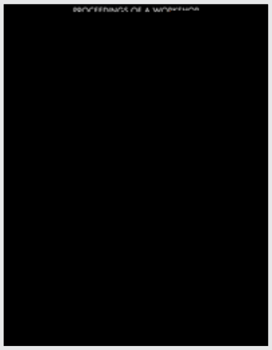

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PLANNING THE FUTURE SPACE WEATHER OPERATIONS AND RESEARCH INFRASTRUCTURE

PROCEEDINGS OF A WORKSHOP

Committee for the Space Weather Operations and Research Infrastructure Workshop

Space Studies Board

Division on Engineering and Physical Sciences

The National Academies of
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Preface

Information about Earth's space environment is of rapidly increasing importance, driven, in part, by the appearance of new government and commercial ventures using technologies sensitive to its variations and by plans for human exploration to the Moon and beyond. In addition, increasing understanding of how the space environment's conditions are physically determined by solar activity and internal dynamics and other factors has made the possibility of significantly improving space weather forecasting a closer reality.

Among the recent steps taken in support of this objective was the creation in 2015 of an interagency task force on Space Weather Operations, Research, and Mitigation (SWORM) and creation in 2019 of a National Space Weather Strategy and Action Plan (NSW-SAP), under the auspices of the Office of Science and Technology Policy (OSTP). SWORM and the NSW-SAP were developed to enhance national preparedness (protection, mitigation, response, and recovery) for space weather events, and to identify the activities, outcomes, and timelines that will be undertaken by the federal government to secure the infrastructures vital to national security and the economy.

As part of this initiative, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF), have begun a series of advice-seeking activities, including National Academies–organized workshops. This proceedings describes the first in a series, with a particular emphasis on future options regarding NOAA's contributions.[1]

In response to a request from NOAA, developed in consultation with NASA and NSF, an ad hoc committee of the National Academies of Sciences, Engineering, and Medicine was formed to explore, via a workshop, options for continuity and future enhancements of the U.S. space weather operational and research infrastructure. In particular, workshop participants (see Appendix A) were asked to

- Review current and planned U.S. and international space weather-related observational capabilities;
- Discuss baseline space weather observational needs;
- Identify programmatic and technological options to ensure continuity of the baseline, giving particular attention to options to extend the Space Weather Follow On program; and

[1] NOAA, which is the primary civilian agency responsible for space weather forecasting, is the principal sponsor of the present workshop. As this activity near its conclusion, NASA and NSF, in consultation with NOAA, requested that the Academies conduct a follow-on workshop that would focus on the research agenda and observations needed to improve understanding of the Sun-Earth system that generates space weather.

- Consider options for technology, instrument, and mission development to support in situ and remote sensing space weather observations from either ground- or space-based vantage points, the latter including L1, L5, L4, GEO [geostationary orbit], and LEO [low Earth orbit].[2]

Originally planned as an in-person workshop, travel and other restrictions imposed in response to the novel coronavirus resulted in a virtual workshop. For convenience, the workshop was held in two parts, on June 16-17 and September 9-11, 2020, both of which were open to the public. Participants invited to the workshops included experts familiar with federal government policy and legislation concerning space weather, as well scientists from the thermosphere, ionosphere, magnetosphere, and solar-heliosphere research communities. In addition, representatives from NOAA, NASA, NSF, the Department of Defense (DoD), and from a range of other government and commercial entities, including international organizations, were invited to the workshops. In total, more than 200 participants attended, via Zoom, either or both of the June oral sessions and the September oral and poster (Appendix B) sessions. Agendas of both workshops are shown in Appendix C; presentations and posters from the workshop are available online at https://www.nationalacademies.org/spacewx-phaseI-presentations.

As specified in the statement of task for the Committee for the Space Weather Operations and Research Infrastructure Workshop (see Appendix A), this proceedings summarizes and synthesizes the discussions at the workshop without providing consensus findings or recommendations.[3] Frequently, this proceedings references the views of "participants." This term is used as a shorthand when several workshop attendees expressed similar views on a particular topic or issue. However, the statements and opinions contained in this proceedings should not be interpreted as representing a consensus among the larger body of participants.

In this workshop references to the "operational" and "research" infrastructure for space weather were not always explicit, in part because there is overlap in usage of some resources, and also because experience obtained with research infrastructure often precedes operational applications. However, implicit in the discussions was the recognition that a critical element for successful operations is access to a robust, dedicated, ground and space-based infrastructure that provides accurate, sustained, secure, and timely observations for space-weather analysis, sufficient for national needs. Examples of such operational infrastructure includes the NOAA Geostationary Operational Environmental Satellites, which provide critical space weather information—both warnings and situational awareness of the space environment—to NOAA and DoD.

Improving the understanding and prediction of space weather requires enhancing existing observational capabilities by deploying new technologies. An example of a research mission with a demonstrated positive impact on operations has been the Large Angle and Spectrometric Coronagraph on board the Solar and Heliospheric Observatory satellite, which provides key input to NOAA's geomagnetic storm watches. Current plans for new operational missions now include coronagraphs. Thus, these categories of infrastructure were not always distinguished during the workshop.

The workshop proceedings that follows is organized by topic. As speakers at the June and September sessions sometimes addressed different aspects of the same topic, the committee has chosen to synthesize comments across sessions when appropriate. To assist a reader looking to identify the presentations that informed the write-up of a particular topic summary, the names of the most relevant presenters are shown. Note that some of the presentations at the workshop were delivered without the use of slides; their comments and those heard in the question and answer part of each workshop session informed the proceedings, but there is no written record.

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[2] L1, L5, and L4 refer to Lagrange points 1, 5, and 4 (https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point); GEO is an acronym for geostationary orbit and LEO is an acronym for low Earth orbit.

[3] Per National Academies' guidelines, this proceedings does not include any recommendations or findings by the workshop organizing committee as the workshop presenters and other participants were not vetted for sources of potential bias and conflicts of interest.

The committee wishes to thank the presenters as well as the online participants for sharing their knowledge, experience, and insights. The committee is solely responsible for the content of this workshop report, which, per National Academies practices, has been reviewed by selected members of the solar and space physics community and by workshop participants for scientific accuracy and fidelity to workshop discussions.

Acknowledgment of Reviewers

This Proceedings of a Workshop has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making its published proceedings as sound as possible and to ensure that the proceedings meets institutional standards for clarity, objectivity and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this proceedings:

Irfan Azeem, ASTRA, LLC,
Sarah Gibson, National Center for Atmospheric Research,
Allison N. Jaynes, University of Iowa,
Michael W. Liemohn, University of Michigan,
T. Paul O'Brien, The Aerospace Corporation,
William A. Radasky, NAE,[1] Metatech Corporation, and
Jeffrey P. Thayer, University of Colorado, Boulder.

Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the Proceedings of a Workshop before its release. The review of this proceedings was overseen by Louis J. Lanzerotti, NAE, New Jersey Institute of Technology. He was responsible for making certain that an independent examination of this proceedings was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content of this proceedings rests entirely with the author(s) and the National Academies.

[1] Member, National Academy of Engineering.

Contents

Summary

In response to a request from the National Oceanic and Atmospheric Administration (NOAA)—and with the support of the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF)—the National Academies of Sciences, Engineering, and Medicine appointed the ad hoc Committee for the Space Weather Operations and Research Infrastructure Workshop and conducted a two-part virtual workshop, "Space Weather Operations and Research Infrastructure," on June 16-17 and September 9-11, 2020. The overall goals of the workshop were to review present space weather monitoring and forecasting capabilities, to consider future observational infrastructure and research needs, and to consider options toward the further development of an effective, resilient, and achievable national space weather program. Specifically, workshop participants were asked to

- Review current and planned U.S. and international space weather-related observational capabilities;
- Discuss baseline space weather observational needs;
- Identify programmatic and technological options to ensure continuity of the baseline, giving particular attention to options to extend the Space Weather Follow On program; and
- Consider options for technology, instrument, and mission development to support in situ and remote sensing space weather observations from either ground- or space-based vantage points, the latter including L-1, L-5, L-4, GEO [geostationary orbit], and LEO [low Earth orbit].[1]

The workshop took a Sun-Earth systems view of space weather and space climate, with a purview covering issues from their drivers in the solar environs and interplanetary medium, to the interconnected magnetosphere-ionosphere-atmosphere system of Earth. Given the broadening perspective for robotic and human space exploration, some workshop presentations also touched on Moon and Mars mission applications.

Workshop participants included agency representatives and other policy makers, space weather professionals, and a broad swath of technological system developers and users whose activities are affected

[1] L1, L5, and L4 refer to Lagrange points 1, 5, and 4 (https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point); GEO is an acronym for geostationary orbit and LEO is an acronym for low Earth orbit.

by space weather. In total, some 200+ individuals participated in the workshop sessions.[2] This proceedings summarizes presentations and discussions at both the June and September workshop sessions.[3]

Society's increasing vulnerability to space weather, and the need for improved predictions and forecasts of its impacts, have been recognized in numerous previous reports. For example, the 2007 National Academies report *Severe Space Weather Events—Understanding Societal and Economic Impacts*[4] noted that "A contemporary repetition of the Carrington Event[5] would cause … extensive social and economic disruptions" because of the many interconnections between the local space environment consequences and society's highly coupled systems (e.g., Figure S.1).

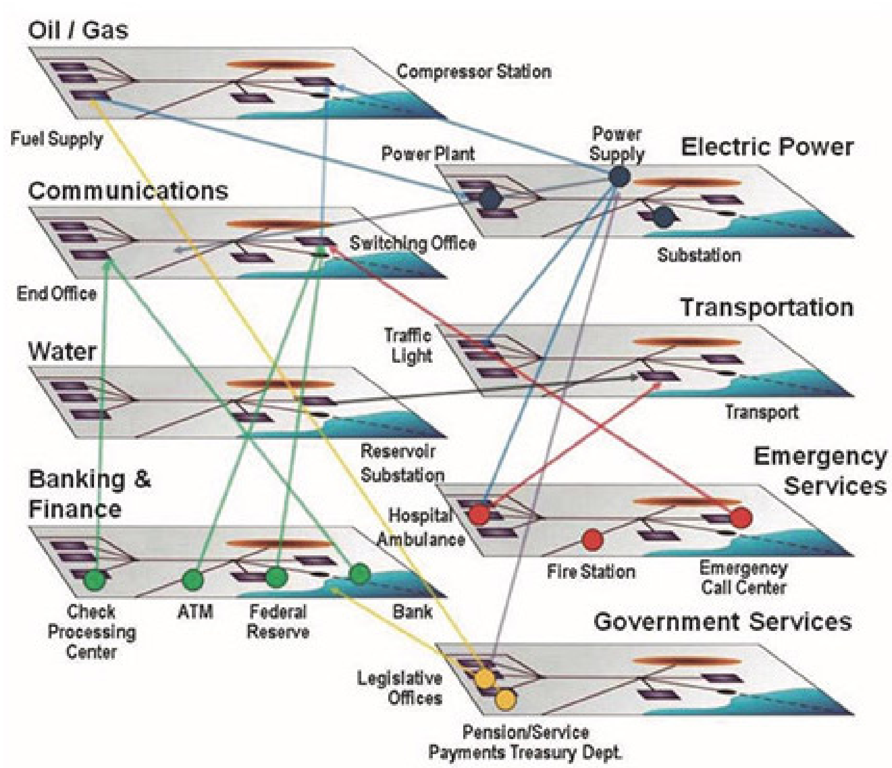

FIGURE S.1 Connections and interdependencies across the economy. This diagram illustrates the high level of integration of the various sectors in the society and points to their vulnerability; for example, during (extended) power outages. NOTE: Some connections are not shown. SOURCE: Daniel Baker, presentation to the workshop, figure courtesy of Sandia National Laboratory in Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, 2008, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures*, http://www.firstempcommission.org /uploads/1/1/9/5/119571849/emp_comm._rpt._crit._nat._infrastructures.pdf.

[2] Presentations and posters from the workshop are available at https://www.nationalacademies.org/spacewx-phaseI-presentations.

[3] In keeping with the internal guidelines of the National Academies, this proceedings does not include National Academies-approved consensus findings or recommendations. Similarly, the views expressed in this proceedings should not be interpreted as representative of the entirety of workshop participants, the workshop organizing committee, or the National Academies. Rather, they provide a sampling, and sometimes a synthesis, of perspectives expressed in the included areas of expertise.

[4] National Research Council, 2008, *Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report*, Washington, DC: The National Academies Press, https://doi.org/10.17226/12507.

[5] The strongest geomagnetic storm on record is the Carrington Event of August-September 1859. A storm of similar magnitude that missed Earth occurred on July 23, 2012. See D.N. Baker, X. Li, A. Pulkkinen, C. Ngwira, M.L. Mays, A.B. Galvin, and K.D.C. Simunac, 2013, "A Major Solar Eruptive Event in July 2012: Defining Extreme Space Weather Scenarios," *Space Weather* 11: 585–591, https://doi.org/10.1002/swe.20097.

The 2013-2022 solar and space physics decadal survey[6] both described current understanding of the physical phenomena that determine space weather, and provided guidance on what constitutes the essential operational space weather observing system. It also suggested how the federal government might enhance the effectiveness of the multiagency National Space Weather Program.

The roles and responsibilities of agencies participating in the federal programs for space weather have since been clarified with the establishment of the Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee under the National Science and Technology Council (NSTC) within the Executive Office of the President Office of Science and Technology Policy (EOP-OSTP), and the development of the National Space Weather Strategy and Action Plan (NSW-SAP). These have notably improved coordination among federal agencies, commercial entities, and academic institutions engaged in space weather operational services and related research efforts. The initial sessions of the workshop featured presentations on the cooperative and individual endeavors that culminated in the SWORM and NSW-SAP.

Agency leaders from NOAA, NASA, and NSF then described both their existing programs relevant to space weather operations and infrastructure and highlighted the new research to operations-operations to research (R2O2R) partnership whose objective is to improve exchanges between operational forecasting and research. NASA and commercial spaceflight companies are moreover poised to embark on human exploration missions outside geospace. For the astronauts, and the equipment and systems they rely on, a space weather observation and forecast capability is essential—including the confident establishment of "all-clear" conditions.

The workshop also included participants and officials from space weather agencies in Europe, Japan, and Canada. As in the United States, there is increasing attention to space weather worldwide with additional resources being devoted to ground- and space-based observations, as well as model development. As described in the full proceedings below, the United States is partnering with foreign space agencies in several efforts. The presentations included reviews of the operational tools, practices, and observing facilities that form the backbone of today's space weather infrastructure.

Scientific platforms that have been a mainstay of space weather observations to date, particularly since the 1990s, include solar observatories (space and ground-based) and in situ measurements of the solar wind measured upstream from Earth, in addition to various suites of spacecraft in Earth orbit, and facilities on the ground, making geospace environment measurements. Particular concern was expressed regarding observing capabilities that have been lost, or that soon will be lost without action in light of the increasing uses of space and demands for information affecting system planning, design, and operations.

Space weather observations are needed not just for extreme events, but for situational awareness to help manage the risks and impacts of day-to-day fluctuations in the space environment. Positioning, navigation, and timing (PNT) applications, power grid management, and many other aspects of societal infrastructure rely on continued delivery of space weather observations and forecasts. It was stated in a number of workshop sessions that continued support of space environment research and model development, and a reliable path for translation to operational tools, are needed to ensure that appropriate capability continues to keep up with future needs. The evolving interagency R2O2R program marks the beginning of such an enterprise, yet to be evaluated for its effectiveness and growth potential.

The focus of the workshop then turned to key observing and knowledge gaps and the potential, over the next 5 to 10 years, for a more affordable and robust space weather observing architecture and related modeling activity. For example, global measurements of solar magnetic field behavior, multiperspective coronal imaging, and measurements of the geospace environment at high latitudes and in LEO could have transformative effects on space weather knowledge and forecasting.

In the area of observing architecture, specific actions that would ensure a successful transition to next generation capabilities were discussed. For example, it was emphasized that a strategy for maintaining continuous solar wind, magnetic field, and particle measurements at L1 is essential. At the same time, there is also need for spacecraft at more distributed vantage points around the Sun, including L5 to improve

[6] National Research Council, 2013, *Solar and Space Physics: A Science for a Technological Society*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13060.

forecasting lead-time, L4 to monitor active regions that pose an immediate threat of producing disruptive and hazardous solar particle events, and, in the long term, observations at high solar inclinations to monitor the solar polar magnetic fields that affect forecast models. Each of these vantage points contributes to better predictions of the probability and timing of coronal mass ejection (CME) effects at Earth, the primary sources of space environment extremes.

Measurements within geospace of the energetic particle environment, which poses a threat to spacecraft, astronauts, and commercial aviation, is an ongoing requirement for improved design of technological systems, spacecraft anomaly resolution, and forecast models. LEO is a particularly data-sparse domain that could use better coverage because it is becoming increasingly populated with commercial and research spacecraft. Along with energetic particle measurements, it was noted that commercial data buys may provide distributed measurements of neutral atmosphere variability needed to improve models essential to space traffic management. Commercial entities may also be motivated to make observations of use to NOAA and the public for space weather purposes.

Spacecraft and space-based instruments alone are not sufficient for a robust space weather architecture. As was noted, a network of ground-based systems, including solar observatories (optical and radio), magnetometers, neutron monitors, and ionospheric monitors, also contribute crucial input to space weather situational awareness. These networks provide data crucial for monitoring space weather impacts, for validating and calibrating in situ satellite measurements, and for providing input to forecast and nowcast space weather models.[7] New applications of more rigorous analysis and data-mining of merged satellite and ground-based observations are emerging. These essential ground-based networks require sustained support for operations and for further developments, such as real-time data availability to enable improvements in space domain awareness, space and ground operations, and anomaly resolution.

The emerging, diverse, and evolving commercial capability, and its potential use in all aspects of future space architectures, was highlighted in several workshop sessions. Representatives of commercial enterprises expressed their readiness to acquire fundamental data and to ensure its continued availability, creating opportunities to convert observations and model output to the focused and tailored products required by society today.

The workshop was tasked to look a decade or more in the future, a recognition of the long acquisition cycle for space systems and the need for continuity of critical space weather observations.[8] With this directive, coupled with the understanding that observations have value only when placed in the context embodied in models, forecasts, and impact assessments, two themes emerged from the discussions: The first was the recognition that funding for model development and the framework for model implementation in space weather forecasting is often fragile, with only short-term funding available.[9] The second centered on the impact of new and more affordable launch options and new space platforms and technologies, which are being developed at a rate far faster than was common for legacy systems.

A core operational system would be maintained in perpetuity, while many more innovative and flexible smaller components could come and go as needed. The system vision that emerged from the collective workshop perspective was one of operational agency (NOAA) leadership, with cooperative elements from science agencies (NASA, NSF) and a wealth of new tools being developed and brought to the table by commercial and academic contributors. Small satellites, agile sensors, big data management and utilization,

[7] In this report, "forecasting" and "prediction" are often used interchangeably when referring to future events while a "nowcast" is effectively a short-term forecast of current conditions. Note that the term "prediction," unlike "forecast," can refer to estimates of past conditions; for example, from an analysis of historical data.

[8] In particular, NOAA is considering options to continue the solar wind measurements and imagery of coronal mass ejections that are to be provided by instruments on the SWFO-L1 satellite, currently planned for launch in February 2025 as a rideshare with NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission.

[9] This fragility of funding was an overarching issue for participants who spoke about future space weather architectures and development and transitioning of research models to operations. It was noted in particular in the session on ground-based space weather architectures where the significant need for long-term funding for ground-based instruments, model development, and transition support was emphasized.

artificial intelligence and machine learning, increasingly realistic numerical simulations, and other emerging capabilities offer significant potential.

Workshop participants also highlighted the importance of the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act, the terms of which were largely known by the time of the September workshop sessions (the Act was signed into law by the President on October 21, 2020). The act, the culmination of efforts begun in 2016, directs government agencies, including NOAA, NASA, NSF, Department of Defense, and the Department of the Interior, to undertake, in coordination, the roles and activities described in the NSW-SAP. It also promotes collaboration among federal agencies, academia, and the private sector toward enhancing space weather research and the transitioning of its results to operations.[10]

The grand challenge for space weather services is to forecast conditions in Earth's space environment with skill, reliability, and timeliness—toward achieving the capability associated with terrestrial weather services. A frequently expressed view at the workshop was that meeting this challenge will require the cooperation and coordination of the government, academic, and private sectors as envisioned in the 2019 National Space Weather Strategy and Action Plan and codified in the 2020 PROSWIFT Act.

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[10] "This bill sets forth provisions concerning improving the ability of the United States to forecast space weather events and mitigate the effects of space weather.

- The bill provides statutory authority for the National Science and Technology Council's Space Weather Operations, Research, and Mitigation Working Group, which coordinates executive branch efforts regarding space weather.
- The bill directs the Office of Science and Technology Policy, National Oceanic and Atmospheric Administration (NOAA), National Science Foundation, Air Force, Navy, National Aeronautics and Space Administration (NASA), and U.S. Geological Survey to carry out specified space weather activities.
- NOAA may establish a pilot program under which NOAA offers to enter into contracts with entities in the commercial space weather sector to provide NOAA with space weather data that meets certain standards.
- The working group must periodically review and update the benchmarks described in the report of the National Science and Technology Council titled Space Weather Phase 1 Benchmarks and dated June 2018, as necessary, based on (1) any significant new data or advances in scientific understanding that become available, or (2) the evolving needs of entities impacted by space weather phenomena."

See S.881-PROSWIFT Act, 116th Congress (2019-2020), https://www.congress.gov/bill/116th-congress/senate-bill/881.

1

Introduction and Workshop Background

As noted in the Preface, in late 2019 the National Academies of Sciences, Engineering, and Medicine was approached by National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the National Science Foundation with a request to "appoint an ad hoc committee to organize a workshop that will consider options for continuity and future enhancements of the U.S. space weather operational and research infrastructure" (see Appendix A for details). In addition to reviewing current and planned capabilities across the space weather research and operations domain, the charge asked the workshop organizers to consider options for the extension of the Space Weather Follow-On (SWFO) program managed by NOAA. The workshop plans were subsequently directed toward the latter after consideration of task magnitude, logistics, and sponsorship. The "Space Weather Operations and Research Infrastructure Workshop" was conducted in two parts, the first taking place on June 16-17, 2020, and the second on September 9-11, 2020.

The more than 100 participants in attendance for both the June and September sessions were generally aware of the current drivers for space weather research and/or applications, including the increased interest in the U.S. agency-sponsored activities generated by the interagency National Space Weather Action Plan (NSWAP) organizational meetings and reports, together with the 2013 solar and space physics decadal survey[1] and its midterm assessment.[2] As seen in this proceedings, the workshop resulted in a broad assessment of

- Space weather "needs" in areas from science research to applications;
- The important observations for both monitoring and improving models;
- The value of coordinated efforts across communities, agencies, and nations; and
- Achievable post SWFO-L1 advances.

[1] National Academies of Sciences, Engineering, and Medicine (NASEM), 2013, *Solar and Space Physics: A Science for a Technological Society*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13060.

[2] NASEM, 2020, *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25668.

SPACE PHYSICS AND SPACE WEATHER

The introduction to Chapter 7, "Space Weather and Space Climatology: A Vision for Future Capabilities," of the 2013 decadal survey provides the following succinct description of space weather, together with an explanation of its importance to a technological and space-faring society:

> The availability of timely and reliable space-based information about our environment underpins elements of the infrastructure that are critical to a modern society. From economic and societal perspectives, reliable knowledge on a range of timescales of conditions in the geospace environment (including the mesosphere, thermosphere, ionosphere, exosphere, geocorona, plasmasphere, and magnetosphere) is important for multiple applications, prominent among them utilization of radio signals (which enables increasingly precise navigation and communication), as well as mitigation of deleterious effects such as drag on Earth-orbiting objects (which alters the location of spacecraft, threatens their functionality by collisions with debris, and impedes reliable determination of reentry). In addition, energetic particles can damage assets and humans in space, and currents induced in ground systems can disrupt and damage power grids.[3]

While tropospheric weather is mainly generated at levels below the stratosphere, Earth's space environment extends past the stratosphere to as far as human interests and technologies reach. The now widely used related term "space weather" was at least initially used primarily in describing space environment "effects" rather than the physics of the space environment itself. However, there has been a gradual shift as the field now referred to as "heliophysics" has grown and shed light on the many solar and space physics phenomena that determine the space environment. This workshop occurred against a backdrop of increasing interest in space weather's origins and impacts and federal agency recognition of the continuum that exists between research to operations (R2O) and operations to research (O2R).

Heliophysics is typically separated into the following three subareas relevant to space weather: solar and heliospheric physics, which encompasses the Sun and interplanetary space; magnetospheric physics, which describes the region of interplanetary space proximate to Earth, where the physics is still controlled by Earth's magnetic field; and upper atmospheric physics, which is focused on the atmosphere layers above stratospheric levels, including the mesosphere, thermosphere, and exosphere and the ionized portions of these making up the ionosphere.

The solar and heliospheric physics subfields are relevant to space weather interests such as solar flare and coronal mass ejection (CME) forecasting and radiation hazards to humans in space. These subdisciplines are coupled to the magnetospheric and upper atmosphere areas because the solar and related heliospheric conditions affect these other domains. Both the magnetospheric and upper atmosphere subfields (which is henceforth referred to as geospace) are key to characterizing the effects of the environment hosting most space assets serving societal needs, as well as determining how solar activity in its various forms and geospace dynamics affects Earth and its infrastructures—from power grids to navigation and communication systems (see Figure 1.1).

SPACE WEATHER FOLLOW-ON

The workshop statement of task included a request for an examination of space weather observational needs beyond SWFO, which is now under development (Figure 1.2). The primary goal of SWFO is to deliver observations that enable space weather forecasting by NOAA; it is comprised of two projects: a compact coronagraph (CCOR) to be carried by the Earth-orbiting GOES U spacecraft, and the SWFO mission that will place a spacecraft in the solar wind upstream of Earth, SWFO-L1.

SWFO-L1 is scheduled to launch in 2025 with NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission. This timing maintains observational continuity of real-time solar imagery and solar-wind

[3] NASEM, 2013, *Solar and Space Physics*, p. 135.

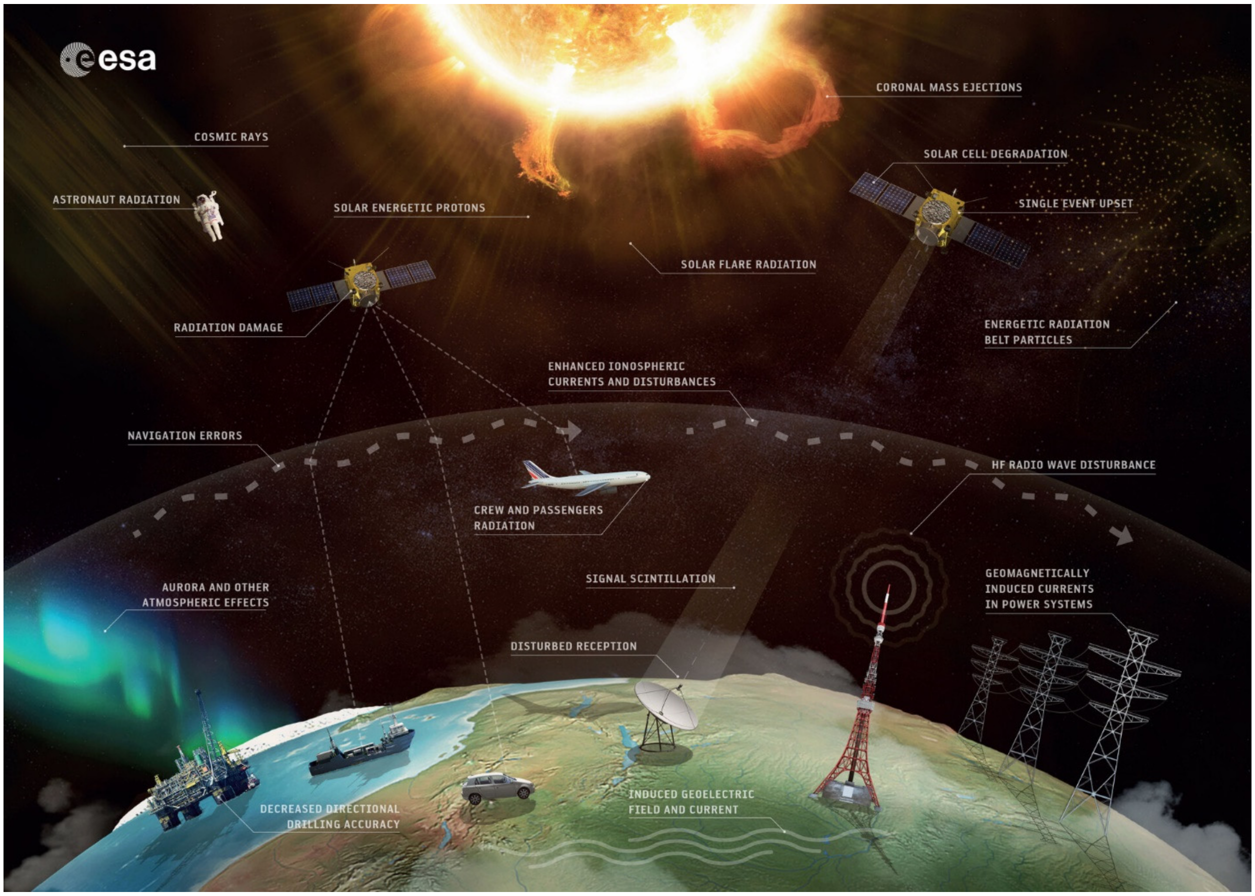

FIGURE 1.1 Space weather affects technological systems in space and on Earth's surface. SOURCE: European Space Agency, 2018, "Space Weather Effects," January 25, © ESA/Science Office, CC BY-SA 3.0 IGO, http://creativecommons.org/licenses/by-sa/3.0/igo.

measurements currently provided by the combination of NOAA's DSCOVR (Deep Space Climate Observatory), NASA's Atmospheric Composition Explorer (ACE), and the NASA/European Space Agency's Solar and Heliospheric Observatory (SOHO). Like ACE and DSCOVR, SWFO-L1 will be located in a halo orbit around the L1 Lagrange point, which is approximately 1.5 million km from Earth, where it will provide images of coronal conditions and in situ measurements of the solar wind approximately 30 minutes before it affects geospace. SWFO-L1 data will also be used in longer-lead forecast models of conditions at Earth's orbital location from several days up to a month ahead.

