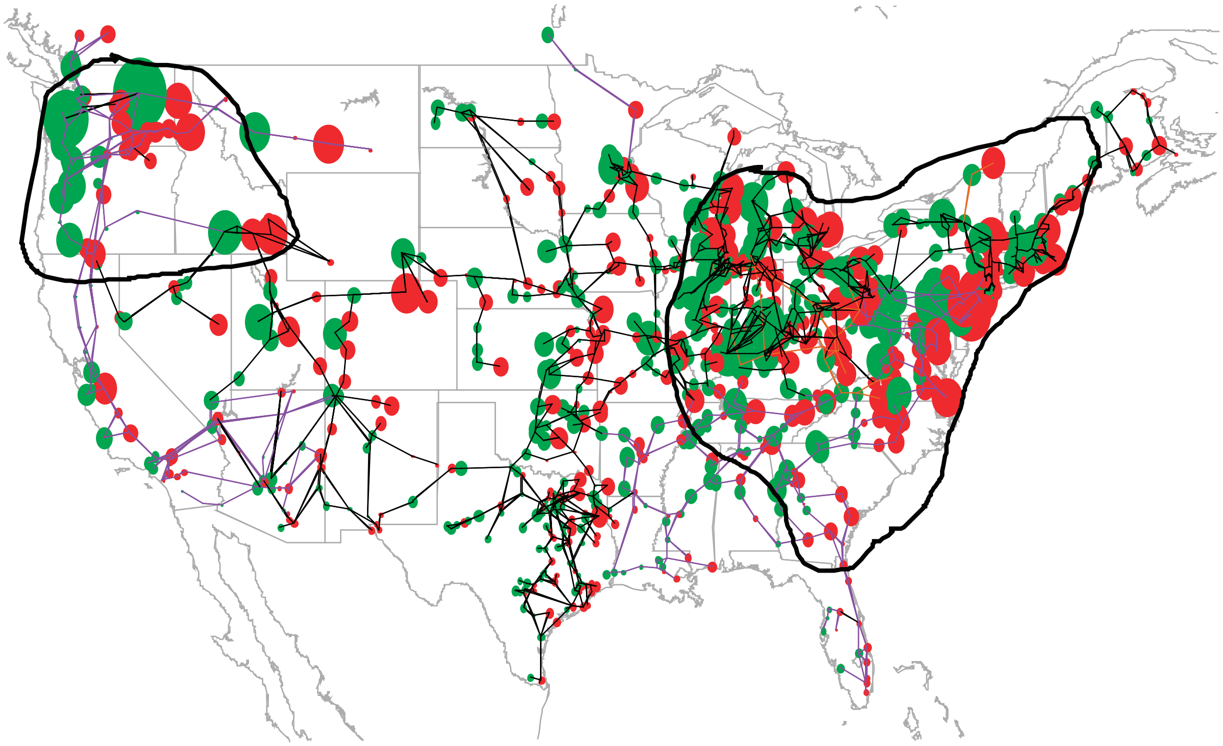


FIGURE 7.1 Scenario showing effects of a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude scenario. The regions outlined are susceptible to system collapse due to the effects of the GIC disturbance; the impacts would be of unprecedented scale and involve populations in excess of 130 million. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

The experience from recent space weather events suggests a threatening outcome for today's infrastructure from historically large storms that are yet to occur.

Recent analysis by Metatech estimates that more than 300 large EHV transformers would be exposed to levels of GIC sufficiently high to place these units at risk of failure or permanent damage requiring replacement. Figure 7.2 shows an estimate of percent loss of EHV transformer capacity by state for a 4800 nT/min threat environment such as might occur during a storm of the magnitude of the May 1921 event. Such large-scale damage would likely lead to prolonged restoration and long-term shortages of supply to the affected regions.

In summary, present U.S. grid operational procedures are based largely on limited experience, generally do not reduce GIC flows, and are unlikely to be adequate for historically large disturbance events. Historically large storms have a potential to cause power grid blackouts and transformer damage of unprecedented proportions, long-term blackouts, and lengthy restoration times, and chronic shortages for multiple years are possible. As Kappenman summed up, "An event that could incapacitate the network for a long time could be one of the largest natural disasters that we could face."

Solutions for the Future

Given the potentially enormous implications of power system threats due to space weather, major emphasis focuses on preventing storm-related catastrophic failure. Trends have been in place for several decades that have

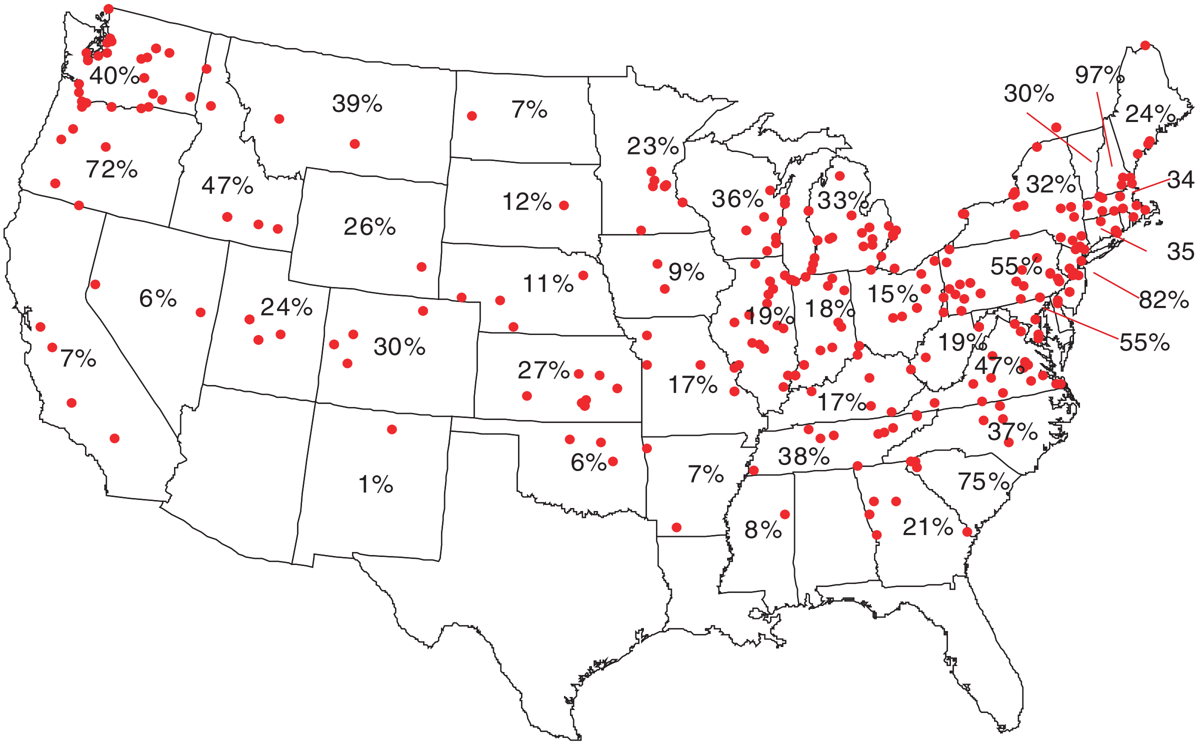


FIGURE 7.2 A map showing the at-risk EHV transformer capacity (estimated at ~365 large transformers) by state for a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude. Regions with high percentages of at-risk capacity could experience long-duration outages that could extend multiple years. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

acted to inadvertently escalate the risks from space weather to this critical infrastructure. Kappenman stated that procedures based on K-index-style alerts provide very poor descriptions of the impulsive disturbance environments and lead to uncertainties about the adequacy and efficacy of operational procedures during large storms. He offered several solutions for the future. With respect to the entire grid, remedial measures to reduce GIC levels are needed and are cost-effective. The installation of supplemental transformer neutral ground resistors to reduce GIC flows is relatively inexpensive, has low engineering trade-offs, and can produce 60-70 percent reductions of GIC levels for storms of all sizes. Additional research work is already under way by the EMP Commission in this area. Kappenman noted that improved situational awareness for power grid operators is needed and is readily available (i.e., with an emphasis on disturbance environments/GIC levels instead of ambiguous K/G indices). In addition, regional system operators require initial and continuing training to understand their assigned roles and responsibilities in protecting the power system during solar events using new tools.

Economic and societal costs attributable to impacts of geomagnetic storms could be of unprecedented levels. For example, consider the following cost estimates:

- August 14, 2003, Northeast blackout: \$4 billion to \$10 billion,[3]
- Hurricane Katrina: \$81 billion to \$125 billion,[4,5]
- Future severe geomagnetic storm scenario: \$1 trillion to \$2 trillion in the first year, and
- Depending on damage, full recovery could take 4 to 10 years.[6]

GLOBAL POSITIONING SYSTEMS AND AVIATION

Future Vulnerability

The FAA is in the process of transitioning the National Airspace System to utilize space-based navigation as the primary means of navigation. This transition is part of an overall modernization of the National Airspace System to implement integrated Communications Navigation and Surveillance (CNS). CNS services required by the FAA for aviation are provided partially by the FAA and partially by private sector operators. One way of achieving navigation is with GPS and augmentation systems. In his presentation, Thomas McHugh noted that the use of GPS for CNS is an evolving process with several different approaches, each offering advantages and challenges. Surveillance services are planned as part of the Automatic Detection and Surveillance-Broadcast system (ADS-B), and an integrated CNS service is planned through the Next Generation Air Transportation system (NextGen).

CNS is vulnerable to space weather: accuracy and integrity can be lost for non-augmented single-frequency GPS users, and availability can be lost for augmented single-frequency GPS users. All GPS users are vulnerable to loss of availability during extreme events such as radio-frequency interference from solar radio bursts and loss of reception of many or all GPS signals due to scintillation. Additional threats to robust CNS include loss of high frequency for oceanic reporting and disruption of the national power and telecommunications infrastructure during an extreme event. As McHugh noted, "The vulnerabilities to CNS are down in the ionosphere." These vulnerabilities are mitigated by new signals and codes for the modernized GPS system, backup navigation systems, and autonomous navigation systems.

Space weather vulnerabilities depend critically on the type of navigation employed, which can be divided into two broad categories, non-precision and precision. Non-precision navigation requirements are looser and apply in operations less vulnerable to space weather, whereas precision navigation requirements, used in landing and approach procedures, are strict, and the availability of navigation services is exchanged for safety.

The ionosphere is the primary source of error for users of single-frequency non-augmented GPS, which uses the Klobuchar model[7,8] to correct ionospheric ranging errors; frequently these corrections are in error. Since accuracy is degraded during even minor ionospheric events, this technology can be used only for non-precision applications. This technology is also vulnerable to scintillation, which causes temporary loss of GPS reception and affects the availability of Receiver Autonomous Integrity Monitoring (RAIM), which can be interrupted by the loss of even a small number of satellite signals. As discussed by McHugh, certification of aviation technology requires 10^{-7} probability of not providing misleading information, and "it is extremely difficult to certify the ionosphere."

Augmented users are less vulnerable to minor and moderate ionospheric disturbances but still can be affected by scintillation, solar radio bursts, and major ionospheric disturbances. The primary source of augmentation over the continental United States, Alaska, and Hawaii is the Wide Area Augmentation System (WAAS). WAAS disables the use of precision navigation in areas affected by ionospheric disturbances and does so using internal detection of the disturbances so that safety is never compromised. When large areas of disturbance are detected, precision navigation is disabled for all areas until 8 hours after disturbances cease. During the October and November 2003 magnetic storms, WAAS was disabled throughout the service area for 30 hours, and similar impacts are expected during the next solar maximum. McHugh expects that for the next solar maximum there will be four or five storms that will lead to widespread outages and that there will be shorter, regional outages "for probably the top 20 storms of the cycle'"

Solutions for the Future

The FAA approach to mitigating space weather impacts is in part to implement new GPS signals and codes and in part to maintain backup systems. Starting with the GPS Block IIF satellites, a new L5 civil GPS signal will be transmitted in an aviation-protected frequency band. The L5 signal along with the L1 civil signal allows GPS receivers to estimate and remove ionospheric errors, a capability that will mitigate the problems with the Klobuchar and SBAS (Satellite-based Augmentation Systems) thin shell models such as WAAS. In addition, the L5 signal design is more robust than the L1C/A signal and will help mitigate unintentional interference. Hegarty stated that the L5 signal has a “dataless component, which will allow the signal to be tolerant to signal fades roughly 7 dBs stronger due perhaps to ionospheric scintillation than the CA” code. The new L2 (discussed below) and L5 signals are expected to be operational by the 2016-2018 time frame.

The second approach to mitigating space weather impacts is to maintain backup navigation systems independent of GPS—which is required even without space weather because of the threat from intentional interference. For the foreseeable future FAA policy is to maintain legacy backup systems for all GPS-based navigation. These backup systems generally are less capable than GPS-based systems. ADS-B and NextGen have analyzed potential backup systems such as eLORAN, DME/DME RNAV, and intertial navigation as likely candidates, but there was no clear conclusion. Fleet equipage and acceptance is a major factor in deciding which legacy or new systems will be maintained.

In addition to the new L5 signal for the FAA, GPS and the larger Global Navigation Satellite System (GNSS) are being modernized in a process that will extend to at least 2020.

Modernization requires launching new satellites that transmit the new signals and codes, resulting in an incremental process. Figure 7.3 shows the current and planned signals and codes. The original GPS satellites, Block I through Block IIR, transmit a C/A (coarse-acquisition) code at L1 (1575.24 MHz) and encrypted precise (P(Y)) codes at L1 and L2 (1227.6 MHz). The first step in GPS modernization began with Block IIR-M satellites in 2005, and 6 of these satellites (out of 30) are currently in operation. The Block IIR-M satellites add a new civilian code (L2C) on L2 and new encrypted military signals (M-code) on both L1 and L2. The advantage of the L2C code is

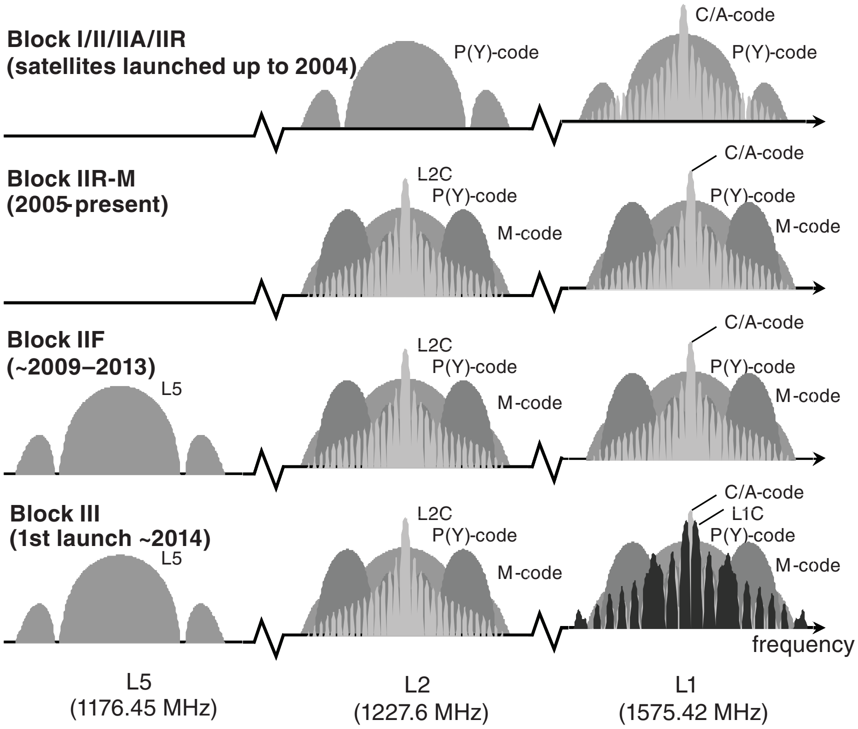


FIGURE 7.3 The evolution of the GPS frequency plan to modernize the signal and codes. The upper panel shows the legacy signals. The next panel down shows the new civilian code L2C and the new M codes on L1 and L2. The third panel from the top shows the addition of the L5 safety-of-life signal, and the bottom panel shows the addition of the L1C signal. SOURCE: C. Hegarty, MITRE Corp., “The Future: Solutions or Vulnerabilities?,” presentation to the space weather workshop, May 23, 2008.

that civilian receivers can estimate ionospheric contributions to ranging errors and remove them. Following the II-RM satellites are the Block IIF satellites transmitting a new signal on L5 in 2009. Following the Block IIF satellites are the Block III satellites, which will introduce a new code on L1 called L1C. The sequence for fully populating the GPS constellation is L2C (2014), L5 (2016-2018), and L1C (2021).

The primary advantage of transmitting a set of frequency diverse signals is the ability to remove ionospheric ranging errors, and this advantage is expected to make augmentation systems unnecessary. In addition, the new signals and codes will be more resistant to fades caused by scintillation or solar radio bursts. This advantage will be provided by transmitting with more power and by employing data-free pilot codes. Using the legacy L1C/A code as a reference, the L2C code has a 3-dB advantage, the L5 signal has a 7-dB advantage, and the L1C code has a 6-dB advantage.

How successful these new signals and codes will be in mitigating space weather effects is an open question. As Hegarty noted, "Ionospheric effects tend to be stronger at lower frequencies where the L2C and L5 signals are located." Added robustness is expected, especially with respect to ionospheric gradients and ionospheric ranging errors. The added robustness with respect to the fading caused by scintillation and solar radio bursts is less clear, in part because these space weather phenomena are not adequately characterized and in part because the space weather impacts on the new signals and code have not been analyzed. Hegarty concluded, "I will leave it to the ionospheric physicist to tell us how much less likely [it is] that we will lose reception."

SATELLITES

Future Vulnerability

Polidan commented that the satellite industry faces two distinct aspects of space weather phenomena in the future: measurement and impact. Space weather is the primary environmental factor in designing missions to be successful. Since spacecraft and instrument technologies continuously evolve, satellite manufacturers must stay abreast of how new technologies will survive in the harsh environment of space. Prior to the last 50 years in space, space weather events occurred that were much larger and would have been more damaging than anything experienced since 1957. In 2001, the Rumsfeld Commission warned of the possibility of a "space Pearl Harbor"—an attack on U.S. space assets by an adversary that would leave the country vulnerable. There is also a real and serious threat to satellites from major space weather events. Polidan noted that the industry "started wondering whether or not we should be a lot more concerned about unexpected space weather events that would produce not a space Pearl Harbor but a space Katrina, a storm that we should have been prepared for but were not, with effects that were much more damaging than they should have been."

Satellite systems will continue to be designed to operate through extremes of the space environment over their designed life. It is highly atypical to intentionally design a system likely to have a vulnerability to extremes of the space environment. Trying to operationally forecast specific instances of extremes of the space environment may be of limited value: either the threshold beyond which to expect a negative impact on any specific technological system is not known, or it is known because such an impact has occurred before and therefore is not unusual or very extreme. There are exceptions: e.g., human extravehicular activity and large-scale infrastructure based on GPS. In general, as discussed by the workshop participants, extremes are often not well understood, and sometimes designs fail to meet specifications.