A primary purpose of SWFO-L1 is to extend NOAA's ability to provide warnings of Earth-directed CMEs that have the potential to cause major geomagnetic storms and their effects. It is important to recognize that in its overall mission, SWFO-L1 does not stand alone. Other key space weather observations from space- and ground-based sensors supported by NOAA, the National Science Foundation (NSF), NASA, and the Department of Defense (DoD)/Air Force were also discussed in this workshop in the context of the following overarching question:

> *What current observations must continue, and what next major step(s) are needed, to produce more comprehensive and accurate space environment information for a society in which space-based and space-sensitive facilities and services increasingly depend on its availability*?

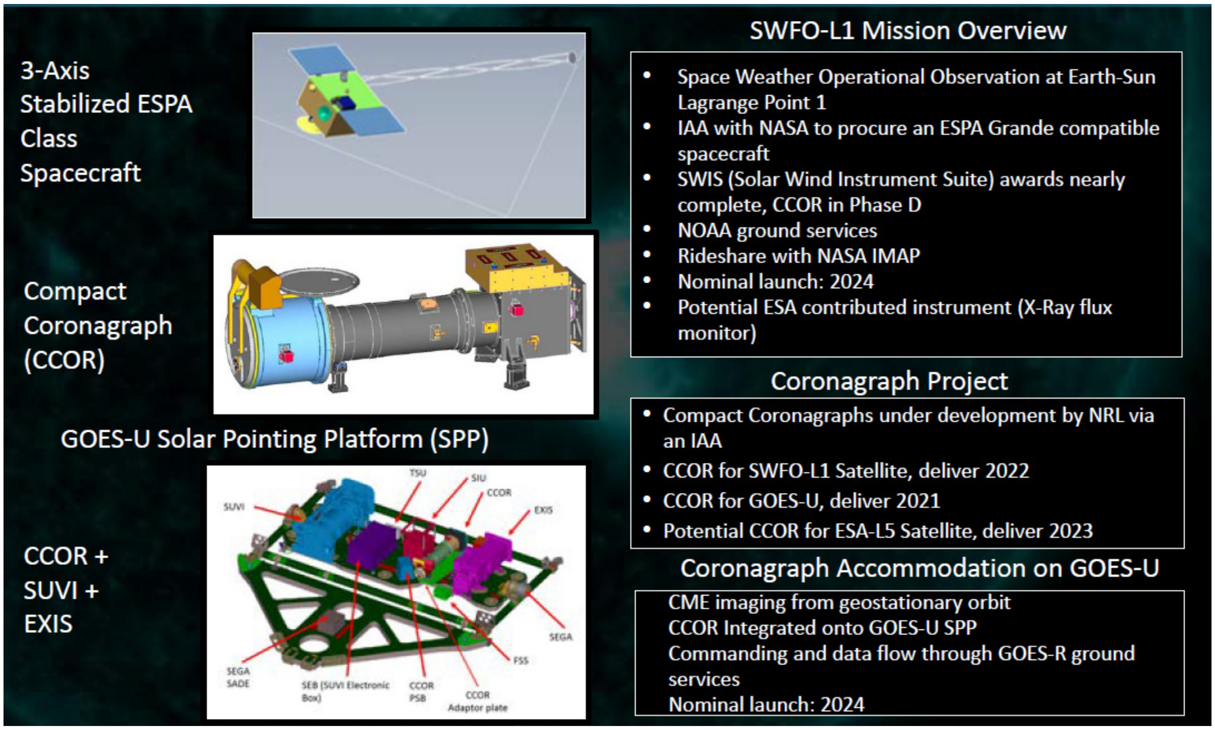

FIGURE 1.2 Space Weather Follow-On (SWFO) program key technical components. NOTE: SWFO-L1 is now scheduled for launch in 2025. SOURCE: Elsayed Talaat, NOAA, "NOAA's Current and Future Space Weather Architecture," presentation to the workshop, June 16, 2020.

2

National Priorities and the Development of a National Strategy for Space Weather

Speakers at June 16-17, 2020, workshop sessions were asked to review key milestones in the development of the current national space weather program—especially the interagency task force on Space Weather Operations, Research, and Mitigation (SWORM) and the National Space Weather Strategy and Action Plan (NSW-SAP)—and speakers at both the June 16-17 and September 9-11 sessions were asked to comment on how national priorities in areas that range from human exploration of space to protection of the electrical grid space weather are reflected in national policy for space weather. This chapter draws on the presentations and discussions throughout the workshop,[1] especially from the following:

- Tamara Dickinson, Science Matters Consulting, LLC, session chair
- John Allen, Program Executive for Crew Health and Safety, National Aeronautics and Space Administration (NASA), "Human Exploration, Moon/Mars"
- Adam Balkcum, Office of Science and Technology Policy (OSTP), "EMP R&D Priorities"
- Mike Bonadonna, National Oceanic and Atmospheric Administration (NOAA), Office of the Federal Coordinator for Meteorology, "SWORM"
- Steve Clarke, Former Deputy Associate Administrator for Exploration, NASA Science Mission Directorate, "Space Weather in NASA's Exploration Campaign"
- W. Craig Fugate, Federal Emergency Management Agency (FEMA) (Former Administrator), "Emergency Manager's Perspective"[2]
- Mark Lauby, Senior Vice President and Chief Engineer, North American Electric Reliability Corporation (NERC), "Mitigating the Effects of Geomagnetic Storms on the Nation's Bulk Power System"
- Joe McClelland, Director, Office of Energy, Federal Energy Regulatory Commission (FERC), "Power Grid, Reliability Standards"
- William Murtagh, NOAA Space Weather Prediction Center (SWPC), "National Space Weather Strategy and Action Plan"

[1] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.
[2] Mr. Fugate spoke without the use of slides; therefore, his presentation is not on the workshop's website.

- Jeff O'Neil, Legislative Director, Rep. Ed Perlmutter (D-CO), "Pending Space Weather Legislation"
- Kevin O'Connell, Director, Office of Space Commerce, Department of Commerce (DOC), "Space Traffic Management and Space Situational Awareness"
- Jim Spann, Space Weather Lead, Heliophysics Division, NASA HQ, "Space Weather Strategy"
- Elsayed Talaat, Director, Office of Projects, Planning, and Analysis, NOAA National Satellite Data and Information Service (NESDIS), "NOAA's Current and Future Space Weather Architecture"
- David Turner, Acting Director, Office of Space and Advanced Technology, U.S. State Department, "Collaboration on Space Weather"
- Louis Uccellini, NOAA, National Weather Service, "SWORM"
- Mike Wiltberger, Geospace Head, National Science Foundation (NSF), "NSF Support for Space Weather Operations & Research Infrastructure"

The first federal interagency body responsible for addressing the needs of space weather information for the United States was the National Space Weather Program (NSWP). Established in 1995, the NSWP focused on advancing space weather research, enhancing space weather operational services, increasing public awareness, and supporting national policy formulation. During this time, FEMA played a key role in elevating space weather in the national and homeland security sectors by recognizing that individual components of the federal government lacked a cohesive national strategy necessary to ready the nation for an extreme space weather storm.[3] Existing response models focused on specific sectors or geographically bounded areas where impacts are greatest. However, for a national or global event such as a pandemic, cyberattack, or extreme space weather, the United States faces much greater challenges. In response, space weather was elevated among government leaders and policy makers, with Congress directing the White House OSTP to improve national preparedness for space weather events and to coordinate federal space weather efforts.[4]

In 2013, the FERC released Order No. 779, "Reliability Standards for Geomagnetic Disturbances,"[5] acknowledging that geomagnetic storms can cause a collapse of the bulk-power system and potentially damage bulk-power system transformers. The FERC order required owners and operators of the bulk-power system to develop and implement operational procedures to mitigate the effects of geomagnetic storms. Then, in 2014, in response to growing concerns over the range of potential space weather impacts, OSTP established the SWORM task force, bringing together over 30 departments and agencies to develop a National Space Weather Strategy (NSWS) and the National Space Weather Action Plan (NSWAP). The SWORM, which superseded the NSWP, was the first interagency body to unite the national and homeland-security enterprise with the science and technology enterprise. Workshop speakers provided a look "under the hood" of what occurred as a result of this transformation in the image of space weather, and in the value of studying it and tracking it as a national service.

In November 2014, the SWORM task force was established by the National Science and Technology Council (NSTC), by its Subcommittee on Disaster Reduction of the Committee on Environment, Natural Resources, and Sustainability (see Figure 2.1).[6] The SWORM charter directed the task force to develop a

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[3] National Research Council, 2008, *Severe Space Weather Events: Understanding Societal and Economic Impacts: A Workshop Report*, Washington, DC: The National Academies Press.

[4] Section 809 of the 2010 NASA Authorization Act: P.L. 111-267, https://www.congress.gov/111/plaws/publ267/PLAW-111publ267.pdf.

[5] Order No. 779, *Reliability Standards for Geomagnetic Disturbances*, 143 FERC ¶ 61,147 (2013), https://www.nerc.com/pa/Stand/Project201303GeomagneticDisturbanceMitigation/GMD_directivesMap_Oct172013.pdf.

[6] National Science and Technology Council, 2015, National Space Weather Strategy, Federal Register, April 30, https://www.federalregister.gov/documents/2015/04/30/2015-10113/national-science-and-technology-council-national-space-weather-strategy.

NSWS that would articulate high-level strategic goals for enhancing U.S. preparedness to space weather events. Released in October 2015, the NSWS and the activities defined in the NSWAP were developed by the SWORM task force, with inputs from stakeholders outside the federal government. Briefly stated, these plans define how the federal government will work to enhance national preparedness for space weather-related events.[7] The White House also released two executive orders (EOs; 13744 in 2016 and 13865 in 2019) to address risks associated with space weather.

The NSWS identified six national goals (see Box 2.1) and established the guiding principles that underpin U.S. efforts to secure the infrastructures vital to the national security and economy of the United States. The strategy was informed by a recognition of gaps in U.S. capacity to understand, model, predict, respond to, and recover from space-weather events, described by subsequent speakers in the later sessions. The strategy and action plan leveraged existing policies and ongoing space weather research and development efforts while promoting enhanced domestic and international coordination and cooperation across public and private sectors. It identified specific initiatives to drive both near- and long-term national protection priorities. It also provided protocols for preparing and responding to space-weather events and for ensuring that information is available to inform decision-making.

FIGURE 2.1 Policy drivers for space weather research-to-operations-to-research (R2O2R). SOURCE: Bill Murtagh, NOAA Space Weather Prediction Center.

[7] The 2015 National Space Weather Strategy and the 2015 National Space Weather Action Plan also called for the Department of Commerce to support research into the social and economic impacts of space-weather effects. This led to the Abt Associates September 2017 report, *Social and Economic Impacts of Space Weather in the United States*, https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf.

BOX 2.1 2015 National Space Weather Strategy Goals

The six strategic goals in the 2015 *National Space Weather Action Plan*[1] are discussed below.

1. Establish Benchmarks for Space-Weather Events

Effective and appropriate actions for space weather events require an understanding of the magnitude and frequency of such events. Benchmarks will help government and industry assess the vulnerability of critical infrastructure, establish decision points and thresholds for action, understand risk, and provide points of reference to enable mitigation procedures and practices and to enhance response and recovery planning.

2. Enhance Response and Recovery Capabilities

There is a need to develop comprehensive guidance to support and improve response and recovery capabilities to manage space-weather events, including the capabilities of federal, state, and local governments and of the private sector.

3. Improve Protection and Mitigation Efforts

Improvements to national preparedness for space weather events will require enhancing approaches to protection and mitigation. Protection focuses on developing capabilities and actions to secure the nation from the effects of space weather, including vulnerability reduction. Mitigation focuses on minimizing risks, addressing cascading effects, and enhancing disaster resilience. Implementation of these preparedness missions requires joint action from public and private stakeholders whose shared expertise and responsibilities are embedded in the nation's infrastructure systems.

4. Improve Assessment, Modeling, and Prediction of Impacts on Critical Infrastructure

Timely, reliable, actionable, and relevant decision-support services during space-weather events are essential to improving national preparedness. Societal effects must be understood to better inform the actions necessary during extreme events and to encourage appropriate mitigation and protection measures before an incident.

5. Improve Space-Weather Services through Advancing Understanding and Forecasting

Opportunity exists to improve the fundamental understanding of space weather and increase the accuracy, reliability, and timeliness of space-weather observations and forecasts (and related products and services). The underpinning science and observations will help drive advances in modeling capability and improve the quality of space-weather products and services. There is also a need to improve capacity to develop and transition the latest scientific and technological advances into space weather operations centers.

6. Increase International Cooperation

In a world of complex interdependencies, global engagement and a coordinated international response to space weather is needed. The United States must not only be an integral part of the global effort to prepare for space-weather impacts, but must also help mobilize broad, global support for this effort by using existing agreements and building international support and policies.

[1] National Science and Technology Council, 2015, *National Space Weather Action Plan*, Washington, DC, October, https://www.hsdl.org/?view&did=789864.

The NSWAP outlined the federal implementation approach for the NSWS. It detailed the activities, outcomes, and timelines that, if undertaken by federal departments and agencies, would lead to progress toward the strategy's goals. Each action indicated the lead federal executive department or agency but did not prescribe a specific approach. The implementation of the NSWS required the action of a nationwide network of governments, agencies, emergency managers, academia, the media, the insurance industry, nonprofit organizations, and the private sector. The underlying idea was that strong public-private partnerships to enhance observing networks, conduct research, develop prediction models, and supply the services necessary to protect life and property and to promote economic prosperity will serve as the backbone of a space-weather-ready nation.

Together, the NSWS and NSWAP are intended to facilitate the integration of space weather considerations into planning and decision making at all levels, ensuring that the United States is prepared for and resilient to future events. The SWORM task force expected to refresh the strategy and action plan every 3 years as needed, following up on this plan in 2019.

In October 2016, the White House released EO 13744, "Coordinating Efforts to Prepare the Nation for Space Weather Events." The EO recognized the potential for space weather to simultaneously affect and disrupt health and safety across entire continents, requiring an all-of-nation response across governments and the private sector, and it recognized that the government needs to have the capability to predict and detect a space weather event. The EO defines agency roles and responsibilities and directs agencies to take specific actions to prepare the nation for the hazardous effects of space weather. Specific to observations, it directed the Department of Defense (DoD), DOC, NASA, and the National Science Foundation (NSF), in collaboration with other agencies, to, "identify mechanisms for advancing space weather observations, models, and predictions, and for sustaining and transitioning appropriate capabilities from research to operations and operations to research, collaborating with industry and academia to the extent possible." The Order recognizes that these efforts will enhance national preparedness and speed the creation of a space-weather-ready Nation.

Space Policy Directive-1, "Reinvigorating America's Human Space Exploration Program,"[8] issued on December 11, 2017, called for the NASA administrator to "lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities." NASA's response—the Artemis program to return to the Moon and prepare for a human mission to Mars—and its connections to space weather are discussed later in this proceedings.

On March 26, 2019, during a meeting of the National Space Council meeting in Huntsville, Alabama, the White House released an update to the 2015 strategy and action plans. With a renewed focus on space policy and national security, the 2019 National Space Weather Strategy and Action Plan (NSW-SAP; also identified as the NSWSAP)[9] combined the separate original documents to focus on the following three main objectives: (1) enhancing the protection of national security, homeland security, and commercial assets and operations; (2) developing and disseminating accurate and timely space weather characterization and forecasts; and (3) establishing procedures for responding to and recovering from space weather events.

Several actions in the NSW-SAP focus on observations of the Sun-Earth system and recognize these measurements as the indispensable foundation for timely and accurate characterization and forecasts of the space environment. While the importance of sustaining baseline observation capabilities was highlighted, the NSW-SAP also called for the development of new technologies and new innovative approaches to achieve these measurements. Further, it is stated that, "Achieving the objectives in this Strategy and Action Plan will require coordination and collaboration within and across the federal government, as well as engagement with the commercial sector, academia, and like-minded nations."

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[8] "Reinvigorating America's Human Space Exploration Program," Federal Register, December 14, 2017, https://www.federalregister.gov/documents/2017/12/14/2017-27160/reinvigorating-americas-human-space-exploration-program.

[9] National Science and Technology Council, 2019, *National Space Weather Strategy and Action Plan*, Washington, DC, March, https://www.hsdl.org/?view&did=823433.

On March 26, 2019, the President also signed EO 13865, "Coordinating National Resilience to Electromagnetic Pulses,"[10] which recognized the potential for space weather to disrupt elements critical to U.S. security and economic prosperity and adversely affect global commerce and stability. This EO differed from the 2016 EO in that it also addressed adversarial electromagnetic pulses (EMPs)—also referred to as high-altitude EMPs (HEMPs)—which is caused by a nuclear device detonated above the surface of Earth. A geomagnetic storm disturbance waveform is similar to that of the last portion of the HEMP waveform (known as the late-time, E3 HEMP, waveform); both of these disturbances interact and affect power grid systems in similar ways.[11]

The order directs DOC and DoD to provide timely operational space weather observations and forecasts to support the nation's need to protect against, respond to, and recover from the effects of an EMP. The EO also directed an assessment of research and development (R&D) needs of agencies conducting preparedness activities for EMPs and to identify gaps in available technologies and opportunities for future technological developments to inform R&D activities. In response, OSTP released the report *Research and Development Needs for Improving Resilience to Electromagnetic Pulses*.[12]

In alignment with Presidential Policy Directive (PPD)-8 on National Preparedness and PPD-21 on Critical Infrastructure Security and Resilience, FEMA released the national Threat and Hazard Identification and Risk Assessment (THIRA) in July 2019.[13] The THIRA assesses the effects of the most catastrophic threats and hazards to the nation and identifies just two natural hazards with the potential to have impacts nationwide: pandemic and space weather. Also in 2019, in response to EO 13744, FEMA released "Federal Operating Concept for Impending Space Weather Events"[14] to inform federal departments and agencies on actions to take for an impending space weather event. It focuses on the operational and crisis planning functions, reporting structure, and reporting requirements of departments and agencies in response to notification of a forecasted space weather event.

Soon after the release of the NSW-SAP in October 2019, Congress began a bipartisan effort to develop legislation that would codify many of the elements in the NSW-SAP. The efforts over the following 5 years culminated in October 2020 with the passage of the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act. The act identifies roles and responsibilities for federal agencies, ensures an interagency government body to implement actions, and directs the development of formal mechanisms for the transition of research to operations. It also establishes a Space Weather Advisory Group for the federal government to receive advice from the academic community, the commercial space weather sector, and space weather end users. The act encourages collaboration among U.S. agencies; partnerships across academia, industry, and government; and engagement with international partners.[15]

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[10] "Coordinating National Resilience to Electromagnetic Pulses," Federal Register, March 29, 2019, https://www.federalregister.gov/documents/2019/03/29/2019-06325/coordinating-national-resilience-to-electromagnetic-pulses.

[11] U.S. Department of Energy, 2017, *Electromagnetic Pulse Resilience Action Plan*, https://www.energy.gov/oe/downloads/doe-electromagnetic-pulse-resilience-action-plan.

[12] National Science and Technology Council, 2020, *Research and Development Needs for Improving Resilience to Electromagnetic Pulses: A Report by the Electromagnetic Pulse Research and Development Assessment Interagency Working Group Subcommittee on Resilience, Science and Technology Committee on Homeland and National Security*, June, https://trumpwhitehouse.archives.gov/wp-content/uploads/2017/12/Research-Development-Needs-For-Improving-Resilience-to-Electromagnetic-Pulses-June-2020.pdf.

[13] Federal Emergency Management Agency, 2019, *2019 National Threat and Hazard Identification and Risk Assessment (THIRA): Overview and Methodology*, https://www.fema.gov/sites/default/files/2020-06/fema_national-thira-overview-methodology_2019_0.pdf.

[14] Federal Emergency Management Agency, 2020, *Federal Operating Concept for Impending Space Weather Events*, https://www.fema.gov/sites/default/files/2020-07/fema_incident-annex_space-weather.pdf.

[15] Section 2a, "Space Weather/Policy," of the Act states that, "It shall be the policy of the United States to prepare and protect against the social and economic impacts of space weather phenomena by supporting actions to

The PROSWIFT Act recognizes that space- and ground-based observations provide data necessary to understand, forecast, and prepare for space weather phenomena, and are essential for the success of human and robotic space exploration. It calls for the director of OSTP to lead the development of an integrated strategy for coordinated observations of space weather across federal departments and agencies. It also directs the sustainment of a baseline capability for space weather observations and directs efforts to obtain enhanced space weather observations beyond the baseline capabilities to advance space weather forecasting. It also acknowledges the potential to leverage the commercial sector and utilize partnerships across, including international partnerships, and hosted payloads are also recognized. However, the release of PROSWIFT Act was accompanied by a signing statement from the President noting its limitations.[16]

2013 SOLAR AND SPACE PHYSICS DECADAL SURVEY AND THE 2020 MIDTERM ASSESSMENT REPORT

The 2013 National Academies decadal survey report, *Solar and Space Physics: A Science for a Technological Society*,[17] identified scientific goals that defined the directions for solar and space physics research ("heliophysics" research) for the decade 2013 through 2022, including priorities for NASA missions and for research programs sponsored by NASA and NSF. It also addressed key roles and partnerships between these agencies and NOAA, DoD, and the Department of Energy toward achieving the primary goals.

The 2013 decadal survey noted that multiple agencies of the federal government have vital interests related to space weather and that efforts to coordinate these agencies' activities were seen in the NSWP. Nonetheless, the decadal survey committee concluded that additional approaches[18] were needed to develop

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improve space weather forecasts and predictions including: sustaining and enhancing critical observations, identifying research needs and promoting opportunities for research-to-operations and operations-to-research collaborations both within and outside of the Federal Government, advancing space weather models, engaging with all sectors of the space weather community, including academia, the commercial sector, and international partners, and understanding the needs of space weather end users."

[16] "The Act, however, does not address the resilience of national security assets or critical infrastructure to the effects of space weather. Without ensuring the resilience of these assets, the United States will remain vulnerable to the effects of space weather, regardless of how accurate forecasting becomes. I look forward to working with the Congress to improve the resilience of national security assets and critical infrastructure to space weather." Signing Statement from President Trump on S. 881," *Mirage News*, October 22, 2020, https://www.miragenews.com/signing-statement-from-president-trump-on-s-881/.

[17] National Research Council, 2013, *Solar and Space Physics: A Science for a Technological Society*. Washington, DC: The National Academies Press, https://doi.org/10.17226/13060.

[18] Chapter 7 of the decadal survey report presented the committee's vision for a renewed national commitment to a comprehensive program in space weather and climatology. The committee made the following multipart recommendation as part of this vision:

A1.0 Recharter the National Space Weather Program

As part of a plan to develop and coordinate a comprehensive program in space weather and climatology, the survey committee recommends that the National Space Weather Program be rechartered under the auspices of the National Science and Technology Council. With the active participation of the Office of Science and Technology Policy and the Office of Management and Budget, the program should build on current agency efforts, leverage the new capabilities and knowledge that will arise from implementation of the programs recommended in this report, and develop additional capabilities, on the ground and in space, that are specifically tailored to space weather monitoring and prediction.

A2.0 Work in a multiagency partnership to achieve continuity of solar and solar wind observations.

The survey committee recommends that NASA, NOAA, and the Department of Defense work in partnership to plan for continuity of solar and solar wind observations beyond the lifetimes of ACE, SOHO, STEREO, and SDO. In particular:

the capabilities outlined in a 2010 National Space Policy document and envisioned in the 2010 NSWP.[19]

The 2013 decadal survey recently underwent a "midterm assessment" by an ad hoc study committee of the National Academies. Included in the midterm assessment report[20] were findings relevant to agency roles in fulfilling the goals of the NSW-SAP. These include a number of explicit references to the various roles for NASA, NOAA, and NSF; they also describe new developments where cooperative programs have arisen to address elements of the NSW-SAP. An overall message conveyed in the midterm report is that NOAA, as a primary conduit for space weather information, has been building fruitful partnerships with NASA and NSF that have the potential to transform space environment services through cooperative developments in observing and research-based modeling.

A2.1 Solar wind measurements from L1 should be continued, because they are essential for space weather operations and research. The DSCOVR L1 monitor and IMAP STP mission are recommended for the near term, but plans should be made to ensure that measurements from L1 continue uninterrupted into the future.

A2.2 Space-based coronagraph and solar magnetic field measurements should likewise be continued.

Further, the survey committee concluded that a national, multifaceted program of both observations and modeling is needed to transition research into operations more effectively by fully leveraging expertise from different agencies, universities, and industry and by avoiding duplication of effort. This effort should include determining the operationally optimal set of observations and modeling tools and how best to effect that transition. With these objectives in mind:

A2.3 The space weather community should evaluate new observations, platforms, and locations that have the potential to provide improved space weather services. In addition, the utility of employing newly emerging information dissemination systems for space weather alerts should be assessed.

A2.4 NOAA should establish a space weather research program to effectively transition research to operations.

A2.5 Distinct funding lines for basic space physics research and for space weather specification and forecasting should be developed and maintained.

Implementation of a program to advance space weather and climatology will require funding well above what the survey committee assumes will be available to support its research-related recommendations to NASA (see Table S.1). The committee emphasizes that implementation of an initiative in space weather and climatology should proceed only if it does not impinge on the development and timely execution of the recommended research program.

[19] *National Space Policy of the United States of America,* June 28, 2010, https://www.hsdl.org/?view&did=22716. *The National Space Weather Program. Strategic Plan*, FCM-P30-2010, Silver Spring, Md.: Office of the Federal Coordinator for Meteorological Services and Supporting Research, http://www.ofcm.gov/nswp-sp/fcm-p30.htm.

[20] National Academies of Sciences, Engineering, and Medicine, 2020, *Progress Toward Implementation of the 2013 Decadal Survey for Solar and Space Physics: A Midterm Assessment*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25668.

3

U.S. Department and Agencies Roles and Current and Planned Capabilities

Numerous departments and agencies of the federal government have responsibilities related to making a "space-weather ready" nation.[1] This chapter, based on workshop presentations and discussions,[2] focuses on those federal departments and agencies that have a major role in space weather–related research and operations, with particular attention to agency roles, current capabilities, and potential future capabilities. Speakers from the departments and agencies included the following:

- Tamara Dickinson, Science Matters Consulting, LLC, Session Chair
- Elsayed Talaat, National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Services (NESDIS)
- Jim Spann, National Aeronautics and Space Administration (NASA) Heliophysics Division (HPD)
- Mike Wiltberger, National Science Foundation (NSF), Division of Atmospheric and Geospace Sciences (GEO/AGS), Geospace Section (GS)
- Rachel Hock-Mysliwiec, U.S. Air Force, Air Force Research Laboratory
- Steve Volz, NOAA NESDIS
- Lt Col Omar A. Nava, U.S. Air Force, Air Force Weather
- Jonathan Margolis Turner, Department of State

[1] A space-weather ready nation would be analogous to a weather-ready nation—resilient to extreme weather, water, and climate events—that is part of the strategic vision of NOAA's National Weather Service. See L.W. Uccellini and J.E. Ten Hoeve, 2019, "Evolving the National Weather Service to Build a Weather-Ready Nation: Connecting Observations, Forecasts, and Warnings to Decision-Makers through Impact-Based Decision Support Services," *Bulletin of the American Meteorological Society* 100(10): 1923–1942.

[2] Links to presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

NOAA CURRENT CAPABILITIES

NOAA is the nation's official source of real-time space weather monitoring for the government, and commercial sectors, exclusive of the Department of Defense (DoD). The agency is also responsible for observations in support of space weather operations; continuous improvement of operational space weather services; and utilizing partnerships, as appropriate, with the research community—including academia and the private sector, and relevant agencies—to develop, validate, test, and transition space weather observation platforms and models from research to operations (R2O) and from operations to research (O2R).[3]

Central to NOAA's space weather responsibilities is its Space Weather Prediction Center (SWPC) in Boulder, Colorado, the nation's official source for space weather alerts, watches, and warnings. SWPC is one of nine National Centers for Environmental Prediction (NCEPs) of the National Weather Service and coordinates its activities, products, and services daily with its DoD counterpart, the 557th Weather Wing, located at Offutt Air Force Base, in Bellevue, Nebraska.

SWPC delivers a diverse range of products and services that cover space weather conditions on the Sun, in interplanetary space, and at Earth, all continually updated and displayed on the SWPC homepage (a screenshot is shown in Figure 3.1). The products are largely data driven and are aimed at a broad range of user groups. The information is presented in both text and graphical form using the NOAA space weather scales for geomagnetic storms, solar radiation storms, and radio blackouts as well as other indices and parameters. The primary means for product distribution include an email product subscription service with over 58,000 subscribers. SWPC also provides access to a multitude of real-time space weather measurements used directly by end users or by commercial service providers to produce value-added products for end users.

Observational needs and requirements are set by SWPC and fulfilled by NOAA NESDIS, other federal agencies, and international partners. NESDIS operates the nation's weather satellites and acquires the next-generation Earth and space weather observation satellites. The Space Weather Follow-on (SWFO) is one of the major development programs in NESDIS and is part of an effort to establish an integrated space weather observing system out to 2030. NOAA conducted a NOAA Satellite Observing System Architecture (NSOSA) analysis to focus on high-value options across the portfolio, including a mix of observations and new business models. The NOAA Space Weather Program is building on the NSOSA findings. The next-generation program will provide real-time imagery and in situ space weather measurements, new data to revolutionize space weather forecast models, and accurate, timely, and high-reliability warning of geomagnetic storm events. NESDIS is analyzing concepts recommended by NSOSA, including spacecraft in either geostationary orbit (GEO) or Tundra (over the Arctic) orbit, space weather satellites rideshares to GEO or L1, hosting instruments on commercial satellites, and partner instruments on NOAA satellites.

NOAA has also been conducting a pilot commercial weather data program (CWDP) for the purchase of GNSS (Global Navigation Satellite System) radio occultation data, with the SWPC evaluating these and additional commercial data sets for possible operational use. These actions are already in keeping with the PROSWIFT Act, which establishes a permanent CWDP for space weather within NOAA.

NOAA's current space-based observational needs require an architecture in which specific instruments are placed on platforms in a variety of orbits. These include the following:

- Low Earth orbit (LEO) is usually defined as altitudes below 1,000 km where many communication, navigation, and surveillance satellites fly. In situ measurements of energetic ion and electron flux have been provided by instruments on NOAA's Polar-orbiting Environmental Satellites (POES)

[3] Executive Order, 2016, "Coordinating Efforts to Prepare the Nation for Space Weather Events," October 13, https://obamawhitehouse.archives.gov/the-press-office/2016/10/13/executive-order-coordinating-efforts-prepare-nation-space-weather-events.

FIGURE 3.1 Images from the NOAA Space Weather Prediction Center homepage on March 15, 2021. SOURCE: NOAA, https://www.swpc.noaa.gov/.

and similarly instrumented MetOp spacecraft,[4] with the previously mentioned commercial GNSS radio occultation measurements providing total electron content to characterize the current state of ionosphere. Replaced by the Joint Polar Satellite System (JPSS)—the first of which launched in 2017 and is now identified as NOAA-20—these polar-orbiting spacecraft are designed principally for monitoring terrestrial weather and no longer carry instruments to make energetic charged particle measurements. MetOp spacecraft will continue to measure >20 keV electrons, which can pose a spacecraft surface and deep dielectric charging hazard, but will not measure electrons in the

[4] European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), 2020, "Operating Satellites," https://www.eumetsat.int/what-we-do/operating-satellites.

0.5-20 keV range. These were measured by earlier generation POES spacecraft and are responsible for most of ionospheric conductivity exclusive of solar ultraviolet ionization.

- Geostationary Operational Environmental Satellite (GOES) is near-equatorial orbit, at ~6.6 Earth radii from Earth's center, typically residing in the outer magnetosphere, although it can extend into the solar wind on the dayside if the magnetosphere is compressed during disturbed solar wind conditions. In situ measurements of the local space environment at this location, including energetic particle radiation fluxes and the magnetic fields, respectively, provide advanced warnings and current state. Imaging of the Sun's state and activity in the X-ray and ultraviolet bands provides a 1- to 4-day advanced warning of geomagnetic storms. The current GOES(-R) series of spacecraft hosts the Solar Ultraviolet Imager (SUVI) to observe and characterize complex active regions of the Sun, solar flares, and eruptions of solar filaments, which may give rise to coronal mass ejections (CMEs), and the Extreme Ultraviolet and X-ray Irradiance Sensors (EXIS), which detects solar flares and monitors solar irradiance impacting the upper atmosphere. The two instruments that measure the space environment include the Space Environment In-Situ Suite (SEISS) to monitor proton, electron, and heavy ion fluxes in the outer magnetosphere and the magnetometer to provide situational awareness.
- L1 (Deep Space Climate Observatory [DSCOVR] spacecraft) is a Lagrange point about 1.5 million km upstream of Earth. It provides a stable orbiting location for monitoring the properties of the solar wind and interplanetary magnetic field, as well as energetic particles, which are destined to impact Earth's magnetosphere. In situ measurement of the solar wind speed and magnetic field provides 15-60 minutes of advanced warning of the time of onset and the likely intensity of geomagnetic storm conditions at Earth. Coronagraph imaging of the Sun for CMEs, combined with modeling, provides a 1- to 4-day advanced warning of geomagnetic storms, but with much lower accuracy (+/− 9 hours) than the more immediate warnings from in situ instruments.

  DSCOVR was launched on February 11, 2015, to provide real-time solar wind monitoring for NOAA, a role previously assumed by NASA's Advanced Composition Explorer (ACE). DSCOVR has two space weather instruments: Solar Wind Plasma Sensor (Faraday Cup) and Magnetometer (PlasMag). These instruments measure solar wind velocity distribution and the magnitude and direction of the solar wind magnetic field to provide rapid warning of geomagnetic storms. However, DSCOVR did not include coronagraph and, until the launch of SWFO-L1, the nation will need to rely on the now over-25-year-old SOHO spacecraft to monitor CMEs.

NOAA's anticipated program of record (Figure 3.2), which is the starting point for this workshop, includes SWFO-L1, GOES- East, GOES-West (with a coronagraph, CCOR1), Cosmic 2—a joint 6-satellite low-altitude radio occultation program with Taiwan, and the NASA Global-scale Observations of the Limb and Disk (GOLD) mission described below. In addition, NOAA plans to leverage NASA and DoD capabilities. NOAA can also leverage the resources of its international partners; for example, the mid-decade program of record is expected to include the ESA (European Space Agency) and EUMETSAT's (European Organisation for the Exploitation of Meteorological Satellites') MetOp-SG (Meteorological Operational-Second Generation) polar-orbiting operational meteorological satellite system.[5] Other

[5] Note added in proof: On November 20, 2020, NOAA awarded its first contracts to purchase commercially available space-based radio occultation (RO) data for use in NOAA's operational weather forecasts. The 2-year Indefinite Delivery Indefinite Quantity (IDIQ) contracts with a total contract ceiling of $23 million, went to the U.S. commercial space firms GeoOptics and Spire Global. Under the overall IDIQ contracts, NOAA also awarded initial delivery orders for this RO data to both companies. Subsequent delivery orders will be released throughout the 2-year contract period at NOAA's discretion. See NOAA, 2020, "NOAA Awards First Commercial RO Contracts Supporting Operational Weather Forecasting," Office of Space Commerce, November 20, https://www.space.commerce.gov/noaa-awards-first-commercial-ro-contracts-supporting-operational-weather-forecasting/.

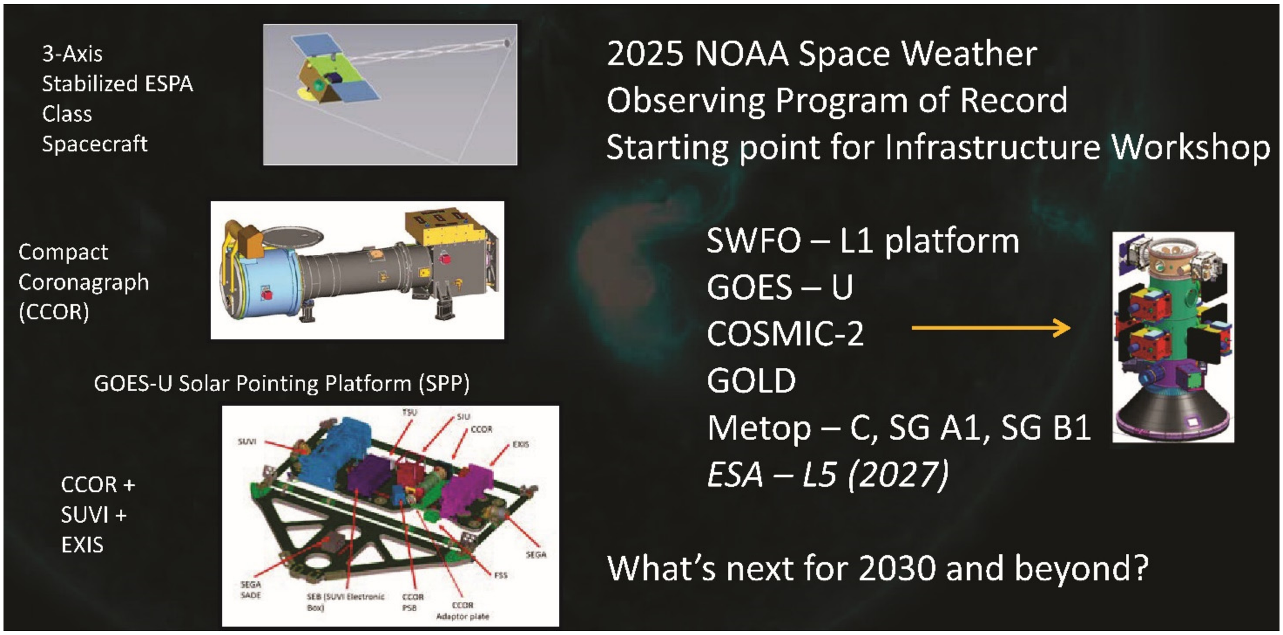

FIGURE 3.2 *Top:* Expected NOAA Space Weather Observing Program of Record in 2025. *Bottom:* NOAA Programs of Record include DSCOVR, SWFO, COSMIC-2, GOES-R series, and the JPSS series. Also shown in this figure are Jason-3, satellite altimeter created by partnership of the European Organisation for the Exploitation of Meteorological Satellites and NASA; and Sentinel-6 Michael Freilich satellite, a radar altimeter satellite developed by the European Space Agency. NOTE: Acronyms defined in Appendix D. SOURCE: *Top:* Elsayed Talaat, "NOAA's Current and Future Space Weather Architecture," presentation to the workshop, June 16, 2020. *Bottom:* Stephen Volz, NOAA, "NESDIS Update to the Space Weather Operations and Research Infrastructure Workshop," presentation to the workshop, September 10, 2020.

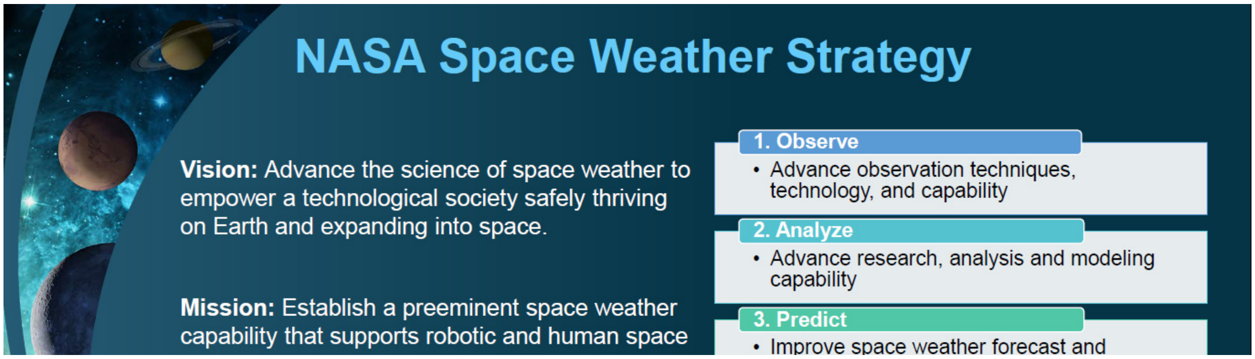

FIGURE 3.3 NASA's Space Weather Strategy. SOURCE: James Spann, NASA, "Heliophysics Division Space Weather Strategy," presentation to the workshop, June 16, 2020.

opportunities will come from leveraging various cooperative agreements and partnerships with, among others, Taiwan's National Space Organisation (NSPO), the Korean Meteorological Administration (KMA), the Japan Aerospace Exploration Agency (JAXA), the Centre National d'Études Spatiales (French Space Agency), the Canadian Space Agency (CSA), and the Indian Space Agency (ISRO).

NASA consistently plays key supporting roles in space weather monitoring and forecasting, with ongoing relationships of several of its research and exploration programs to NOAA's and SWPC's goals. NASA HPD leads several research programs dedicated to the understanding of the Sun and its interactions with Earth and the solar system. In addition to missions and projects that explore aspects of the physics of the coupled space weather system, it seeks to advance space weather modeling and prediction capabilities through programs such as Living With a Star. Most recently, it has partnered with NOAA to support explicitly the transition of space weather models and technology from R2O and from O2R (see discussion below).

As noted in Jim Spann's presentation to the workshop on June 16, 2020, NASA's Space Weather Strategy[6] ties directly to the priorities outlined in the 2020 NASA Science Plan, the 2015 and 2019 National Space Weather Strategy and Action Plans, and the recommendations made in the 2013 decadal survey.[7] The strategy is designed to address national, international, and societal needs for space weather information through research and advancements in measurement and analysis. It also includes maintenance and enhancement of capabilities to support robotic and human exploration (Figure 3.3).

[6] See NASA, "Space Weather," https://science.nasa.gov/heliophysics/space-weather.

[7] See NASA Science Mission Directorate, 2020, "Science 2020-2024, A Vision for Scientific Excellence," Washington, DC, https://science.nasa.gov/files/science-pink/s3fs-public/atoms/files/2020-2024_Science.pdf; National Science and Technology Council, 2019, *National Space Weather Strategy and Action Plan*, Washington, DC, March, https://www.hsdl.org/?view&did=823433; and National Research Council, 2013, *Solar and Space Physics: A Science for a Technological Society*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13060.

NASA is in the process of establishing a Space Weather Council (SWC) as a means to secure input from community experts across diverse areas relevant to space weather in support of the NASA HPD. The SWC is a subcommittee of the Heliophysics Advisory Committee. NASA is also developing a space weather implementation plan, establishing a NASA Space Weather Science Applications team to serve as a sounding board and implementation team, and conducting a space weather science and measurement gap analysis.[8]

NASA CURRENT CAPABILITIES

As of June 2020, NASA had 20 operating heliophysics missions with 27 spacecraft and 6 missions in formulation (see Figure 3.4). Five MIDEX Phase A missions announced by NASA HPD on August 28, 2020, have a space weather focus. Although NASA missions are formulated and launched for research purposes, some of them have been particularly important to operational space weather.

The ACE spacecraft, launched in 1997, was designed to study spaceborne energetic particles from the Sun-Earth L1 Lagrange point. It collects and analyzes particles of solar, interplanetary, interstellar, and galactic origins. The data contributes to understanding of the Sun, its interaction with Earth, and the evolution of the solar system. ACE continues to provide space weather reports and warnings of geomagnetic storms that can disrupt communications on Earth and harm astronauts in space. The spacecraft has operated far beyond its 2-year minimum lifetime and goal of 5 years.

Currently ACE is backup to DSCOVR. In addition, the NASA/ESA SOHO, spacecraft, launched in 1995, provides important images of coronal activity with its Large Angle and Spectrometric Coronagraph (LASCO) instrument. LASCO images are used by the SWPC forecast office to characterize the solar corona heating and transient events, including CMEs, and to see the effects of the corona on the solar wind. The LASCO images have also been essential for running the WSA-Enlil solar wind model that became operational at SWPC in October 2011. This model is now one of the tools routinely used for forecasting the time of arrival of Earth-impacting CMEs.

The Ionospheric Connection Explorer (ICON) was launched on October 10, 2019, with a nominal 2-year mission to observe conditions in both the thermosphere and ionosphere. ICON's science objectives are to understand (1) the source of strong ionospheric variability, (2) the transfer of energy and momentum from Earth's atmosphere into space, and (3) how solar wind and magnetospheric effects modify the internally driven atmosphere-space system.[9] ICON is investigating the low-latitude ionosphere, which is an important operational arena as communications are impacted by scintillation and other plasma structures in the region.[10]

Another relatively new addition to the suite of NASA research missions that has potential uses in space weather operations and forecasting is GOLD, which was launched on January 28, 2018. Instruments on GOLD are used to examine the response of the upper atmosphere to forcing from the Sun, the magnetosphere, and the lower atmosphere. GOLD is designed to explore the near-Earth space environment from its geostationary orbit, measuring the temperature and composition of neutral gasses in Earth's thermosphere.

Participants noted that GOLD's measurements could be used to improve models of the neutral atmosphere, which, in turn, are a critical element of plans for space traffic management. In addition, a type of space weather event investigated with GOLD involves large-scale bubbles that rise up through the equatorial ionosphere to altitudes exceeding 1,000 km, affecting radio frequency communications. Other

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[8] See James Spann, NASA, "Heliophysics Division Space Weather Update," presentation to the workshop, September 9, 2020.

[9] K. Rider, T. Immel, E. Taylor, and W. Craig, 2015, "ICON: Where Earth's Weather Meets Space Weather," *2015 IEEE Aerospace Conference*, March, https://doi.org/10.1109/aero.2015.7119120.

[10] ICON Level 2 Data Products are all available at ftp://icon-science.ssl.berkeley.edu/pub/LEVEL.2.

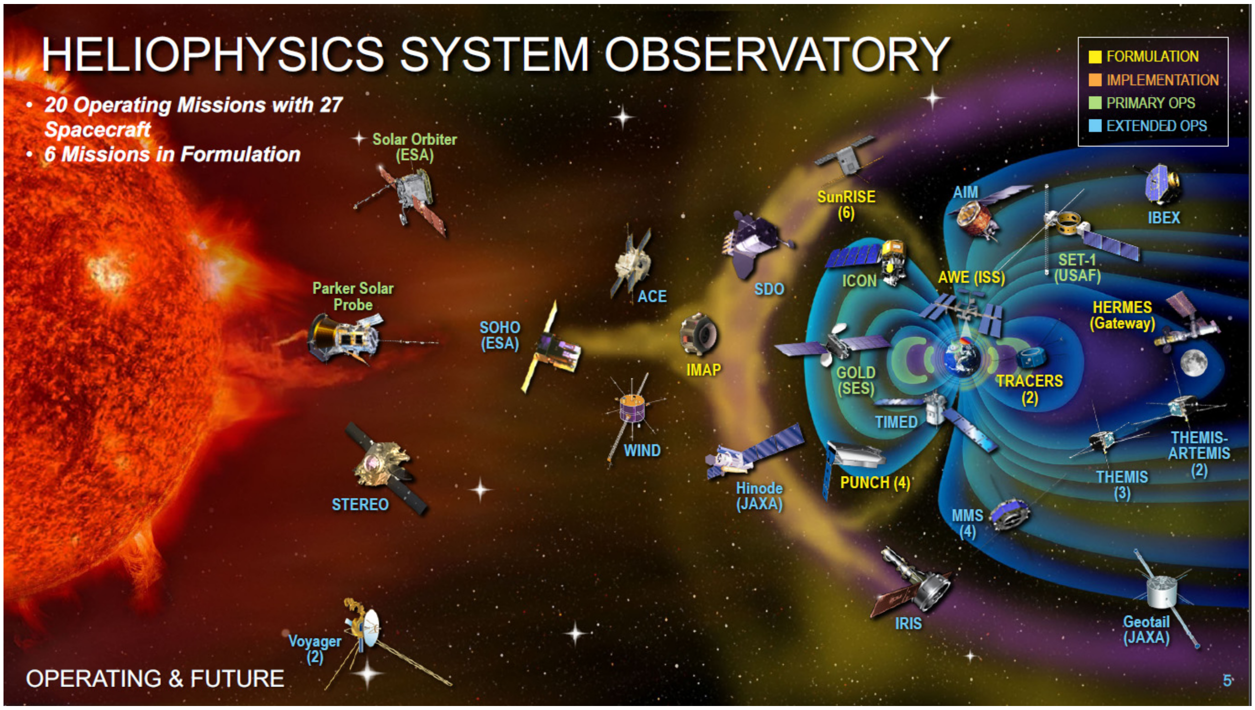

FIGURE 3.4 Heliophysics System Observatory. SOURCE: James Spann, NASA, "Heliophysics Division Space Weather Strategy," presentation to the workshop, June 16, 2020.

newly selected NASA research missions and projects described below also have the potential to contribute to the space weather enterprise, as will missions and projects still to be selected in the period prior to the end of the SWFO-L1 era.

NSF CURRENT CAPABILITIES

NSF supports fundamental research linked to societal needs for space weather information through investments and partnerships.[9] NSF focuses on basic research into the processes that drive space weather. As part of this activity, the agency supports a wide range of ground-based facilities that provide related observations, examples of which include ground-based radars for ionospheric measurements, neutron monitors for cosmic ray flux diagnostics, solar and auroral observatories, and magnetometer networks that support the evaluation of geomagnetically induced currents (GICs). Several ground-based networks supported by NSF are actively providing measurements used as input to space weather operational forecast models or could be used for forecasts. The Global Oscillations Network Group (GONG) consists of six identical solar observing stations that are distributed around Earth. These stations provide nearly continuous solar observations, including magnetograms showing the Sun's magnetic field on the visible disk at the time it passes over each station. The global distribution of the GONG observatories then provides, in effect, full 24-hour coverage of the Sun's magnetic field state, including emerging and evolving activity. GONG is operated by the National Solar Observatory. A memorandum of understanding (MOU) between NSF and NOAA supports data input into the operational forecast system. The Bartol Research Institute (University of Delaware) currently operates 10 neutron monitors around the world that measure galactic cosmic rays and solar energetic particles. Similar to the GONG data, this network is currently used predominantly for research. At the workshop, some participants expressed interest in using its data in an operational role relevant to the aviation radiation environment.

NSF supports several groups through the DASI (Distributed Array of Small Instruments) program to monitor Earth's magnetic field and to provide input into geo-electric field modeling—both are of interest in space weather research and applications (see the June 16, 2020, presentation by Mike Wiltberger). For example, DASI awards include MagStar, which will support development of six new magnetometer stations for GIC studies. These magnetometers add to the sparse coverage of the continental U.S. and provide reliable data for the science as well as operations communities. The SuperMAG project combines worldwide magnetometer data sets in a common public data archive. Other DASI awards relevant to space weather include a collaboration between the Ham Radio Citizen Science Investigation and the Tucson Amateur Radio Corporation to develop a network of personal space weather stations. These instruments will provide research-grade observations of signals-of-opportunity across the high-frequency bands from volunteer observers. The stations will consist of a multi-instrument device that will include a receiver, a ground magnetometer, and a Global Positioning System (GPS)/GNSS receiver to provide precision time stamping. The Space Weather Underground is another DASI award relevant to space weather. This project uses undergraduate and high school students to develop and deploy fluxgate magnetometers across northern New England.

NSF also supports uses of certain data sets obtained in space, such as the conversion of magnetometer data from the commercial iridium communications satellites into global maps of magnetic field-aligned current systems known as the AMPERE project. NSF is also making a major investment in the construction, commissioning, and operation of the Daniel K. Inouye Solar Telescope (DKIST) solar telescope nearing completion on Maui, Hawaii. DKIST is designed primarily for investigating the Sun's surface and atmosphere at high spatial resolution, toward understanding its fundamental nature. How the knowledge gained from its observations will affect space weather models and/or forecasts is yet to be determined.

JOINT AGENCY INITIATIVES

NASA, NOAA, and NSF representatives at the workshop referenced the "Tri-Agency MOU," a NASA, NOAA, NSF MOU signed in 2018 that enables ongoing multiagency coordination of research topics in support of the National Space Weather Strategy. A key aspect of this collaboration is the R2O and O2R pipeline. Through independent calls for proposals, NASA, NOAA, and NSF are supporting efforts to facilitate the transition of space weather data and modeling capabilities to U.S. space weather prediction providers and provide feedback from prediction providers to the research community on new research activities needed to improve the operational models. Further information about this forward-looking program is below.

DOD CURRENT CAPABILITIES

The Air Force 557th has the responsibility to provide 24/7 space weather support to all DoD agencies and units and to the national Intelligence Community. Their mission is two-fold—to collect space weather data from DoD ground- and space-based sensors and to provide environmental battlespace awareness through mission-tailored analyses, forecasts, and warnings of mission-impacting space weather to operators, warfighters, planners, and decision makers from command level down to individual units. To accomplish this mission, the 557th operates the Space Weather Operations Center, or Space WOC, the only U.S. military space weather analysis and forecast center, at Offutt Air Force Base, Nebraska.

Users of the 557th space weather services include every branch of service—Army, Air Force, Navy, Marine Corps, Space Force, and Coast Guard—and the national Intelligence Community, from leadership and senior decision makers to specific individual units. Space weather information is provided in support of long-distance radio or satellite communications for command and control, precision navigation and timing from GPS signals, over-the-horizon or tactical radars, high-altitude manned aerial reconnaissance, orbiting spacecraft and sensors, and strategic space launch.

The U.S. Air Force (USAF) operates a two-component, ground-based, real-time, solar observing network, known as the Solar Electro-Optical Network (SEON). SEON consists of the Solar Optical Observing Network (SOON) and the Radio Solar Telescope Network (RSTN), which monitors for solar radio bursts. The internationally located SOON optical telescopes and the RSTN radio telescopes together provide continuous observations of the Sun. SOON captures images of the Sun in the hydrogen-alpha line and white light, as well as producing coarse magnetograms of selected regions. RSTN monitors for solar radio bursts. The Air Force also collects, processes, and disseminates ionospheric data via the Next Generation Ionosonde (NEXION) and the Ionospheric Scintillation TEC Observatory (ISTO) sensor networks.