Solutions for the Future

Polidan offered several possible solutions for the future. A new factor to be considered when developing future space weather measurement missions is the availability of lower-cost launches. While there are well-known efforts to develop lower-cost launch vehicles such as the Falcon family being developed by SpaceX, there are also other approaches to low-cost access to space that are less well known. For example, the Lunar CRater Observation and Sensing Satellite (LCROSS), currently being built by Northrop Grumman Space Technology for NASA Ames, is expected to launch in 2009 as a secondary payload with the Lunar Reconnaissance Orbiter (LRO). (The LCROSS mission objective is to guide the upper stage of the launch vehicle to an impact in a permanently shadowed lunar crater and analyze the ejecta for the presence of water. The LCROSS mission is not small; it has a wet mass of more than 800 kg and has significant on-board propulsion.) Northrop Grumman is examining LCROSS-based space weather mission concepts that utilize this secondary payload approach for access to space. This approach can offer much lower launch costs and provide a vehicle with enough propulsion to get it to an ideal location to perform space weather measurements.

To mitigate some of the future effects of severe space weather, Polidan remarked that companies will look to new electronics technologies that are more tolerant of space radiation. "Radiation-hardened-by-design" approaches may yield affordable space electronics that could help "weather" such storms. There are a variety of potential technologies in the marketplace to draw from to build future missions. Currently almost all of these technologies are in early stages of development and need both sustained technology development and rigorous testing in an appropriate space environment before they are ready for incorporation into a mission.

Workshop participants discussed the prospect that new approaches and new technology on the horizon could make the next 50 years in space more affordable and more secure than the previous 50 years. The measurement of space weather phenomena and their impacts on space mission hardware are being considered by space mission providers. They are exploring new ways to assist the science community in acquiring the needed measurements. Polidan remarked that future solutions for the satellite industry depend on accurate space weather data, modeling, and forecasts for the design of billion-dollar space systems, billion-dollar launch decisions, operations, and anomaly investigations. He concluded that the industry is "very interested in working with the [space weather] community to understand space weather, to get the measurements, and to also assess how those events can impact our designs so we can provide very long-lived and viable spacecraft."

RISK AND PREDICTING FUTURE EXTREMES

As noted earlier, technological systems and especially satellites are designed to operate in or through the extremes of environmental impacts that may occur during the system lifetime. For the designer, therefore, prediction of specific space weather events is not useful. Instead, knowledge of climatology and especially the extremes within a climate record are required. Fennell noted that "engineers want to be able to design through extremes" and an important aspect of space weather research is being able to predict extremes. Designers would like to know the probability of a damaging environmental parameter, such as MeV electron fluence, exceeding a set value. In some cases the damage may be accumulative, requiring knowledge of the long-term climate; in other cases it may be temporary, such as MeV electron fluence causing spacecraft charging. The designer then can trade cost and complexity against the probability or risk of losing a satellite as a result of space weather. Unfortunately, the NASA science programs that gather the data for characterizing the space climate are typically short term, and the space age itself has been too short a period for evaluating the possible risks.

Of course many other fields of engineering, economics, and actuarial science would also like to be able to predict extremes. Fortunately, there is a class of functions that model extremes in distributions with large numbers of samples. These are extreme value functions ($H(x)$), which are probability density functions that estimate the likelihood of a single sample falling outside extreme minimum or extreme maximum limits (x). For example, given the history of daily rainfall in any given month, it is possible to predict with an extreme value function the probability of a daily rainfall exceeding any previous daily rainfall, or some other arbitrary value, in a future month. These functions are described in O'Brien's abstract (see Appendix C), and for the class of functions describing a maximum value, the value k describes the asymptotic behavior of $H(x)$. For $k = -1$, $H(x)$ is bounded and an extreme possible value can be found. For $-1 < k < 0$, the slope of H is steep and low probabilities for extreme values can be determined. For the case of daily rainfall, if $-1 < k < 0$, there is a small probability that in a future month, a daily rainfall will exceed any previous daily rainfall.

Extreme-value analysis has been applied to a variety of space weather phenomena with some success. For example, deep dielectric charging associated with the maximum fluence of 100s keV to MeV electrons,[9,10] single-event upsets associated with MeV protons,[11] and total radiation dose[12] have been analyzed with some success and consequence for satellite design.

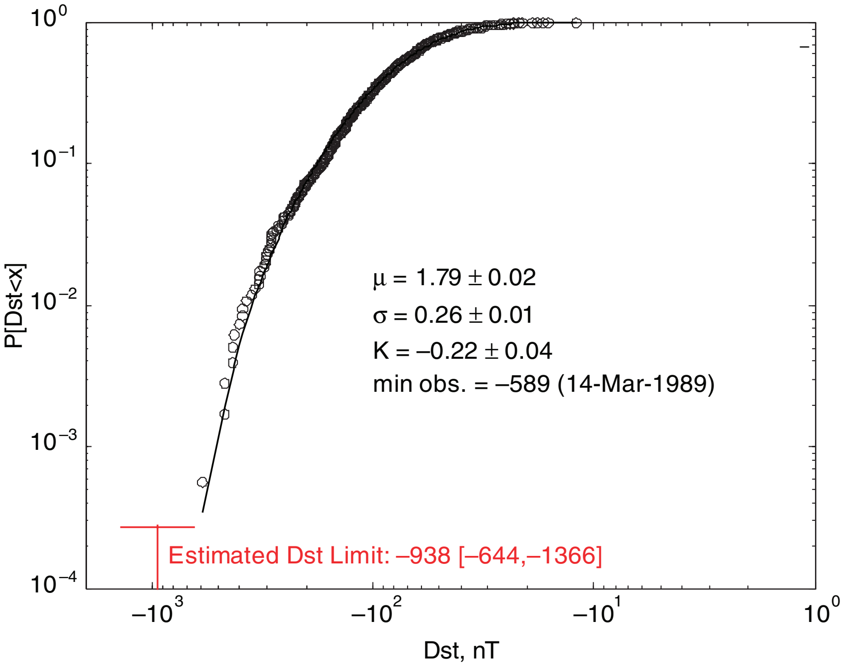


FIGURE 7.4 The extreme value distribution function for Dst as estimated from 20-day blocks. Each data point represents a minimum Dst measured during an independent, historical 20-day period. It predicts that the probability of Dst being less than −938 nT in any future 20-day period is 10^{-4}. SOURCE: T.P. O'Brien, Aerospace Corporation, "Extreme Events in Space Weather," presentation to the space weather workshop, May 23, 2008.

Perhaps more interesting is the application of extreme-value analysis to the Carrington event of 1859. In this case the parameter analyzed is 1-hour averages of Dst. Dst, the perturbation of the terrestrial magnetic field near the equator, is typically negative during magnetic storms. The extreme-value distribution function ($H(x)$) estimated from 1-hour averages of Dst organized into 20-day blocks is shown in Figure 7.4. This data set has $k = -0.22$. From this function the estimated lower limit to Dst is −938 nT. That is, in any 20-day block of data the probability of Dst exceeding (being less than) −938 nT is 10^{-4}. Now compare this estimate of the minimum possible value of hourly averaged Dst with that estimated from Colaba (Bombay) magnetometer data during the Carrington event: −883 nT (Tsurutani et al., 2003; X. Li, personal communication).[13] Of course, there are multiple assumptions implicit in the conclusion that the Carrington event was nearly the extreme possible. These include the geophysics of the data set in Figure 7.4 being the same as that which produced the Colaba magnetometer extreme value during the Carrington event. Fennell remarked that "we many not be measuring what we would classically call Dst when you get down in this part of the probability distributions." Additionally, the above conclusion assumes that the Sun's variability is statistically unchanged over the time it has been observed and into the foreseeable future.

SUMMARY

As society becomes more interconnected, and as its systems become more efficient and connected, with risk transferred among them, as noted by James Caverly in an earlier session of the workshop, space weather impacts on electric power grids, satellites, and GPS are going to affect almost every area of our lives. The challenge for society is understanding the true nature of the vulnerability now and in the future.

A frequent theme throughout the workshop was the uncertainty in attempting to analyze future vulnerabilities. Uncertainty is introduced by the use of systems in ways not expected, or engineered for, by their designers. In some cases, the system providers may not even know who the users are. For example, the International GNSS Service

(IGS) network is used for tsunami warnings and tracking ground movement during an earthquake. Yield mapping by farmers is another example of a high-precision, time-sensitive application of GPS. Even NASA depends on the IGS to point the antennas in the Deep Space Network.

There also exist organizational challenges for the future; the privatization of systems introduces uncertainty. For example, La Porte noted that ENRON was able to game the power industry in ways the original designers never envisioned. Furthermore many systems are designed based on recent experience and not the potential for extreme events.

As discussed throughout the workshop, the U.S. economy is highly dependent on electricity and wireless technology (for banking, energy, transportation, food, water, emergency services, and other necessities). Future systems and procedures will continue to cope not only with evolving user needs and new technological advances, but also with a variable space weather environment.

NOTES

1. Tsurutani, B.T., W.D. Gonzalez, G.S. Lakhina, and S. Alex, The extreme magnetic storm of 1-2 September 1859, *J. Geophys. Res.* 108(A7), 1268, 2003, doi:10.1029/2002JA009504.
2. Graham, W., et al. *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack*, Volume 1, Executive Report, 2004, available at http://www.house.gov/hasc/openingstatementsandpressreleases/108thcongress/04-07-22emp.pdf.
3. U.S.-Canada Power System Outage Task Force, *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*, 2004.
4. National Oceanic and Atmospheric Administration, The Deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2006, NOAA Technical Memorandum NSW TPC-5, April 2007, available at http://www.nhc.noaa.gov/pdf/NWS-TPC-5.pdf.
5. *USA Today,* Katrina damage estimate hits $125B, September 9, 2005.
6. Estimates derived by Metatech Corporation, presented by J. Kappenman at the space weather workshop, May 22, 2008.
7. Klobuchar, J.A., Ionospheric effects on GPS, Chapter 12 in *Global Positioning System: Theory and Applications,* Vol. 1 (B.W. Parkinson and J.J. Spilker, Jr., eds.), American Institute of Astronautics and Aeronautics, Reston, Va., 1996.
8. Navstar GPS Joint Program Office, *Navstar GPS Space Segment/Navigation User Interfaces, Interface Specification,* IS-GPS-200, Revision D, El Segundo, Calif., 2006, pp. 123-125.
9. Fennell, J.F., H.C. Koons, M.W. Chen, and J.B. Blake, Internal charging: A preliminary environmental specification for satellites, *IEEE Trans. Plasma Sci.* 28(6), 2029-2036, 2000.
10. O'Brien, T.P., J.F. Fennell, J.L. Roeder, and G.D. Reeves, Extreme electron fluxes in the outer zone, *Space Weather* 5, S01001, 2007, doi:10.1029/2006SW000240.
11. Xapsos, M.A., C. Stauffer, T. Jordan, J.L. Barth, and R.A. Mewaldt, Model for cumulative solar heavy ion energy and linear energy transfer spectra, *IEEE Trans. Nucl. Sci.* 54(6), 1985-1989, 2007.
12. Thomsen, M.F., M.H. Denton, B. Lavraud, and M. Bodeau, Statistics of plasma fluxes at geosynchronous orbit over more than a full solar cycle, *Space Weather* 5, S03004, 2007, doi:10.1029/2006SW000257.
13. Tsurutani, B.T., W.D. Gonzalez, G.S. Lakhina, and S. Alex, The extreme magnetic storm of 1-2 September 1859, *J. Geophys. Res.* 108(A7), 1268, 2003, doi:10.1029/2002JA009504.

8

Facilitated Open Audience Discussion: The Way Forward

In the workshop's final session, participants were invited to synthesize connections between topics, as well as identify important issues that might have been overlooked previously. The goals for the discussion were to highlight potential needs in the U.S. system of space weather risk management and to identify potential needs and opportunities for further research and analysis. The session was organized as an open discussion structured around a prepared set of questions crafted to encourage a "big picture" perspective:

- Which impacts of severe space weather events stand out as being the most important, in terms of their potential social and economic consequences? Concerning these potential impacts, are there any issues of first-order importance that have not been addressed in the workshop thus far?
- Does the nation have at present a reasonably robust and effective system for managing space weather risks? If not, what necessary capacities are missing from the nation's systems for space weather management?
- Are there any areas—in infrastructure, programs, or research—that seem urgently in need of attention? If you could effect one change in current arrangements for managing the risks of severe space weather events, what would that be? In other words, what development in the current system of space weather risk management would yield the greatest benefit?
- Which potential impacts of severe space weather events stand out as being the least understood? Which areas stand out as being promising targets for future research and analysis?

Participants responded with a range of observations, impressions, and opinions about the current status and future direction of the nation's systems for understanding, monitoring, predicting, and responding to severe space weather events.

INSTRUMENTATION AND MONITORING: THE SPACE WEATHER OBSERVATION SYSTEM

A number of participants offered comments on the current status and future prospects of the nation's system for monitoring space weather. One of these comments was the observation that there in fact *is no* system specifically dedicated to monitoring space weather. As noted by Daniel Baker (University of Colorado at Boulder), many of the measurements used by the Space Weather Prediction Center (SWPC) for operations are actually taken from instruments designed and tasked for scientific missions. Baker raised the question: Should our operational capacity for space weather monitoring be dependent on scientific instruments and satellites? Is it prudent to rely in this way on “the kindness of strangers”?

Pursuing this theme, several participants commented on a perceived fragility, or lack of robustness, in the nation’s capacity for space weather monitoring. John Kappenman (Metatech Corporation) observed that many key parts of the system have no backups: single points of failure, he argued, could substantially degrade or even halt operations. A critical weakness in the present system, noted by a number of participants, is the reliance on the aging Advanced Composition Explorer (ACE) spacecraft as virtually the nation’s sole upstream solar wind monitor. ACE, positioned at L1,[1] is now 11 years old, well beyond its planned operational life, and the detector heads are losing gain. “There could be an electronic failure,” Charles Holmes (NASA Headquarters) pointed out. “So it is a vulnerable system.”

As Baker noted, the loss of L1 solar wind measurements such as are provided by ACE “would be a devastating loss to the national space weather capability.” In a presentation given the previous day, Thomas Bodgan of NOAA’s Space Weather Prediction Center listed as one of NOAA’s “critical new directions” to “secure [an] operational L1 monitor.” It was clear from the comments of the participants, however, that no clear replacement for ACE is coming on line soon. Devrie Intriligator (Carmel Research Center, Inc.) noted that the possibility of an L1 monitor supplied by private industry had been discussed at other workshops. Although the Chinese are planning an L1 monitor as part of the KuaFu space weather project, it will not be launched for several years. Moreover, as William Murtagh (NOAA) cautioned, national security concerns must be taken into account when decisions about the follow-on to ACE are being made. On an encouraging note, Murtagh reported that the NASA Authorization Act (House Rule 6063, Section 1101) charges the Office of Science and Technology Policy to work with NOAA, NASA, other federal agencies, and industry to develop a plan for sustaining solar wind measurements from an L1-based spacecraft.

OUR CAPACITY FOR UNDERSTANDING AND PREDICTING SPACE WEATHER

Observations have limited value, of course, if not paired with a capacity for converting raw data into useful information. Several participants addressed the perceived adequacy or shortcomings of the models, data series, and other assets needed to convert observations into useful predictions.

What kinds of predictions would be useful? One workshop participant asserted that the chief desire of industry is for 24-hour advance warnings of severe space weather events. Another participant highlighted the utility of “all-clear” windows, i.e., predictions indicating periods during which the probabilities of severe space weather events are deemed very low.

The conversation turned to consider the resources and breakthroughs that would be required to offer such forecasts, as distinct from information on present space weather conditions. A few participants argued that advances in the capacity for prediction will require breakthroughs in basic understanding of solar processes. There is, it was suggested, a need for better structural models of space weather informed, for example, by space physics. Another participant noted the lack of a well-organized system for collecting and archiving historical data on space weather conditions. A good data archive was held to be essential for calibrating any models used for prediction. Still another participant noted the importance of systems for transferring technology from research to operations.

Much of the discussion appeared to support, explicitly or implicitly, the proposition that the nation does in fact need a strong capacity for producing predictions and warnings about space weather events. One participant, though, offered a contrarian view. Thomas Stansell (Stansell Consulting) argued that attention should focus first not on prediction, but on mitigation—on construction of hardened infrastructure able to continue operations without interruptions straight through severe space weather events. For electric power delivery, satellite operations, and other core systems, he claimed, extended service interruptions are unacceptable: hardened systems are essential. Better mitigation would in turn make prediction less valuable. Advances in mitigation, Stansell argued, would undermine the rationale for allocating resources toward monitoring space weather conditions, or predicting severe space weather events. A strategy based on mitigation would also imply different priorities for research.

A NATION AT RISK? ASSESSING THE POTENTIAL DISRUPTION TO INFRASTRUCTURE FROM SEVERE SPACE WEATHER EVENTS

Deficiencies in the system for space weather monitoring, prediction, and communication do not by themselves imply that the nation is vulnerable to severe space weather events. Stansell's thesis raises natural questions: What parts of the nation's infrastructure, if any, are at risk of serious disruption from severe space weather events? When would impacts most likely be seen?

Recalling presentations delivered over the previous day and a half, several participants focused on the electric power system as an area of particular concern.[2] Turning to issues that had not received attention previously in the workshop, Kappenman noted the potential impact of severe space weather on submarine communication cables, which, he noted, are still an important part of the world's communications infrastructure. These cables are highly geographically concentrated at six or seven nodes around the world. As one example of how this concentration creates potential vulnerability, Michael Bodeau (Northrop Grumman) recalled the effects of an earthquake centered near Taiwan in 2006. The quake set off undersea landslides that in turn caused the failure of a concentrated node of submarine cables carrying Internet traffic. In that case, recovery took approximately a month.[3] The case of the submarine cables illustrates how, in a tightly connected system, a single point of failure can set off widespread disruption.

To understand the full potential impacts of a severe space weather event requires understanding not just direct impacts—e.g., disruption to electric power grids—but also the indirect impacts—e.g., how loss of electric power may affect delivery of other services, in computing, transportation, health care, and so on. Several audience members touched on the theme of dependencies and interdependencies between systems.[4] As the loss of core systems leads to failure in other, dependent systems, a cascade of system failure can result. It was noted that the potential for a severe space weather event to set off a cascade of failures in critical system has implications for national security. In this context, the question of system robustness becomes central. Todd La Porte (George Mason University) raised the question of how to design institutional systems that are robust to disruptions from extreme space weather events.

RISK ANALYSIS AND RISK MANAGEMENT

The identification of potential impacts from severe space weather events led to questions about how to quantify and manage the associated risks. A widely accepted approach to risk analysis involves estimating event probabilities and then making estimates of event consequences. It was noted, though, that in complex systems characterized by strong interdependencies, it is very difficult to identify all impacts from a large-scale disruption, let alone to quantify their physical and financial consequences.

A fair amount of time was spent in discussing how the insurance industry handles the challenges of estimating risks posed by severe space weather events. Louis Lanzerotti (NJIT) and Michael Hapgood (CCLRC Rutherford Appleton Laboratory) noted a report by Swiss Re that addressed the challenges of analyzing space weather risks for a number of industries.[5] Workshop attendee Arthur Small (Pennsylvania State University) raised a question about whether the actuarial methods generally used by the insurance industry to quantify risks are adequate to analyze risks associated with severe space weather events. Actuarial methods, he noted, draw on historical data and incorporate an implicit assumption that past experience is a reasonable guide to the future. For severe space weather, the few available historic incidents offer only a very sparse record upon which to base estimates of event probabilities. As with hurricanes, earthquakes, terrorist attacks, and other rare catastrophic events, severe space weather events raise unusual challenges for the insurance and risk management industries. (For example, do insurance companies consider dependencies?) One participant offered the view that risks are to some extent being transferred to customers.