The 557th and SWPC are partners in providing space weather service to the United States. Each has clearly defined roles and responsibilities, leveraging the capabilities of the other to realize significant cost and resource savings. In simplest terms, the 557th is responsible for military and national intelligence support, and SWPC supports civilian and commercial users. SWPC is a major user of Air Force space weather data, while the 557th relies on NOAA data to accomplish its own space weather mission. The Space WOC relies on ground- and space-based magnetometer data provided through SWPC to analyze, warn, and forecast global geomagnetic activity important to the national intelligence agencies and to the North American Aerospace Defense Command (NORAD). The 557th also depends on alerts of geomagnetic activity from NOAA satellites and solar activity forecasts provided by SWPC to warn and forecast impacts to specific military communications links. The 557th and SWPC forecast centers also provide limited back-up operations for each other in the event of computer equipment or communication outages. Space WOC and SWPC coordinate on forecasts and engage in multiple daily space weather teleconferences. The complementary nature of the two missions allows both NOAA and the Air Force to realize cost-sharing advantages and to acquire needed data.

OTHER DEPARTMENTS AND AGENCIES

While much of the workshop focused on NOAA, NASA, NSF, and DoD space weather programs, attention was also given to activities to other departments and agencies that contribute to the space weather enterprise, including the U.S. Geological Survey (USGS), the Department of Energy (DOE), and the Department of State.

USGS supports the development, deployment, and operation of facilities that enhance the understanding of variations of Earth’s magnetic field, a critical component of space weather monitoring associated with solar-terrestrial interactions.[9] The USGS magnetometer network constantly measures the surface field at 14 ground-based observatories whose geographic distribution is determined by the need to know the field’s behavior on a global scale. The generation of these continuous records of magnetic field variations, which NOAA’s SWPC uses in its daily reporting, also enables research efforts relevant to interpreting hazards from GICs. Interestingly, it was mentioned at the workshop that there exists the possibility to expand the USGS magnetometer network via contributions from private sources.

Participants also noted the importance of lesser resources. In October 2016, EO 13744 directed DoD, DOE, and DOC to make historical data publicly available from the GPS constellation “to enhance model validation and improvements in space weather forecasting and situational awareness.” The GPS satellites carry DOE/Los Alamos National Laboratory (LANL) energetic particle sensors. In response, in January 2017, 16 years of LANL GPS energetic particle data, covering the period from December 2000 to December 2016, were publicly released. These data are available at NOAA’s National Center for Environmental Information (NCEI) for retrospective studies that can contribute to improved space weather modeling and forecasting. In addition, DoD energetic particle measurements from LANL-GEO satellites and total electron content (TEC) information calculated from the radio frequency data from GPS satellites were made available. (The radio frequency sensors provide TEC measurements from broadband terrestrial radio sources, primarily lightning.) Broader access to such historical data sets has become much more straightforward with improvements in storage devices and the Internet. The potentially high value for research of this previously unavailable information was noted at the workshop.

The Department of State recognizes, at yet higher administrative levels, that space weather is a global challenge requiring a coordinated international response. The NSW-SAP emphasizes that the world has become increasingly dependent on interconnected and interdependent infrastructure and that any disruption to these critical technologies could have widespread consequences. Many countries are becoming increasingly aware of the risks associated with space weather and the need to monitor and manage these risks. The Department of State takes an active role in mitigating space weather risks through international cooperation. In response to the NSW-SAP, the Bureau of Oceans and International Environmental and Scientific Affairs (OES) organizes the annual Space Weather as a Global Challenge (SWGC) events in Washington, D.C., to strengthen international coordination and cooperation on space weather preparedness. SWGC events have been hosted by the embassies of Italy and Japan. OES also represents U.S. space weather interests in U.N. agencies such as the Committees on the Peaceful Uses of Outer Space and the World Meteorological Organization.

FUTURE PLANNED U.S. CAPABILITIES

NOAA

As noted in the introduction to this proceedings, the current centerpiece of NOAA's space weather service plan is the SWFO program (see presentation by Elsayed Talaat, September 9, 2020). The SWFO program follows directly from the 2015 and 2019 National Space Weather Strategy and is comprised of two projects: the Compact Coronagraph (CCOR), which will be placed on the GOES-U spacecraft that is currently scheduled for launch in 2024; and the Space Weather Follow-on L1 mission (SWFO-L1), which is planned to launch as a rideshare with the NASA Interstellar Mapping and Acceleration Probe in early 2025.[11]

The CCOR will image the solar corona with the primary objective of observing Earth-bound CMEs. With CCOR data the size, mass, speed, and direction of CMEs can be derived, giving forecasters the information needed to provide alerts for geomagnetic storms up to days in advance. CCOR is about half the size and weight of a traditional coronagraph. This small size allows CCOR to be accommodated easily on a large variety of spacecraft platforms, including GOES-U as well as SWFO-L1. The L1 orbit allows for continuous unobstructed observation of the corona without interference from Earth. CCOR will replace SOHO's LASCO imaging of CMEs.

SWFO-L1 will provide real-time 24/7 operations to accommodate the needs of SWPC. Instruments on the spacecraft will collect upstream solar wind data[12] and coronal imagery[13] and NESDIS/NCEI will archive all space weather data products. NOAA will also be responsible for the development and operation of the ground service that will support all the sensors and the SWFO-L1 spacecraft; the agency is evaluating the addition of 13-16 m dishes near Madrid, Spain, and Dongara, Australia, for this purpose. The current timeline for SWFO planning through 2030 is summarized in Figure 3.5.

[11] Charts in this report date before a December 2020 announcement that the preliminary design review for NASA's Interstellar Mapping and Acceleration Probe (IMAP) had been moved from February to May 2021, a delay attributed to the precautions taken in response to the COVID-19 pandemic. As a result, the launch readiness date for IMAP was delayed from October 1, 2024, to February 1, 2025.

[12] The spacecraft will carry a suite of instruments to make in situ measurements of the solar wind plasma, magnetic field, and energetic particles. Ball Aerospace is under contract to build, integrate, and operate the spacecraft. The Supra Thermal Ion Sensor is under construction at the Space Sciences Laboratory at the University of California, Berkeley, and the magnetometer is being provided by the Southwest Research Institute.

[13] Like GOES-U, SWFO-L1 will carry a compact coronagraph developed by the Naval Research Laboratory.

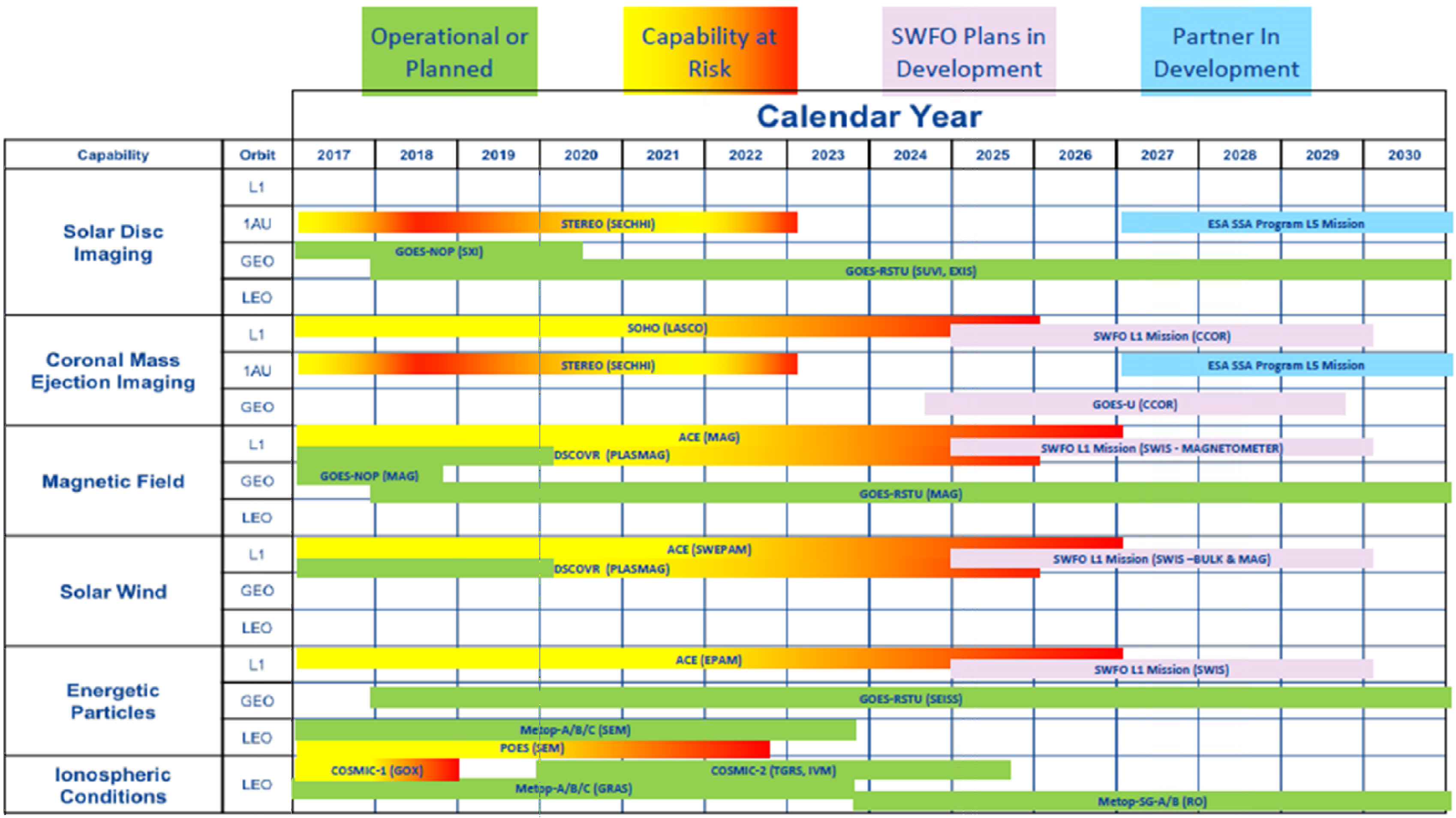

FIGURE 3.5 The current “constellation” is a mix of research and operational space and ground assets. NOAA, working with partners, is leading the transition to an operational SWx constellation. The future system will continue to feature research (NASA, ESA, USAF, ISRO) and operational (NOAA, EUMETSAT, USAF, others) assets. NOTE: Acronyms are defined in Appendix D. SOURCE: Stephen Volz, NOAA, “NESDIS Update to the Space Weather Operations and Research Infrastructure Workshop,” September 10, 2020.

NASA

This section lists only some of the planned missions described at the workshop that are relevant to future space weather observations. They are listed by program element.

MIDEX

In August 2020, NASA announced the selection of five Medium-Class Explorer (MIDEX) proposals for concept studies of missions to help improve understanding of the dynamics of the Sun and Earth's space environment.[14] Each of these proposals will receive $1.25 million to conduct a 9-month mission concept study. Following the study period, NASA will choose up to two proposals to go forward to launch. The selected proposals are as follows:

- HelioSwarm: The Nature of Turbulence in Space Plasmas,
- Solaris: Revealing the Mysteries of the Sun's Poles,
- STORM: Solar-Terrestrial Observer for the Response of the Magnetosphere,
- MUSE: Multi-slit Solar Explorer, and
- ARCS: Auroral Reconstruction CubeSwarm.

SMEX

The Polarimeter to Unify the Corona and Heliosphere (PUNCH)[15] is a NASA Small Explorers (SMEX) program mission—led by the Southwest Research Institute (SWRI)—that will provide the first global images of how the solar corona infuses the solar wind with mass and energy. In addition, the PUNCH satellites will track in three dimensions the Sun's CMEs as they erupt from the corona out into interplanetary space. The PUNCH mission consists of a constellation of four small satellites in Sun-synchronous LEO, which together will produce deep-field, continuous, three-dimensional (3D) images of the solar corona as it makes a transition to the young solar wind. The PUNCH cameras sense normal visible light and its linear polarization, which allows the 3D location of solar wind features to be measured. Although PUNCH was selected as a basic science mission, NOAA is expecting it to have significant operational benefits.

Launching as a secondary payload on the same rocket with PUNCH will be another recent SMEX selection, TRACERS (Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites).[16] TRACERS will observe particles and fields at Earth's northern magnetic cusp region and will study for the first time the extent to which magnetic reconnection is continuous or transient. The mission has three major scientific objectives:[17] (1) determine whether magnetopause reconnection is primarily spatially or temporally variable for a range of solar wind conditions; (2) for temporally varying reconnection, determine how the reconnection rate evolves; and (3) determine to what extent dynamic structures in the cusp are associated with temporal versus spatial. The instrumentation consists of ion and electron spectrometers, DC electric and magnetic field and AC wave measurements.

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[14] See NASA, "NASA Selects Proposals for New Space Environment Missions," https://explorers.larc.nasa.gov/HPMIDEX/announcements.html.

[15] For details on the mission, see Southwest Research Institute, "PUNCH: The Polarimeter to Unify the Corona and Heliosphere," https://punch.space.swri.edu/index.php.

[16] NASA, 2019, "NASA Selects Missions to Study Our Sun, Its Effects on Space Weather," June 20, https://www.nasa.gov/press-release/nasa-selects-missions-to-study-our-sun-its-effects-on-space-weather.

[17] C Kletzing, 2019, "The Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS) Mission," *AGU Fall Meeting Abstracts* 2019 (December): A41U2687, https://ui.adsabs.harvard.edu/abs/2019AGUFM.A41U2687K/abstract.

Living With a Star

The Geospace Dynamics Constellation (GDC) is a science mission to dramatically improve scientific understanding of the upper atmosphere and its strong variability in response to energy inputs from the Sun, from near-Earth space, and from the lower atmosphere. This mission concept was recommended by the 2013 decadal survey, *Solar and Space Physics: A Science for a Technological Society*, for implementation as the next Living With a Star (LWS) mission. The mission has been defined by a community-based Science and Technology Definition Team (STDT)[18] and is currently scheduled for launch in 2024.

Artemis

HPD is working across NASA and with partner agencies to support exploration and the agency's Artemis mission. HPD will fly heliophysics instrumentation in Phase 1 of Artemis to provide an early science return for the program and provide critical space weather and radiation observations needed to protect the astronaut crew. HPD was invited to develop a lunar space environment capability with the Human Exploration and Operations Mission Directorate to launch with the Power and Propulsion Element of Gateway Phase 1. The instrument package was to be delivered no later than November 2021, an insufficient amount of time to do a traditional solicitation. HPD opted to take advantage of this opportunity and directed the task to NASA Goddard Space Flight Center. Moving forward, HPD fully intends to compete all future opportunities and to put themselves in a position to be able to better take advantage of quick turnaround with full community participation. The first heliophysics instrument to fly on Gateway will be the Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) instrument. HERMES will help scientists to understand the causes of space-weather variability as driven by the Sun and modulated by the magnetosphere.

NSF

The NSF Atmospheric and Geospace Sciences Section, which provided early support for CubeSat development at universities, recently selected two CubeSat constellation projects: SWARM-EX,[19] a constellation of three satellites for study of the ionosphere and thermosphere; and VISORS,[20] three CubeSats acting as a single solar telescope to study coronal heating. Responding to a 2013 decadal survey recommendation, NSF has developed a Midscale-1 funding line for projects in the $6 million to $20 million range in addition to the Midscale-2 funding line supporting $20 million to $70 million projects, which can provide infrastructure support spanning the gap between DASI and DKIST.

R2O2R

A number of participants at the workshop expressed a concern that the United States lacks a formal structure to ensure an efficient space weather research-to-operations-to-research (R2O2R) cycle. They observed that while the foundational components of a cross-organizational structure exists among science

[18] NASA, 2019, GDC STDT Final Report, October 4, https://science.nasa.gov/files/science-red/s3fs-public/atoms/files/GDC%20STDT%20Report%20FINAL.pdf.

[19] "NSF Award Search: Award#1936665 - Collaborative Research: CubeSat Ideas Lab: Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX) CubeSats," NSF.gov, 2019, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1936665&HistoricalAwards=false.

[20] "NSF Award Search: Award#1936663 - Collaborative Research: CubeSat Ideas Lab: VIrtual Super-Resolution Optics with Reconfigurable Swarms (VISORS)," NSF.gov, 2019, https://www.nsf.gov/awardsearch/showAward?A WD_ID=1936663.

agencies, a framework is needed that incorporates the contributions from industry, academia, and partner-agencies such as DOE, the Department of Homeland Security, the Federal Aviation Administration, and others.[21] The fiscal year 2021 Administration Research and Development Budget Priorities joint memorandum identified space weather R2O2R as a budgetary priority that will support critical infrastructure resilience. Both the 2015 and 2019 National Space Weather Strategy and Action Plans directed departments and agencies to identify mechanisms for transitioning models and observational capabilities from research to operations.

In response, NOAA and NASA, in partnership with NSF and the USAF, have embarked on an initiative to develop a formal space weather R2O2R framework that will facilitate the transition of new research into operations and enable the improvement and maintenance of existing operational models. The proposed space weather testbed and proving grounds will bring together forecasters, researchers, and end users in a quasi-operational setting where new models and techniques are assessed and transitioned to operations.

The testbed will be collocated with the SWPC. Proving grounds, such as the NASA Community Coordinated Modeling Center, will emulate operational practices and evaluate new models, data sets, and forecast techniques that can be integrated into the testbed to assess value to the forecast process.

[21] This concern is discussed further in Chapter 7, “Space Weather and Space Climatology: A Vision for Future Capabilities,” of the 2013 decadal survey, *Solar and Space Physics: A Science for a Technological Society*.

4

Complementary and Collaborative International Activities

While numerous countries engage individually on space weather activities, there are also several intergovernmental organizational groups focused on space weather. These include the United Nations (UN) World Meteorological Organization, the UN Committee on the Peaceful Uses of Outer Space, the UN International Civil Aviation Organization, and the North Atlantic Treaty Organization. In addition, the International Space Environment Service (ISES), a collaborative network of 21 space weather service-providing organizations around the globe, provides a broad range of services, including forecasts, warnings, and alerts of solar, magnetospheric, and ionospheric conditions.

The speakers below spoke at either the June or September portions of the workshop.[1,2] A summary of their presentations and discussions among all participants follows.

- Mamoru Ishii, National Institute of Information and Communications Technology, Space Weather Forecast Center, Japan, "Japan's Space Weather Plans"
- Juha-Pekka Luntama, Space Situational Programme Office, European Space Agency (ESA), European Space Operations Centre, "ESA's Space Weather System Plans"
- David Boteler, Canadian Space Weather Forecast Centre, "Space Weather Monitoring in Canada"

The Canadian Space Weather Forecast Center in Natural Resources Canada (NRCan) is the Government of Canada's provider of space weather services. The forecast center monitors, analyzes, and forecasts space weather and dispatches warnings and alerts across Canada. The F10.7 radio flux has been measured consistently in Canada since 1947, first at Ottawa, Ontario, and then at the Penticton Radio Observatory in British Columbia.

A new multi-frequency solar radio telescope is currently being commissioned. In support of the Canadian power grid, NRCan operates a broadly spaced network of 14 magnetometers that spans Canada. Similar to the U.S. magnetometer distribution, the Canadian network coverage is not sufficient to accurately

[1] In addition to the activities described by these participants, there is a growing number of space weather centers being initiated abroad. For example, the South African Space Agency is standing up a space weather center, DLR-institute of solar-terrestrial physics in Neustrelitz is establishing a space weather program, Britain has the UKMET Office Space Weather Operations Centre, and the Royal Netherlands Meteorological Institute has a space weather center.

[2] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

specify power systems effects. However, three different networks of research magnetometers currently supplement the NRCan network, providing temporary support to NRCan's operational network.

NRCan monitors the ionosphere to assess degradation to communications in support of aviation, especially polar operations. A network of riometers operated by the University of Calgary provide key ionosphere information on high-frequency communications. NRCan have deployed additional riometers at their magnetometer stations, significantly improving the network coverage. The Canadian Geodetic Survey operates a network of GNSS receivers, which are augmented by a network of scintillation receivers operated by the University of New Brunswick as part of the Canadian High Arctic Ionospheric Network. Similar to the United States, Canada is heavily dependent on observations from research instruments. The proposed tundra orbit Canadian Arctic Observing Mission, primarily focusing on climate and meteorology needs, may provide NASA and NOAA opportunities for space weather sensors.

David Boteler, Head of the Geomagnetic Laboratory of NRCan, led the discussion of Canada's space weather monitoring in Canada, providing the following conclusions:

- Ground networks often taken for granted—but most do not have long term funding;
- Cost-effective for space weather monitoring;
- Provide direct measure of the parameters relevant to effects on critical infrastructure;
- Limited resources for operational space weather monitoring;
- Used research facilities to fill the gaps—not sustainable in the long term
- Increasing requirements for space weather monitoring
- New opportunities (e.g., multi-frequency riometers).

Japan has implemented the Project for Solar Terrestrial Environment Prediction, which is a nation-wide project in Japan for space weather and space climate study involving 20 institutes and 100 researchers. This project brings together the user, operations, and research communities to establish the basis for next-generation space weather forecasting. This project seeks to answer some of the fundamental questions concerning the solar-terrestrial environmental system. The space weather forecasting function in Japan resides in the National Institute of Information and Communications Technology (NICT). The NICT is a UN International Civil Aviation Organization center responsible for providing space weather services in support of global aviation. The center began 24/7 operational space weather services in December 2019, and it is in the process of developing operational models including a radio propagation model and radiation exposure model. Japan has recently completed a survey of potential impacts of space weather on Japanese infrastructure and the economy. The survey included a 1/100 year storm scenario that would likely result in partial power blackouts in Japan.

NICT is exploring new, operational, space environment sensors, including an ion and electron detector and magnetometer for monitoring high-energy particles and radiation belts; satellite charging sensor; and an ionospheric imager to monitor global distribution of plasma bubbles. It also hopes to sustain, and perhaps extend, ground-based observations in Southeast Asia. Japan will also cooperate across space station, Artemis, and Lunar Gateway projects, and consequently its space weather research will soon expand outside Earth's magnetosphere.

Space weather in ESA, within its Space Safety Programme, is based on the following three elements: (1) ground observations, (2) a Distributed Space Weather Sensor System (D3S), and (3) satellite systems positioned at the Lagrange point L5.

ESA will take on a role of improving the coordination and availability of existing ground-based observations. These observing capabilities are largely funded through national programs and may, or may not, already be part of an existing network such as InterMagnet. ESA will focus on improving the availability of the data to facilitate easier and more reliable access to the wider space weather community.

Within Earth's magnetosphere, ESA is implementing D3S (Figure 4.2). This will initially include magnetic field, neutral/charged particle, plasma and micro-particle environment measurements, and auroral

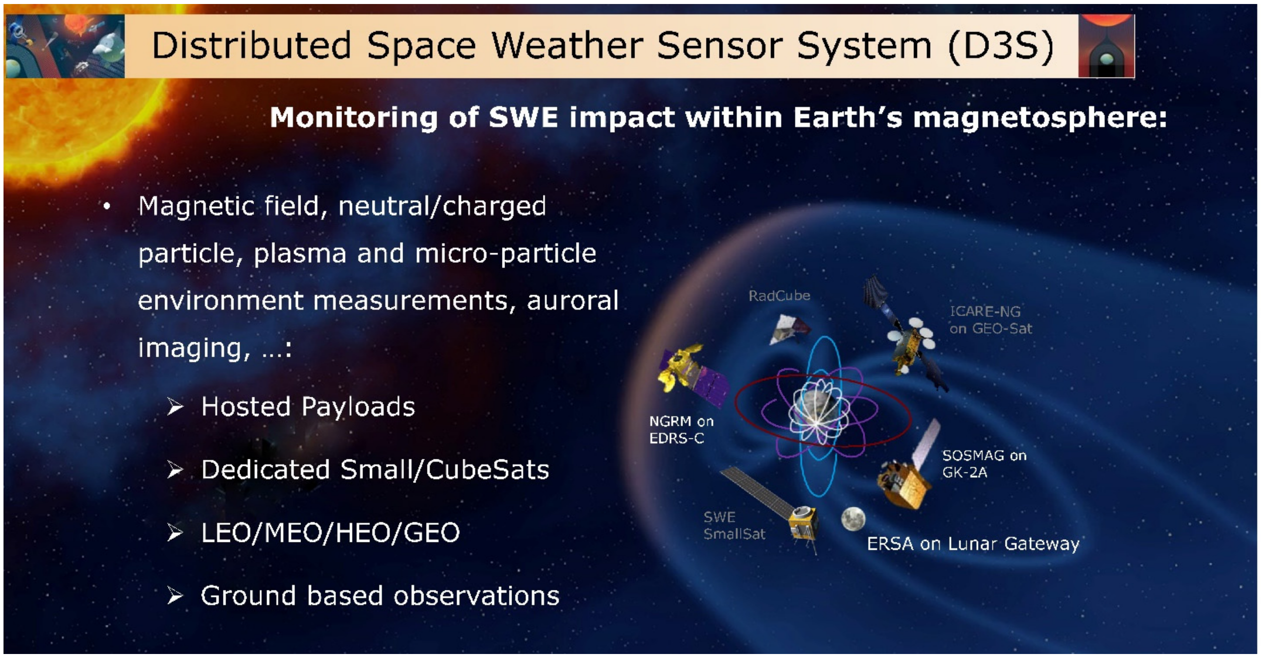

FIGURE 4.2 The European Space Agency's Distributed Space Weather System (D3S). SOURCE: Juha-Pekka Luntama, European Space Agency, "ESA's Space Weather System Plans," presentation to the Workshop, June 16, 2020.

imaging utilizing hosted payloads as part of the D3S. Two such hosted payloads have recently been launched: a versatile magnetometer on the Korean Geo-Kompsat-2A satellite and a radiation monitor hosted on EDRS-C. In addition, small, dedicated missions may be used to complement hosted payload instruments.

ESA plans a mission, scheduled for launch in 2027, to the Lagrange point L5 to observe the Sun and the space in between the Sun and Earth. This gives visibility of the propagation of coronal mass ejections and views of the solar disk before it rotates into a geoeffective position. Instruments planned for the L5 mission include a magnetograph, heliospheric imager, coronagraph, EUV coronal imager, radiation monitor, plasma analyzer, magnetometer, and X-ray flux monitor.

5

Space Weather User Community Needs

The speakers shown below addressed space weather impacts as well as the role of the private sector in providing and managing the infrastructure needed to mitigate deleterious space weather effects.[1] A theme that emerged from these presentations and participant discussions is U.S. dependence on government, academic, and private-sector assets working in harmony to be prepared for space weather events now and in the future.

- Conrad Lautenbacher, CEO, GeoOptics, *Session Chair*
- Mark Olson, North American Electric Reliability Corporation (NERC), “Electric Power Industry”
- Steve Jolly, Commercial Civil Space, Lockheed Martin Space Systems, “Satellite Operations”
- Mike Stills, Past Director, Flight Dispatch (Network Operations) United Airlines, “Commercial Aviation”
- Eddie Semones, Space Radiation Analysis Group, NASA Johnson Space Center, “Human Exploration”
- Mark MacAlester, Department of Homeland Security, “Space Weather Effects on Communications”
- Joe McClelland, Director, Office of Energy, Federal Energy Regulatory Commission (FERC), “Power Grid, Reliability Standards”[2]
- Susan Skone, Professor, University of Calgary, Canada, “PNT-Reliant Industries”
- Bob McCoy, Director, Geophysical Institute, University of Alaska, Fairbanks, “Arctic Space Weather Impacts”
- Nicole Kinsman, Alaska Regional Advisor, National Oceanic and Atmospheric Administration (NOAA), National Geodetic Survey, “Relevance of Space Weather Prediction to Applied Positioning Activities”

User needs for space weather information reflect the broad range of space weather impacts. A longstanding concern is the potential impact—both short- and long-term—of space weather on electrical grids, which form the backbone of a modern society. A more recent concern is the impact of space weather

[1] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.
[2] Mr. McClelland spoke without the use of slides; therefore, his presentation is not on the workshop’s website.

on the increasing numbers of Earth-orbiting satellites and space domain awareness—the new name for space situational awareness.[3]

Worldwide commercial aviation, which has grown significantly over the past several decades, is dependent on continuous ground- and space-based communications to ensure safety of flight. Avoiding exposure to hazardous radiation levels generated by solar storms is also a primary concern, particularly for airlines operating polar routes.

As noted by many speakers, the expansion of a human presence in space, especially for extended missions and/or exploration beyond low Earth orbit (LEO), will require improvements in understanding and prediction of the radiation environment.[4] Already, the International Space Station (ISS) receives daily updates of current and predicted space weather; the planned exploration of the Moon, and potentially of Mars, will require continued improvement in forecasting and protecting against the potentially higher levels of solar radiation.