WHO IS RESPONSIBLE? MANAGEMENT OF THE SPACE WEATHER MONITORING AND RESPONSE SYSTEM

As the conversation turned to issues of policy, several observers commented on the fragmentation of responsibility that characterizes the space weather monitoring and response system. There is, it was noted, no single agency responsible for handling matters related to space weather, no "Space Weather Tsar." Instead, responsibility is scattered throughout different agencies across the U.S. federal government, which in turn relies in various ways on foreign governments, international agencies, and the private sector.

Within the public sector, one participant claimed to discern an "evolving mind-set" within the government that all such issues are the responsibility of the Department of Homeland Security (DHS). But DHS, it was argued, is vastly understaffed and does not necessarily have the technical capacity required to assess the risks of severe space weather events, or to respond to those events that do occur.

Joseph Reagan observed that the present fragmented system lacks a robust system for accountability and analysis in matters related to space weather. Lanzerotti countered that the National Space Weather Program is supposed to fill that role. Lanzerotti went on to recommend the creation of a stronger, high-profile presence for space weather issues at the Office of Management and Budget (OMB) or in OSTP. He noted that that the assessment report of the NSWP recommended stronger oversight of the program in OMB and OSTP, "similar to what is done for weather and climate now." Murtagh noted the recent introduction in Congress of legislation that would require that OSTP develop a plan for sustaining operational measurements of solar winds. Lanzerotti lamented the challenge of maintaining continuity of interest and effort on the topic, especially across changes in administration.

Space weather is, of course, a global phenomenon: space weather monitoring naturally embraces an array of international issues. Several comments touched on the sensitivity of relying on satellite assets controlled by foreign governments, including China as well as various European entities. As noted above, particular concern was raised about the national security implications of relying on China to maintain key infrastructure for monitoring at L1, a capacity needed, it was claimed, for national security.

The private sector has, of course, a stake in the effectiveness of the nation's space weather monitoring system, as well as much of the capacity to carry out monitoring activities. One participant noted that the lightning detection network in the United States is essentially entirely private and asked whether this privatized system could serve as a model for a system for managing space weather risks. Another participant wondered whether commercial providers could be relied on to provide detectors at L1. Lanzerotti observed that commercial provision of services always involves a tension between cost-competitiveness and robustness. Markets, he argued, can provide an efficient mechanism for the delivery of low-cost solutions. The costs of overdesign will put private firms at a competitive disadvantage, however—even when these extra costs make sense from the viewpoint of maintaining the overall robustness of the system.

How do the contributions from all these players—U.S. civilian government, U.S. military, foreign, and private sector—fit together? How should they be coordinated? Which parts of the system require centralized coordination and governance? Which parts can be decentralized? Part of the discussion addressed these big-picture themes concerning the overall design architecture for the entire space weather system. One participant noted ruefully that there *is* no overall design architecture, one that would embrace space weather monitoring, modeling, analysis, data archiving, prediction, risk estimation, and communications. The creation of such an architecture remains an outstanding challenge. Ronald Polidan (Northrop Grumman) argued that a successful process to design and develop such an architecture must involve multiple stakeholders, including industry.

EDUCATION, TRAINING, AND PUBLIC AWARENESS

Many workshop audience members noted that progress on all these fronts has been hampered by a profound lack of public awareness about space weather and about the risks posed by severe space weather. The need for public education about the importance of space weather was touched on by Paul Kintner (Cornell University), Howard Singer (NOAA), and Vladimir Papitashvili (National Science Foundation), among others. One participant noted the possibility of including space weather as a regular topic on the Weather Channel, an outlet identified as the premier vehicle for public education about weather.

Closely linked with public awareness is the problem of awareness in the policy community. Policy makers, it was noted, generally attend to matters that the public is worried about: when the general public does not perceive a problem, the attention of the policy community will be scant at best. Another audience member noted a problem of translation: the policy community doesn't speak "weather."

It was lamented that, in the eyes of the public and policy communities, severe space weather lacks salience as a problem: it is very difficult to inspire non-specialists to prepare for a potential crisis that has never happened before, and may not happen for decades to come. Attention inevitably is drawn toward higher-frequency risks and immediate problems. To counteract this tendency, Roberta Balstad (CIESIN) cited the importance of crafting well-articulated scenarios of what could happen and how it could affect the public in the case of a severe space weather event. Balstad and others also noted the need for opportunities for specialists to have access to education and advanced training in space weather. Bodeau noted at one point that it is very rare, even in the commercial satellite industry, to encounter specialists who understand both the physics of space weather and the engineering requirements necessary to harden satellites against space weather events. One participant raised the possibility of creating specialized M.S. programs in space weather. Paul Kintner noted that he teaches a small amount on space weather in a single course at Cornell University but that his students respond with deep indifference.

THE WAY FORWARD

What developments in the current system of space weather risk management would yield the greatest benefit? In synthesizing the ideas and discussion offered in this session and in the entire workshop, audience members offered several perspectives and suggestions about current needs:

- Improved physical understanding of solar processes to enable forecasting (Chenette).
- Effective means of transitioning from models to operations (Singer).
- The addition of space weather coverage to the Weather Channel.
- The codification of risk assessment standards for space weather events, including space weather analogs to 100-year risks (Hapgood).
- Analysis of cascading effects on complex, coupled systems (La Porte).
- The articulation of scenarios that illustrate the effects of space weather, as a means to educate the public and policy community about the importance of space weather (Balstad).

In a spirit of concern mixed with optimism, the conference adjourned.

NOTES

1. L1 is the point between Earth and the Sun at which the gravitational pull of these two bodies is evenly balanced. The significance of L1 is that a satellite placed at this node will tend to stay there, with only minor positional adjustments.
2. The potential impacts of space weather events on electric power grids are discussed extensively in other chapters of this report.
3. International Cable Protection Committee (ICPC), Subsea landslide is likely cause of SE Asian communications failure, press release, March 21, 2007; see www.iscpc.org/information/ICPC_Press_Release_Hengchun_Earthquake.pdf.
4. A *dependency* was characterized as a relationship in which one system relies for its operation on functions provided by another system: a subway transport system depends on the power grid for delivery of electricity. An *interdependency* was characterized as a relationship in which two systems rely on each other for their smooth operation. If an electric power grid requires operational support from a computing system that is itself powered by that same power grid, then the grid and the computing system are interdependent.
5. Jansen, F., R. Pirjola, and R. Favre, *Space Weather: Hazard to Earth?,* Swiss Reinsurance Co., Zürich, 2000, available at http://www.swissre.com/pws/research%20publications/risk%20and%20expertise/risk%20perception/space_weather.html.

Appendixes

A

Statement of Task

An ad hoc committee, operating under the auspices of the Space Studies Board (SSB) of the National Academies, will convene a public workshop that will 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 will include an analysis of the effects of historical space weather events, and will use the record solar storms of October and November 2003 to focus the presentations and provide data to project future vulnerabilities. The inclusion of historic events and intervals will be important to capture the breadth of space weather impacts, which can be different from event to event, and impacts that occur during non-storm times. There will also be sessions on how space weather impacts might change as technologies evolve and new technologies appear.

Topics to be addressed at the workshop include:

- What are the socioeconomic consequences to the nation of severe space weather events?
- What were the specific effects of the October-November 2003 events?
- How likely are events that are more intense than the 2003 events and what might be the consequences of such events?
- Given existing space weather services, what losses were avoided, or could have been avoided, in recent events?
- Are there specific ground- or space-based sensors that might mitigate or avoid the effects of future severe space weather events? In particular: How will assimilation of data from the Advanced Modular Incoherent Scatter Radar (AMISR) and the Frequency-Agile Solar Radiotelescope (FASR) be used? How might the arrays of instruments envisioned for implementation of the Distributed Arrays of Small Instruments (DASI) concept be employed? How would the loss of Advanced Composition Explorer (ACE) data affect forecast capabilities? What steps might better facilitate the transition to operations of the current and planned solar and space physics missions that have application to monitoring and prediction of severe space weather events?

A report of the workshop will be written.

B

Workshop Agenda and Participants

AGENDA

May 22, 2008

8:00 a.m. **Breakfast Meet and Greet**

8:30 a.m. **Introduction**
Daniel Baker, Laboratory for Atmospheric and Space Physics, University of Colorado-Boulder

8:50 a.m. **Panel Session: Space Weather Impacts in Retrospect**
Moderator: Peggy Shea, Air Force Research Laboratory (emeritus) and Senior Researcher, CSPAR
Rapporteur: Kevin Forbes, Catholic University of America
Panel Speakers and Discussion
Speakers: **Peggy Shea**, Air Force Research Laboratory (emeritus) and Senior Researcher, CSPAR
Frank Koza, PJM Interconnection
Leo Eldredge, Federal Aviation Administration
Michael Bodeau, Northrop Grumman Space Technology
Angelyn W. Moore, Jet Propulsion Laboratory

10:30 a.m. **Break**

10:45 a.m. **Panel Session: Collateral Impacts of Space Weather**
Moderator: Louis Leffler, North American Electric Reliability Council (retired)
Rapporteur: Roberta Balstad, Center for International Earth Science Information Network
Panel Speakers and Discussion
Speakers: **Todd M. La Porte, Jr.**, George Mason University
R. James Caverly, Department of Homeland Security

12:00 p.m. **Lunch**

1:00 p.m. **Panel Session: Current Space Weather Services Infrastructure**
Moderator: Joseph Fennell, Aerospace Corporation
Rapporteur: Leonard Strachan, Jr., Smithsonian Astrophysical Observatory
Panel Speakers and Discussion
Speakers: **O. Chris St. Cyr**, NASA
Charles P. Holmes, NASA
William Murtagh, NOAA Space Weather Prediction Center
Herbert Keyser, USAF, Space and Intel Weather Exploration
Michael A. Hapgood, CCLRC Rutherford Appleton Laboratory

2:15 p.m. **Panel Session: User Perspectives on Space Weather Products**
Moderator: Michael Bodeau, Northrop Grumman Space Technology
Rapporteur: Louis Leffler, North American Electric Reliability Council (retired)
Panel Speakers and Discussion
Speakers: **Michael Stills**, United Airlines, Inc.
James McGovern, ISO New England, Inc.
Lee Ott, OmniSTAR, Inc.
David Chenette, Lockheed Martin Advanced Technology Center
Kelly J. Hand, U.S. Air Force

3:30 p.m. **Break**

3:45 p.m. **Panel Session: Satisfying Space Weather User Needs**
Moderator: Joseph B. Reagan, Lockheed Martin Missiles and Space Company, Inc. (retired)
Rapporteur: Thomas A. Stansell, Stansell Consulting
Panel Speakers and Discussion
Speakers: **Thomas J. Bogdan,** NOAA (joining speakers from the previous session)

4:55 p.m. **Session: Summation of Panel Themes**

5:30 p.m. **Adjourn for the Day**

May 23, 2008

8:00 a.m. **Breakfast Meet and Greet**

8:30 a.m. **Session: Extreme Events in Space Weather**
Moderator: William S. Lewis, Southwest Research Institute
Rapporteur: Eugene Cameron, United Airlines, Inc.
Speakers: **James L. Green**, NASA
T. Paul O’Brien, Aerospace Corporation

9:15 a.m. **Panel Session: The Future: Solutions or Vulnerabilities?**
Moderator: Paul M. Kintner, Cornell University
Rapporteur: Genene M. Fisher, American Meteorological Society
Panel Speakers and Discussion
Speakers: **Ronald S. Polidan**, Northrop Grumman
John Kappenman, Metatech Corporation
Christopher J. Hegarty, MITRE Corporation
Thomas McHugh, FAA
Todd M. La Porte, Jr., George Mason University

10:30 a.m. **Break**

10:45 a.m. **Session: The Way Forward**
Moderator: Daniel Baker, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder
Rapporteur: Arthur A. Small, Pennsylvania State University
Open Discussion with Workshop Attendees

11:30 a.m. **Summation of the Workshop (Rapporteurs and Moderators)**

12:30 p.m. **Workshop Adjourns**

PARTICIPANTS[1]

Kate Agatone, Government Accountability Office
Daniel Baker, Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder
Roberta Balstad, Center for International Earth Science Information Network
Mike Beavin, Office of Space Commerce
Rich Behalu, National Science Foundation
J. Michael Bodeau, Northrop Grumman Space Technology
Thomas J. Bogdan, NOAA
Kevin Briggs, NCS
Eugene Cameron, United Airlines, Inc.
Simon Cantrell, WxAnalyst
R. James Caverly, Department of Homeland Security
David Chenette, Lockheed Martin Advanced Technology Center
Gerald Ditterberner, G.J. Dittberner Science and Technology
Leo Eldredge, Federal Aviation Administration
Don Fairfield, NASA
Joseph F. Fennell, Aerospace Corporation
Genene M. Fisher, American Meteorological Society
Kevin F. Forbes, Catholic University of America
Sandra J. Graham, National Research Council
James L. Green, NASA
John Greenhill, Department of Energy
Kelly J. Hand, U.S. Air Force

---

[1] Only registrants who signed in upon arrival are listed.

Michael A. Hapgood, CCLRC Rutherford Appleton Laboratory
Christopher J. Hegarty, MITRE Corporation
Charles P. Holmes, NASA
Devrie Intriligator, Carmel Research Center, Inc.
John Kappenman, Metatech Corporation
Herbert Keyser, USAF, Space and Intel Weather Exploration
Paul M. Kintner, Cornell University
Frank Koza, PJM Interconnection
Joseph Kunches, NOAA
Louis Lanzerotti, NJIT
Todd M. La Porte, Jr., George Mason University
Louis G. Leffler, North American Electric Reliability Council (retired)
Irving Leveson, Leveson Consulting
William S. Lewis, Southwest Research Institute
Kara Lovett, Government Accountability Office
James McGovern, ISO New England, Inc.
Thomas McHugh, FAA
Norman Modlin, NPOESS/PEO
Angelyn W. Moore, Jet Propulsion Laboratory
William Murtagh, NOAA Space Weather Prediction Center
T. Paul O’Brien, Aerospace Corporation
Lee Ott, OmniSTAR, Inc.
Vladimir Papitashvili, National Science Foundation
Maria Pirone, AER, Inc.
Simon Plunkett, Naval Research Laboratory
Ronald S. Polidan, Northrop Grumman
Antti Pulkkinen, NASA/Goddard Space Flight Center
Joseph B. Reagan, Lockheed Martin Missiles and Space Company, Inc. (retired)
Jennifer Rumberg, NASA
Roger Seifert, Bonneville Power Administration, Department of Energy
Peggy Shea, Air Force Research Laboratory (emeritus) and CSPAR
Howard Singer, NOAA
Arthur A. Small III, Pennsylvania State University
Don Smart, AFRL
Dennis Socker, Naval Research Laboratory
O. Chris St. Cyr, NASA
Thomas A. Stansell, Stansell Consulting
Leonard Strachan, Jr., Smithsonian Astrophysical Observatory
Michael Stills, United Airlines, Inc.
David Turner, Analytic Services, Inc.
Rodney Weiher, NOAA

C

Abstracts Prepared by Workshop Panelists

IMPACTS OF SPACE WEATHER ON SATELLITE OPERATORS AND THEIR CUSTOMERS

Michael Bodeau, Technical Fellow, Northrop Grumman Corporation

Satellites provide a wealth of services to mankind:

- Satellites (e.g., GOES, POES, DMSP) provide continuous monitoring of terrestrial weather and allow governments to warn citizens of adverse conditions such as hurricanes.
- Hundreds of communication satellites cost-effectively connect remote populations to news, education, and entertainment (e.g., global cell phones).
- Communication satellites also provide one of the most cost-effective means for interconnecting businesses (one-to-many and many-to-one networks) and customers.
- Satellites provide a critical backup to terrestrial cable systems critical to restoring services during catastrophic events (earthquakes, hurricanes) that damage the ground-based systems.
- Precision location made possible by GPS satellites is now becoming a ubiquitous feature embedded in many commercial products (automobile navigations systems, cell phones, dog collars).
- Science satellites study the universe (e.g., Hubble, Chandra, and other astronomy satellites) and our planet (e.g., NASA's Aura and Aqua).

Since the beginning of the space age in the 1960s and the commercialization of space in the 1970s, space weather has posed a constant challenge to designers and operators of satellites, and indirectly to their customers. The impacts of space weather have ranged from momentary interruptions of service to a total loss of capabilities when a satellite fails.

This presentation reviews the impact of one space weather "storm" on a pair of communication satellites to show the dramatic impact to the satellite operator and its customers when space weather interrupts services. Some of the direct costs of the satellite anomalies are reported, while the more far-reaching impacts on society as a whole are discussed.

SPACE SYSTEMS USER PERSPECTIVE ON SPACE WEATHER DATA PRODUCTS

David Chenette, Lockheed Martin Space Systems Company Advanced Technology Center

Lockheed Martin and its customers rely on high-quality space weather data products from the NOAA/NWS Space Weather Prediction Center to help manage the risks of a variety of critical, high-value activities. These include go/no-go criteria in launches, planning of on-orbit operations (including radiation protection), and support of post-anomaly investigations, which are essential to our product improvement process.

Our customers accept launch delays due to poor terrestrial weather, so launch vehicles need not be designed to operate reliably through tornados or hurricanes, for example. Similarly, significant cost efficiencies are realized by not designing launch vehicles for assured performance in unusually hazardous space weather conditions. Managing the risk of the resultant vulnerability requires that launch decisions take into account the space weather conditions expected during the launch and early on-orbit operations. Because the Sun is a significant and impulsive source of high-energy radiation that can disrupt electronics, near-real-time measurements and accurate short-term predictions of solar activity are essential to maintaining the high reliability of launch systems. Predictions of an hour to several hours in advance are required, depending on the mission.

Beyond the initial launch, other on-orbit operations may be susceptible to unusual or extreme space weather conditions. For example, some communications satellites at geosynchronous orbit are more sensitive to the effects of spacecraft charging during orbit maintenance operations than during normal operations. Planning these operations to avoid this susceptibility requires predicting the level of geomagnetic activity from several days to a week in advance. Real-time monitors of geomagnetic activity and predictions for up to a day in advance are required during the actual operations.

Forecasts and knowledge of high-energy solar activity also are critical to radiation safety in manned space operations. The amount of radiation shielding provided by a space suit during extravehicular activity, for example, is significantly less than the maximum shielding that can be provided by a spacecraft. Systems in low Earth orbit are shielded from high-energy solar radiation by Earth and its magnetic field, but for high-inclination orbits, depending on the longitude of the orbit ascending node, Earth's magnetic shielding is not effective, and systems and people can be exposed to radiation at dose rates that are thousands of times higher than average. Also, the shielding effect of Earth's magnetic field does not extend to the Moon; and for flights to Mars humans could be susceptible to solar events on the far side of the Sun, which are not visible from Earth.

Accurate predictions of major solar events are required to protect man and space systems against the radiation risks posed by major solar flare events. Today we can identify active regions that are likely to produce large solar particle events, and we can classify events and predict expected radiation levels after they occur, but we do not have sufficient data and understanding to predict the timing of these events. Improvements are required both in understanding the precursors to major solar events and in the type and resolution of the data necessary to reveal the signatures of those precursors.

Finally, Lockheed Martin depends on comprehensive space weather data products to support post-anomaly investigations. Detailed data are required to describe the space weather conditions at the time and location of any anomaly to assess whether or not the anomaly was related to those conditions. In cases where a causal relationship can be identified, the results are used to improve the design, to modify the implementation of the design, or to modify operations to protect against future occurrences.