Back on Earth, the Department of Homeland Security and the emergency response community are dependent on local and worldwide communications that can be interrupted by space weather effects on the ionosphere. In addition, space weather–induced irregularities in electron density in the ionosphere are a major source of error in precise time transfer using Global Positioning System (GPS) satellites. For a society increasingly reliant on GPS for position, navigation, and timing (PNT) information, there is an accompanying need to support research that will improve understanding of the space weather effects that affect PNT. This need is of growing importance as new capabilities, such as GNSS smart phones with 30 cm localization, and the Internet of Things (IoT), are developed.[5]

Below is a summary, based on workshop discussions at both the June and September sessions, that highlights some of the information needs of key users of space weather information.

POWER INDUSTRY

FERC is an independent agency that regulates the interstate transmission of natural gas, oil, and electricity. FERC is responsible for protecting the reliability of the high-voltage interstate transmission system through mandatory reliability standards. FERC also participates, as a member of the Office of Science and Technology Policy (OSTP) Space Weather Operations, Research, and Mitigation (SWORM) Working Group. FERC oversees NERC in the United States, as do provincial governments in Canada.

NERC is a not-for-profit organization with the mission to ensure the reduction of risks to the reliability and security of the power grid.[6] NERC has as its area of responsibility (AOR) the United States, Canada, and northern Baja California in Mexico. In general, space weather information is used, along with other information, to plan, assess, and mitigate risks to the bulk power system.

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[3] This report will use SSA as that is how it was referenced during the workshop. Regarding the new term of SDA: Introduced by the newly created U.S. Air Force Space Command, SDA is defined as “the identification, characterization and understanding of any factor, passive or active, associated with the space domain that could affect space operations and thereby impact the security, safety, economy or environment of our nation.” John E. Shaw, Maj Gen, USAF, *Space Domain Awareness (SDA)* [Memorandum], Peterson AFB, CO: Air Force Space Command, October 4, 2019.

[4] J. Chancellor, G. Scott, and J. Sutton, 2014, “Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit,” *Life (Basel, Switzerland)* 4: 491-510, doi: 10.3390/life4030491.

[5] These issues were recognized in the *2019 Federal Radionavigation Plan*. See U.S. Department of Homeland Security, 2020, “Nav Pubs and Documents General Library,” https://www.navcen.uscg.gov/?pageName=pubsMain; also Department of Defense, Department of Homeland Security, and Department of Transportation, *2019 Federal Radionavigation Plan*, 22161DOT-VNTSC-OST-R-15-01, Springfield, Va.: National Technical Information Service, https://rosap.ntl.bts.gov/view/dot/43623/dot_43623_DS1.pdf.

[6] Mark Olson, “Space Weather Information and Electric Reliability,” presentation to the workshop, June 16, 2020, and Mark Lauby, “Geomagnetic Disturbances Reducing Risk to the North American Electric Grid,” presentation to the workshop, September 9, 2020.

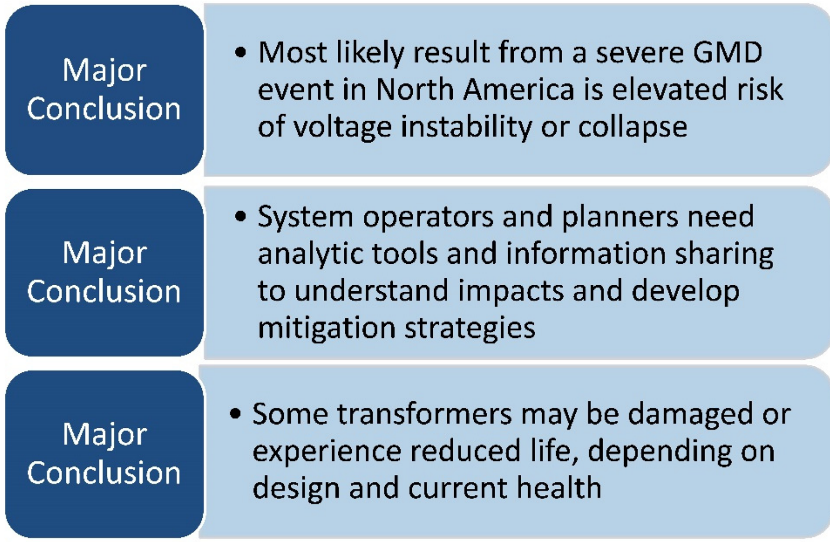

FIGURE 5.1 National Electric Reliability Corporation (NERC) conclusions from the 2012 Task Force Report. SOURCE: Mark Lauby, NERC, "Geomagnetic Disturbances Reducing Risk to the North American Electric Grid," presentation to the workshop, September 9, 2020.

Geomagnetic disturbances (GMDs), the result of space weather, cause geomagnetically induced currents (GIC) to flow in long engineered conductor systems such as power grids, pipelines, and railway systems.[7] Severe GMDs—a low-frequency, high-impact natural hazard—can result in GICs that have the potential to cause major disruptions in high-voltage power transmissions systems, including system blackouts. The most well-known recent example is the March 13, 1989, event, which led to a short-term blackout of the electrical system in Quebec, Canada.[8] This event highlighted the need for GMD risk mitigation.[9] Figure 5.1 summarizes NERC conclusions regarding the effects of geomagnetic disturbances on the bulk power system. Box 5.1, based on the presentations by Mark Lauby and Mark Olson, describes the scope of FERC and NERC activities in more detail.

The NOAA Space Weather Prediction Center's (SWPC's) "Alerts, Watches and Warnings" for GMDs are used, along with other indicators, to provide system operators with situational awareness and to trigger operator actions. For example, SWPC's initial watch (issued up to 3 days in advance of GMD impacts) prompts operators to prepare for power system contingencies and to posture the electric system for resilience.[10] Preparations may include notification to field personnel for onsite monitoring, assessment of black start (service restoration) capabilities, and readying the system and equipment for potential GIC impacts. Decisions can also be made regarding the equipment that should be in service and whether any plans for maintenance should be delayed.

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[7] A. Pulkkinen, E. Bernabeu, A. Thomson, A. Viljanen, R. Pirjola, D. Boteler, J. Eichner, et al., 2017, "Geomagnetically Induced Currents: Science, Engineering, and Applications Readiness," *Space Weather* 15(7): 828–856, https://doi.org/10.1002/2016sw001501.

[8] D.H. Boteler, 2019, "A 21st Century View of the March 1989 Magnetic Storm," *Space Weather* 17(10): 1427–1441, https://doi.org/10.1029/2019sw002278.

[9] See North American Electric Reliability Corporation (NERC), 2019, *2019 ERO Reliability Risk Priorities Report*, November, https://www.nerc.com/comm/RISC, and the NERC, 2012, *Special Reliability Assessment Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System*, February, https://www.eenews.net/assets/2012/02/29/document_pm_01.pdf.

[10] A resilient system is usually thought of as one able to withstand low-probability, high-impact threats.

BOX 5.1 FERC, NERC, and Space Weather

The Federal Energy Regulatory Commission (FERC) has been active in geomagnetic disturbance (GMD) matters since Congress established the EMP Commission in 2001 to assess and report on the threat from electromagnetic pulses (EMPs). The EMP Commission recognized that a GMD could seriously degrade or shut down a large part of the electric power grid, and that effective mitigation against GMDs can provide mitigation against the impacts of a high-altitude nuclear detonation. FERC recognizes that large GMD disturbances are inevitable—with only the timing and magnitude subject to variability.

In 2010 FERC co-sponsored a study conducted by the Oak Ridge National Laboratory to better understand the effects of EMP and GMD on the power grid. Results were consistent with prior studies that suggested EMP and GMD events pose substantial risk to the nation's electric grid, which could include a major long-term power outage.[1]

In 2013, FERC directed the North American Electric Reliability Corporation (NERC) to develop and submit for approval proposed reliability standards that address the impact of geomagnetic disturbances on the reliable operation of the bulk-power system in two stages. The standards have continued to evolve, requiring the GMD assessments to be completed by 2023, and completion of the corrective action plans by 2024 with implementation in two stages: non-hardware mitigation by 2026 and hardware mitigation by 2028. In addition, a requirement was established for entities to collect geomagnetically induced current monitoring and magnetometer data and to make such data publicly available. FERC recognized that collecting such data would enable model validation and situational awareness and contribute to the development and implementation of corrective action plans as necessary.

NERC's Geomagnetic Disturbance Task Force works with researchers, agencies, and utilities across North America to develop tools, procedures, and standards for reducing GMD risks to the power system. GMD Operations standards became effective in April 2015; and in January 2017 GMD Vulnerability Assessment standards were implemented. The outcome is that NERC requires grid operators to have procedures for mitigating GMD impacts. The operators receive alerts from the National Oceanic and Atmospheric Administration's Space Weather Prediction Center and Space Weather Canada. They have tools to predict the risk of voltage collapse and transformer thermal response to a 100-year GMD event. A ground-induced current (GIC) estimate is produced and risk assessment is made. Events are analyzed to establish GIC levels; study voltage collapse and transformer thermal risks; and identify corrective actions.

[1] While high-level CME-induced storms may cause voltage collapse, a new study indicates that coronal hole high speed streams from the Sun, and the resulting smaller storms that repeat over the course of months, can result in serious thermal heating in transformers. See CIGRE, "Understanding of Geomagnetic Storm Environment for High Voltage Power Grids," CIGRE Technical Brochure 780, October 2019.

SOURCE: Mark Lauby, "Geomagnetic Disturbances: Reducing Risk to the North American Electric Grid," presentation to the workshop, September 9, 2020, and Mark Olson, "Space Weather Information and Electric Reliability," presentation to the workshop, June 16, 2020.

SWPC warnings, issued up to 30 minutes before GMD event onset, prompt additional operator actions, including monitoring of system voltage and reactive power resources in critical areas, starting of offline generation, further restricting system maintenance, and limiting electricity supply transfers out of areas where supply constraints are being observed or are anticipated. Alerts indicate that the GMD event has started and observed GMD conditions have crossed a preset threshold.

SWPC has developed a new near-real-time geoelectric field mapping capability that provides improved situational awareness to system operators. Completion of the U.S. magnetotelluric survey is needed to

FIGURE 5.2 Low Earth orbit (LEO) satellite operations. SOURCE: Steve Jolly, Lockheed Martin Space Systems, "Satellite Operations," presentation to the workshop, June 16, 2020.

expand the coverage of this geoelectric field map to the entire contiguous United States. Survey results are also being used by electric industry planners to inform GMD vulnerability assessments.

The Electric Power Research Institute is concluding a 2-year research program that has brought together the elements of the system from Earth conductivity maps, and geoelectric field evaluation to the analysis of the elements in the power grid (e.g., transformers). The electric industry applies this research to make GMD vulnerability assessments as accurate and complete as possible.

SPACECRAFT DESIGN AND MISSION OPERATIONS

Space weather is the main source of uncertainty in the position of all objects in LEO below about 1,000 km. The main impact is strong variation in the neutral density of the thermosphere as it responds to radiative inputs from the Sun in the extreme ultraviolet wavelength range, energetic particle precipitation in the high-latitude auroral zones, and global-scale electrical currents generated during geomagnetic storms.[11]

Managing the rapidly increasing number of satellites on orbit and the need for improved forecasts of space weather and understanding of its impacts on satellite operations and space traffic management was a subject at both the June and September workshop sessions.[12]

As shown in Figure 5.2, satellite operations are already being impacted by the large number of objects in LEO. The point of closest approach of two objects is called a conjunction and the process performed for mitigating the risk of an operational satellite colliding with a cataloged object is known as a conjunction

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[11] Per remarks from workshop participants Berger, Sutton, and Thayer as reported in T.E. Berger, M.J. Holzinger, E.K. Sutton, and J.P. Thayer, 2020, "Flying Through Uncertainty," *Space Weather* 18(1), https://doi.org/10.1029/2019sw002373.

[12] See Steve Jolly, Lockheed Martin Space Systems, "Satellite Operations," presentation to the workshop, June 16, 2020; Ted Muelhaupt, The Aerospace Corporation, "The Impact of Space Weather on Space Traffic Management in the NewSpace Era," presentation to the workshop, September 10, 2020.

(assessment risk) analysis.[13] Participants at the workshop were informed that the increasing number of objects is leading to an excessive number of conjunction (collision) warnings. Some operators are receiving 10 warnings a day. Addressing the warnings and determining if avoidance maneuvers are necessary is an increasing burden for satellite system operators, especially for smaller operators with limited resources.

SPACE TRAFFIC MANAGEMENT AND SPACE SITUATIONAL AWARENESS

In June 2018, the White House released Space Policy Directive 3 (SPD-3), *National Space Traffic Management Policy*. SPD-3 recognizes that space is becoming increasingly congested and contested, presenting challenges for the safety, stability, and sustainability of U.S. space operations, including the ISS. SPD-3 identifies emerging commercial ventures such as satellite servicing, debris removal, in-space manufacturing, space tourism, and new technologies enabling small satellites and very large constellations of satellites. Current government policies and processes do not adequately address these new activities.

There are currently over 2,000 operational satellites in orbit; however, three American companies alone have applied for licenses to launch a combined 57,000+ satellites over the next decade.[14] In addition, the NASA Orbital Debris Program Office indicates there are more than 23,000 pieces of orbital debris larger than 10 cm in diameter, and approximately 500,000 particles between 1 and 10 cm. Maintaining a safe space environment is paramount to U.S. security and economic vitality. The global space economy is approximately $400 *billion*, with about 80 percent commercial activity, almost half attributable to the United States.

Timely and actionable space traffic management (STM) and space situational awareness (SSA) data and services are essential for safe and efficient space activities. SPD-3 indicated that a civil agency should be the focal point for the execution of duties associated with STM and SSA, and designated the Department of Commerce (DOC) as that civil agency. Within DOC, the Office of Space Commerce (OSC) was selected as the agency responsible for developing and implementing DOC's efforts to support STM and SSA. In 2020, Congress called for the National Academy of Public Administration (NAPA) to assess which federal department or agency is best suited for responsibility for space traffic management. On July 20, 2020, NAPA released the *Report on Space Traffic Management*.[15] The NAPA report recommended that the DOC/OSC lead collaborative federal efforts to improve the safety and sustainability of the space domain.

The NAPA report described SSA as the characterization of the entire near-Earth space environment including space object location and physical characteristics, and the natural space environment as characterized by space weather data, analysis, and forecasts. The largest uncertainty in determining orbits for satellites operating in LEO is atmospheric drag, which can vary significantly during space weather storms. Electrostatic discharge and single event effects associated with space weather events are also a concern for satellite operators.

As described at the workshop, the OSC is moving forward in establishing capabilities for private industry and international SSA notifications. SPD-3 directs DOC to develop a modern, open architecture data repository (OADR) as the place from which to ultimately provide conjunction notifications. The OSC will soon launch the OADR leveraging cloud-computing resources already available within NOAA. Data from NOAA/SWPC and from NASA's database of micro-meteorites will be the first data sets available in the OADR. These data will be key input to ensure timely, precise conjunction analysis and notification to private sector and international users. According to workshop participants, OSC is actively engaged with international allies and finding great interest—spurred in part by their private-sector companies—in

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[13] National Research Council, 2011, *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13244.

[14] J. Morin, 2019, "Four Steps to Global Management of Space Traffic," Comment, *Nature* 567: 25.

[15] National Academy of Public Administration, 2020, *Report on Space Traffic Management*, August, http://napawash.org.

bringing civil capabilities to bear on emerging issues in SSA and STR; these allies also support use of an open architecture.

In summary, presentations and discussions at the workshop indicated that the connection between space weather and SSA is critically important, and that working together with the private sector is essential to ensure that the necessary measurements are available to support the fast-developing global needs for satellite-based products and services.

COMMERCIAL AVIATION

Insights regarding civil aviation interests were provided by Mike Stills;[16] a summary follows.

Federal regulations require authorization of commercial flights which place requirements on the dispatcher and the pilot. The dispatcher and pilot have to be familiar with the weather forecast/conditions along the flight route, and must have two-way communication over the entire route, a particular issue for transpolar flights. The current operational scheme relies on radio frequency (HF and VHF) communications, to be enhanced in the future by a space-based communications network, FANS (Future Air Navigation System).

Airlines have a regulatory basis for looking at space weather in addition to other aspects of weather. In November 2018, the International Civil Aviation Organization selected SWPC as one of the three global space weather centers (SWXCs) to monitor and provide advisory information on space weather phenomena expected to affect high-frequency radio communications, communications via satellite, GNSS-based navigation and surveillance systems, and/or pose a radiation risk to aircraft occupants.[17]

The SWXCs are required to disseminate advisory information to a variety of users regarding the extent, severity, and duration of the space weather. The key parameters generally relevant include any changes in solar conditions that impact the radio frequency communications environment, in particular, ionospheric D-region absorption. For polar routes, auroral absorption is important. This imposes a need to be able to forecast conditions on timescales sufficient to plan routes. Current indices used in planning include the planetary K index as well as GOES (Geostationary Operational Environmental Satellite) monitoring of X rays and energetic particle events.

Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) associated with a space weather event may create a cascade of other high-energy particles and secondary particles that can have significant health effects to airline crew and passengers, especially when flying over polar routes (Figure 5.3). In response to warnings, pilots may fly at lower altitudes where the higher atmospheric density reduces the threat from ionizing radiation, or even divert in their planned routing to avoid higher-latitude regions where exposure risk is higher. Both steps increase flight costs.

[16] Mike Stills, past director, Flight Dispatch (Network Operations) United Airlines, “Commercial Aviation,” presentation to the workshop, June 16, 2020.

[17] The other International Civil Aviation Organization-designated space weather providers are the Pan-European Consortium for Aviation Space Weather User Services (PECASUS: Austria, Belgium, Cyprus, Finland, Germany, Italy, Netherlands, Poland, and the United Kingdom; see http://pecasus.eu/) and the consortium of Australia, Canada, France, and Japan (ACFJ, see https://www.swpc.noaa.gov/sites/default/files/images/u59/05%20David%20Boteler%20Official.pdf).

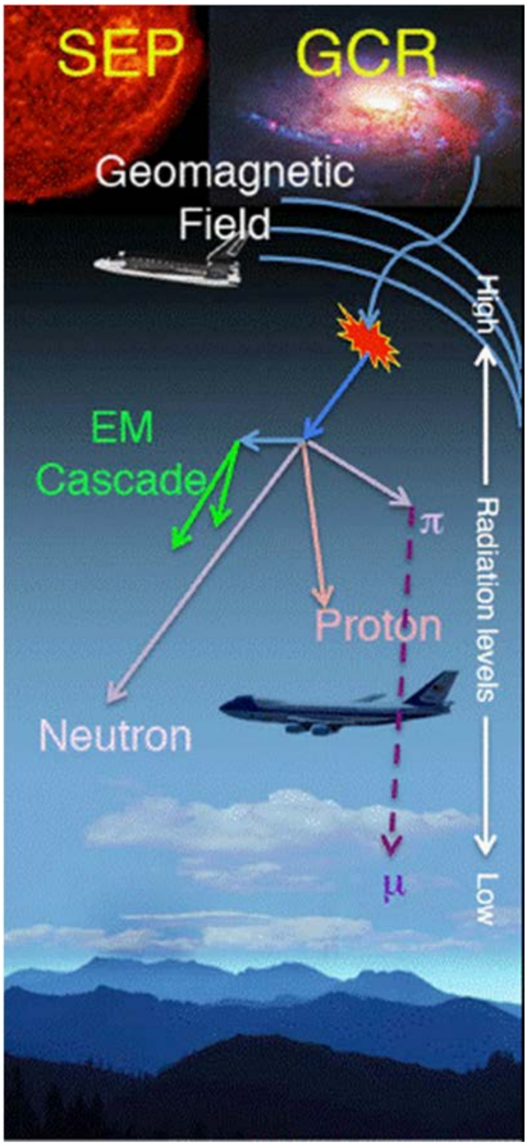

FIGURE 5.3 Galactic cosmic rays (GCRs) and solar energetic particles (SEPs) may create a cascade of other high-energy particles and secondary particles that can have significant health effects to airline crew and passengers. SOURCE: Lika Guhathakurta, 2020, "Next Generation Ionizing Radiation Characterization from Aviation Altitude to Deep Space," presentation at Heliophysics Summer School, July 17, https://cpaess.ucar.edu/heliophysics/summer-school/2020-schedule.

Extreme space weather events fall into a category of natural hazards that have potentially high impact, but occur with low probability. However, while the most recent extreme event (actually events) dates to the "Halloween storms" of 2003,[18] significant SEP events that disrupted radio communications over the polar cap occurred in January 2005 and during the last solar activity maximum in 2012-2014. An issue noted at the workshop was how aviation training and operations can maintain an awareness of the potential for a significant space weather impact even during times of low solar activity. In addition, it was noted that the impact of space weather and, in particular, the radiation environment via SEP events on air crew and passengers, will grow as the number of transpolar routes increases.

[18] N. Gopalswamy, L. Barbieri, E.W. Cliver, G. Lu, S.P. Plunkett, and R.M. Skoug, 2021, "Introduction to Violent Sun-Earth Connection Events of October–November 2003," *Journal of Geophysical Research: Space Physics* 110(A9). A potentially very-high-impact space weather event that missed Earth occurred in 2012; see D.N. Baker, X. Li, A. Pulkkinen, C.M. Ngwira, M.L. Mays, A.B. Galvin, and K.D.C. Simunac, 2013, "A Major Solar Eruptive Event in July 2012: Defining Extreme Space Weather Scenarios," *Space Weather* 11: 585– 591, doi: 10.1002/swe.20097.

HUMAN SPACEFLIGHT

In December 2017, the White House released SPD-1, *Reinvigorating America's Human Space Exploration Program*. SPD-1 calls for a U.S.-led, integrated program with private sector partners for a human return to the Moon, followed by missions to Mars and beyond. In response, NASA committed to landing U.S. astronauts, including the first woman and the next man, on the Moon by 2024. Through collaboration with commercial and international partners, NASA's Artemis program[19] calls for investigation of the lunar surface in previously unexplored regions, starting with the lunar South Pole. The return of human spaceflight to destinations outside the protection of Earth's atmosphere and magnetic field introduces new challenges for NASA. Enhanced capabilities for the characterization and forecasting of the space radiation environment will be vital to protect astronauts during these missions.

Human exploration places additional constraints on space weather both in terms of the timeliness of the prediction and the ability to extrapolate to conditions at a location removed from that of the sensors themselves.[20] Human operations and exploration of the Moon and Mars present significant challenges. The ISS environment is, by comparison, fairly well understood, with regular, predictable hazards (e.g., South Atlantic Anomaly and the polar region). In LEO, SEPs are a polar region phenomenon. Threats beyond LEO include GCRs as well as SEPs.

Requirements differ for different mission types. For example, the goal is to design around radiation standard models for a range of events. Timescales for predictions vary depending on the mission—lunar excursions, critical maneuvers, and missions to Mars. Each demands a different temporal fidelity. The return to the cis-lunar environment and robotic exploration in that environment increases challenges—for example, radiation shielding outside Earth's atmosphere and magnetosphere.

Solar storms may generate a substantially enhanced intensity of energetic charged particles, mostly protons accelerated during solar flares and CMEs. Major concerns for human spaceflight include such solar particle events (SPEs) during which the flux of protons with energies greater than 10 MeV exceeds 10 pfu (particle flux unit; 1 pfu = 1 particle per square cm per second per steradian), and protons with energies greater than 100 MeV exceed 1 pfu. These events may require the crew to shelter in protected areas within orbital vehicles or surface habitats, leading to canceled lunar surface explorations for example. Generally, X-ray flares are not a concern for ISS astronaut safety unless they are accompanied by a significant increase in SEPs. Earth's magnetic field generally deflects SEPs except near the Earth's poles, away from the ISS orbit. A major geomagnetic event could enlarge the polar holes to mid- to low latitudes, exposing ISS to increased exposure if the event is accompanied by enhanced flux of SEPs.

Neutrons are produced by both GCR and SPEs in secondary reactions within shielding and from the surrounding lunar surface. These additional neutrons contribute significantly to astronaut exposure within vehicles. The planetary (or lunar surface) neutron albedo is not an issue in Earth orbit due to the presence of the thick, absorbing atmosphere, but must be accounted for in exploration missions.

The Space Radiation Group (SRAG)[21] at NASA Johnson Space Center monitors space weather conditions for NASA's human exploration program. This is generally adequate for ISS operations. Beyond Earth orbit, operational warning and actions must reflect the evolution of the event (<5 hours), which can be an issue for extra-vehicular activities, including lunar surface excursions. NASA will continue to use SWPC for forecasting NASA particle monitors and dosimeters for real-time radiation levels. Human exploration and radiation threat assessment are different from the focus of the scientific community. Needs

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[19] Artemis is the umbrella under which NASA's lunar plans reside as part of a broader Moon-to-Mars approach; NASA hopes to establish a sustainable human presence on the Moon by 2028. NASA has created a website for Artemis at https://www.nasa.gov/artemisprogram.

[20] See Eddie Semones, Space Radiation Analysis Group, NASA Johnson Space Center, "Human Exploration and Radiation, presentation to the workshop, June 17, 2020.

[21] NASA, 2019, "Space Radiation Analysis Group—NASA, JSC," https://srag.jsc.nasa.gov/MissionSpace Weather/SpaceWeather.cfm.

are centered on reliable all-clear and event forecasts, peak flux and temporal evolution, as well as duration predictive capability rather than replicating past events.

SRAG and the CCMC[22] (Community Coordinated Modeling Center) have collaborated on a joint project to assemble an Integrated Solar Energetic Proton Event Alert/Warning System (ISEP). This integrated product is intended to incorporate research into actionable information. Challenges remain to communicate evolving forecast needs and to support cis-lunar operations. Building the foundation for future human Mars missions is the final goal.

PNT-RELIANT INDUSTRIES

The following is based largely on the presentation of Susan Skone.[23]

As society becomes increasingly dependent on PNT services, so too is the importance of understanding and mitigating space weather impacts on Global Navigation Satellite System (GNSS) systems. According to Skone,

- PNT is critical to defense, agriculture, transportation, marine, surveying, and emerging industry applications;
- Timing applications include financial services and mobile networks;
- There is currently approximately $200 billion annual GNSS revenue (devices and services);[24]
- The added-value markets for road and consumer solutions is growing (>50% of global GNSS revenue).

Space weather is known to impact PNT via polar/auroral structures, equatorial irregularities, and mid-latitude variability. The Federal Radio Navigation Plan of 2019 established requirements for user positioning and navigation and sample timing requirements. Next step benchmarks include examining the impact of ionospheric disturbances. The key needs are insuring that phenomena are parameterized correctly; physical properties are captured; and these phenomena are translated to operator impacts.

New capabilities are coming on-line including dual-frequency GNSS smart phones with 30 cm localization. It should be noted that the IoT will be impacted by ubiquitous position information. This technology can be used to support science as illustrated with an example using TREx—a distributed network of auroral imagers across Canada.

PNT plays an important role in the telecommunications industry. Cell phone towers require the timing signal from GNSS but can maintain their own independent timing for about 2 hours. Note that the cell phone tower only needs one good signal from a single GNSS satellite.

Plans to improve the monitoring of space weather in the high latitude regions—regions currently lacking dense networks of atmospheric sensors[25]—was described in the presentation of Bob McCoy, who directs the Geophysical Institute of the University of Alaska. The institute also has many capabilities for carrying out scientific research, and its facilities include the Alaska Aerospace launch facility that uses space weather information for the North Polar Region.

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[22] See NASA, 2018, "CCMC: Community Coordinated Modeling Center," https://ccmc.gsfc.nasa.gov/.

[23] Susan Skone, University of Calgary, Canada, "PNT-Reliant Industries," presentation to the workshop, June 17, 2020.

[24] For the value of GNSS, see European Commission Publications Office, 2019, "GNSS Market Report," Issue 6, https://www.gsa.europa.eu/system/files/reports/market_report_issue_6.pdf, and I. Leveson, 2015, "The Economic Value of GPS: Preliminary Assessment," Leveson Consulting, https://doi.org/www.gps.gov/governance/advisory/meetings/2015-06/leveson.pdf.