Comments on Data and Predictions

The data now provided from the combination of POES and GOES space weather sensors provide excellent real-time monitors of space weather conditions at low Earth orbit and at geosynchronous orbit, and together they can be used to estimate conditions at intermediate altitudes. These data also monitor solar energetic particle radiation intensity near Earth and the extent to which this radiation penetrates into the magnetosphere. They do not support predictions of space weather events, beyond extrapolations that can describe the evolution of a space weather event after it has occurred.

Real predictions depend on measurements of the Sun and the solar wind. The state of the art of these predictions has improved significantly over the past few years, but in many cases it is only slightly better than a prediction based on persistence. Both the level of detail in our understanding of conditions at the Sun and the fidelity of our models for transport from the Sun to Earth contribute to the current deficiencies. The increases in data quality and resolution that are being and will be provided by the GOES Solar X-ray Imagers, the NASA STEREO mission, the Japanese Hinode Solar Optical Telescope, and soon by NASA's Solar Dynamics Observatory promise major improvements in our understanding of conditions at the Sun.

One way to reduce the deficiencies due to the transport models is to measure solar wind conditions upstream of Earth. The ACE spacecraft has provided such measurements, including limited data in real time, and has demonstrated their value. It is essential to "near-real-time" predictions (taking advantage of the tens of minutes of advance warning possible from L1) that these measurements be continued, and augmented with multipoint observations to enable corrections for geometrical effects.

THE 1859 GEOMAGNETIC SUPERSTORM

James L. Green, NASA

The great geomagnetic storm of 1859 is really composed of two closely spaced massive worldwide auroral events. The first event began on August 28 and the second began on September 2. It is the storm on September 2nd that resulted from a white-light flare, observed by Carrington and Hodgson, that occurred on the Sun on September 1. Although still not widely believed at the time, the flare and storm observations showed that the Sun and aurora were connected and that auroras do generate strong ionospheric currents. Since the weather was mostly clear over many of the inhabited areas of Earth, over the several days of the storm an enormous number of people observed the aurora. In addition to published scientific measurements, newspapers, ship logs, and other records of that era provide an untapped wealth of firsthand observations giving time and location along with reports of the auroral forms and colors. At its height, the aurora was described as being a blood or deep crimson red that was so bright that one "could read a newspaper by it."

Several important aspects of this great geomagnetic storm are simply phenomenal. Significant portions of the world's 200,000 km of telegraph lines were adversely affected. Many of them were unusable for 8 hours or more, and there was a small but notable economic impact. At its peak, the Type A red aurora lasted for several hours and was observed to reach extremely low geomagnetic latitudes on August 28-29 (25 degrees) and on September 2-3 (18 degrees). Auroral forms of all types and colors were observed below 50 degrees latitude for about 24 hours on August 28-29 and about 42 hours on September 2-3. Kenneth McCracken at the University of Adelaide discovered among the ice core data from Greenland and Antarctica that the 1859 nitrate anomaly, generated by the storms accompanying solar particle events (SPEs), stands out as the most extreme event during the last 500 years, with an intensity roughly equivalent to the sum of all the major SPEs during the last 40 years. According to Brian Thomas at Washburn University, the 1859 superstorm was strong enough to actually reduce atmospheric ozone by 5 percent for up to 4 years afterward.

From a large database of ground-based observations the extent of the aurora in corrected geomagnetic coordinates can be determined over the duration of the event. Based on modern understanding of how aurora and ionospheric and magnetospheric currents reflect the rearrangement of the magnetosphere in response to changes in the solar wind, the extreme nature of this event can be better understood. It is most likely that these two major auroral storms are from two closely spaced interplanetary coronal mass ejections (ICMEs) reaching Earth very close together in time. The interaction of a fast ICME plowing through a slower ICME has been observed and produces a much stronger shock. This effect may be partially responsible for the extreme nature of the September 2-3 auroral event. If these ICMEs did not interact, it is clear that the August 28-29 event must have cleared a path in the solar wind, thus allowing the September 2nd CME to transit to Earth in 17.5 hours rather then the average ICME transit time of about 80 hours. It is clear that we have not experienced space weather anything like the 1859 superstorm event in the modern spacecraft era, which to date may have been unusually benign from an SPE perspective. We should be fully aware of what the Sun is capable of producing as we increase our reliance on our space mission assets.

SPACE WEATHER, A DOD PERSPECTIVE

Kelly J. Hand, U.S. Air Force Space Command

Successful military operations rely on our ability to effectively integrate weather information into the planning and execution of land, air, and sea operations, but do space weather and its effects matter to military operations? On the terrestrial weather side, practical examples of weather's importance to the effectiveness of military operations are numerous. Successful air operations require knowledge of weather over the target and include plans for weather conditions on ingress and egress routes to and from the target. Land force operations would certainly be at risk without understanding the actual and forecast soil conditions and their impact on land force trafficability. Accurate observations and forecasts of sea-state and littoral conditions are required in order to safely and effectively conduct naval and marine operations. But does space weather matter to the effectiveness of space and terrestrial military operations? The answer is yes.

The military's need for space weather knowledge is linked directly to environmental conditions relevant to impacts on space and terrestrial technological systems and the services those systems are intended to provide. Ultimately, the military value of actual and predicted space weather information is dependent on our ability to apply it effectively. As with terrestrial weather, the benefits are realized when military system operators and users can proactively mitigate or plan for the effects on their specific system or service. In this regard our nation's military relies on our national space weather information infrastructure in general and on the Air Force Weather Agency in particular. The capability of this infrastructure is to monitor, specify, and predict environmental conditions to serve a variety of national needs, including those relevant to military system and mission effects. We call this the space weather piece of space situational awareness (SSA).

For effective space weather SSA it is important to realize that environmental conditions can significantly affect a military system's performance and therefore may impact its ability to bring intended services to the warfighter. For example, satellite systems, spacecraft components and their payloads, communication links for satellite command and control and mission data, and the satellite's respective ground sites can all be affected by the environmental conditions in which they operate. Likewise, terrestrial systems like high-frequency (HF) communications, surveillance, or missile-tracking radars that contribute to missile warning missions can also be affected by the environment. Thus the degree to which the environment impacts these systems and information can be applied to improve performance or protect these systems defines the type of space weather information needed. Fortunately, the natural space environment information the military is concerned about is very similar to information of interest to scientists, NASA operations, and the civil and commercial sectors. This environment of common interest includes the Sun and its energy and mass emissions, interplanetary space and what it contains, and the near-Earth space environment, including the physical parameters that define the magnetosphere, thermosphere, and ionosphere.

To illustrate how the military applies this information, a few military satellite systems are described as practical examples. Figure C.1 is a screen capture of a display of the near-Earth space environment generated by an Air Force Research Laboratory software program. It illustrates the complexity of the natural space environment in the context of low Earth orbit (LEO), medium Earth orbit (MEO), geosynchronous orbit (GEO), and highly elliptical orbit (HEO) satellites. Figure C.1 shows, high above Earth, a cross section of the inner Van Allen belt (~1500-8000 miles altitude—just outside most LEO satellite orbits) and outer radiation belts (MEO intersects the most intense portion at ~12,000 miles altitude).

LEO satellites such as those in the Defense Meteorological Satellites Program (DMSP) operate through the upper atmosphere (at about 600 miles) and are affected by atmospheric drag and sometimes trapped and solar particle radiation. MEO satellites such as the Global Positioning System (GPS) satellites operate in the Van Allen radiation belts at about 12,000 miles altitude and are subject to constant bombardment by the highly energetic electrons that populate this region as well as energetic solar protons and high-energy electrons. Geostationary satellites, like the Defense Satellite Communication System (DSCS) satellites, are at the outside of the radiation belts but operate in a region where charging and discharging can occur on the surface of the spacecraft. Also, GEO satellites experience effects from highly energetic cosmic and solar radiation not as prevalent at LEO altitudes. For these satellite system examples, the users of natural space environmental information include satellite operators and engineers. An example of applications of space weather data includes enabling quicker resolution of

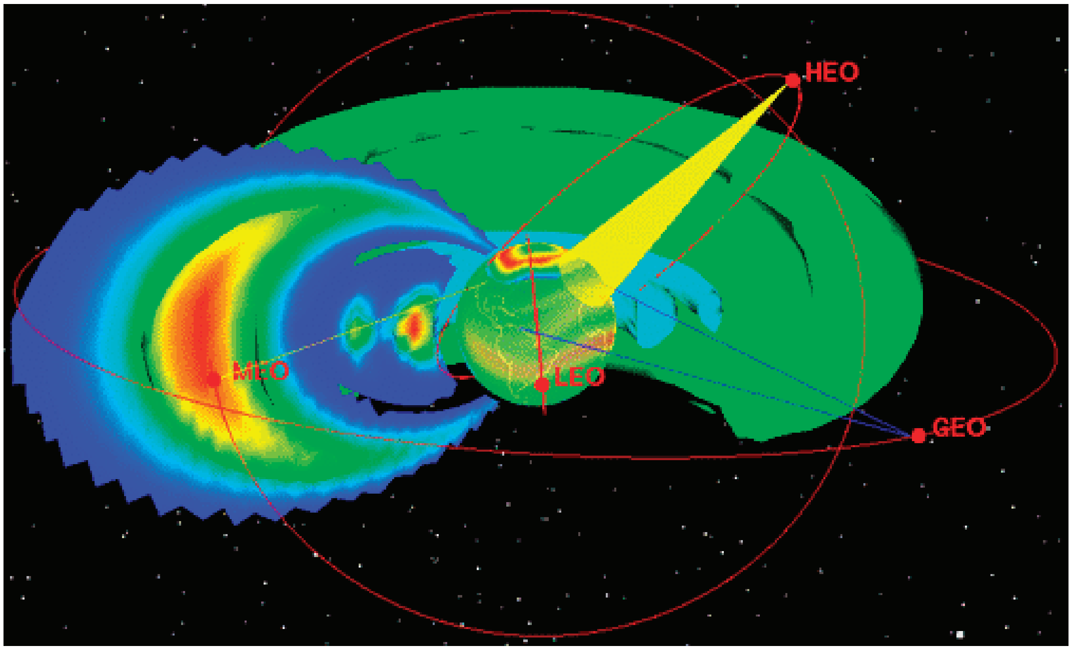


FIGURE C.1 Display of the near-Earth space environment generated by an Air Force Research Laboratory software program.

spacecraft anomaly investigations to get the satellite back into operations and reduce downtime. Also, prediction of when conditions will occur and how bad they will be in the future at the particular satellite can be incorporated into scheduled maintenance procedures.

Finally, all satellites and some ground-based space systems must propagate their radio signals through the ionosphere to reach terrestrial users. Depending on the frequency of the radio signal, the ionosphere can significantly degrade the performance of space system and services, such as communication and GPS services. An example of a terrestrial military system impact concerns high-frequency long-haul communications. An energetic solar x-ray burst can completely black out this type of communication system across the entire Sun-lit Earth. With sufficient space weather awareness, users can plan for and work around these impacts. These few examples highlight the importance of accurate knowledge of the current and predicted state of the natural space environment on military operations.

Conclusion

Space weather has impacts on both terrestrial and space technological systems and services used by the military. Thus the military will continue to depend on our nation's space weather support infrastructure to provide current knowledge and predictions of the natural space environment. In the future as the nation's dependence on space evolves, its reliance on space weather support infrastructure will increase and will benefit from improvements in the state-of-the-science and transition of that science to improved operations.

CURRENT SPACE WEATHER SERVICES INFRASTRUCTURE IN EUROPE

Michael A. Hapgood, CCLRC Rutherford Appleton Laboratory
Chair, ESA Space Weather Working Team

The past 10 years have seen huge progress in developing space weather as a discipline in Europe. In particular there is now a well-established European space weather community comprising scientists and engineers who work together to advance the discipline. However, this bottom-up unity is not yet reflected at higher levels. Space weather services in Europe are set in a complicated, indeed fragmented, landscape that contains a mix of national and European activities.

At a European level space weather activities are supported by a number of actors. The most prominent, of course, is the European Space Agency (ESA). The ESA has done much to stimulate space weather activities. In particular, it has provided seedcorn funding for programmatic studies and for a pilot project on space weather services. These have been very successful and have played a huge part in building the present European space weather community. The pilot project has established a network of 25+ space weather services (SWENET, Space Weather European Network). This network is ideally positioned to be the foundation of an operational European space weather infrastructure. However, to do that, it now needs to find an appropriate long-term home in the broader European landscape. ESA cannot be that home as its task is to carry out research and development—and, having developed new services, it needs to spin them out into an operational body (as it has previously done in building a space meteorology system for Europe—now EUMETSAT). The proposed European program on space situation awareness, which includes space weather as a major element, may provide a path toward that home, especially if, as planned, it builds by federating existing European services.

The other prominent European actor is the European Union (EU). The EU is developing a deeper involvement in space activities; for example, the new EU constitutional treaty, when ratified, will give it a formal legal competence in matters of space policy. This is expected to reinforce its relationship with ESA (their memberships overlap but are not identical), with the EU providing overall policy direction while ESA leads the technical activities that implement those polices. But even without the treaty the EU has been supporting space activities, including some in the space weather domain. EU research funding has supported a variety of activities. Most important is probably the support of human networking under the so-called COST (Cooperation on Space and Technology) actions. There have been several COST actions on trans-ionospheric radio propagation (including space weather effects), and a COST action on space weather has just been completed successfully. A proposal for a new action on space weather is under review. The EU has also funded the development of a coordinated system for digital ionosonde measurements and their dissemination (the DIAS project); a proposal for a follow-up project to combine ionosonde and GPS total electron content measurements is under review as part of a February 2008 call for research infrastructure projects. The EU has also recently funded a major project (SOTERIA) to enable the better science exploitation of space weather data.

The EU-funded COST action on space weather has produced a Space Weather Portal that has the potential to be a gateway to a range of European services. This is likely to be a major focus for future efforts by the European space weather community, especially if the new COST action is approved.

These European projects all provide cross-national support that focuses on front-end services, e.g., generation and dissemination of data products. There has so far been limited European support for space weather monitoring activities that generate the data needed as input to services. (We assume a model where space weather services deliver data products that are of use to end users and those data products are outputs from models of the space weather environment driven by measurements of the environment upstream from the region of interest.) The provision of space weather monitoring is predominantly done by national bodies. A 2001 survey for ESA identified over 100 sensors—most ground-based and focused on measurements of the Sun, ionosphere, and ground-level effects (magnetic field and neutrons). European space-based measurements are limited but include (1) by-products from European space science instruments (e.g., the SWAP solar imager on Proba-2 and the Heliospheric Imager on STEREO), (2) ESA's program to fly space radiation monitors on a wide range of missions, and (3) some limited space weather monitoring on EUMETSAT missions, e.g., the NOAA package on METOP. ESA is seeking to stimulate better coordination of measurements and data handling related to spacecraft effects through a networking activity that taps into relevant expertise across Europe (Spacecraft Environment and Effects Network of Technical Competence, SEENoTC).

In some cases current national provision puts the monitoring activities at some risk in terms of funding; the national agencies that fund space weather monitoring often have limited understanding of space weather and its European and global context. This is especially true if space weather is funded by agencies that are focused on fundamental science and lack appreciation of modern scientific thinking on complex natural environments. Space weather sits comfortably with environmental disciplines such as atmospheric physics. It sits less well with disciplines that are dominated by a reductionist approach to science. European coordination is an important tool for raising awareness of the importance of individual space weather measurements and allowing national decision makers to understand the global context into which measurements fit.

There are emerging national space weather programmes in several countries—in particular Belgium, France, Germany, and Spain. Denmark and Norway have specialized interests through leadership roles in specific projects—for Denmark the ESA/SWARM mission to study Earth's magnetic field with greater resolution and for Norway the exploitation of Svalbard as a super-observatory for space weather phenomena. Other countries with strong space weather interests include Finland, Italy, Poland, Portugal, Switzerland, Sweden, and the United Kingdom.

Finally we present a SWOT analysis of the European scene. The strengths in respect of space weather services are their value as an application of existing skills in solar-terrestrial and space plasma physics and the ability of developers to engage the wider engineering community. The weaknesses are the fragmented programs discussed above, together with the limited awareness of space weather among decision makers, the poor quality of many existing products, and the risks that arise when space weather is seen as part of astronomy rather than the geosciences. The opportunities are the ability to set a global context in which to make a case for space weather services, and the way that human networking can help to build service context and fix the quality of products. The threats are the risk of piecemeal funding cuts at the national level, possibly exacerbated by competition with other areas. Space weather is also under threat when decision makers think of space as being empty and thus fail to appreciate the effects of the plasmas that pervade outer space.

GLOBAL POSITIONING SYSTEM

Christopher J. Hegarty, The MITRE Corporation

The Global Positioning System (GPS) is a satellite navigation system operated by the United States that includes a constellation of nominally 24 satellites in medium Earth orbit with an approximate altitude of 20,000 km. As illustrated in Figure C.2, new civil and military signals are being introduced. These include the L2 civil (L2C) and military (M code) signals that began with the launch of the first Block IIR-M satellite in 2005. In 2009, the first Block IIF satellite will add a new civil signal, referred to as L5, at 1176.45 MHz. In 2014, the first Block IIIA satellite will add an additional civil signal, L1C, at 1575.42 MHz. Based upon current schedules, the GPS constellation will be fully populated by 2014, 2016, and 2021, respectively, with L2C-, L5-, and L1C-capable satellites.

All of the new civil and military signals include advanced capabilities that are anticipated to result in a significant increase in robustness against space weather effects, specifically ionospheric scintillation and solar radio noise bursts. These capabilities include pilot components for more robust tracking (e.g., a reduction of the minimum signal-to-noise ratio necessary for tracking by ~3-5 dB) and forward error correction of the broadcast navigation data to enable demodulation in lower signal-to-noise conditions.

Two of the new civil signals, L2C and L5, also provide modest increases (1.5 dB and 4.5 dB, respectively) in received signal power relative to C/A code. The addition of L2C and L5 furthermore allows civil GPS receivers to more robustly measure ionospheric delays as compared to the only current civil alternative to employ codeless or semi-codeless techniques to track the encrypted GPS P(Y) code signals on the GPS L2 frequency.

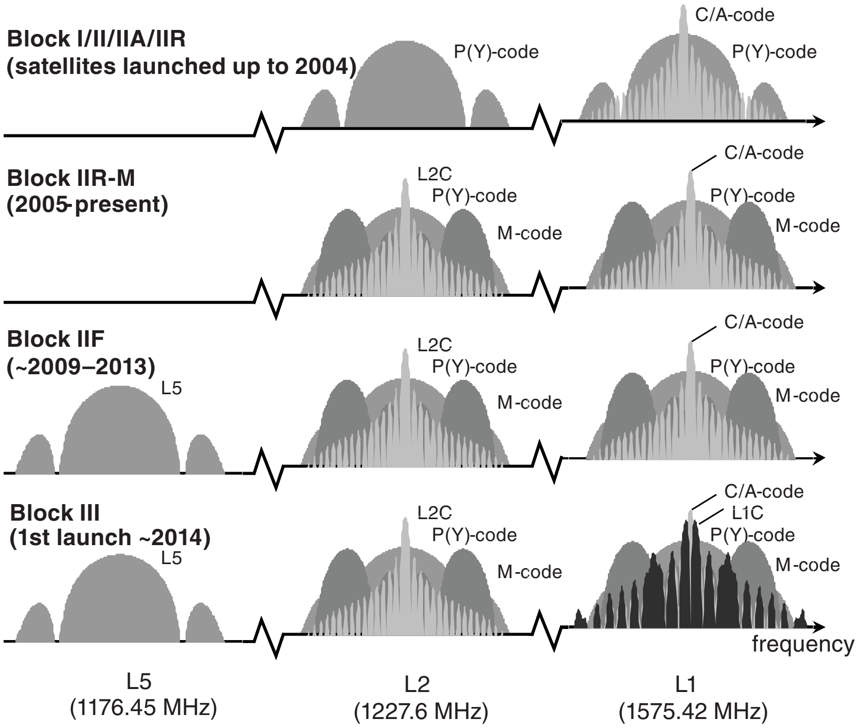


FIGURE C.2 Evolution of GPS signals.