[25] A. Coster, S. Skone, D. Hampton, and E. Donovan, 2017, "Monitoring Space Weather with GNSS Networks Expanding GNSS Networks into Northern Alaska and Northwestern Canada," *Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017)*, September.

6

Strategic Knowledge and Observation Gaps

The "Strategic Knowledge and Observations" session considered how the physical understanding of space weather phenomena enters into the applications domain in diverse and complex ways that do not naturally lead to a simple one-to-one mapping. The goal of the basic research is to understand the causes and development of a particular natural phenomenon, be it a solar flare that produces a radio burst, a change in the magnetic field producing enhanced ionospheric current systems, or an ionospheric electrojet that produces scintillation-making structures.

While the space environment as a whole is often separated into spatial domains where different expertise is required, it is also a highly coupled system and its various behaviors are generally inter-related. For example, a user is interested in forecasts of induced currents during a geomagnetic storm. A geomagnetic storm's intensity and progression is determined by the details of the process that creates a coronal mass ejection (CME) at the Sun that produces a disturbance with particular attributes in the solar wind at the location of Earth that in turn responds in different ways depending on conditions in the magnetosphere and upper atmosphere at the time of impact. Such chains are common and do not typically lend themselves to concise cause-and-effect relationships. However, there are usually certain missing or inadequately covered areas of knowledge that have the potential to make major differences in forecasting. To incorporate this point, the organizing committee selected a few high profile, known observation and knowledge "gaps" that, if filled, would greatly improve the prospects for achieving National Space Weather Action Plan (NSWAP) forecasting goals.

SUN/HELIOSPHERE GAPS

The Sun is the ultimate driver of much of Earth's space weather environment, through its effects on Earth's surface and atmosphere at its lower boundary, to the variable solar wind particles and fields that both form the magnetosphere and control the planets' exposure to galactic and solar cosmic rays (see Figure 6.1).

FIGURE 6.1 Many solar outputs affect Earth's space environment. SOURCE: NASA, 2013, "Heliophysics and Space Weather," December 2, https://svs.gsfc.nasa.gov/30481.

The strategic knowledge that is central to the nowcasting and forecasting of solar effects concerns the state of the solar magnetic fields, the coronal structure that depends on those fields, and the related electromagnetic emissions in a broad range of wavelengths from radio to X ray. Various users of this information are often interested in (1) the general fluxes of solar extreme ultraviolet (EUV) emission over time scales of days to years—for use in various space weather models ranging from satellite drag/orbit decay to ionospheric properties, (2) the level of solar activity in the forms of flares and CMEs that are precursors to disruptions of systems such as power grids and pipelines, Global Positioning System (GPS) and other spacecraft, and space launch operations; or (3) the fluxes of cosmic rays at commercial aviation, the International Space Station (ISS), and satellite altitudes.

The corresponding knowledge of the solar wind plasmas and fields, especially at the L1 point ~200 Re (1.5 million km) upstream of Earth where SWFO-L1 will be stationed, provides the user with the local interplanetary conditions that will affect Earth both almost instantly (X rays and energetic particles), and in roughly 30-45 minutes in cases where the incident solar wind plasma and field conditions are of interest. These conditions are often used in models—some of which are L1 data-driven—for a wide range of geospace consequences ranging from energetic particle exposure of Earth-orbiting spacecraft and the ISS, to forecasting the expected strengths of the magnetospheric ring current and auroral electrojets, and their related upper atmosphere and ionosphere perturbations.

The topics selected for this session represent long-identified, high-profile issues in improving capabilities within the National Oceanic and Atmospheric Administration's (NOAA's) Space Weather Prediction Center (SWPC), and within other agencies and entities that both generate and use space weather information. The first presentation highlighted the now-appreciated importance of understanding the global Sun in making both nowcasts and longer-lead forecasts for Earth's space environment. The second presentation topic, "Bz," or the north-south component of the local interplanetary field, was chosen in recognition of its critical importance in determining the geospace response to solar activity, and because it has proven to be a particularly difficult task to predict it for the purpose of forecasting geomagnetic storm severity. As noted in the discussions that followed the presentation by Pete Riley of Predictive Science, Inc., an enhanced Bz at L1 from a CME that is pointing northward or southward can determine the difference between a modest geomagnetic disturbance and a Carrington-class event.[1]

The third session topics address the recent trend toward realizing the potential superiority of off-Sun-Earth-axis observations for forecasting purposes. For example, the direction and velocity of an Earth-bound CME, which impacts its "geoeffectiveness," is better determined from observations at L5 or L4 than L1. The final topic is more climatological in nature, relevant to both decadal-scale solar activity–level forecasting and is also relevant to tracking longer term trends in cosmic ray and solar EUV fluxes.

The following section is a summary and synthesis of the views expressed by the following workshop presenters:[2]

- Janet Luhmann, Space Sciences Laboratory, University of California, Berkeley, Session Chair
- Todd Hoeksema, Stanford University, "Value of Solar Farside and Polar Perspectives"
- Pete Riley, Predictive Sciences, Inc., "Bz Forecasting"
- Mark Gibbs, UK Met Office, "L5 Perspective"
- Natchimithuk Gopalswamy, NASA GSFC, "L4 Perspective"
- Lisa Upton, Space Systems Research Corporation, "Solar Activity Cycle Forecasting"

A theme expressed in this session was that the space weather community is now in a position to take advantage of global, whole-Sun and coronal "situational awareness," derived largely from multi-wavelength, multi-perspective imaging of the Sun combined with integrative modeling. The Sun is a constantly evolving, sometimes highly dynamic star that affects Earth's space weather in a variety of ways, requiring different information for both long-term-trend monitoring and shorter-term nowcasting and forecasting. For example, flares—related to ionospheric perturbations and communications disruptions—are often detected and ranked by their radio and disk-integrated X-ray emissions, with EUV images providing details of their location and coronal context.

CMEs are observed in combinations of coronal EUV emissions and scattered white light beyond the limb imaged by coronagraphs. CMEs that have the largest impacts on Earth's magnetosphere and geospace most often originate just west (to the right in the solar disk definition) of the central meridian. These typically take 2-4 days to arrive, although in extreme cases <1 day delays have been experienced. The enhanced solar wind plasma and magnetic field associated with the arrival if the interplanetary mass ejection (ICME; defined as the in situ counterpart of the CME observed in coronagraph and EUV images), can last hours or days depending on the details of the disturbances. Of primary interest is its speed, including whether it is preceded by a shock, with its following dynamic pressure enhancement from the plowed-up solar wind ahead of the coronal ejecta, and the magnetic field strength and orientation throughout its passage.

Solar energetic particles (SEPs), also referred to as solar cosmic rays, generally precede and accompany ICMEs, with their fluxes sometimes the highest upon arrival of the ICME shock. However, the most energetic ("hardest") and fastest arriving SEPs often arise from events close to, and sometimes behind, the western limb. Considering both these possibilities, forecasting a potentially significant SEP event ultimately involves identifying potentially eruptive sites both on and behind the solar disk visible from L1. However ICMEs are particularly important to space weather watchers because they can have a broad range of space environment, upper atmospheric, and surface consequences. These may include radiation belt and

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[1] The solar flare on September 1, 1859, and its associated geomagnetic storm remain the standard for an extreme solar-terrestrial event. For a popular description of the event, see C. Klein, 2012, "A Perfect Solar Superstorm: The 1859 Carrington Event," *History.com*, March 14, https://www.history.com/news/a-perfect-solar-superstorm-the-1859-carrington-event. Technical details are at E.W. Cliver and W.F. Dietrich, 2013, "The 1859 Space Weather Event Revisited: Limits of Extreme Activity," *Journal of Space Weather and Space Climate* 3: A31, https://doi.org/10.1051/swsc/2013053.

[2] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

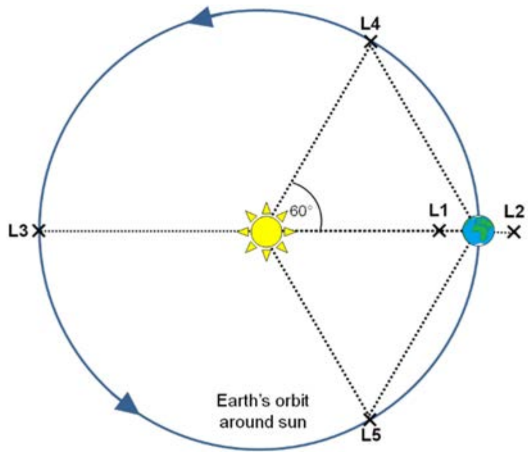

FIGURE 6.2 Illustration of the L1-L5 Earth-Sun Lagrangian point locations; planetary bodies and Sun not to scale. SOURCE: UK Met Office, 2018, "Watch This Space!" March 23, https://blog.metoffice.gov.uk/2018/03/23/watch-this-space.

auroral enhancements, upper atmosphere heating and ionospheric current generation, and induced currents in conductors on the ground related to ring current injections associated with the dynamically changing boundary conditions presented by the ICME.

For nonexplosive phenomena, lower cadence observing is often sufficient. Coronal holes near the central meridian can produce high-speed solar wind streams and interstream compressions that modulate geomagnetic activity and the radiation belts on a regular basis-sometimes over a sequence of ~27 day solar rotations. Unlike the flares and CMEs produced by rapidly evolving active regions, these are related to relatively steady coronal structures that can have months-long lifetimes—making it possible to use solar observations well-east of the central meridian to forecast solar wind-related responses in geospace days to weeks later.

Results of longer-term investigations relating the 1 AU ecliptic measurements to the sunspot numbers and other solar activity measures are also of interest. The recent weak sunspot cycles have been accompanied by some on-average weaker solar wind parameters, including the interplanetary field magnitude and solar wind density. These, together with the related weaker solar EUV fluxes, have changed the average conditions in geospace, resulting in generally weaker geomagnetic storms and consequences. Solar cycle prediction studies not based on persistence, on the other hand, are built on real or partially physics-based modeled global solar behavior, usually relying on magnetic field and surface velocity measurements requiring synoptic observing programs providing regular, inter-calibrated images over long periods of time.

Based on this current knowledge, some participants advocated for a "whole heliosphere approach" (not just Sun-Earth line) with measurements/predictions on four timescales: (1) photon radiation events (seconds to minutes), (2) SEP events (minutes to days), (3) local magnetic field and solar wind plasma disturbances (days to years), and (4) space climate (years to centuries). In part based on the experience of whole-Sun observing with STEREO (Solar Terrestrial Relations Observatory), observations taken at the L5 and L4 Lagrangian points (Figure 6.2) have become a widely discussed option for continuous space-based imaging and in situ measurements.

The L3 location could potentially fulfill the desire for regular "farside" information on the solar magnetic fields and EUV structures invisible from Earth, but destined to rotate into view, allowing global model-based forecasting of the fields and structures expected to affect Earth several weeks ahead. While simpler line-of-sight solar surface magnetic field measurements at L3 may be adequate for this purpose (vector measurements are highly desired from L1), the same measurement cadence is needed as at L1 for global situational awareness.

The roles of similar measurements from the "side-looking" L4 and L5 perspectives are also of value for global perspective and modeling, however the three observing sites (L1, L4, and L5) would always leave a gap in the global picture if not carried out in combination with L3 measurements. For example, one space-based observatory concept "SHOES" (Solar-Heliospheric Optical Environment Satellites) was described where a Sun-surrounding constellation could provide the essential imaging and in situ observations, based on what was available from various mission programs and sponsors. In some ways, the present Heliophysics Observatory[3] is used in this spirit, NASA's individual-mission-focused strategy (at least for the prime phase of operation) results in a system that depends to a large extent on the serendipity of the locations and timing of various missions relative to the solar and heliospheric events of interest.

A potentially revolutionary leap in knowledge would result from a similarly instrumented mission with a solar polar perspective. In particular, the out-of-ecliptic imaging perspective provides an opportunity to observe the full longitudinal extent of CMEs, including those that will perturb Earth's space environment. While the STEREO mission imagers allowed some multidimensional model-aided rendering of CMEs, the lack of the out-of-ecliptic third viewpoint needed for three-dimensional (3D) constraints was limiting.

The Sun's polar magnetic fields also figure prominently in the boundary conditions for coronal and solar wind modeling used in forecasting. Presently they are reconstructed using synoptic ground-based or space-based magnetograms, stitched together to form a map of the global solar magnetic field. Because the poles are poorly observed from the ecliptic perspective, schemes have been developed to "fill in" the fields there based on the occasional observations at times when the solar axis is tilted toward or away from Earth as the year progresses, or by "evolving" the surface field in time using physics-based simulations of the surface fields.

The Solar Orbiter mission, launched on February 9, 2020, will achieve a fairly high inclination (as much as 35° with respect to the Sun's equator), has an instrument suite that provides both imaging and magnetograms,[4] but it is in an elliptical orbit that constantly changes its perspective. Thus, while it will provide the first full observations of one pole for a period of several months every orbit, it will not provide the kind of regular synoptic information needed for space weather purposes. Nevertheless, the new insights from the Solar Orbiter may well have significant impact on the design and physics of global coronal and solar wind forecast models. The stationing of a permanent solar polar monitoring platform is desired for both research and operational purposes.[5] Concepts relevant to achieving this future objective were presented during the workshop poster session.[6]

There are perhaps more obvious, and immediately useful observational benefits from an L5 mission, where a spacecraft is stationed at the Lagrangian position trailing Earth (see Figure 6.2). As the Sun rotates in a right-handed sense with a period of roughly 27 days, an active region or a coronal hole observed in the center of the disk by an imager at the L5 location would be in the center of the disk seen from Earth about 4 days later. The L5 perspective thus regularly provides a preview of conditions that will affect its space environment several days in advance, as long as the solar and coronal conditions evolve in a predictable

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[3] NASA's Heliophysics flight missions form a fleet of solar, heliospheric, geospace, and planetary spacecraft that operate simultaneously to understand the dynamics of the solar system. This fleet can be thought of as a single observatory, the "Heliophysics System Observatory (HSO)." From NASA, "Heliophysics System Observatory (HSO)," at https://www.nasa.gov/content/goddard/heliophysics-system-observatory-hso.

[4] European Space Agency, 2020, "Solar Orbiter Instruments," https://www.esa.int/ESA_Multimedia/Images/2020/01/Solar_Orbiter_Instruments. See also S.K. Solanki, J.C. del Toro Iniesta, J. Woch, A. Gandorfer, J. Hirzberger, A. Alvarez-Herrero, T. Appourchaux, et al., 2019, "The Polarimetric and Helioseismic Imager on Solar Orbiter," *Astronomy and Astrophysics* 642: A11, https://doi.org/10.1051/0004-6361/201935325.

[5] S.E. Gibson, A. Vourlidas, D.M Hassler, L.A. Rachmeler, M.J. Thompson, J. Newmark, M. Velli, A. Title, and S.W. McIntosh, 2018, "Solar Physics from Unconventional Viewpoints," *Frontiers in Astronomy and Space Sciences* 5, https://doi.org/10.3389/fspas.2018.00032.

[6] These included HISM (The High Inclination Solar Mission) and Solaris (SOLAR sail Investigation of the Sun). HISM is a concept study, conducted at the Marshall Space Flight Center, Advanced Concepts Office (ACO), which would use a large solar sail for thrust to maneuver out of the ecliptic. Solaris, led by Don Hassler of the Southwest Research Institute, is one of five science investigations selected as a possible future NASA MIDEX mission. It would first travel to Jupiter and use the planet's gravity to slingshot out of the ecliptic plane and fly over the Sun's poles at 75 degrees.

(modelable) way. In addition, when an Earth-directed CME occurs, the L5 imagers obtain details of its direction, latitudinal extent and speed that cannot be readily obtained from Earth's perspective.

In situ instruments would measure the solar wind plasma and field properties that would be experienced at L1 in several days provided that the coronal structures controlling the ecliptic solar wind streams maintain their configuration over that time span—a situation often realized during undisturbed times. The desirable instruments for an L5 mission are mostly the same as those for L1 missions, including EUV imagers and coronagraphs, plus in situ instruments (solar wind plasma, magnetic field, and energetic particles). However, participants noted that a magnetograph is also important for the purpose of evaluating the evolution of magnetic fields rotating onto the Earth-facing disk, including flare and CME-producing features.

Similarly, a Heliospheric Imager, like those on the STEREO mission to image the propagation of CMEs from the corona to Earth in faint scattered white light, provides the opportunity to monitor the evolution of the structure as it interacts with the ambient solar wind along the way—affecting its properties and time of arrival. Considering there is currently +/−12 hours accuracy in the estimated arrival time for an ICME based on current (L1) observations alone, the regular availability of a heliospheric imager watching the Sun-to-Earth space would represent a significant advancement in predictive space weather capability. Plans in process for an European Space Agency (ESA) L5 mission, "Lagrange," are perhaps the most developed at this writing. Both NOAA and NASA are involved in that endeavor in various collaborative roles.

There are also distinct advantages of an alternative (or added) L4 Lagrangian point monitor, located at the same longitudinal separation, but instead leading Earth in its orbit (Figure 6.2). This location would allow for the same Sun-to-Earth imaging of Earth-directed CMEs as the L5 point. Moreover, this additional perspective on CME/ICME appearance and behavior would further constrain any predictions of Earth impacts, give the added ability to properly visualize, orient and infer the direction of the 3D, traveling structure. Although an L4 monitor would not have the ability to preview solar features and solar wind structures that would affect Earth days later, it would replace that L5 contribution with a different unique ability for major SEP event forecasting.

CMEs/ICMEs move predominantly in the radial direction from the Sun, extrapolation of their average trajectory is fairly straightforward-even though they change shape and speed. However, SEPs to first order travel from their sources in flares or at interplanetary shocks along the Archimedean spiral magnetic field lines of the Parker Spiral interplanetary field.[7] The most energetic SEPs are generally born close to the Sun in either flare sites or at fast CME shocks when they are still low in the corona. Tracing the nominal Parker Spiral shape from Earth back to the Sun intersects the Sun west of the central meridian, where ~80% of SEP events originate. Sometimes this location can be near or behind the west (right hand in images) limb, making the source event/region invisible from L1 (and especially from L5).

Occasionally SEPs can reach ~GeV energies and travel at nearly the speed of light along the Parker Spiral field to Earth, at about the same time the flare or fast CME is detected in solar images. Observing the magnetic field structure of evolving active regions from L4 could contribute to early pre-event warnings or could contribute to "all clear" forecasts when eruptions are deemed unlikely. An EUV imager at L4, supplemented by an X-ray detector and radio antenna for detecting the Type II radio bursts associated with a shock wave in the corona, would provide the possibility for several minutes warning for astronauts on an EVA in an exposed part of near-Earth space.

An added benefit of the L4 location for Earth-directed CME/ICME imaging is that this location avoids the SEP-produced "snowstorm" of background noise in the solar images because of its geometry relative to Earth. It was suggested that the combination of L1, L5, and L4 missions with similar instrumentation

[7] "The heliospheric magnetic field (HMF) is the extension of the coronal magnetic field carried out into the solar system by the solar wind. It is the means by which the Sun interacts with planetary magnetospheres and channels charged particles propagating through the heliosphere. As the HMF remains rooted at the solar photosphere as the Sun rotates, the large-scale HMF traces out an Archimedean spiral." From M.J. Owens, R.J. Forsyth, 2013, "The Heliospheric Magnetic Field," *Living Reviews in Solar Physics* 10: 5, https://doi.org/10.12942/lrsp-2013-5.

would fulfill most needs for a space weather infrastructure with improved outcomes based on observables alone.[8]

Attention was also focused at the workshop on a particularly important and challenging forecasting problem without which Earth impacts are essentially impossible to evaluate: inferring the direction and strength of the out-of-ecliptic (North-South) component of the interplanetary magnetic field Bz in Earth-bound ICMEs. As mentioned above, because of the nature of the solar wind interaction with Earth's nearly dipolar global field, a large southward component of the interplanetary field literally opens the magnetospheric shield external driving and other influences. Thus an ICME which carries large southward Bz can cause major consequences compared to the same ICME with a flipped Bz polarity.

Research has led to various Bz forecast attempts and techniques: mechanistic, statistical, and empirical. Most of the long lead-time approaches have used solar magnetograms and coronagraph images to envision the magnetic topology of the erupting 3D structure. The structure is then either assumed to simply expand outward to 1 AU, with their basic geometry unaltered by the solar wind interaction, or is fed into a solar wind propagation model/simulation that provides at least a rough estimation of the expected sign of the arriving Bz. But there are intrinsic uncertainties in this methodology: 45 percent of ICMEs have no observed solar event, including 10 percent producing moderate-to major geomagnetic storms. Only 56 percent of halo CMEs produce the flux rope-like magnetic clouds at L1 often assumed by these models.

The other observational possibilities are either remote-sensing the sign of Bz in the CME/ICME views from the side (e.g., L5 or L4) using radio signal Faraday rotation, light polarization along the Sun-Earth axis, or one or more spacecraft measuring in situ plasma and field closer to the Sun than L1. Numerical simulations of the full eruption and propagation process provide an alternative, but these must be data-driven and perhaps assimilative to address real events, and the results of such efforts to date suggest they are not yet in a state to be used operationally. More empirical projections can be made based on previous statistics and probabilities; for example, the ICME flux ropes show systematic solar cycle trends in observed Bz behavior, but these are best suited to climatological uses rather than to individual events. Forecasting the interplanetary field orientation out of the ecliptic, especially in Earth-directed ICMEs, remains a top priority and goal of space weather forecasting for the coming decade.

Long-term solar activity forecasts are of value for advance planning of operational monitoring projects as well as for anticipating extremes in space weather conditions. Every solar cycle NOAA and NASA convene a panel to consider the range of sunspot number predictions offered by the broader scientific community and various space weather forecasting centers, in order to discuss their merits and release an "official" value of the maximum and length. There are 61 sunspot number predictions for Solar Cycle 25. Cycle 24, which lasted 11.4 years, is the fourth smallest on record and the smallest for the Space Age.

An analysis released in 2019 forecasts Cycle 25 to be of comparable magnitude and length to Cycle 24. Part of the rationale behind this latest prediction is that the active region gap that preceded Cycle 24 appears to be similar for Cycle 25. Strong cycles start with active regions at higher latitudes and have significant overlap in their temporal distributions. Both 24 and 25 started/are starting at lower latitudes and exhibit extended sunspot minima including the gap (large number of spotless days) between the cycles in the standard time series and butterfly diagrams.

Of the 61 predictions considered by the panel, significant fractions used numerical methods (e.g., statistics, neural networks), while others used physics-based methods (e.g., polar fields or other precursors, surface flux transport, dynamo modeling). The polar field precursor method is a particularly popular approach, which is of interest considering the lack of observations and understanding of the polar fields described above. The polar fields also figure in the physics-based models, such as surface flux transport, which relates the polar field behavior to the decaying active region magnetic fields of the previous cycle—providing a "memory" or seeding effect from cycle to cycle. The latter is potentially powerful for long-term predictions of solar activity although the physical details of the surface field connections to the solar

[8] Several other mission concepts, presented in the workshop poster session, would expand solar longitude coverage. They include Magnetic Explorer, a Pearl Necklace Concept, and Solar Cruiser.

dynamo activity remains to be understood. Only recently has the science of helioseismology had a long enough and consistent enough record from which to study the solar cycle development in the interior.

On the basis of the solar/heliosphere session presentations, which necessarily focused on only a few of the highest profile topics of interest toward defining future space weather infrastructure, it is possible to see several specific directions of major potential value for the post SWFO-L1 era. Prominent among these was the view that multi-perspective imaging and distributed/multipoint in situ measurements were highly desired. Global perspectives on both the Sun and corona, as well as in the inner heliosphere provide what was deemed invaluable situational awareness and fodder for assimilative model forecasting that can be realized in the next decades. These can address some of the NSW-SAP initiative outstanding goals such as longer-lead forecasting for both geomagnetic storms and space radiation hazards.

For predictions of a major space weather event, the capability to watch a large and complex active region evolve as it rotates onto the visible disk, especially in its magnetic field configuration and EUV emission features, is highly desired. Special challenges such as the prediction of Bz will require modeling/simulation developments that are discussed in a later session of this workshop proceedings. Similarly, solar cycle predictions will require both model development and longer timelines of helioseismology observations to fulfill their promise. Simply realizing action on the set of items featured in this workshop would represent the kind of major advancement sought in the SWFO program of the future.

Table 6.1 provides a summary of workshop presentations and discussions regarding solar and heliospheric knowledge gaps, and options to those fill gaps.

GEOSPACE GAPS

The "Strategic Knowledge and Observations—Geospace" session was organized in a manner similar to the "Sun/Heliopshere Gaps" session summarized above. Speakers at this session were the following:[9]

- Mary Hudson, National Center for Atmospheric Research (NCAR)/High-Altitude Observatory (HAO) and Dartmouth College, *Session Chair*
- Drew Turner, Johns Hopkins University Applied Physics Laboratory (JHU/APL), "Inner Magnetosphere Measurements"
- Delores Knipp, University of Colorado, Boulder, "Low Altitude Measurements—Particles"
- Brian Anderson, JHU/APL, "Low Altitude Measurements—Fields"
- Tim Fuller-Rowell, University of Colorado, Boulder, and NOAA, "Ionosphere Measurements"
- Eric Sutton, University of Colorado, Boulder, "Satellite Drag"

The session covered inner magnetosphere measurement requirements (Turner), particles (Knipp) and fields (Anderson) measurements at low altitudes, and ionosphere (Fuller-Rowell) and thermosphere (Sutton) measurement gaps. Figure 6.3 shows a sketch of an interplanetary shock produced by a CME from the Sun impacting Earth's magnetosphere driving modifications to the radiation belts and enhanced current systems and particle precipitation at high latitudes that ensue from this type of space weather event. Figure 6.4 shows a complementary sketch of the ionosphere-thermosphere system which is coupled to solar and magnetospheric input as well as drivers from below. Dynamic processes in this complex coupled system drive space weather effects extending throughout the domain shown in both figures.

Inner magnetosphere space weather threats related to charged particle radiation effects that require ongoing measurement include the following: (1) total ionizing dose due to MeV electrons and multi-MeV protons, which cause damage to spacecraft over hours to years timescales; (2) single-event effects due to spacecraft-penetrating multi-MeV particles, which can cause instantaneous disruption of spacecraft performance; (3) internal charging due to >100 keV electrons; and (4) surface charging due to ~keV

[9] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

TABLE 6.1 Solar/Heliosphere Knowledge Gaps, Space Weather Operations Impacts, and Measurement Options

Knowledge Gap	Space Weather Operations Impacts	Measurement Options (Some Existing)
Global solar and heliosphere features and behavior (solar photon emissions, magnetic fields, active regions, coronal holes and streamers, solar wind stream structures)	Currently inferred from incomplete or sparse observations, lacking high latitude and farside coverage. This gap limits "situational awareness" modeling and forecasts (e.g., of farside activity affecting Earth; of conditions at remote sites including locations of planetary missions)	• Multi-perspective images (spectrally resolved EUV and visible light, including magnetograms, with additional insights possible from X-ray and radio images); • Multipoint in situ (solar wind plasma, magnetic field, and solar energetic particle) measurements • "Observer" locations optimized for obtaining global information including high latitudes.
Properties of Earth-directed solar wind structures and transient features before their arrival	Currently inferred from solar magnetograms and coronal images, and related models. Unknown details of evolution in-transit limit both the lead time and information content of forecasts.	• Upstream in situ measurements (at L1 and closer to the Sun, of solar wind properties and solar energetic particles (SEPs), with local multipoint option to provide structure orientation); • L5 or Earth-trailing measurements (for evaluating corotation and evolution of 1 AU solar wind properties; • coronal and heliospheric imaging of Earth-directed events and structures); • images from L4 (to assess magnetic connections to near-Sun SEP sources)
Characteristics of potentially eruptive features at the Sun	Currently inferred from helioseismology, solar magnetograms and coronal images, and related models. Unknown details of evolution limit both short and long term (e.g., solar cycle) activity forecasts.	• Helioseismological observations to understand magnetic flux emergence onto the visible disk; • Vector magnetograms for assessing field energization and orientation during evolution (e.g., production of Southward interplanetary field). • Helioseismological observations of solar interior dynamics, and their spatial and temporal trends.

NOTE: This table is a synthesis derived from session presentations and discussions.

electrons. Additional space weather threats for the ionosphere/thermosphere/ground and orbital threats at low Earth orbit (LEO) are discussed below. In discussions, it was observed that additional triage and resolution analysis (forensics) as well as spacecraft design require measurements over disparate timescales, distinguishing between space weather for spaceflight operational decisions and space climatology for space mission design considerations.