THE VULNERABILITY OF THE U.S. ELECTRIC POWER GRID TO SEVERE SPACE WEATHER EVENTS, AND FUTURE OUTLOOK

John G. Kappenman, Metatech Corporation

Severe space weather events have the potential to pose operational threats to the North American electric power grid; both contemporary experience and analytical work support this general conclusion. A large geomagnetic storm on March 13-14, 1989, triggered a blackout of the Quebec power grid. This same storm also came uncomfortably close to causing similar widespread collapse across northeastern, upper midwestern, and mid-Atlantic regions of the U.S. power grid. More recently, Metatech has carried out investigations under the auspices of the EMP Commission and also for FEMA under Executive Order 13407 to examine the potential impacts on the U.S. electric power grid of severe geomagnetic storm events. These assessments indicate that severe geomagnetic storms pose the risk for long-term outages to major portions of the North American grid. While a severe storm is a low-probability event, it has the potential for long-duration catastrophic impacts to the power grid and its affected users. The impacts could persist for multiple years with a potential for significant societal impacts and with economic costs that could be measurable in the several trillion dollars per year range.

Electric energy supply is the largest segment of energy usage in the U.S. economy, accounting for nearly 40 percent of all energy consumed (in contrast, petroleum accounts for only 22 percent of current U.S. energy consumption). In addition, the operation of many other infrastructures is dependent on a reliable and continuous supply of electricity to maintain their operational continuity. Because of the underlying importance of this service, the electric power grid is a national critical infrastructure. Severe geomagnetic storms may be one of the most important hazards and are certainly the least understood threat that could be posed to the reliable operation of the power networks. As recent detailed examinations have been undertaken concerning the interaction of geomagnetic storm environments with power grids, the realization has developed that these infrastructures are becoming more vulnerable to disruption from geomagnetic storm interactions for a wide variety of reasons. This trend line suggests that even more severe impacts can occur in the future for recurrences of large storms. These trends of increasing vulnerability also remain unchecked, as no design codes have been adopted to reduce geomagnetically induced current (GIC) flows in the power grid during a storm.

Unlike the more familiar terrestrial weather threats, geomagnetic storms can have a large geographic footprint that can readily encompass major portions of the U.S. electric power grid. This can create in many extra high voltage (EHV) transformers GIC flows that disrupt their normal AC operation. For large storms, widespread and simultaneous disruption can cause correlated multipoint failures and severe voltage regulation problems on the network that can threaten the integrity of the network with the potential for large blackouts. GIC also causes intense internal heating of the exposed EHV transformers, which can lead to permanent damage of these key and difficult to replace assets.

Impulsive geomagnetic field disturbances are an important aspect of the geomagnetic storm environment for electric power grids and other ground-based infrastructures that can be affected by GIC. Significant power grid impacts in present day networks have been observed at relatively low levels of intensity; for example, the Quebec grid blackout during the March 13-14, 1989, storm occurred at a peak intensity of 480 nT/min, and permanent damage to large power transformers has occurred at even lower intensity levels. An analysis of both contemporary and historic storm data and records indicates that dBh/dt impulsive disturbances larger than 2000 nT/min have been observed on at least three occasions since 1972 at latitudes of concern for power grid infrastructures in the United States. In extreme scenarios, available data suggest that disturbance levels as high as 5000 nT/min may have occurred during the great geomagnetic storm of May 1921, an intensity ~10 times larger than the disturbance levels associated with the major impacts observed on North American power grids in March 1989.

Present operational procedures utilized by U.S. power grid operators stem largely from experiences in recent storms, including the March 1989 storm. These procedures are generally designed to boost operational reserves and do not prevent or reduce GIC flows in the network. For large storms (or increasing dB/dt levels) both observations and simulations indicate that as the intensity of the disturbance increases, the relative levels of GICs and related power system impacts will also proportionately increase. Under these scenarios, the scale and speed of problems that could occur on exposed power grids have the potential to impact power system operators unlike anything they have ever experienced. Therefore, as storm environments reach higher intensity levels, it becomes more likely that these events will precipitate widespread blackouts of exposed power grid infrastructures. The possible power system collapse from a 4800 nT/min geomagnetic storm (centered at 50° geomagnetic latitude) is shown in Figure C.3a.

The more difficult aspect of this threat is the determination of permanent damage to power grid assets and how that will impede the restoration process. As previously mentioned, transformer damage is the most likely outcome, although other key assets on the grid are also at risk. In particular, a transformer experiences excessive levels of internal heating brought on by stray flux when GICs cause the transformer's magnetic core to saturate and to spill flux outside the normal core steel magnetic circuit. Previous well-documented cases have noted heating failures that caused melting and burn-through of large-amperage copper windings and leads in these transformers. These multi-ton apparatus generally cannot be repaired in the field, and if damaged in this manner, they need to be replaced with new units, which have manufacture lead times of 12 months or more in the world market. In addition, each transformer design (even from the same manufacturer) can contain numerous subtle design variations. These variations complicate the calculation of how and at what density the stray flux can impinge on internal structures in the transformer. Therefore the ability to assess existing transformer vulnerability or even to design new transformers to be tolerant of saturated operation is not readily achievable. Again, the experience from contemporary space weather events is revealing and potentially paints an ominous outcome for historically large storms that are yet to occur on today's infrastructure. In recent analysis that has been conducted, it is estimated that over 300 large EHV transformers would be exposed to sufficiently high levels of GIC to place these units "at risk" of failure or permanent damage requiring replacement. Figure C.3b provides an estimate of "percent loss" of EHV transformer capacity by state for the same 4800 nT/min threat environment. Such large-scale damage would

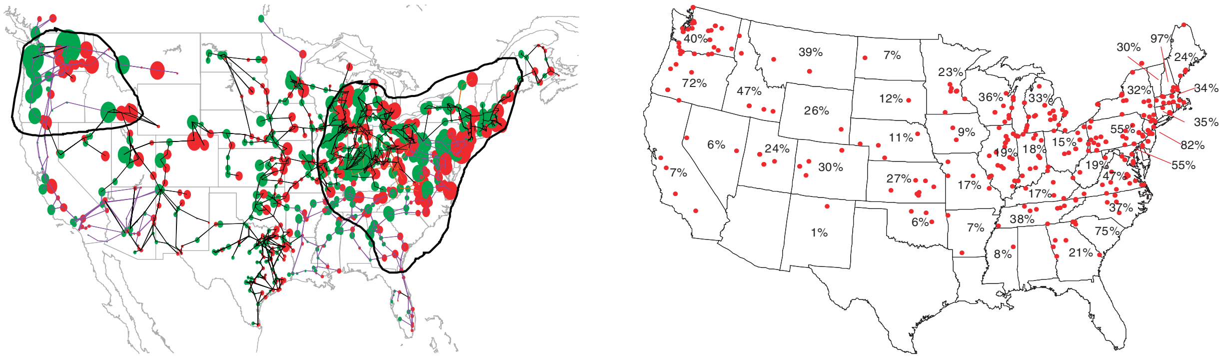


FIGURE C.3 (a; *left*) 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude scenario. The regions outlined are susceptible to system collapse due to the effects of the GIC disturbance. The region impacted would be of unprecedented scale and involve populations in excess of 130 million. (b; *right*) A map showing the at-risk EHV transformer capacity by state for this disturbance scenario. Regions with high percentages could experience long-duration outages that could extend multiple years.

likely lead to prolonged restoration time and long-term chronic shortages of electric energy supply capability to the impacted regions.

Given the potentially enormous implications of power system threats due to space weather, it is important to develop effective means to prevent a catastrophic failure. Trends have been in place for several decades that have acted to unknowingly escalate the risks from space weather to this critical infrastructure. Procedures based on K-index-style alerts provide very poor descriptions of the impulsive disturbance environments and lead to uncertainties about the adequacy and efficacy of operational procedures during large storms, because these indices saturate at relatively benign intensity levels. Much good work is being done to develop better means of characterizing and forecasting the threat environments so that power system operator situational awareness of this important threat is better communicated. In terms of the entire grid itself, remedial measures to reduce GIC levels are needed and cost-effective. The installation of supplemental transformer neutral ground resistors to reduce GIC flows is relatively inexpensive, has low engineering trade-offs, and can produce 60-70 percent reductions of GIC levels for storms of all sizes. Additional research work is already under way by the EMP Commission on this task.

AIR FORCE CURRENT SPACE WEATHER INFRASTRUCTURE

Herbert Keyser, USAF, Space and Intel Weather Exploration

The U.S. Air Force (USAF) provides space weather capability for the Department of Defense (DOD) and the nation. Air Force Space Command (AFSPC) is responsible for flying space-based DOD space weather sensors, and Air Force weather procures and operates ground-based space weather sensors and operational space weather models. The Air Force Weather Agency (AFWA), working in conjunction with the National Weather Service's Space Weather Prediction Center (SWPC), collects data, analyzes and forecasts the space weather environment, and provides that information to its customers.

The USAF is focusing on a presidential policy for providing space situational awareness to the nation, to address not only DOD interests, but civil and commercial interests as well. USAF weather and AFSPC are programming to recapitalize current capabilities, develop new capabilities, and mitigate the loss of capability from the National Polar-orbiting Operational Environmental Satellite System (NPOESS) post-Nunn-McCurdy restructuring. With suitable investments, not only by DOD but also by all national partners, we can improve our space weather forecasting capabilities.

The environment is critical in all DOD operations. Specifically, space weather impacts all military operations, whether using communications, Global Positioning System (GPS) services, or flying satellites. When problems occur, the first step is to rule out the environment—and to do this, we need to know the environmental conditions in detail. As the science improves and space weather forecasts become reliable and usable, we can then start planning around expected space weather events, and even configure systems to take advantage of the environment.

Various space weather events cause effects on myriad DOD systems and missions. For instance, an energetic particle event could cause problems with troops communicating in the field, it could expose aircrews to hazardous levels of radiation, or it could interfere with the launching of a satellite. We use various systems to observe and forecast these events, both ground- and space-based; however, we need to be able to do better. This is where modeling comes into play.

Just as in terrestrial weather, we cannot measure the environment everywhere. Currently, AFWA is fielding the first generation of assimilative, physics-based modeling. The Global Assimilation of Ionospheric Measurements (GAIM) model is running at AFWA, with plans to upgrade to a full-physics version in the next couple of years. Models for the magnetosphere, Sun, and solar wind are not as mature; however, AFWA is working to make sure that they can be incorporated, as appropriate.

The DOD network of space weather sensors is in need of a refresh. To this end, the USAF director of weather created a plan to "get well" that focused on our role—ground sensors and modeling. The solar observing sensors and network of ionosondes have been around for a while and are becoming impossible to maintain. USAF weather is taking a phased approach to modernize these systems, with ionosondes being purchased and development work started on the optical solar observing system. We are also increasing our investment to transition current space weather modeling capabilities into operations.

AFSPC is working on replacing capabilities lost on NPOESS as well as helping to sample the rest of the space environment. Because a free-flying satellite would be too expensive, AFSPC is pursuing individual sensors to fly on rides of opportunity from our national and commercial partners. They will also invest in modeling to provide knowledge of effects on their systems. At the same type, we are advocating to NASA and NOAA the development of partnerships to collect information from the rest of the space domain, particularly a solar wind sensor.

As the director of weather says, space weather is a "team sport." No one agency or institution can go it alone. To that end, we already partner with others to get the data we need. First and foremost is the SWPC. Our two forecast centers share virtually all the data, and make combined forecasts every day. Also, the U.S. Geological Survey provides vital magnetometer data to both centers. The USAF also leverages NASA JPL TEC (total electron content) data as well as helping to fund the international tracking of ACE. We have started talks with the National Solar Observatory to get GONG data to AFWA to fill in the gaps in our solar observing and help out while we upgrade our solar optical system.

Of course, to take advantage of the increased data, we need to make corresponding investments in models. USAF weather is increasing its investment in its Space Weather Analysis and Forecasting System (SWAFS) to better use these data, as well as to improve modeling capabilities. AFSPC is making a corresponding investment in effects-based decision aids to take advantage of the improved capability to specify and forecast the environment.

Finally, USAF weather is making sure that we continue to have the needed experts to carry out the space weather mission. We will continue to create advanced academic degree space weather officers, as well as formalize an internal USAF space weather training program.

SPACE WEATHER IMPACTS ON THE ELECTRIC POWER SYSTEM

Frank Koza, PJM Interconnection

Exposure and Vulnerability

The impacts of space weather events on the power system have been well documented. The fact that the major elements of the power system are exposed and particularly vulnerable to space weather can be disconcerting to power system operators. The superposition of extraneous currents onto the normal operational flows on power system equipment can create conditions that are capable of causing damage in a very short period of time, such that operator action cannot respond in time. Fortunately, most events have relatively benign power system impacts. However, the occasional serious event can have wide-ranging impacts.

March 1989 Event

During March 1989, a solar superstorm created severe impacts on the power system. Most notably, the province of Quebec was blacked out, and there were less severe but serious impacts in other portions of the system. In Quebec on March 13, 1989, a large solar magnetic impulse caused a voltage depression that could not be mitigated by automatic voltage compensation equipment. The failure of the compensation equipment resulted in a voltage collapse in the province in an event that took only 90 seconds to propagate.

Also, during this storm, a large step-up transformer failed at the Salem Nuclear Power Plant, located in southern New Jersey. That failure was the most severe of approximately 200 separate events that were reported during the storm on the North American power system. The other events ranged from generators tripping out of service, to voltage swings at major substations, to other lesser equipment failures.

Assessment of Risk

The operators of the North American power grid constantly review and analyze the potential risks associated with space weather events. Grid operators have access to space weather forecasts, monitor voltages and ground currents in real time, and have mitigating procedures in place. PJM, as an example, has monitoring devices in place at key locations on its system, which are monitored in real time. At the onset of significant ground currents at the monitoring stations, PJM will invoke conservative operations practices that will help mitigate the impacts if the solar event becomes more severe.

What has changed on the power system since 1989? The evolution of open access on the transmission system has fostered the transport of large amounts of energy across the power system in order to maximize the economic benefit of delivering the lowest-cost energy to areas of demand. The magnitude of power transfers has grown, and the risk is that the increased level of transfers, coupled with multiple equipment failures, could aggravate the impacts of a storm event.

The "Perfect Storm"

In trying to conceive of an event that could pose serious implications to the power system, one would think that the peak load case could produce the most severe impacts. However, at peak loads, almost all of the generators are running and there is a lot of spinning mass on the system. Loss of multiple facilities at this time, while problematic, can be handled with emergency procedures and other well-established practices.

The situation that could be more troublesome is a light load case with unusually heavy transfer patterns, as is prevalent in the middle of the night. Loss of multiple facilities at lighter loads and high transfers sets up the potential for voltage collapse with minimal ability for mitigation. (The 1989 Quebec blackout occurred at 2:45 a.m.) It would take the loss of several elements at strategic locations, but if such losses happened at about the same time, a voltage collapse and associated blackout would be possible.

SPACE WEATHER: PUBLIC VULNERABILITIES, INSTITUTIONAL AND PUBLIC POLICY ISSUES

Todd M. La Porte, Jr., George Mason University School of Public Policy

Space weather potentially affects large complex technical systems that are vital for economic and social stability and functioning. Assuring that such systems, principally electric power, communications, and navigation systems, are not damaged or disrupted is a critical problem. Severe space weather events are rare but could wreak considerable havoc, as has occasionally occurred in previous solar cycles. Such events are known as low-frequency/high-consequence events.

A key issue affecting our ability to prevent disruption to large technical systems is the difficulty of developing the appropriate institutions to deal with the problem on a long-term basis. We know from other emergency and disaster management and planning agencies that institutional development occurs most often under conditions of frequent accidents or errors. When nothing bad appears to happen from one year to another, sustaining preparedness and planning in out-years is extraordinarily challenging. Consequently, space weather is not on the radar screen of many people outside the small technical community and some businesses.

In addition, the systems that would be affected by severe space weather epitomize contemporary society: network systems such as electric power, or navigation and timing systems such as GPS, are increasing (inter)dependent. Operating these systems such that they virtually never fail is critical to economic and social order and human welfare. At the same time, running them is extraordinarily challenging: so-called highly reliable organizations are rare; taken for granted; not well understood; hard to replicate; costly; involve many institutions, technologies, and publics; and require very specific political and administrative conditions. Space weather may threaten failure-free operation of large complex technical systems and organizations.

Developing robust institutions that can respond to extreme space weather events in the absence of a catastrophe, for example a solar superstorm or "solar tsunami," is difficult. There are many discouraging examples: Hurricanes Katrina and Rita, the Christmas tsunami, Three Mile Island, and the shuttle explosions, among others.

But there are some instructive examples as well: e.g., FAA air traffic control and navigation systems, California's earthquake hazard mitigation and management, nuclear power plant safety practices, Dutch storm surge management and engineering institutions, and U.S. nuclear weapons stewardship. All have experienced catastrophic failures in the past, or face clear existential threats in the present. All have institutionalized political constituencies, policy networks, and regulatory structures. All exhibit characteristics of highly reliable organizations as well. Again, understanding the institutional dimension of large technical system operation is critical.

Dependency creep, risk migration, and new technologies are additional potential problems for large technical system operators. As systems become more complex, and as they grow in size, understanding and oversight become more difficult. Subsystems and dependencies may evolve that escape the close scrutiny of organization operators. Dependencies allow risk present in one part of the overall system to "migrate" to others with potentially damaging results. GPS and electric power systems have clearly accelerated dependency creep, and consequent risk migration. New technologies, such as nanoscale components, may not be adequately understood in the context of 11-year solar cycles.

One of the most fundamental concerns for operators of large technical systems is the efficiency-vulnerability trade-off, i.e., how much reserve capacity is available to deal with uncertainty and contingencies. In stable protected environments, systems operate with excess capacity: costs are passed on to users and the society. In competitive market but benign environments, however, systems operate at close to their efficiency frontiers. Slack resources are consumed, buffers shrink, costs fall, and profits rise. But in competitive market and hostile environments, systems become brittle and have trouble operating outside relatively narrow parameters. Vulnerability can be the consequence of increased efficiency. "Security externalities" emerge due to interdependencies, lack of knowledge, lack of slack, lack of trust, and lack of ways to overcome coordination problems. The communities most affected by severe space weather all face this situation.

How might we think about designing for severe space weather events? Space weather is not just a technical matter. It is also importantly a problem of institutions and of society. Solving the recurrent problem of severe space weather entails a number of thorny issues that may ultimately not be resolved without a catastrophic failure to prompt reforms.

USER PERSPECTIVE ON SPACE WEATHER PRODUCTS

James McGovern, ISO New England, Inc.

Impact on Electric Power System

The North American electric power grid acts much like a large antenna, picking up electromagnetic radiation from Earth's geomagnetic field during times of solar storm activity. Only a few amps from geomagnetically induced currents (GICs) in the grounding connections of bulk electric system power stations can wreak havoc on power system operations.

GICs can overload the capability of the electric power system, especially with respect to voltage regulation. They can cause misoperation and malfunction within power relay and protection systems, which can degrade overall system reliability.

Forecast and Real-time Situational Awareness

When a significant amount of solar storm activity occurs, in order for an electric power system to be able to withstand the impact of GIC flows and the resulting harmonics, a system operator must have available timely information that can allow for efficient system re-dispatch and posturing of generation and transmission resources. Without accurate forecast and real-time situational awareness of such solar events, power system failures are likely to occur.

Case in point: On March 13, 1989, at 0245 hr, with Montreal temperatures at minus 15 degrees Celsius, GICs saturated Quebec bulk power system transformers, resulting in a system-wide collapse.

It was over an hour before the system operators realized that the cause of the electrical system failure was a geomagnetic storm of K9 intensity, which resulted in a significant amount of GICs.

Develop Modeling Tools

Additionally, data on solar storms and coronal massive ejection (CME) events made available early on to the operator could allow for a more timely and effective response to their impacts. Also, in the future it may be necessary to develop models of the North American bulk power grid overlaid on a model of the crustal and upper mantle to determine ground resistivity to GICs.

When a frontal or side branch CME event occurs, a forecast of intensity is derived and ultimately provided to the system operator. Often, the estimated time for the ejected matter to reach Earth's surface is not known, due to a lack of understanding of the speed at which the ejected matter is traveling toward Earth.

An understanding of the directional polarity of the ejection is also a critical indicator, as the polarity is a key factor influencing how the event will interact with Earth's geomagnetic field and create GICs. However, often such information is also not available.

In summary, detailed information on space weather forecast data incorporated into a model that correlates the data with the characteristics of the North American bulk power grid is critical to ensure that the system operator has adequate time to posture the system. Regional system operators will also require initial and continuing training to understand their assigned roles and responsibilities in protecting the power system during solar events using these new tools.

SPACE WEATHER: AVIATION VULNERABILITIES AND SOLUTIONS

Thomas McHugh, Department of Transportation FAA

Background

The Federal Aviation Administration (FAA) is in the process of transitioning the National Airspace System (NAS) to utilize space-based navigation as the primary means of navigation. This transition is part of an overall modernization of the NAS to implement integrated Communications Navigation and Surveillance (CNS). Augmented GPS and un-augmented GPS will provide the space-based navigation function. The transition to integrated CNS utilizing space-based navigation will take a long time, and equipage will still be minimal by the next solar peak.

Un-augmented GPS has been in use by aviation for many years. Un-augmented GPS utilizes Receiver Autonomous Integrity Monitoring (RAIM) to provide integrity. Currently RAIM only supports non-precision modes of navigation.

The Wide Area Augmentation System (WAAS) is the FAA's Space Based Augmentation System (SBAS). Other SBASs are under development or already in service. WAAS augments GPS for both non-precision and precision flight operations and covers the entire NAS as well as most of Canada and Mexico. Japan's MSAS was commissioned for non-precision operations in September 2007. MSAS is the acronym for MTSAT Satellite Augmentation System. The European Geostationary Navigation Overlay Service (EGNOS) SBAS is in the final stages of being certified. The Indian GPS Aided GEO Augmented Navigation (GAGAN) SBAS completed initial proof of concept testing in July of 2007 and entered full-scale development testing.

In addition to SBAS systems, Ground Based Augmentation Systems (GBASs) are under development. The first GBAS was recently commissioned in Europe. GBASs are eventually expected to support Category 3 (CAT-3) instrument approaches. Currently SBASs are not believed to be capable of supporting CAT-3 approaches unless the aircraft assumes more of the safety burden.

Space Weather, the Ionosphere, and GPS

The ionosphere delays the GPS signal proportional to the path length, the total electron count (TEC) density along the path, and the frequency of the GPS signals. The density of TEC varies with height, time of day, latitude, and point in the 11.5-year solar cycle, and with solar weather. At midlatitudes TEC density is reasonably well behaved except during strong solar weather events. At equatorial latitudes small quickly moving holes of low TEC and significant levels of scintillation can be observed even under benign solar weather.

GPS is designed to use the difference in delay between the L1 frequency signals and the L2 frequency signals to compute the ionosphere delay at either of the frequencies.

Currently all civil aviation GPS receivers use only the L1 C/A signal. Un-augmented single-frequency GPS receivers use the Klobuchar model (Jack Klobuchar, Boston College) to estimate the ionosphere delay. That model uses a set of polynomial coefficients to describe a lumped vertical (zenith) ionosphere delay on a surface at a fixed altitude above the surface of Earth. Those coefficients are estimated well in advance and broadcast as part of the GPS navigation message. This type of model is sometimes called a thin shell model. SBAS systems broadcast a set of ionosphere grid points to define a patch of a thin shell based on real-time measurement data. WAAS updates the information every 5 minutes. For a GBAS, the ionosphere delay is common between nearby aircraft and the ground system so that the lumped differential correction broadcast by the GBAS includes the ionosphere delay correction.

The Klobuchar model has limited accuracy and is not real time. During solar maximum, the accuracy decreases as the nominal magnitude of the delays increases. Since the Klobuchar model is not real time, it does not react to solar storms, and the error increases further during those events.

The SBAS thin shell model reacts in real time. However, the SBAS thin shell model becomes invalid during severe disturbances in the ionosphere. For example, two different receivers using the same pierce point from two very different look angles could experience significantly different ionosphere delays but would calculate the same correction. When WAAS detects this type of condition it increases the uncertainty on the ionosphere corrections. This increased uncertainty disables precision navigation.

When the ionosphere is heavily disturbed by solar storm activity there will often be significant scintillation. During very severe events the scintillation could be enough to cause loss of reception on multiple GPS satellites simultaneously. If the scintillation were to be bad enough, it is conceivable that GPS positioning service could be temporarily interrupted.

During at least two events in the last several years, solar flares have emitted radiation in the GPS frequency bands and caused degradation in the received signal-to-noise levels. For WAAS the degradation was about 6 to 10 dB and did not cause significant problems. It is conceivable that a much stronger event could cause enough jamming to cause all GPS reception to be lost for the duration of the portion of the flare emitting radiation at that frequency.

Solution

The first part of the solution is the addition of the L5 civil GPS signals starting with the GPS Block IIF satellites. The first of 12 IIF satellites will be launched in mid-2009. Civilian use of L5 will mitigate the problems with the Klobuchar and SBAS thin shell models. L5 is a protected frequency and has about 400-MHz frequency diversity from L1. The L5 signal design is better than the L1 C/A signal design. The frequency diversity and signal characteristics of L5 will help mitigate unintentional interference.

The second part of the solution is backup navigation systems independent of GPS. Even without considering space weather, backup navigation systems will be needed to mitigate the threat from intentional interference.

The FAA currently plans on maintaining a subset of the existing inventory of ground-based navigation aids for the foreseeable future. This subset of ground-based navigation aids is referred to as the “basic” or “backbone” network. I do not foresee the FAA decommissioning critical navigation aids until the user fleet has installed the necessary satellite navigation equipment. Equipage changes do not happen quickly to that fleet.

Existing ground-based navigation aids do not provide as much capability as GPS and do not fully support the needs of ADS-B and NextGen. Both of those programs have performed backup studies with no clear winner. A mix of eLORAN, DME-DME RNAV, and inertial navigation are the front runners as the backup for the requirements not met by the backbone network. There are also proponents for multilateration. Multilateration is a concept of using the difference in time of arrival of the aircraft’s transponder replies at multiple ADS-B locations to compute the position and trajectory of the aircraft.

National Infrastructure

As much as it is becoming more dependent on the national infrastructure component known as GPS, the FAA is already dependent on the national infrastructure for telecommunications and power. If an extremely massive solar weather event disrupts power and telecommunications over a large area, then the FAA will most likely be affected.

The FAA extensively uses terrestrial communications and satellite-based communications. The contracts for those services require high reliability and diversity, but if both the primary and the backup suppliers were affected simultaneously over a wide area, then there would be impacts on the NAS.

All critical FAA systems are required to have backup power. This essential power is usually provided by a hybrid of battery and motor generator uninterruptible power supplies. Short power outages would not severely impact the NAS. However, there are procedures that constrict the functions some facilities are permitted to perform while operating on backup power. If the power outages were widespread and of a long duration, then the NAS would eventually be impacted.

Disclaimer

Opinions expressed in this paper are the technical opinion of the author and are not an official statement of FAA policy.

THE INTERNATIONAL GNSS SERVICE AND SPACE WEATHER

Angelyn W. Moore, Jet Propulsion Laboratory, California Institute of Technology

The International GNSS Service (IGS; formerly the International GPS Service) is a voluntary federation of more than 200 worldwide agencies that pool resources and permanent GNSS station data to generate precise GNSS products.[1] Participants include mapping agencies, space agencies, research agencies, universities, and so on. Currently the IGS supports two GNSS: GPS and the Russian GLONASS. Over 350 permanent, geodetic GNSS stations operated by more than 100 worldwide agencies constitute the IGS network. These civilian, dual-frequency stations contribute data to multiple data centers at a minimum on a daily basis at a 30-second sampling rate; subsets contribute hourly and four times hourly, and an IGS real-time pilot project is getting under way. The IGS maintains a vendor-neutral stance and only specifies functional requirements; the network is therefore very heterogeneous in instrumentation. The IGS dataset is analyzed independently by multiple analysis centers to form the suite of IGS products, including precise orbits, clocks, station positions, and atmospheric products at a range of latencies. All IGS data and products are openly available and are used routinely by Earth scientists and related applications around the globe. Investigators leverage the collective effort of the IGS's network, archive, and analysis infrastructure when they use IGS products with their own GPS and related data.

The material presented in this talk will sample the IGS's response to the October 2003 ionospheric storms from several perspectives. A representative station suffered intermittent loss of tracking on some or all channels during periods of this storm. The effect of such a loss of data will vary according to how many stations in the area are available and whether all of them are affected, and on the application under consideration. The IGS Ultrarapid orbits are a key IGS product that in 2003 were generated twice daily. Through the final week of 2003, some degradation of the Ultrarapid accuracy can be discerned: not all IGS analysis centers were able to contribute orbit products, and accuracies slipped a few centimeters. Nevertheless, the combined IGS Ultrarapid product achieved <10-cm accuracy for most satellites throughout the week. This would generally not have much of an impact on some types of geodetic processing, such as long-term monitoring of plate motion. However, high-rate and real-time GPS analysis is rapidly improving in detecting seismic surface waves and co-seismic displacement.[2,3,4] Brief or partial loss of tracking due to space weather during a critical event could certainly degrade applications with societal and economic impacts, such as tsunami warning systems.[5] The IGS historical dataset is an openly available archive that can be used to evaluate sensitivity to past space weather events; however, care must be taken when using historical data to allow for the improvement over time of the quality of equipment in the network and the density of the network.

The IGS has an active Ionospheric Working Group with four centers routinely analyzing the IGS dataset to produce ionospheric total electron content (TEC) maps: Center for Orbit Determination (CODE), Berne, Switzerland; European Space Operations Center (ESOC), Darmstadt, Germany; Jet Propulsion Laboratory (JPL); and Universitat Politecnica de Catalunya (UPC). The chair is at the University of Warmia and Mazury in Poland.

---

[1] Dow, J.M., R.E. Neilan, and G. Gendt, The International GPS Service (IGS): Celebrating the 10th anniversary and looking to the next decade, *Adv. Space Res.* 36(3):320-326, 2005, doi:10.1016/j.asr.2005.05.125.

[2] Larson, K.M., P. Boudin, and J. Gomberg, Using 1-Hz GPS data to measure deformations caused by the Denali fault earthquake, *Science* 300:1421, 2003, doi:10.1126/science.1084531.

[3] Choi, K., A. Bilich, K. Larson, and P. Axelrad, Modified sidereal filtering: Implications for high-rate GPS positioning, *Geophys. Res. Lett.* 31: L22608, 2004, doi:10.1029/2004GL021621.

[4] Bock, Y., L. Prawirodirdjo, and T. Melborne, Detection of arbitrarily large dynamic ground motion with a dense high-rate GPS network, *Geophys. Res. Lett.* 31:L06604, 2004, doi:10.1029/2003GL019150.

[5] Blewitt, G., C. Kreemer, W.C. Hammond, H.-P. Plag, S. Stein, and E. Okal, Rapid determination of earthquake magnitude using GPS for tsunami warning systems, *Geophys. Res. Lett.* 33:L11309, 2006, doi:10.1029/2006GL026145.

TABLE C.1 The Suite of IGS Ionospheric Products

	Accuracy	Latency	Updates	Sample Interval
Final Ionospheric TEC Grid	2-8 TECU	~11 days	Weekly	2 hours; 5 deg(lon) by 2.5 deg(lat)
Rapid Ionospheric TEC Grid	2-9 TECU	<24 hours	Daily	2 hours; 5 deg(lon) by 2.5 deg(lat)

The Ionospheric Working Group notified the IGS community of extremely high TEC values in the 2003 event, and the combined IGS product reflects the magnitude of the storm. Like the raw dual-frequency data from the IGS network, the IGS ionospheric products (Table C.1) are openly available and archived indefinitely, and can be valuable tools for researching past space weather events.

CURRENT SPACE WEATHER SERVICES INFRASTRUCTURE

William Murtagh, NOAA Space Weather Prediction Center

NOAA's Space Weather Prediction Center (SWPC) monitors, measures, and specifies the space environment and provides timely and accurate operational space weather forecasts, warnings, alerts, and data to end users in the United States and around the world. The program develops space weather observational requirements for NOAA's sensors, ingests and processes NOAA's (and others') data, and transitions research into operations to improve services.

The SWPC staffs a 24-hour/day Operations Center, through which both in situ and remotely sensed data and imagery flow. SWPC forecasters analyze solar images to assess the current state of the solar-geophysical environment (from the Sun to Earth and points in between). Space weather forecasters also analyze the 27-day recurrent pattern of solar activity. Based on a thorough analysis of current conditions, comparing these conditions to past situations, and using a limited suite of space weather models, forecasters are able to predict space weather on times scales of hours to weeks.

NOAA radiation storm and solar flare radio blackout alerts and forecasts are dependent primarily on GOES data. All SWPC space weather alert messages for geomagnetic phenomena are based on real-time data from the Boulder-NOAA magnetometer, which can be taken as a proxy for other midlatitude locations. Most alert products correspond with the NOAA Space Weather Scales thresholds.

During severe storm periods, these products are distributed both by Web access over the Internet and by direct contact with high-priority customers. These data types are also key for the U.S. weather enterprise, and they support the private and commercial sector in the development of products and services using space weather-related information. The USAF provides critical operational data from the Solar Optical Observing Network (SOON) and the Radio Solar Telescope Network (RSTN).

NASA provides key science data from its research satellites (SOHO, ACE, and STEREO) and plans to provide science data from future approved missions. Data from these research satellites are now deeply ingrained in SWPC forecasting processes. The United States Geological Survey (USGS) provides key ground-based data. SWPC also receives data from many countries and their space agencies throughout the world.

These diverse data streams are analyzed continuously, and that information is applied to both predictions and specifications of various aspects of the space environment. These include the behavior of the geomagnetic field, the character of the ionosphere, and the strength of the near-Earth radiation environment.

SWPC currently relies on a limited suite of empirical and physics-based models. SWPC is committed to bring the new generation of numerical space weather prediction models into the forecast office. To accomplish this, SWPC will leverage the prediction and specification models developed by partner agencies (NASA, NSF, and DOD) and transition them to operations. Data-driven and data-assimilative, physics-based models will provide more accurate, longer-lead-time predictions of severe space weather storms on regional and local scales.

SWPC provides a comprehensive database and Web display of space weather products. SWPC also has a product subscription service that allows customers to register to receive products via e-mail. This allows customers to manage their own records and product selections, while providing SWPC with specific customer and product-usage information. Over 6500 unique customers subscribe to SWPC's product subscription service. Many data files and products are also available on an anonymous FTP server. Selected products are also distributed on the NOAA/NWS Dedicated Broadcast Systems.

The SWPC customer base is large and growing. More than 50 million files are transferred from the SWPC Web page each month. Over 500,000 files are created monthly with near-real-time data for 176 different products serving more than 400,000 unique customers every month in over 120 countries.

Accurate and timely space weather information is vital in mitigating the potential impact of these storms on our technological infrastructure. Geomagnetic storms can cause widespread electrical blackouts, which could result in significant loss of life, as well as a potential GDP loss in the billions of dollars. Polar flights rerouted due to space weather can cost the airline over $100,000 per flight. If airborne survey data, or marine seismic data, are useless or poor because of solar activity, the financial impacts are significant, with costs in the $50,000 to $1 million range. Primary users of SWPC data include the following:

- *Electric power grid operators* use geomagnetic storm detection and warning systems to maximize power grid stability and to mitigate power grid component damage and large-scale blackouts.
- *Spacecraft launch operators* use radiation products to avoid electronic problems on navigation systems and thus prevent launch vehicles from going off course and being destroyed or misplaced.
- *Spacecraft operations and design* rely on space weather products to ensure spacecraft survival in the face of electronic problems. Space weather effects on satellites vary, but effects range from simple upsets to total mission failure.
- *Manned spaceflight* activities are altered to avoid or mitigate effects of radiation storms that impact crews and technological systems.
- *Navigation systems* users need space weather data as a critical input to ensure the integrity and safe use of electronic (i.e., GPS, Loran) navigational systems.
- *Aviation* uses crucial information on space weather impacts, such as communication outages, potentially harmful radiation, and navigation errors to adjust routes and altitudes.
- *Communications operators* anticipate and react to space weather over a wide range of communications frequencies used by emergency management officials, search and rescue systems, and many others.
- *Surveying and drilling operations* rely on accurate and timely space weather data for safe and efficient high-resolution land surveying and sea drilling.

A growing number of customers are realizing social and economic benefits from applications of SWPC products and services. Expect this trend to continue as we become increasingly dependent on space-based systems and other technologies vulnerable to hazardous space weather.

SPACE WEATHER EXTREMES

T. Paul O'Brien, Aerospace Corporation

In general, systems are and will continue to be designed to operate through extremes of the space environment over their designed life. This assumes an accurate climatology, which is not always available. My expertise is in the area of hazards to the health and operation of satellites, so I will use that as the backdrop for a story about extremes of the space environment. For hazards to spacecraft, the principal concerns are surface charging, internal charging, single-event effects, and total dose. Where possible, I will try to highlight general principles that can be applied broadly.

The reader is advised of an important distinction: "space weather" is the description of a short-term phenomenon: a new forecast might lead to a change of operations. "Space climatology" is a long-term statistical description: a new climatology model might lead to a change of system design.