A concern of some participants is how radiation belt and ring current energy populations will be monitored going forward now that the NASA Van Allen Probes mission (2012–2019) has ended, as will measurements of energetic electrons and protons at LEO by the National Oceanic and Atmospheric

FIGURE 6.3 Inner and outer zone radiation belts are highlighted in red in this cutaway view of the magnetosphere showing arrival of an interplanetary shock which compresses the dayside magnetosphere, enhances plasma convection from the geomagnetic tail, the ring current at tens to hundreds of kiloelectron volts of energy, field-aligned currents and precipitation into the atmosphere at high latitudes, along with dramatic changes to outer zone electrons. Ultra-low frequency (ULF) waves are excited enhancing diffusive radial transport of radiation belt electrons along with very low frequency (VLF) waves (not shown) are responsible for local acceleration and enhanced atmospheric loss of radiation belt electrons. SOURCE: NASA, "Van Allen Probes," http://vanallenprobes.jhuapl.edu/Multimedia/Images.php.

Administration (NOAA) Polar-orbiting Environmental Satellite (POES) and Department of Defense (DoD) DMSP (Defense Meteorological Satellite Program) spacecraft. In addition, low-energy plasmaspheric electrons, ~eV energy, play a critical role in determining the inner edge of outer zone radiation belt electrons and an important boundary for spacecraft surface charging. Concerning internal and surface charging threats, it was noted that spacecraft charging/discharge monitors on every spacecraft could provide a low-cost resource for anomaly resolution and model development short of direct measurements of the energetic particle environment.

There are differences between the information that users want or need and what scientists study in order to understand the system variability. Operators desire accurate (preferably data assimilative) nowcasts/forecasts of environmental quantities related to various hazards and user-friendly anomaly diagnostic tools. Designers could use climatological models for specific spacecraft and locations. Versions of a Space Environment Monitor on board DMSP and NOAA POES spacecraft began measuring fluxes

FIGURE 6.4 Depiction of the major processes occurring in the atmosphere-ionosphere-magnetosphere system, which are embedded within the system shown in Figure 6.3. Absorption of short-wavelength solar radiation dominates heat input. Energetic particles enhance ionospheric conductance at high latitudes and modify electrical M-I currents. Solar wind driven convection imposes electric fields that drive currents in the lower ionosphere setting ionospheric plasma into motion at higher altitudes, with ions escaping into geospace and beyond. Coupling drives global thermospheric circulation redistributing heat and upwelling molecular species. Waves and tides propagate upward from the lower atmosphere generating electric fields via the dynamo mechanism in the ionosphere. Dynamo electric fields are also created by disturbance winds. Neutral winds and electric fields from these sources redistribute plasma over local, regional, and global scales. SOURCE: Courtesy of Joe Grebowsky, NASA Goddard Space Flight Center.

and boundaries of low-to-medium energy particles in the late 1970s. The relatively simple measurements have produced an important climatology of boundaries and particle effects for strong and weak solar cycles.

Commercial data buys may provide such energetic particle measurements in the future and will be most useful for improving forecast models if made publicly available by NOAA. Measurements of the geomagnetic cutoff translates to a boundary for SEP access to high latitudes. SEPs are a known space weather threat both to commercial aircraft via disruption of communications as well as radiation exposure threat to crew. Further, the ISS and its crew spends more time above SEP cutoff latitudes during active times when the polar cap is expanded.

The Iridium satellite constellation of 66 (75 including on-orbit spares) high-latitude spacecraft for global phone and data communications, recently replaced with the NEXT constellation (Iridium 2nd Generation Satellite Constellation), is equipped with magnetometers now used to map global magnetic field aligned current systems through the AMPERE (Active Magnetosphere Polar Electrodynamics Response Experiment) project funded by the National Science Foundation (NSF). Monitoring these current systems in real time, combined with global magneto hydro-dynamics (MHD) models of solar wind-magnetosphere-ionosphere coupling, can facilitate ground induced current (GIC) forecasting, a significant space weather threat.

The global Birkeland current measurement provides a stringent validation check of the operational MHD models used to derive space weather predictions of LEO and ground impacts. The global, continuous nature of the Iridium sampling via AMPERE complements ground magnetometer observations as a validation check of the operational MHD models used to derive space weather predictions of LEO and ground impacts. The Birkeland currents and LEO magnetic observations also provide key inputs for thermospheric heating, and ionospheric electrodynamics specification, which informs scintillation and GIC forecasts. These observations are, in principle, available in real time and resample the entire orbit tracks every 90 minutes.

In situ measurements of energetic ion and electron flux have been provided in the energy range of 30 keV to more than 200 MeV by instruments on NOAA's POES and similarly instrumented MetOp spacecraft, developed by the ESA and operated by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites). The last of the spacecraft in the POES series, NOAA-19, launched in 2009 while MetOp-C, the last in the MetOp series, launched in November 2018. The POES series follow-on is the Joint Polar Satellite System (JPSS); JPSS-1 successfully launched on November 18, 2017, and is now identified as NOAA-20. The second generation of MetOp, MetOp-SG, is composed of two series of spacecraft, MetOp-SG A and B, flying on the same mid-morning orbit as the current MetOp satellites. Launch of MetOP-SG A1 is planned for 2024 and MetOP SG B1 is planned for launch in 2025.[10]

MetOp-SG will continue measurement of auroral particles affecting ionospheric conductivity and radiation belt populations, SEPs, and the lower-energy galactic cosmic rays. Enhanced fluxes of these particles entering the atmosphere can produce significant and widespread degradation in short-wave radio propagation; in extreme cases even radio blackouts. The energetic particles also contribute to astronaut radiation exposure, especially on high-inclination-orbit missions during energetic solar particle events. However, as noted earlier in this report, energetic particle measurements are not part of the measurements planned on JPSS.

In addition to the loss of energetic particle measurements in next-generation POES, there is concern that drift-meter measurements from DMSP, which provide equivalent electric field measurements, will be lost. This measurement can be replicated on a global scale, but not locally, to understand ionospheric convection patterns using the NSF-supported SuperDARN (Super Dual Auroral Radar Network) ground-based radar network. These measurements, which determine the cross polar cap potential, are critical to validating global MHD models of the magnetosphere. It was also noted at the workshop that AMPERE and SuperDARN could provide operationally useful data streams, while SuperMAG,[11] a worldwide collection of geomagnetic ground station data with disparate sources, is useful for retrospective analysis of space weather events. Improved knowledge of surface conductivity remains critical to addressing the GIC problem.

The thermosphere-ionosphere system is currently modeled with 10-100 times lower data assimilation constraint than terrestrial weather, and yet it can change on a (10 times) faster timescale. Whereas 6-hour data assimilation cycling is adequate for terrestrial weather, the upper atmosphere and ionosphere requires 5- to 15-minute updates of the state due to the rapid response to geomagnetic activity. Monitoring the ionospheric plasma and its structure is needed to help mitigate the impact on communications and navigation. Total electron content (TEC) measurement using the GPS satellite constellations provides valuable data to constrain the system but is highly nonuniform in global distribution of ground stations with two-thirds of the globe covered by oceans. A system of buoys for TEC measurements combined with satellite-based radio occultation measurements to produce ionospheric density profiles for assimilation into models is needed.

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[10] European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), 2020, "Metop—Second Generation," https://www.eumetsat.int/metop-sg.

[11] J.W. Gjerloev, 2012, "The SuperMAG Data Processing Technique," *Journal of Geophysical Research* 117: A09213, doi:10.1029/2012JA017683.

Global coverage of thermospheric neutral density is also required for improvement in satellite drag and space traffic management in LEO, for orbit prediction and collision avoidance. It is imperative that physical modeling and data assimilation capability develop alongside improvement in observations. With a robust modeling capability, it opens the door to characterizing the upper atmosphere and ionosphere space weather by monitoring the drivers of the system. To this end, observations of plasma drift, neutral composition, neutral dynamics, and the source of energy from the magnetosphere (Poynting flux) and solar radiation (EUV flux) are required.

There have been 45,000 objects launched and tracked during the space age with over 17,000 currently in or passing through LEO. With Iridium (75), PlanetLabs (200), Spire Global (100), and now SpaceX (600) planning to launch 60 satellites every 2 weeks to configure the 12,000-satellite Starlink global internet service, there is a growing concern and need for satellite debris and satellite conjunction analysis. Forecasts that include collision avoidance depend sensitively on the neutral density profile, which in turn is strongly affected by episodic energy deposition during space weather events.

Recent studies have shown that low-to-medium–energy (0.5–20 keV) particle deposition significantly modulates electromagnetic energy transfer from the magnetosphere to the ionosphere-thermosphere by ionization changes in ionospheric conductivity. Loss of such measurements will hamper future neutral-atmosphere modeling efforts required to keep up with collision-avoidance needs in the increasingly busy LEO environment. Mass density measurements made by accelerometers on a limited number of scientific satellite missions are ongoing. There is however a need for improved chemical composition measurements to guide orbit prediction methods based on models of the neutral atmosphere.

Relevant to filling these knowledge gaps and needs are plans that include NASA's implementation of the Geospace Dynamics Constellation;[12] NSF's support for the SWARM-EX CubeSat mission,[13] an initial three-satellite pathfinder towards a larger constellation of 6 to 12 CubeSats, each with a more elaborate suite of instruments; and ESA's Daedalus mission,[14] a concept that is based on a mother satellite, which carries a suite of instruments along with four small satellites carrying a subset of instruments that are released into the atmosphere. It was also noted that space traffic management, which requires improved models of the neutral atmosphere, will become a shared DoD-NOAA responsibility as space commerce increases dramatically in the current decade (Figure 6.5).

Table 6.2 summarizes workshop presentations and discussions regarding geospace knowledge gaps and options to fill those gaps.

[12] See NASA, 2019, *GDC STDT Final Report*, https://science.nasa.gov/files/science-pink/s3fs-public/atoms/files/Oct_2_4b_GDC%20STDT%20Report%20to%20HPAC_Ridley_Jaynes--20191002.pdf.

[13] J. Zehnder, 2019, "Building a Satellite Swarm to Investigate an Atmospheric Anomaly," News and Events, Ann and H.J. Smead Aerospace Engineering Sciences, University of Colorado, Boulder, October 16, https://www.colorado.edu/aerospace/2019/10/16/building-satellite-swarm-investigate-atmospheric-anomaly.

[14] See the Daedalus.earth website at https://daedalus.earth/.

FIGURE 6.5 Space is getting crowded. NOTE: Not all will be at 1,325 km; around 7,500 will fly at the very low Earth orbit (335-346 km). SOURCE: Courtesy of and reprinted by permission of The Aerospace Corporation.

TABLE 6.2 Geospace Knowledge Gaps and Measurement Implementation Concepts and Plans

Knowledge Gap	Measurement Options
Charged particle radiation effects requiring continuous measurements. These include the following:	
• Total ionizing dose due to MeV electrons and multi-MeV protons which damage spacecraft over hours to years timescales;	Measure radiation belt electron, proton, ring current energy and plasmaspheric electron populations in (1) near equatorial plane and (2) LEO polar orbits along with Solar Energetic Particle access to high latitudes.
• Single event effects due to spacecraft-penetrating multi-MeV particles causing instantaneous disruption of spacecraft performance;	Low-cost spacecraft charging/discharge monitors on every spacecraft.
• Internal charging due to >100 keV electrons; and	Low-cost spacecraft charging/discharge monitors on every spacecraft.
• Surface charging due to ~ keV electrons	Low-cost spacecraft charging/discharge monitors on every spacecraft.
Ground-induced current forecasts	Regional and global magnetometer networks linked in real time.
Global ionospheric convection	SuperDARN coherent radar network.
Global B-field aligned current systems	Iridium satellite constellation for global phone/data communications carry magnetometers, may provide real-time currents (AMPERE).
Global measurement of ionospheric irregularities— affecting communications and real-time ionospheric density profiles	TEC measurement using GNSS satellites and ground/buoy receivers combined with radio occultation measurements providing ionospheric density profiles.
Global measurement of thermospheric neutral density, plasma drift, neutral composition, neutral dynamics, and the source of energy from the magnetosphere (Poynting flux) and solar radiation (EUV flux), affecting satellite drag, Space Traffic Management	NASA is planning the Geospace Dynamics Constellation, NSF is supporting the SWARM-EX CubeSat constellation pathfinder, and ESA is planning Daedalus.

7

Other Infrastructure Issues

SPACE-BASED ARCHITECTURE

The "Space-Based Architecture" session from the September workshop began with an introduction by Harlan Spence followed by a keynote address by Dan Baker. The following summarizes their remarks as well as the other session presenters shown below.[1]

- Harlan Spence, University of New Hampshire, *Session Chair*
- Dan Baker, University of Colorado, Boulder, "Space Weather Observing Architecture: A System View"
- Conrad C. Lautenbacher, GeoOptics, "Leveraging the Commercial Sector"
- Justin Kasper, Director of R&D at BWX Technologies, "Solar Wind Particle Measurements"
- Jerry Goldstein, Southwest Research Institute, "ENA and EUV Imaging"
- Robyn Millan, Dartmouth College, "Distributed LCAS, CubeSats"
- David Malaspina, University of Colorado, Boulder, "Fields and Waves Measurements"

According to Baker and Spence, a well-conceived and well-executed space-based architecture is critically important for assuring a robust space weather program. Further, a diverse set of broadly positioned space-based assets provides not only valuable real-time situational awareness, but also ground truths for validation of space weather models. It was noted that the present space-based architecture evolved from one that was deeply rooted in scientific and engineering discovery. Initially, single spacecraft typically explored the regions and processes relevant to space weather. Focused science drivers and/or technology goals meant that most missions stood alone. As the science community developed a fuller appreciation of how the regions and processes interrelate, a deeper understanding of the coupled system of systems generally required information gathered through the synergies of simultaneous missions operating both stand alone and as part of a loosely coordinated fleet.

Early space weather space-based architecture emerged in parallel during this period of scientific exploration and discovery. Nascent space weather operational needs also identified the importance of a diverse set of measurements strategically placed throughout the system, but with the additional requirement

[1] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

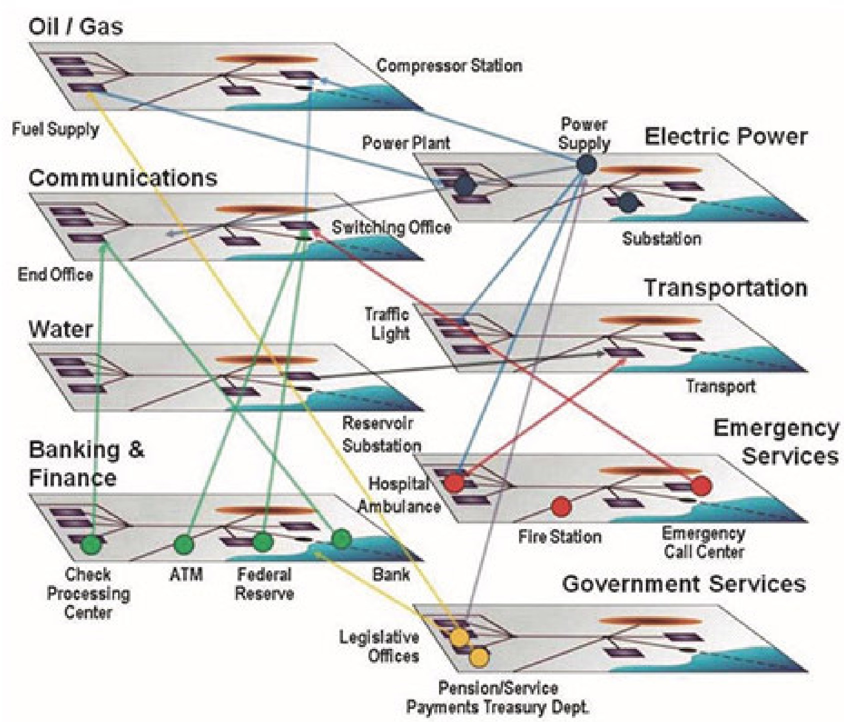

FIGURE 7.1 Connections and interdependencies across the economy. This diagram illustrates the high level of integration of the various sectors in the society, and points to their vulnerability; for example, during (extended) power outages. NOTE: Some connections are not shown. SOURCE: Daniel Baker, University of Colorado, Boulder, presentation to the workshop, September 10, 2020; figure courtesy of Sandia National Laboratory in Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, 2008, *Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures*, http://www.firstempcommission.org/uploads/1/1/9/5/119571849/emp_comm._rpt._crit._nat._infrastructures.pdf.

for continuous observations geared primarily for monitoring than for scientific discovery. Future space-based observational architectures can be optimized by the following:

1. Building on current understanding of the science and engineering underpinning space weather impacts;
2. Meeting the demands, needs, and requirements of a growing and diverse user community;
3. Leveraging a wide variety of existing programs and observational capabilities;
4. Recognizing that the space weather domain often operates as a system of systems; and, finally
5. Developing new approaches, systems, and capabilities to fill remaining gaps—current and future—that limit the ability to advance knowledge of space weather and the predictability of its impacts.

The other panelists at the September workshop addressed this topic from a variety of perspectives, identifying gaps, and discussing pathways forward. Those various perspectives and insights are summarized next.

SOCIETAL AND ECONOMIC NEEDS

The risk awareness of our society has grown with the increasing use and reliance on technology. There are strong interdependencies between the different sectors (e.g., energy and power, transportation, communications, finance, water, emergency services) that make society increasingly dependent on flawless operation of technological assets and communication systems (Figure 7.1). Failures in one sector quickly penetrate to others causing major disruptions of daily operations. Many of these sectors, most notably communication and navigation services, increasingly rely on space assets, highlighting the importance of continuous and complete monitoring of the Sun and solar wind as well as Earth's space environment, both in the high-altitude magnetosphere and at low Earth orbit (LEO).

As the use of space assets has increased from primarily government operations to a wide variety of commercial and private sector uses—affecting all segments of the U.S. economy—the need for productive, cost effective collaboration among all players has significantly increased. Additionally, the society at large still has little understanding of the space weather concepts or risks, and thus there is a significant need for further education of the general public, as well as potential customers for space weather services.

The importance of realizing and understanding the rapid development of the private commercial sector in countering potentially catastrophic space weather events was noted by several workshop speakers and participants. Additionally, it was observed that government leadership over the past 15 to 20 years has recognized the national and worldwide need for better understanding of space weather events and the importance of collaboration among all components of society equipped to contribute to the amelioration of hazardous effects from space weather. The culmination of this interest and development has resulted in detailed planning for the future, which now includes a National Space Weather Strategy officially recognizing the importance of private commercial sector collaboration with the government (safety, regulation), industry (efficiency, competition), and academia (research).

The commercial space weather industry now covers the entire value chain from upstream (research, observations, instrumentation, data) to mid-stream (data processing, computation, algorithms and models) to downstream (forecasts, warnings, services and emergency management). It is known that space weather events can lead to extraordinary damage across a vast, essential, and mostly civilian infrastructure, as was seen on March 13, 1989, when geomagnetic storms resulted in a nine-hour blackout for about 6 million people in Canada's province of Québec after damage to the electrical power grid operated by Hydro-Québec. Thus, it was asserted, this is not solely a government challenge, but will require the continuing involvement of all available resources to absorb and recover. At the workshop, it was said that the commercial space weather sector is fully able and is currently playing a role in planning, preparing, and recovery activities. The American Commercial Space Weather Association (ACSWA) has assessed the role of a variety of associated companies, and concluded that most operate in multiple sectors. This organization could be used to provide input addressing user needs.

The Space Weather Operations, Research, and Mitigation (SWORM) interagency task force released the *Space Weather Phase 1 Benchmarks* report in 2018.[2] Following its release, the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) asked the Institute for Defense Analyses (IDA) to engage the expertise of the U.S. and international space weather scientific community to make recommendations that would improve the Phase 1 benchmarks, including identifying any outstanding gaps. IDA's Science and Technology Policy Institute released the *Next Step Space Weather Benchmarks* document in December 2019.[3] The report was written by a 32-member panel of experts who had been divided into five working groups to assess Phase I benchmarks in the following areas: induced

[2] "National Science and Technology Council, 2018, *Space Weather Phase 1 Benchmarks: A Report by the Space Weather Operations, Research, and Mitigation Subcommittee*, Committee on Homeland and National Security, June, https://www.whitehouse.gov/wp-content/uploads/2018/06/Space-Weather-Phase-1-Benchmarks-Report.pdf.

[3] Institute for Defense Analyses, 2019, *Next Step Space Weather Benchmarks*, IDA Group Report NS GR-10982, Science and Technology Policy Institute, https://www.jstor.org/stable/resrep22832.1.

geo-electric fields, ionizing radiation, ionospheric disturbances, solar radio bursts, and upper atmosphere expansion. Each working group was asked to assess the Phase 1 benchmarks and to provide near- and long-term research recommendations that would improve the ability to understand and benchmark extreme space weather events. Comparing current commercial private-sector capabilities with the recommendations identified in the IDA *Next Steps* document, representatives at the workshop from the commercial sector thought it clear that the expertise present in multiple commercial sector companies could contribute to all five benchmark categories.

Commercial space weather service companies provide value-added products and services to monitor and mitigate space weather hazards effecting multiple sectors. Representatives from the commercial sector stated that strong coordination and collaboration is necessary across federal agencies and commercial service providers was needed to support critical infrastructure owners, operators, and users, and to improve America's ability to understand, predict, and prepare for space weather events. For the future, it was said that much more work is needed to determine the optimal distribution of assignments among the various government-, private-, and commercial-sector sources.

CURRENT AND FUTURE OBSERVATIONS

Participants reviewed current and upcoming observational assets, while noting the widely shared concern that many current space weather services rely on scientific satellites that have no continuity or backup in case of instrument failures. Moreover, these ambitious and often complex missions are poorly suited for 24/7 monitoring and/or real-time data downlinking. The potential exists in the next few years for what was termed an alarmingly reduced monitoring capability that could create significant risks to the society.

In discussion of the necessary observations, the question of what the users actually need was raised. Given the short lead time and uncertainties related to single-point solar wind measurements at L1, experience suggests that power grid operators are not yet ready to power down their systems based on warnings issued from that information only. In order to improve forecasts and models, as well as the reliability of the observations, it may be necessary to replace single-point L1 observations with multipoint solar wind monitoring via multiple probes in the vicinity of L1, as well as monitors further upstream in order to increase the lead time. As discussed below, this may now become financially possible with the use of small satellite technologies.

New Technologies

New, smaller mission concepts, allow key measurements to be done at much lower cost than those done with the currently operative missions. Over the past decade, there has been a rapid increase in the use of CubeSats (Figure 7.2) for a wide variety of applications targeting research and education, including, most recently, commercial operations. CubeSats are low cost, flexible in their configuration, and potentially offer rapid turnaround with the proliferation of coordinated launch opportunities. Their increasing utility was attributed to the development of standardized deployment modules, the availability of miniaturized instrumentation; and the recent increase of mission robustness and lifetime. Small satellites are frequently employed in targeted investigations, the augmentation of other capabilities, technology development and testing, and distributed or high-risk orbit measurements. Even CubeSats are now capable of delivering foundation scientific results.[4]

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[4] National Academies of Sciences, Engineering, and Medicine, 2016, *Achieving Science with CubeSats: Thinking Inside the Box*, Washington, DC: The National Academies Press, doi:10.17226/23503.

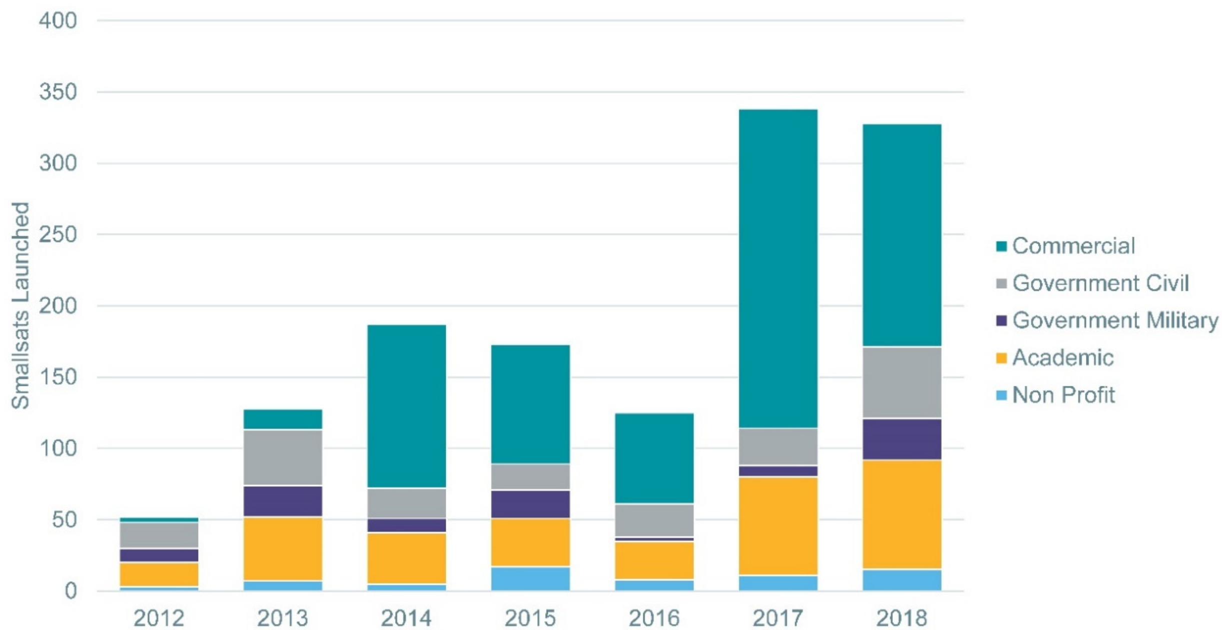

FIGURE 7.2 The rapid growth of the number of small satellites and their much widened user base. NOTE: Most commercial SmallSats are for remote sensing or broadband services. SOURCE: Robyn Millan, Dartmouth College, "Potential of Small Satellites for Space Weather," presentation to the workshop, September 10, 2020, courtesy of Bryce Space and Technology, 2019, *Smallsats by the Numbers 2019*, https://brycetech.com/reports.html.

Several speakers noted that the constellation missions enabling multipoint observations are becoming realistic and offer significant improvements for the quality of data in all regions, from solar and solar wind to the different parts of the magnetosphere and upper ionosphere. Just one example is the opportunity to use a geostationary transfer orbit constellation covering the region between geostationary altitude and LEO for space weather monitoring in a scientifically critical part of the system hosting Earth's radiation belts.

Solar and Solar Wind Observations

For convenience, the list below aggregates key observations made by presenters at the workshop regarding solar and solar wind observations.

- Monitoring the Sun and the solar wind from space-based assets complements ground-based measurements, forming the foundation for any space weather monitoring system. The most widely used and routinely accessible data have been obtained upstream at L1 (WIND, ACE [Advanced Composition Explorer], and DSCOVR in situ plasma, field and solar energetic particles [SEPs]; SOHO [Solar and Heliospheric Observatory] images) or in Earth orbit (GOES [Geostationary Operational Environmental Satellite] X rays and SEPs; Solar Dynamics Observatory [SDO] images).
- Remote monitoring of solar flare and coronal mass ejection (CME) activity gives a very short lead time before SEPs arrive at Earth, limiting current predictive capabilities for that aspect of space weather.
- Space-based in situ measurements of electric and magnetic fields in the solar wind form the backbone for quantitative space weather forecasts and are extensively used as model input. The measurements can provide "real-time" (about half-hour lead time) warnings of

geomagnetic storm effects, and indications of the severity of the upcoming storm, but are not always available by mission design. It is also not clear how widely such information would/could be used; for example, by commercial system operators or government entities.
- On the other hand, monitoring the CME activity from multiple vantage points can provide up to 2 days lead time for actions to mitigate the effects of an interplanetary mass ejection (ICME) impacting Earth's space environment. The STEREO (Solar Terrestrial Relations Observatory) mission has shown the usefulness of monitoring the ICME activity away from the Sun-Earth line (most notably from the L4 and L5 vantage points), and several speakers at the workshop mentioned off-L1 and further upstream solar wind observations as a key future need. Moreover, to resolve the three-dimensional (3D) structure of arriving solar wind disturbances, requires multipoint in situ measurements in the upstream wind.
- Participants also highlighted the limitations of the current observational fleet. For example, as shown in Table 7.1 from David Malaspina's presentation, observatories inside 1 AU do not provide continuous coverage or real-time data. Improved planning for a sustainable system of essential observations could involve commercial entities, international cooperation, and strategic re-purposing of missions (e.g., post-prime L1 solar/solar wind missions could become Earth-trailing "drifters," providing additional perspective and corotating structure previews, as noted in presentation to the workshop by Justin Kasper).