TABLE C.2 The Present State of Space Environment Hazard Climatology of Extremes

Hazard	Responsible Particles	Climatology	Extreme Value Analysis?
Internal charging	100s keV to MeV electrons	Fennell et al. (2000), O'Brien et al. (2007), NASA-HDBK-4002a	Yes, finite upper limit expected
Surface charging	10s keV electrons	MIL-STD-1809, NASA-TP-2361	No
Single-event effects	MeV protons, ions	October 1989 event, Xapsos PSYCHIC model	Yes, finite upper limit expected (debated)
Total dose over mission	eV to keV electrons, protons, oxygen keV to MeV electrons, protons MeV to GeV protons, heavy ions (cosmic rays)	Partial: Thomsen et al. (2007), JPL91 and Xapsos models, AE-8 and AP-8	Partial: only for solar particles, similar to SEE

Planning for Extremes

Engineers typically design to operate through the extremes. It is highly atypical to intentionally design a system to have a likely susceptibility to extremes of the space environment. Trying to operationally forecast specific instances of extremes of the space environment may be of limited value: either we do not know the threshold beyond which to expect a negative impact on any specific technological system, or we do know because it's happened before and therefore is not unusual or very extreme. There are exceptions: e.g., human extravehicular activity and large-scale infrastructure based on GPS.

A solar radio burst on December 6, 2006, resulted in ~25 dB loss in the signal/noise ratio for many GPS receivers (Carrano and Bridgwood, 2008). The radio flux in the GPS L1 and L2 bands likely exceeded 10^6 solar flux units. Based on climatology (Nita et al., 2002), this should occur about once very 30 years, perhaps less often. For most consumer uses, an outage every few decades is reasonable. However, for critical uses, like aircraft navigation, a backup system or an engineering mitigation must be implemented (see also Gary, 2008).

Extremes are often not known well, and sometimes designs fail to meet specifications: mission assurance is a systems engineering approach to ensuring that systems meet specifications; climatology is a scientific approach to ensuring accurate characterization of worst cases.

At present, important aspects of space environment climatology are not explicitly included in NASA, NOAA, and NSF observation objectives. Climatology is obtained as a side-effect of some other priority (e.g., fundamental science, situational awareness), or it is not obtained at all. See Table C.2.

Extreme Value Analysis

Extreme value analysis is a statistical method, primarily developed in the financial and insurance industries. The analysis determines the shape of the "tail" of the statistical distribution of a quantity. It characterizes intensity of the N-year event (e.g., the 100-year flood). Sometimes (especially for geophysical phenomena) it determines a finite upper limit to the intensity or size of the largest possible event. The results allow designers to quantitatively trade design and specifications against risk. Most relevant space environment phenomena appear to have finite upper limits, but quantitative knowledge of those limits is often poor due to a relatively short history of observations.

The extreme value distribution describes the distribution of largest values taken from multiple independent sample sets, where H gives the probability that any sample maximum will be larger than x. H has three parameters: position, μ; scale, σ; and shape, k. Depending on the sign of k, one obtains one of three different families of the extreme value distribution.

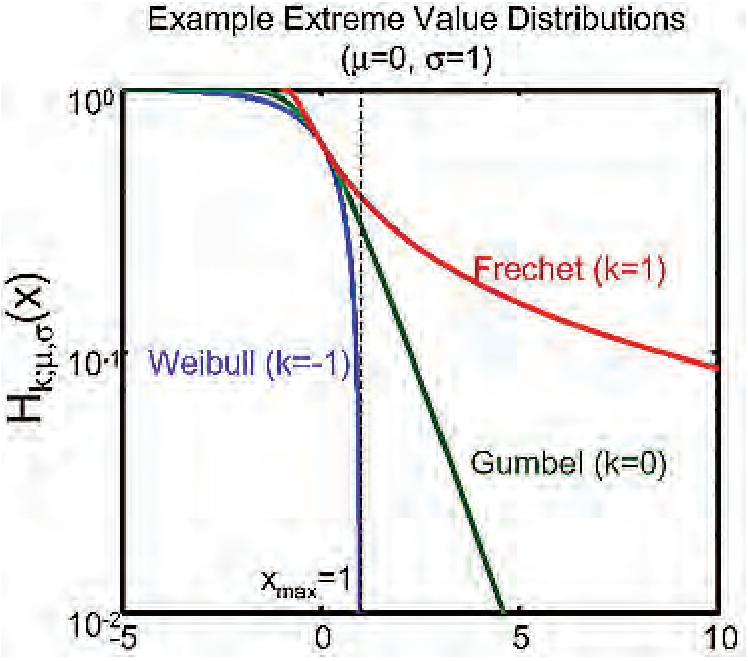


FIGURE C.4 The three families of the extreme value distribution. The Weibull family, $k < 0$, exhibits a finite upper limit and is common in geophysical data. From O'Brien et al. (2007). Copyright 2007 by the American Geophysical Union. Reproduced by permission of the American Geophysical Union.

Figure C.4 illustrates the three families of the extreme value distribution. Using a maximum likelihood method, one can obtain the parameters of *H*, with the most important being *k*. O'Brien et al. (2007) applied this method to the electrons that cause internal charging in the outer radiation belt and found a finite upper limit to the fluxes over a large spatial and energy domain. My own analysis (not shown) and that of Tsubouchi and Omura (2007) show that the tail of the distribution of the Dst index of magnetic storm intensity does include the Carrington event (September 1-2, 1859) type intense magnetic storm (Dst < −1600 nT; Tsurutani et al., 2003). Extreme-value analysis thus allows us to bound the largest events expected and to put extremely large events in context.

Concluding Observations

With accurate climatology of extreme events, engineers can make sensible cost-benefit decisions about worst cases: harden design or accept risk. Policy makers must be aware when designs accept risk, just as with earthquakes, hurricanes, and so on. Critical systems must either be hardened or have robust backups.

The following recommended actions might ameliorate the shortcomings of the present state of knowledge of space weather extremes, especially for satellite operations: First, break down cultural and systemic barriers that prevent engineers and scientists from working together to set priorities and develop solutions. Second, promote long-term space environment observation or monitoring as a legitimate scientific objective for NASA; currently, only NSF and NOAA seem to be allowed to do this, while NASA has historically flown the most capable sensors. Given the longer operational life of non-NASA missions, it may be most cost-effective for NASA to exploit more missions of opportunity on operational vehicles.

Acknowledgments

The author acknowledges useful discussion with D. Gary, NJIT, on this topic, and directs the interested reader to his presentation to IES2008 (Gary, 2008). This work was funded by the Aerospace Corporation's Independent Research and Development Program. Available as Aerospace Tech. Report ATR-2008(8073)-1.

References

Carrano, C.S., and C.T. Bridgwood. 2008. Impacts of the December 2006 Solar radio bursts on GPS operations. *5th Symposium on Space Weather.* New Orleans, La., January 20-24, 2008. American Meteorological Society, Washington, D.C.

Fennell, J.F., H.C. Koons, M.W. Chen, and J.B. Blake. 2000. Internal charging: A preliminary environmental specification for satellites. *IEEE Trans. Plasma Sci.* 28(6):2029-2036.

Gary, D. 2008. Cause and extent of the extreme radio flux density reached by the solar flare of 2006 December 06. 12th International Ionospheric Effects Symposium, Alexandria, Va., May 13-15, 2008.

Nita, G.M., D.E. Gary, L.J. Lanzerotti, and D.J. Thomson. 2002. The peak flux distribution of solar radio bursts. *Ap. J.* 570:423-438.

O'Brien, T.P., J.F. Fennell, J.L. Roeder, and G.D. Reeves. 2007. Extreme electron fluxes in the outer zone. *Space Weather* 5:S01001, doi:10.1029/2006SW000240.

Thomsen, M.F., M.H. Denton, B. Lavraud, and M. Bodeau. 2007. Statistics of plasma fluxes at geosynchronous orbit over more than a full solar cycle. *Space Weather* 5:S03004, doi:10.1029/2006SW000257.

Tsubouchi, K., and Y. Omura. 2007. Long-term occurrence probabilities of intense geomagnetic storm events. *Space Weather* 5:S12003, doi:10.1029/2007SW000329.

Tsurutani, B.T., W.D. Gonzalez, G.S. Lakhina, and S. Alex. 2003. The extreme magnetic storm of 1-2 September 1859. *J. Geophys. Res.* 108(A7):1268, doi:10.1029/2002JA009504.

Xapsos, M.A., C. Stauffer, T. Jordan, J.L. Barth, and R.A. Mewaldt. 2007. Model for cumulative solar heavy ion energy and linear energy transfer spectra. *IEEE Trans. Nucl. Sci.* 54(6):1985-1989.

MEETING THE CHALLENGES OF NATURE— THE IMPACT OF SPACE WEATHER ON POSITIONING SERVICES SOLAR CYCLE PROGRESSION AND THE MATURING OF GPS

Lee Ott, OmniSTAR, Inc.

Background of OmniSTAR Groups

OmniSTAR companies were formed by Fugro NV in 1996 to provide differential GPS signals to the offshore oil and gas industry and to the agriculture and geographic information system (GIS) industries. There are three operating companies responsible for the entire world. OmniSTAR, Inc., is responsible for North and South America. OmniSTAR BV is responsible for Europe, Africa, and the Middle East, while OmniSTAR Pty is responsible for Australia and Asia. The three OmniSTAR groups maintain and operate over 130 reference sites around the world. Their task is to retrieve real-time data from reference sites and to create data that are injected into over 14 L-band satellite beams. Due to the criticality of user-base operations, elaborate mechanisms are in place to ensure quality control for the inbound data and in the formation of the broadcast streams to provide integrity to users. All areas of the world are covered by more than one satellite beam, and all uplinks to the satellites can be controlled from each of the OmniSTAR network control centers (NCCs). Each satellite beam contains information for four different types of services. These services are called the VBS, HP, Glonass, and Iono.

Service Descriptions

The VBS service provides GPS single-frequency corrections to users that have single-frequency receivers. The process in the user receiver calculates L1 range corrections using a weighted average of near-reference-station corrections. The process creates range corrections for a virtual base station that is effectively at the user position. This process uses the Klobuchar Iono model to calculate ionosphere delays. The problem with the VBS process is that when the ionosphere delays are disrupted due to space weather phenomena, the accuracy of the VBS solution is degraded. To alleviate this problem the reference stations around the world were upgraded to dual-frequency receivers, and measurements of the local ionosphere delays are calculated. These delays are then sent to the NCCs and broadcast over the satellite beams, which is our Iono service. VBS users can augment or replace the ionosphere delays calculated by the Klobuchar model with actual delay calculations from nearby stations. Further, a user with a dual-frequency receiver can actually use ionosphere-free measurements to calculate a position. However, on average the ionosphere-free solution has more high-frequency noise due to the codeless tracking of the L2 GPS signal.

The Glonass service is simply a differential Glonass similar to the VBS process. Clients that have a combined GPS-Glonass receiver use this.

The HP (high precision) service consists of two different modes and combinations of both. The first service provides ionosphere-free code and carrier information from its reference sites. The process in the user receiver navigates using the phase measurements only. Code measurements are used at startup to estimate the initial phase offsets and position. The second service does not use reference station information, but rather only precise orbit and clock corrections. It is a phase-based process as well. This service is referred to as XP. Another mode where users can use the reference station corrections along with orbit and clock corrections is called HP/XP.

Space Weather Effects on OmniSTAR Services

When ionosphere disturbances occur, the single-frequency users suffer the worst. Theoretically, the use of Iono service will alleviate some of these issues, but isolated ionosphere disturbances cannot be corrected effectively unless a reference site is extremely close to the user.

Since the HP/XP service uses ionosphere-free corrections, the results will not be affected nearly as much as the single-frequency user set. However, with severe-enough ionosphere disturbances and codeless L2 tracking, receivers may not be able to maintain lock on the GPS satellites. Also, because of limited bandwidth on the broadcast satellites, corrections may be updated too slowly due to the fast changes in corrections at reference sites.

If receivers cannot maintain lock on a sufficient number of satellites, then the accuracy of the solution is degraded due to rising position dilution of precision (PDOP).

Many of our clients rely on positioning to maintain their operations. They use multiple broadcast beams and multiple solutions to maintain reliability and quality control. However, a sudden loss of navigation that can affect all systems can occur as a result of severe ionosphere disturbances. If usage losses cannot be predicted in advance, then it can become extremely costly to our clients:

- *Example 1.* Oil drilling from a semi-submersible that has to disconnect quickly can easily cost the operator a million dollars.
- *Example 2.* Dive boat operations can risk the lives of the divers if the mother ship is driven off position.
- *Example 3.* The cost to an agriculture user is the possible destruction of crops if the guidance system veers off. Multiplied by the number of agriculture users this could have a significant impact.

What Is Needed by the User Community

Better alerts and predictions are needed of areas where ionosphere disturbances will occur. Most of the OmniSTAR user base cannot interpret the information that is currently disseminated. Their only interest is in when their navigation system is going to work.

OmniSTAR does send out bulletins to its users via e-mails and postings on our websites when we know that conditions are such that accuracy might be affected due to PDOP holes and possible ionosphere disturbances. However, more often than not our ionosphere predictions do not come to pass for most of our users due to the localized nature of the disturbances. Thus, our alerts oftentimes are ignored, because we have cried wolf too often.

A SPACE MISSION PROVIDER'S PERSPECTIVE ON SPACE WEATHER

Ronald S. Polidan, Civil Systems Division, Northrop Grumman Space Technology

As a space mission provider, we recognize two distinct aspects of space weather phenomena: measurement and impact. We are interested in helping the science community develop and build future space weather mission concepts, and we recognize the impacts of space weather as our primary environmental factor in designing missions to survive long and well in space and deliver all the mission objectives.

Northrop Grumman has a long history of building missions with space weather payloads, from the earliest Pioneer and Orbiting Geophysical Observatory missions up to the modern-day NPOESS. Since our spacecraft and instrument technology continuously evolves we must stay abreast of how this new technology will survive in the harsh environment of space. We are also very aware of the variability of space weather phenomena and the research that has shown that, prior to our short 50 years in space, space weather events occurred that were much larger and would have been more damaging than anything experienced since 1957. In 2001 the Rumsfeld Commission warned us of the possibility of a "space Pearl Harbor"—an attack on our space assets by an adversary that would leave us vulnerable. We feel there is also a real and serious threat to our space assets from major space weather events. We would also like to avoid a "space Katrina"—a natural space weather storm that severely impacts, disables, or destroys our space assets.

A new factor to be considered when developing future space weather measurement missions is the availability of lower-cost launches. Almost everyone is aware of the efforts to develop much lower cost launch vehicles such as the Falcon family that is being developed by SpaceX. But there are other approaches for low-cost access to space that are less well known. The Lunar CRater Observation and Sensing Satellite (LCROSS), currently being built by Northrop Grumman Space Technology for NASA Ames, is expected to launch in 2009 as a secondary payload with the Lunar Reconnaissance Orbiter (LRO). The LCROSS mission objective is to guide the upper stage of the launch vehicle to an impact in a permanently shadowed lunar crater and analyze the ejecta for the presence of water. While this is a very exciting mission, I would like to focus on how LCROSS is getting into space. The LCROSS mission is not tiny; it has a wet mass of over 800 kg and has significant on-board propulsion. We are looking at LCROSS-based space weather mission concepts that utilize this secondary payload approach for access to space. We feel that this can offer much lower launch costs and provide a vehicle with enough propulsion to get you where you would like to be to perform your space weather measurements.

Switching now to the impacts, rather than measurement, of space weather phenomena on space missions, I would like to discuss two aspects: the possible impacts of superstorms and what new technologies may be on the horizon that could mitigate some of the effects. Fortunately, the possible impacts of a superstorm on our current space assets have already been analyzed by Odenwald, Green, and Taylor (*Advances in Space Research* 38:280-297, 2006). This excellent paper addresses what might happen to our space assets if a superstorm similar to the 1859 Carrington-Hodgson event were to occur today. They suggest that the impacts would be widespread and severe, especially for geosynchronous and medium Earth orbit (GEO and MEO) missions.

To mitigate some of the effects of such superstorms we can look to new electronics technologies that are more tolerant of space radiation. Radiation-hardened-by-design approaches may yield affordable space electronics that could help us "weather" such storms. There are a variety of potential technologies in the marketplace for us to draw from to build our future missions. Currently almost all of these technologies are in early stages of development and need both a sustained technology development and rigorous testing in an appropriate space environment before they are ready for incorporation into a mission. But the promise is high. One small example is the DuraBit^{TM} non-volatile memory being developed by TransEL: it offers the possibility of an upset rate of 1 upset per device every 10^8 years in "worst-case" geosynchronous solar storm conditions, and 1 every 10^{12} years for quiet solar conditions. This wide range of new technology needs to be aggressively evaluated by space mission providers to assess the true value to space missions.

New approaches and new technology are on the horizon that could make our next 50 years in space more affordable, better, and more secure than the first 50 years. We have a better understanding of space weather and its effects, but much more information is still needed. We are in the earliest stages of lower-cost access to space that could greatly benefit space weather measurement. New electronics technology, currently in development, offers the possibility of mitigating all but the severest effects of space weather storms. We believe that a solid and integrated partnership between industry and the space weather community in developing the missions for the next 50 years of space can lead to more affordable and survivable missions and reduce the impacts of a "space Katrina" on our space assets.

SPACE WEATHER IMPACTS IN RETROSPECT

M.A. Shea, Air Force Research Laboratory (emeritus) and
CSPAR Senior Researcher, University of Alabama, Huntsville

The effect of solar-initiated disturbances on Earth's environment has been known for more than a century. Even before the first visual observation of a solar flare, disruptions in telegraph communications were associated with geomagnetic disturbances. During World War II radar observations were disrupted during solar radio bursts, a fact that was classified until the end of the war. It wasn't until 1946, however, that the emission of energetic particles from the Sun was recognized.

The International Geophysical Year (1957-1958), which coincided with the advent of the Space Age, provided an unprecedented increase in our knowledge of the geophysical and spatial environment. The desire to exploit our spatial environment propelled the engineering community to produce increasingly smaller electronics without, at first, any concrete knowledge of the harshness of the space environment. While solar activity was very high during the 19th solar cycle (1954-1965), this magnitude of activity did not prevail over the next two solar cycles. With the exception of the events in August 1972, solar activity was relatively quiet until 1988. The events over the past two decades together with the major technological advances in the industrial community have resulted in some rather unexpected surprises for scientists, engineers, and even the general public.

This presentation will summarize the chain of events from major solar activity to conditions in Earth's environment that can lead to disruptions in what is now considered to be routine activities. Effects such as communication disruptions, electronic circuitry upsets, and increased radiation dose will be discussed. Specific examples of space weather impacts will be presented. Finally a review of historical solar proton events will be mentioned as cautionary advice that technological planners should consider the possibility of these extremely large events in the design of their operating systems.

NASA'S CURRENT SPACE WEATHER SERVICES INFRASTRUCTURE

O. Chris St. Cyr, NASA Goddard Space Flight Center, and
Charles P. Holmes, NASA Headquarters

Two NASA directorates participate in the national space weather infrastructure: the Science Mission Directorate (SMD) includes the Heliophysics Division, and the Space Operations Missions Directorate (SOMD) sponsors the Space Radiation Analysis Group (SRAG), whose concern is radiation exposure for human explorers in space.

The focus of the programs of the Heliophysics Division is to "understand the Sun and its effects on Earth and the solar system." In particular the programs seek to understand the following:

- How and why does the Sun vary?
- How do Earth and planetary systems respond?
- What are the impacts on humanity?

In pursuit of these questions, the Heliophysics Division has laid out these research objectives:

1. Understand the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium.

2. Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields.
3. Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers.

The division executes a series of programs designed to achieve these research objectives. The programs include the flight missions, suborbital flights, and an active research program employing the data gathered from these flight activities as well as pursuing investigations and technologies needed for future missions.

The Heliophysics Division's flight strategy is to deploy modest-sized space missions, frequently, to form a small fleet of solar, heliospheric, and geospace spacecraft that function in tandem to understand the coupled Sun-Earth system. Operating this group of spacecraft as a single observatory (the Heliophysics Great Observatory, or HPGO) allows measurements across distributed spatial scales to be linked with a variety of models and provide capabilities for improving techniques for forecasting space weather. The HPGO has 17 missions currently operating, with 2 scheduled for launch and 4 more under development.

Current members of the HPGO include ACE and STEREO, which have the added feature of real-time data beacons that broadcast current space environment data for use by the space environment reporting and prediction centers at NOAA, USAF, and others. Also near-real-time data from SOHO provide valuable information on current solar activity and warnings of solar energetic particles. The SDO mission's high-resolution solar imagery will be made available in near-real time to the space environment community. Plans are in the works to consider data beacons on the future mission RBSP (2012) and possibly MMS (2014).

The Heliophysics Division solicits through NASA Research Announcements up to nine annual competitions for investigations directed at achieving the division's research objectives. Many of the investigations involve improving models, theory, or physical interpretations fundamental to space weather topics.

The Heliophysics program incorporates a data environment that retains and broadly distributes data gathered from the science instruments of the HPGO. Heliophysics sponsors NASA's participation in the Community Coordinated Modeling Center (CCMC), a multiagency partnership to enable, support, and perform the research and development for next-generation space science and space weather models. The CCMC is a primary vehicle for demonstrating that community research models are suitable for consideration for space weather production uses.

Radiation protection is essential for humans to live and work safely in space. The goal of NASA's Radiation Health Program is to achieve human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation. Legal, moral, and practical considerations require that NASA limit postflight risks incurred by humans living and working in space to "acceptable" levels.

The Space Radiation Analysis Group (SRAG) at the Johnson Space Center is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. To fulfill this responsibility, the group provides:

- Radiological support during missions.
- Preflight and extravehicular activity (EVA) crew exposure projections.
- Evaluation of radiological safety with respect to exposure to isotopes and radiation-producing equipment carried on the spacecraft.
- Comprehensive crew exposure modeling capability.
- Radiation instruments to characterize and quantify the radiation environment inside and outside the human-bearing spacecraft.

The SRAG is NASA's only real-time space environment operations activity. It is a principal customer of NOAA/SWPC. NASA's Office of the Chief Engineer is conducting a comprehensive study toward understanding agency requirements and capabilities needed to support the future human exploration program.

POLAR OPERATIONS AND SPACE WEATHER

Michael Stills, International Operations Flight Dispatch, United Airlines

When planning polar operations, United Airlines relies on the NOAA Space Weather Prediction Center's website to provide the latest space weather data.

SATCOM capability is lost at approximately 82 degrees north latitude as a result of satellite positioning. United has found that solar activity can impede HF capability, and therefore United monitors absorption data in the polar region. Degraded HF in the polar region can limit an aircraft's ability to communicate with air traffic control and the company. This situation will be accounted for in the planning process and avoided. United is also aware of proton flux levels that may be a reason for concern during solar events.

The Space Weather Prediction Center in Boulder has created on its website the tab "Space Weather for Aviation Service Providers," which focuses on the information pertinent to airline operations. In conjunction with alerts based on the NOAA space weather scales, the aviation tab provides a quick snapshot of current space weather.

Airline operations require a considerable amount of preplanning, and terrestrial weather forecasts are an integral part of this process. For polar flights any and all space weather trends or forecasts are taken into account and may include avoidance of the region if the severity of the event dictates per internal policy.

Space weather events do not regularly impact airline operations. There have only been several occurrences since 1999 that have caused United flights to deviate from optimum routes. Though infrequent, these events have been costly and significantly impact some of the long-haul flights. The duration of the events is also of importance.

When space weather events cause operational restrictions, the results have caused delays and fuel stops for flights normally capable of nonstop operations. Current policies protect for solar events, but having information in advance and increasing lead time for planning would be advantageous for the industry. United realizes that much of the data currently available is not specifically geared for aviation.

D

Biographies of Committee Members and Staff

DANIEL N. BAKER, *Chair,* is director of the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder and is a professor of astrophysical and planetary sciences and a professor of physics there. His primary research interest is the study of plasma physical and energetic particle phenomena in planetary magnetospheres and in Earth's vicinity. He conducts research in space instrument design, space physics data analysis, and magnetospheric modeling. Dr. Baker has published over 700 papers in the refereed literature and has edited six books on topics in space physics. He is a fellow of the American Geophysical Union, the International Academy of Astronautics, and the American Association for the Advancement of Science (AAAS). He currently is an investigator on several NASA space missions, including the MESSENGER mission to Mercury, the Magnetospheric Multi-Scale (MMS) mission, the Radiation Belt Storm Probes (RBSP) mission, and the Canadian ORBITALS mission. He has won numerous awards for his research efforts and for his management activities, including recognition by the Institute for Scientific Information as being "highly cited" in space research. Dr. Baker was chosen as a 2007 winner of the University of Colorado's Robert L. Stearns Award for outstanding research, service, and teaching. He currently serves on several national and international scientific committees and on advisory panels of the U.S. Air Force and other federal agencies. He was a member of the Panel on Atmosphere-Ionosphere-Magnetosphere of the National Research Council's (NRC's) 2003 solar and space physics decadal survey and he was a member of the 2006 decadal review of the U.S. National Space Weather Program.

ROBERTA BALSTAD is a senior research scientist at Columbia University and a senior fellow with the Center for International Earth Science Information Network (CIESIN) at Columbia University. Dr. Balstad has published extensively on science policy, information technology and scientific research, remote sensing applications and policy, and the role of the social sciences in understanding global environmental change. Before joining Columbia University, Dr. Balstad was the director of the Division of Social and Economic Sciences at the National Science Foundation, the founder and first executive director of the Consortium of Social Science Associations (COSSA), and president of CIESIN. She is chair of the NRC U.S. National Committee for CODATA, a member of the Committee on a Survey of the Scientific Use of the Radio Spectrum, and a member of the U.S. National Committee for the International Institute for Applied Systems Analysis. Dr. Balstad was chair of the NRC Steering Committee on Space Applications and Commercialization.

J. MICHAEL BODEAU has 28 years of experience in the satellite industry and is currently a technical fellow at Northrop Grumman Space Technology. During his career, he has supported the system engineering and detailed design of commercial telecommunication satellites, meteorological satellites, NASA great observatories, and government satellites. His expertise covers the various impacts space weather has on satellite performance and in-orbit anomaly resolution. He has briefed NASA, the U.S. Air Force, NOAA, and other agencies, as well as commercial satellite operators and insurers, on space weather impacts and mitigation. Mr. Bodeau has made multiple presentations to the space weather community on the needs of satellite designers, led a satellite industry splinter group at the October 2002 NASA-sponsored Radiation Belt Model Workshop, and has worked with the space science community to generate new plasma climatology models for GEO satellite design based on 15 years of accumulated in-orbit environment data.

EUGENE CAMERON is manager of Global Support Flight Dispatch for United Airlines and is responsible for coordinating policies and procedures for United Airlines' International Flight Dispatch Operations. Mr. Cameron has been instrumental in the development of cross-polar operations between North America and Asia. He has been associated with the flight dispatch operations of United during his entire career and is active on several International Air Transport Association (IATA) working groups, along with various international air traffic working groups, in the development of new international routes and procedures. Mr. Cameron was the first airline representative to work with the Space Environment Center in 1999 and 2000 to coordinate information exchanges concerning space weather effects on commercial flights in the polar region.

JOSEPH F. FENNELL holds the position of distinguished scientist in the Space Science Application Laboratory at the Aerospace Corporation. Dr. Fennell's recent research has included studies of magnetic storm and radiation belt processes, high-altitude plasma sheet, ring current composition studies, and magnetospheric boundary regions. Dr. Fennell has been involved in the development, fabrication, testing, and flight of many different particle instruments, ranging from auroral and magnetospheric plasma instruments to medium- and high-energy electron and ion sensors. His most recent instrumentation efforts have involved the energetic particle and energetic ion composition measurements on the CRRES, POLAR, and Cluster satellites. Dr. Fennell was a member of the NRC Committee on Solar-Terrestrial Research, and he served on the Panel on Solar Wind-Magnetospheric Interactions of the Committee on Solar and Space Physics: A Community Assessment and Strategy for the Future. He is a member of the NRC Committee on Solar and Space Physics.

GENENE M. FISHER is a senior policy fellow at the Policy Program of the American Meteorological Society (AMS) and a visiting assistant professor of physics at North Carolina State University. Her policy research interests include space weather and atmospheric policy, federal funding of science research, and the interaction between the federal government, scientific community, and private sector. Dr. Fisher's work focuses on policy research and analyses to improve how decisions are made by space weather scientists, end users, and policy makers regarding the impact of space weather on present and future technologies.

KEVIN F. FORBES is an associate professor of economics and chair of the Business and Economics Department at the Catholic University of America, where he teaches courses in microeconomics, industrial organization, and econometrics. He is an active participant in Stanford University's Energy Modeling Forum in which energy experts from government, industry, universities, and other research organizations meet to study important energy and environmental issues of common interest. With the support of the National Science Foundation, he has also written and lectured on the effects of geomagnetic storms on the electricity market. He has recently coauthored a study that examines space weather effects on electricity market outcomes in 12 power grids.

PAUL M. KINTNER is a professor of electrical and computer engineering at Cornell University. Dr. Kintner's research focuses on investigating the interaction of radio signals, both natural and man-made, with Earth's ionosphere or magnetosphere. Dr. Kintner's studies include the propagation of electromagnetic signals (such as VLF signals initiated by lightning or navigational stations), the amplification of both natural and man-made signals in space, the acceleration of ionospheric plasma by waves to form the radiation belts, and the effect of the space environment on the propagation of radio signals, specifically GPS signals. Dr. Kintner is an experimentalist who acquires electric field and magnetic field measurements from sounding rockets and satellites as well as ground-based measurements using arrays of GPS receivers. He has served on the Arecibo Scientific Advisory Committee, and he chaired the Geospace Mission Definition Team, NASA's Management Operations Working Group, and the Living With a Star-Science Architecture committee. He is a former chair of the NASA Sun-Earth Connections Advisory Subcommittee. He was a member of the NRC Committee on Solar and Space Physics.

LOUIS G. LEFFLER retired in June 2006 after a 47-year career in the electric power industry. He was a manager of critical infrastructure protection with the North American Electric Reliability Council (NERC), where he helped electric utilities develop policy and practices to ensure protection of the nation's electric infrastructure against such hazards as geomagnetic disturbances created by space weather. He also helped develop tools to assist power system operators and reliability coordinators to help ensure bulk electric system reliability. Prior to joining NERC, he worked for the Public Service Electric and Gas Company of New Jersey, and his assignments included working with fossil power production, power station engineering (fossil and nuclear), and power system operations. He was chief engineer of a 1300-MW power station and general manager of system operations. As project manager for the General Agreement on Parallel Paths, he assisted in shaping policy and practices intended to ensure reliable and equitable use of the interconnected transmission systems of the eastern United States and Canada. Mr. Leffler was involved in studying the March 1989 geomagnetic storm, and he was a presenter at the Space Weather Industry Day in Washington, D.C., in May 2006. He is a registered professional engineer and licensed steam plant engineer in New Jersey.

WILLIAM S. LEWIS is principal scientist with the Space Research and Engineering Division of the Southwest Research Institute. Dr. Lewis' primary research interest is in the area of auroral physics. He has co-authored papers on Jupiter's x-ray and far-ultraviolet aurora, Earth's proton aurora, Europa's sputter-produced atmosphere, and the Cassini Ion and Neutral Mass Spectrometer (INMS) investigation. He is currently involved in studies using data obtained with the far-ultraviolet imaging system on the IMAGE spacecraft, with particular emphasis on the proton aurora. Dr. Lewis has been involved in the preparation of several NRC documents. As consultant to the Solar and Space Physics Survey Committee, he worked with the committee and NRC staff on the preparation of the first decadal survey in solar and space physics, *The Sun to the Earth—and Beyond*. He has also worked closely with the NRC Committee on Solar and Space Physics on the *Plasma Physics of the Local Cosmos* report and on a popular booklet based on the decadal survey report. Dr. Lewis is a member of the American Geophysical Union and chaired the Web site committee of the AGU Space Physics and Aeronomy section (1998-2000). He was a member of the NRC Committee on Solar and Space Physics and of the Workshop Organizing Committee on Solar System Radiation Environment and NASA's Vision for Space Exploration.

JOSEPH B. REAGAN is a technology and senior management consultant. He retired in 1996 after a 37-year career at Lockheed Martin Corporation that included serving as vice president and general manager of the Palo Alto Research Laboratories and as a corporate vice president. His primary area of interest is technology development, and he has a broad range of experience in developing technologies in the sensor, software, cryogenics, instrumentation, materials and electro-optical areas. Dr. Reagan spent 25 years of his early career in the study of space radiation and its impact on space systems, the ionosphere, and the atmosphere. He was involved with the first satellite measurements of the aurora borealis in 1960 and led more than 20 space experiments during his career. He was a principal advisor on space radiation effects to Lockheed military and civil space programs. Dr. Reagan is a fellow of the American Institute of Aeronautics and Astronautics and has received numerous awards for his achievements. He was elected to the National Academy of Engineering in 1998 and chaired the Aerospace Engineering section from 2005 to 2007. He also served as vice chair of the NRC Naval Studies Board from 2000 to 2004.

ARTHUR A. SMALL III is an associate professor in the Department of Meteorology at Pennsylvania State University. Dr. Small, an economist, conducts research that focuses on how variations in weather and climate create economic and financial risks, and on the means to manage these risks effectively. He also applies tools and concepts from quantitative finance to analyze markets for energy products, emissions, and weather derivatives. One of his objectives is to develop models of weather risk that can be integrated with financial models to create tools for derivative pricing, asset valuation, trading, and risk management. Dr. Small's research results have appeared in publications that include the *Journal of Political Economy, Review of Economics and Statistics, Journal of Environmental Economics and Management,* and the BE Press *Topics in Economic Analysis and Policy*. He has served as an editorial reviewer for numerous scholarly publications and currently serves on the editorial council for the *Journal of Environmental Economics and Management.*

THOMAS A. STANSELL heads Stansell Consulting, which he founded in 1999. Previously he was a vice president at Leica Geosystems, where he was involved in technology development and strategic relationships. Mr. Stansell is a pioneer of satellite navigation and has served the satellite navigation community for more than 43 years. Mr. Stansell began his career in 1960 when he joined the Johns Hopkins University Applied Physics Laboratory Navy Navigation Satellite System development program. He led teams that developed the first integrated microcomputer-based satellite navigation receiver and the first microcomputer-based Doppler survey instrument, also called Geoceiver, the primary instrument employed by the Defense Mapping Agency for nearly two decades. In the 1980s he led the transition of Magnavox's commercial satellite navigation and positioning technologies and products from Transit (the first operational satellite positioning system) to the Global Positioning System (GPS). He also led the development of miniature GPS survey receivers, pioneered precise and real-time GPS control of earth-moving machinery, and received patents for multipath mitigation techniques. Mr. Stansell is the recipient of the 1996 Institute of Navigation (ION) Weems Award, the 2000 Institute of Electrical and Electronics Engineers (IEEE) Position and Navigation Symposium (PLANS) Kershner Award, the 2002 GPS Joint Program Office Navstar Award, and the ION Satellite Division's 2004 Johannes Kepler Award. He is a member of the "GPS World" and "Inside GNSS" editorial advisory boards and was elected a fellow of the ION in 1999. Mr. Stansell holds several GPS-related patents, and currently he is serving as the ION western regional vice president.

LEONARD STRACHAN, JR., is an astrophysicist at the Smithsonian Astrophysical Observatory. Dr. Strachan is a co-investigator with the Ultraviolet Coronagraph Spectrometer (UVCS) team on the Solar and Heliospheric Observatory (SOHO) mission. His research involves using space-based ultraviolet spectroscopy to understand the physical properties of the solar corona. These measurements are important for understanding the processes that drive both steady and dynamic solar wind. His previous experience includes participating in the instrument development, science operations, and data analysis for the Spartan 201 Space Shuttle experiment. Dr. Strachan has been a member of the NASA Solar and Heliospheric Management and Operations Working Group and the NASA Sun-Solar System Connection Roadmap Committee. Most recently he served on the NRC Committee on Solar and Space Physics and on the ad hoc Workshop Organizing Committee on Solar System Radiation Environment and NASA's Vision for Space Exploration.

Staff

SANDRA J. GRAHAM has been a senior program officer at the Space Studies Board since 1994. During that time Dr. Graham has directed a large number of major studies, many of them focused on space research in biological and physical sciences and technology. More recent studies include an assessment of servicing options for the Hubble Space Telescope, reviews of the NASA roadmaps for space sciences and the International Space Station, and a review of NASA's Space Communications Program while on loan to the Aeronautics and Space Engineering Board. Before receiving her Ph.D. in inorganic chemistry from Duke University in 1990, she carried out research focused primarily on topics in bioinorganic chemistry, such as the exchange mechanisms and reaction chemistry of biological metal complexes and their analogs. From 1990 to 1994, she held the position of senior scientist at the Bionetics Corporation, where she worked in the science branch of the Microgravity Science and Applications Division at NASA Headquarters.

THERESA M. FISHER is a program associate with SSB. During her 25 years with the Academies, she has held positions in the executive, editorial, and contract offices of the National Academy of Engineering and positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

CATHERINE A. GRUBER is an assistant editor with SSB. She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has worked as an outreach assistant for the NAS-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

VICTORIA SWISHER joined the Space Studies Board in December 2006 as a research associate. She recently received a B.A. in astronomy from Swarthmore College. She has presented the results of her research at the 2005 and 2006 American Astronomical Society (AAS) meetings and at various Keck Northeast Astronomy Consortium (KNAC) undergraduate research conferences. Her most recent research focused on laboratory astrophysics and involved studying the x-rays of plasma, culminating in a senior thesis entitled "Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment."

E

Select Acronyms and Terms

ACE	Advanced Composition Explorer
AFSPC	Air Force Space Command (headquartered at Peterson Air Force Base Colorado)
AFWA	Air Force Weather Agency
CCMC	Community Coordinated Modeling Center (a NASA-supported program)
CME	coronal mass ejection
COST	Cooperation in Science and Technology
CRRES	Combined Release and Radiation Effects Satellite
DOD	Department of Defense
Dst	distributed storage time
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Administration
GIC	geomagnetically induced current
GOES	Geostationary Operational Environment Satellite
GPS	Global Positioning System
HF	high frequency (3-30 MHz)
JSpOC	Joint Space Operations Center
Kp index	A planetary index of geomagnetic activity that ranges from Kp0 to Kp9 where Kp9 represents the most severe storm
LF/HC	low-frequency/high-consequence
LRO	Lunar Reconnaissance Orbiter (NASA Space Exploration Mission)
LWS	Living With a Star (NASA program)
NSF	National Science Foundation
now-cast	near-term space weather forecast
NSWP	National Space Weather Program
PCA	polar cap absorption
R&D	research and development
RF	radio frequency
SA	situational awareness

SDO	Solar Dynamics Observatory
SEC	Space Environment Center
SEP	solar energetic particle
SOHO	Solar and Heliospheric Observatory
STEREO	Solar-Terrestrial Relations Observatory
SWENET	Space Weather European Network
SWPC	Space Weather Prediction Center (NOAA)
SWWT	Space Weather Working Team
TEC	total electron content
USAF	U.S. Air Force
USGS	U.S. Geological Survey
WAAS	Wide Area Augmentation System