High-Altitude Magnetosphere Observations

The inner magnetosphere is the home of the ring current and the Van Allen radiation belts, which are a major source for energetic particles that can be hazardous to spacecraft and their subsystems and instruments. At the moment, there is no mission that would routinely monitor the continuously varying outer electron belt populations or the wave environment driving the acceleration and loss processes of those particles.

Global imaging of the inner magnetosphere is a proven way to gain a global perspective of the extent and intensity of the particle populations in the inner magnetosphere, as was done by the NASA Imager for Magnetopause to Aurora Global Exploration (IMAGE) MIDEX mission. While the low densities of the magnetospheric plasma makes imaging challenging, the technological developments since the NASA IMAGE mission have shown that it is indeed possible to gain useful information from both EUV observations of the plasmasphere and the ENA observations of the ring current populations. Such observations, while they would be highly desirable for giving a global context to in situ particle and field measurements, are not included in the near-term plans of any organization. As a simple example, images can be used to monitor the plasmaspheric boundary characterized by strong density gradients, which affect keV electrons associated with spacecraft surface charging. Furthermore, imaging in the ultraviolet wavelengths provides a natural linkage of inner magnetospheric and ionospheric processes.

The inner magnetospheric particles are guided by the local magnetic field, which under strong geomagnetic activity is highly variable in multiple timescales from fraction of seconds to several days. These measurements are key for radiation belt dynamic models and SEP transport models, which are needed to protect U.S. assets in space. One concept presented for inner magnetosphere particle and field measurements would use a fleet of small satellites positioned at geostationary transfer orbits (Figure 7.3). Such a fleet could capture the full extent of the radiation belts between LEO and GEO with about minute temporal exposure time. Due to the massive constellation of simultaneous measurements, the operational and scientific utilization of the data would require using modern machine learning and big data mining capabilities. It was estimated that such a system could be ready for deployment within 1-2 years, and could be realized by contributions from multiple organizations including national and international, government and private sector players. Such measurements would serve beyond their use for real-time monitoring and forecasting as a valuable dataset for development of data-augmented physics-based and data-driven models of the inner magnetosphere dynamics.

TABLE 7.1 Measurement Gaps in the Solar Wind and Magnetosphere

Fields / Waves Measurement Type	Location	Primary Space Weather Application(s)	Platforms: Current	Platforms: Planned	Major Gap
DC Magnetic fields	Low Earth orbit	• World Magnetic Model maintenance • Ionospheric current system dynamics	Swarm, Ampere, DMSP	MagQuest, GDC, AMPERE	• No operational data for WMM
DC Magnetic fields	Inner magnetosphere	• Geomagnetic field dynamics, Modeling radiation belts, precipitation	GOES, DSX, MMS, Arase, THEMIS, Cluster	GTOsat	• Few planned future missions
DC Magnetic fields	Beyond Earth (L1, L5, L4, near Sun)	• CME early warning (+/- Bz) • Upstream solar wind monitor	ACE, Wind, DSCOVR, STEREO, Solar Orbiter, PSP, BepiColumbo	SWFO, Lagrange L5, IMAP	• No observatory at L4, L5
VLF plasma wave fields	Inner magnetosphere	• Climatology of plasma wave drivers of radiation belts, precipitation	Arase, THEMIS, DSX	?	• No planned future observations
Radio frequency electric fields	Beyond Earth (L1, L5, L4, Moon, near Sun)	• CME propagation • SEP event prediction • Radio blackout warnings	Wind, STEREO, PSP, Solar Orbiter	CURIE, SunRISE	• No operational observations
High frequency electric fields for dust impact detection	Beyond Earth (L1, L5, L4, Moon, near Sun)	• Climatology of interplanetary dust hazard	Wind, STEREO, Solar Orbiter, PSP	?	• No planned future observations

SOURCE: David Malaspina, University of Colorado, Boulder, "Fields and Waves Measurements," presentation to the workshop, September 10, 2020.

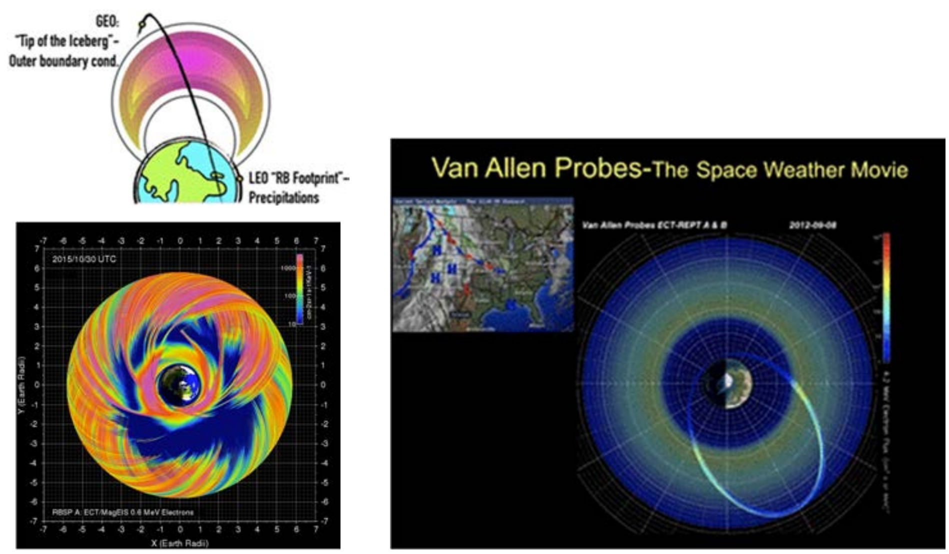

FIGURE 7.3 *Left:* A constellation of small satellites at geosynchronous transfer orbits can provide comprehensive monitoring of the radiation belt environment. *Right:* Such a constellation would be especially valuable, as the re-entry of the Van Allen Probes has left a significant gap in the capacity to follow the most hazardous particle population to U.S. space assets. SOURCE: *Left:* Robyn Millan, Dartmouth College, "Potential of Small Satellites for Space Weather," presentation to the workshop, September 10, 2020. *Right:* Daniel Baker, University of Colorado, Boulder, "Space Weather Observing Architecture: A Systems View," presentation to the workshop, September 10, 2020.

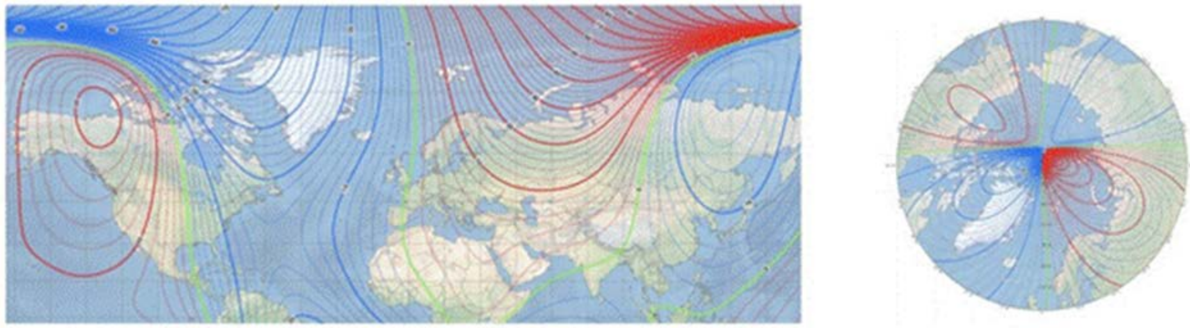

FIGURE 7.4 An illustration of the World Magnetic Model updated every 5 years from the presentation by David Malaspina, who highlighted the continuous need for accurate maps for situations when satellite positioning is not available. SOURCE: David Malaspina, University of Colorado, Boulder, "Fields and Waves Measurements," presentation to the workshop, September 10, 2020.

The risks associated with not monitoring this key region are associated with rapid anomaly attribution (not being able to trace the particles and fields conditions that led to an observed anomaly), space domain awareness (not being able to monitor the radiation level in space in real time along satellite orbits), high-altitude nuclear explosion analysis (not being able to promptly diagnose trapped radiation from anthropogenic sources), and lacking capabilities to feed (near) real-time observations to radiation models to issue warnings and forecasts as enhanced radiation conditions commence.

Low-Altitude Observations

LEO is the optimal location for monitoring global ionospheric conditions (electron density, currents, instabilities), thermospheric parameters (temperature, composition, winds, waves), and the characterizing parameters of the ionospheric electrodynamics (auroral and higher-energy electron precipitation location, intensity, and dynamics).

As this is the region densely populated with satellites, it is also the region where the commercial sector has highest interest. Companies that are part of ACSWA have programs that address ionospheric scintillation, ionosphere and thermosphere specification both by in situ and remote sensing technologies, and the different aspects related to radio wave propagation within and through the upper atmosphere. However, the observations are not necessarily well coordinated, nor are the data freely available to other potential users, which calls for a coordinated national public-private effort to fulfill the national needs as well for the government and academia as for the commercial actors.

Commercial constellations are already being used for space weather measurements: A prime example is the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) project, which uses commercial Iridium communication satellites and their onboard magnetometers to deduce the global distribution of auroral currents into and out of the ionosphere. This unprecedented capability to monitor the space environment in LEO has been realized in partnership with private companies and government research laboratories. Such a model could well be adopted to other measurements as well.

As the navigation accuracy requirements increase, it is important to know the accurate state of the geomagnetic field. The World Magnetic Model shown below (Figure 7.4), which is updated every 5 years, is devised using in part space-based high-accuracy measurements of the main field. Such maps enable navigation when Global Positioning System (GPS) positioning is not available and are widely used in civilian navigation systems.

The interest of the commercial sector in using and developing space-based observations for space weather monitoring and forecasting purposes is well-known and was reflected in workshop discussions. Representatives from the commercial sector stated that while industry can and would use the services provided by others in academia and government, it also the capability to develop the requisite space hardware, data processing systems, and model algorithms. Speakers noted the importance of coordination and collaboration across the academic, government, and private sectors in creating an optimal operational space weather architecture. It was also observed that the market for commercially-provided data is still underdeveloped: data are commercially available mainly from remote-sensing LEO satellites, while most other data rely on non-commercial and/or scientific mission data sets. The latter poses a challenge for the real-time availability of the observations. In 2003, the National Research Council published the report *Fair Weather: Effective Partnership in Weather and Climate Services.*[5] In his presentation, an ACSWA representative stated that the recommendations in this report provide guidance on how to optimize the effectiveness of public-private partnerships for space weather. Notably, the first recommendation in the *Fair Weather* report is that, "The NWS (National Weather Service) should replace its 1991 public-private partnership policy with a policy that defines processes for making decisions on products, technologies, and services, rather than rigidly defining the roles of the NWS and the private sector."

The space-based architecture panel, and those addressing questions and comments to the panel, clearly recognized that the space weather challenge revolves around a "system of systems." Traditional operational observing platforms in space have been large, costly, and slow in their development. The panel members all recognized that smaller, more distributed, and more affordable platforms could help meet the rapidly evolving needs of the future users of space. By every means possible, it was recognized that all sectors need space-based observing platforms at key observing points in the connected Sun-Earth system. Moreover, these platforms need to be dedicated and truly operational in perpetuity.

GROUND-BASED ARCHITECTURE

The "Ground-Based Architecture" session at the September workshop built on presentations and discussions begun at the June workshop. Participants emphasized that ground-based observations can and do contribute significantly to the suite of space weather products, spanning all regimes of the geospace environment, including critical measurements of solar properties, of the solar wind, of magnetospheric and ionospheric states, and finally of ground-based magnetic field perturbations (geomagnetically induced currents, or GICs). It was also noted repeatedly that ground-based measurements are an integral part of any space weather architecture for both research and operations. Yet, there was also concern that ground-based measurements are primarily supported as research instruments, and that their use in operations will require stable funding sources and mechanisms to secure operational support, both of which are uncertain at present. Speakers at the session are shown below;[6] a summary of their remarks follows.

- Anthea Coster, MIT Haystack Observatory, Introductory Remarks, Session Chair
- Dan Eleuterio, Office of Naval Research, Navy Space Weather Interests[7]
- David Boteler, Head, Canadian Space Weather Observations and Forecasts Centre (CSFC), "Space Weather Monitoring in Canada"
- Michael Starks, Air Force Research Laboratory (AFRL), AF Ground-Based Observations and Space Weather Interests[8]
- Valentin Pillet, Director, National Solar Observatory (NSO), "Next Generation GONG (ngGONG)"

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[5] National Research Council, 2003, *Fair Weather: Effective Partnership in Weather and Climate Services*, Washington, DC: The National Academies Press, https://doi.org/10.17226/10610.

[6] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

[7] Dr. Eleuterio spoke without the use of slides; therefore, his presentation is not on the workshop's website.

[8] Dr. Starks spoke without the use of slides; therefore, his presentation is not on the workshop's website.

- Tim Bastian, National Radio Astronomy Observatory (NRAO), “Radio Inputs to Space Weather Operations and Research”
- Josh Semeter, Boston University, “The LEO Ground-Based Collaborative”
- Jenn Gannon, Computational Physics, “Ground-based Measurements: Magnetometers”

Current Geospace Ground-based Observations: Canadian Space Weather Observations and Forecasts Centre

Ground-based space weather measurements are used to monitor solar, geomagnetic, and ionospheric parameters. These observations taken together can provide the basis for a space weather warning center. One example of this is CSFC. As the CSFC is a microcosm of the larger space weather community, a review of the utilization of these ground-based measurements can offer insights into the current state of ground-based instrumentation.

In Canada, the specific space weather concerns are the geomagnetic effects on power systems (following the Hydro-Quebec incident), space environment effects on satellites (e.g., Telesat Anik E), and ionospheric effects on Artic communication channels. To address the issue of power systems, the CSFC accepts data from a network of magnetic observatories and variometers. To study the ionospheric effects on Arctic communication, the center receives data from multiple Global Navigation Satellite System (GNSS) total electron content and scintillation receivers as well as running and collecting data from a network of riometers. For monitoring space environment effects on satellites, the CSFC provides the solar radio flux at 10.7 cm (F10.7 index), a critical input to a number of atmospheric and ionospheric models. A new multi-frequency solar radio telescope is in the process of being commissioned and new multi-frequency riometers are being developed.

There are also new opportunities in the Arctic for space weather research, including the Artic observing mission. Many of the ground-based networks that feed data into the CSFC are run by universities for research, not operational purposes. This leads to issues with the transition from research to operations; for example, most university researchers do not sign up to the 24/7 operations required by most warning systems nor are they prepared to deliver the data with the latency required for operational use and forecasts.

In summary, although often taken for granted, ground-based instruments are a cost-effective means to provide needed space weather measurements. However, the incorporation of ground-based instruments in future space weather architectures will require long-term funding commitments, a problem in need of a solution in the view of a number of participants.

Ground-Based Solar and Solar Wind Observations

Optical Solar Observations

The current and potential next generation of the Global Oscillations Network Group (GONG and ngGONG) was described. GONG is a worldwide network of six identical telescopes designed to provide full-time observations of the Sun (91% duty cycle). It was started in 1995 to measure solar oscillations (unrelated to space weather). In 2006, although not designed with space weather in mind, it was modified for space weather applications, in particular, it was modified to make magnetic field measurements of the Sun. Currently, its operations are funded by the National Oceanic and Atmospheric Administration (NOAA; $1 million per year), and there is an interagency agreement with NSF that expires in 2021.

In addition to NOAA, observations from GONG are currently used by the Air Force Weather Service, NASA’s Virtual Solar Observatory, the UK Met office, and other international partners. Referencing GONG in his presentation, Valentin Pillet, director of the NSO, observed that NOAA considers GONG an essential facility: its data are critical to the proper initialization of the WSA-ENLIL model, and in fact, the model cannot currently be initialized and run in the absence of these input data. Pillet also noted that the

FIGURE 7.5 Next Generation Global Oscillations Network Group (ngGONG) network definition. SOURCE: Valentín M. Pillet, National Solar Observatory, "Next Generation GONG (ngGONG)," presentation to the workshop, September 10, 2020.

Air Force recognizes that optical solar observations are outdated, and that GONG should be updated. However, while upgrade costs have been investigated, workshop participants were told that it remains unclear when a decision on the upgrade will be made. Cost is an issue and participants were informed that one solution might be a partnership between the Department of Defense (DoD) and the civil and international communities to share the non-recurring engineering costs associated with the upgrade, but then have these communities separately build their own sites.

Of note, despite solar monitoring by satellites such as SOHO and LASCO (Large Angle and Spectrometric Coronagraph) and different modeling scenarios, the orientation of the magnetic field of the CMEs when they arrive at Earth cannot be accurately predicted (the Bz problem). This is important, because without this information, the geo-effectiveness of the CME cannot be reliably predicted.

The current status of the next generation solar synoptic network is that it is "under consideration." AFRL has contacted the High-Altitude Observatory (HAO) and NSO to generate plans for a prototype to be considered for a next generation solar synoptic network. Included in the prototype plans were coronagraphs such as the white light coronagraph (K-Cor) located at the Mauna Loa Solar Observatory (MLSO). The concept that was proposed to AFRL has now been sent to NSF, and a site characterization effort has begun. Both AFRL and NOAA Space Weather Prediction Center have sent operational requirements to the NSF for ngGONG and NSO and HAO are finalizing research requirements. Figure 7.5 shows an initial definition for the ngGONG network.

Solar Radio Observations

Radio observations of the sun are also important to space weather operations and research. In particular, solar radio bursts (SRBs) are known to have impacts on navigation and communication systems. SRBs occur without warning, simultaneously, over a large region. In the case of GNSS, the effects of SRBs are manifested over the entire sunlit hemisphere. Current radio monitoring systems, which only monitor a few widely spaced frequencies, are not always sufficient as high radio flux density can occur in relatively narrow frequency ranges—and unless all bands are monitored, the impact can be underestimated.

FIGURE 7.6 The Heliophysics System Observatory lacks a strong ground-based component. NOTE: DKIST, Daniel K. Inouye Solar Telescope; HAO/MLSO, High Altitude Observatory/Mauna Loa Solar Observatory; BBSO, Big Bear Solar Observatory; ngRH, Next Generation Radioheliograph. Although not mentioned on this slide, EOVSA (Expanded Owens Valley Solar Array, http://www.ovsa.njit.edu), a 15-antenna solar-dedicated interferometric radio array currently operating in the range 1-18 GHz, is considered a pathfinder for ngRH. SOURCE: Tim Bastian, National Radio Astronomy Observatory, "Radio Inputs to Space Weather Operations and Research," presentation to the workshop, September 11, 2020.

In addition, current observing systems do not monitor the polarization state of SRBs, despite the fact that this information can be essential to gauge effects on systems such as GNSS for particular users. In fact, even the statistics of the occurrence rate of extreme events gathered by the current radio monitoring systems are suspect, as there are large discrepancies when their reports are compared to well-calibrated radio measurements. There is also the potential that radio observations can be used as tracers of space weather, such as radio observations of type II/IV and type III solar radio bursts.

In summary, the view expressed at the workshop was that the current state of ground-based radio observations is one where existing data sources are over-reliant on an observational system that saturates on large events, has sparse frequency coverage, does not measure the degree or sense of circular polarization, and is poorly calibrated.

Radio observations also offer the possibility to provide new diagnostics of space weather drivers and their impacts. Radio observations have the sensitivity to monitor chromospheric and coronal magnetic fields, thermal, nonthermal (keV-MeV electrons), and coherent emissions. They have the ability to image phenomena on the solar disk and above the limb and to observe the solar atmosphere as a system.

Although there are over 20 space missions being planned to monitor and study the heliosphere, plans for the ground-based elements of the HSO remain comparatively incomplete as can be seen in Figure 7.6. While DKIST (Daniel K. Inouye Solar Telescope), MLSO, and the Big Bear Solar Observatory provide optical and infrared solar imaging, and ngGONG will contribute solar magnetic field and additional synoptic imaging as described above, other types of ground-based installations can enhance currently available information. For example, a participant described a solar-dedicated instrument capable of

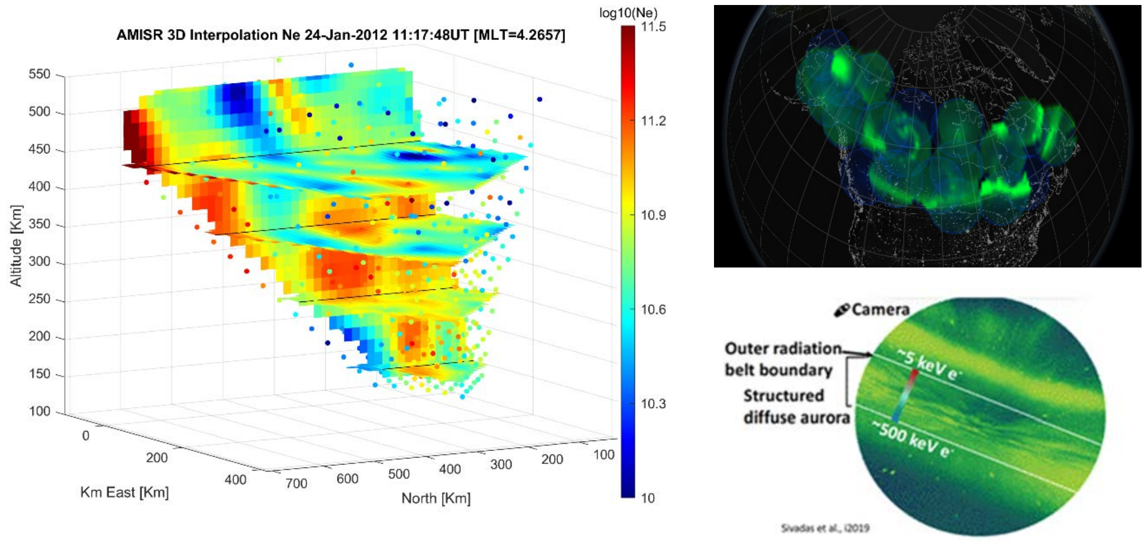

FIGURE 7.7 Views of the ionospheric response to magnetospheric processes. *Left:* Three-dimensional view of ionospheric structure produced by a substorm, as captured by the electronically steerable Poker Flat Incoherent Scatter Radar (PFISR). *Upper right:* Global snapshot of substorm aurora, obtained using the network of all-sky cameras comprising the THEMIS Ground-based Observatory. *Lower right:* Newly discovered optical signature of relativistic electron precipitation from the outer radiation belt, highlighting a new capability for auroral imagery. NOTE: See also J. Semeter, T. Butler, C. Heinselman, M. Nicolls, J. Kelly, and D. Hampton, 2009, "Volumetric Imaging of the Auroral Ionosphere: Initial Results from PFISR," *Journal of Atmospheric and Solar-Terrestrial Physics* 71(6-7): 738-743; N. Sivadas, J. Semeter, Y. Nishimura, and S. Mrak, 2019, "Optical Signatures of the Outer Radiation Belt Boundary," *Geophysical Research Letters* 46(15): 8588-8596. SOURCE: Courtesy of Joshua Semeter, Boston University; left and bottom right images from the Earth and Space Science Open Archive (ESSOAr). *Top right:* NASA's Scientific Visualization Studio, 2009, "SVS: THEMIS/ASI Nights-High Resolution," July 7, https://svs.gsfc.nasa.gov/vis/a000000/ a003500/a003590.

performing imaging spectroscopy at radio wavelengths, yielding unique observables that could be used operationally (see Figure 7.6 and caption).[9]

Ground-Based Magnetosphere-Ionosphere Observations

Ground-based observations provide important insights into magnetosphere-ionospheric coupling processes. For example, merging data from optical imagers and incoherent scatter radars can provide more comprehensive views of the ionospheric response to magnetospheric processes. Figure 7.7 illustrates this with the juxtaposition of a 3D image of an ionospheric response to a substorm measured with the incoherent scatter radar at Poker Flat with ground-based imaging from networks such as THEMIS (Time History of Events and Macroscale Interactions during Substorms Mission).

Networks of GNSS receivers measure global total electron content, and can be used to monitor global ionospheric changes following ionospheric storms. Networks of magnetometers measure currents that define the dynamics of the magnetosphere-ionosphere and provide the data used to define global magnetic

[9] See T.S. Bastian, "Radio Inputs to Space Weather Operations and Research," presentation to the workshop, September 11, 2020. For details on the FASR (Frequency Agile Solar Radiotelescope) concept, see T. Bastian et al., *Frequency Agile Solar Radiotelescope: A Next Generation Radio Telescope for Solar Astrophysics and Space Weather,* a white paper submitted to the Astro2020 Decadal Survey, https://science.nrao.edu/science/ astro2020/apc-white-papers/201-dea27a2fda59160361b76946a46b3f82_FASR_APC_White_Paper.pdf.

activity indices. Incoherent radars provide precise measurements of a variety of ionospheric properties as a function of altitude. Optical instruments provide important information about magnetospheric properties.

A new magnetometer network, MAGSTAR, is being developed under an NSF distributed array of small instruments (DASI) award. The current operational magnetometer network is sparse with only five NRCAN and eight U.S. Geological Survey (USGS) stations. Most U.S. scientific magnetometer arrays are sponsored by NSF, with each array having its own scientific goal and infrastructure. MAGSTAR is focused on operational infrastructure and is partnered with a multitude of educational, commercial, and government institutions. Specific operational issues for these, and in fact all, ground based sensors include the need for: secure communications links over long-range wireless connections; low-latency data transfer; low-noise sensors, low-power consumption; and solutions for relative and absolute calibration issues.

Merging of scientific and operational needs shows numerous common areas of concern, such as the requirements for high-quality data, reliable uptime, and better coverage. Better coordinated, collaborative efforts can minimize cost outlays between the scientific and operational communities. Discussions at workshop emphasized the importance of identifying support for long-term maintenance and the need to cultivate public-private partnerships in order to leverage synergies between industry tools and academic advanced sensors and expertise.

DoD Interests

Navy and Air Force interests in space weather research are mission oriented, and include the requirement for operational space weather nowcasts and forecasts. The Navy specifically relies heavily on high-frequency (HF) communication and is concerned with day-to-day variability of the ionosphere and its effect on their regional HF-communication links. A major focus of the Navy's Space Weather research is to obtain a better understanding of the bottom-side ionosphere and trans-ionospheric radio wave propagation and to improve now-casting and forecasting capabilities for HF-comm users. They are interested in obtaining a better characterization of the D and E layers, of traveling ionospheric disturbances, sporadic E, and equatorial spread F. They sponsor several projects involving inexpensive sensors in space-based and ground-based platforms, and they are developing a suite of atmospheric models that assimilate information from multiple ground-based and space-based sensors for the use of space weather analysis and prediction.

The Air Force is particularly interested in addressing areas that expose potential DoD vulnerabilities when either a lack of knowledge or resources compromises decision making/anomaly resolution. One challenge in the current and near-future architectures is the need to reduce the "latency" of information. DoD data sources are constrained by concerns about the security of the data source as well as its resiliency. DoD owned sources have another security issue—their data streams are encrypted; therefore, the encryption devices must be protected. Physical security requires, for ground-based sensors, that they be located at protected locations, restricting the number of suitable locations. Resiliency can be addressed by adding more sources—this can include international sources as well as commercial sources but those sources have to be free from tampering or alteration.

One target area for DoD investment is provision for communications support, in particular, for HF and ultrahigh-frequency (UHF) voice support. NEXION, the next generation ionosonde network, directly supports this via ionospheric characterization. HF and UHF voice support is a global issue. In addition, DoD is concerned with space-based communications that operate in the S- and L-band frequency range. These frequencies are susceptible to equatorial ionospheric scintillation especially at the control sites of Diego Garcia and Guam.

Rapidly proliferating LEOs are a whole new space weather concern. More satellites in equatorial orbits or passing through the equatorial region more frequently means more knowledge of scintillation is required

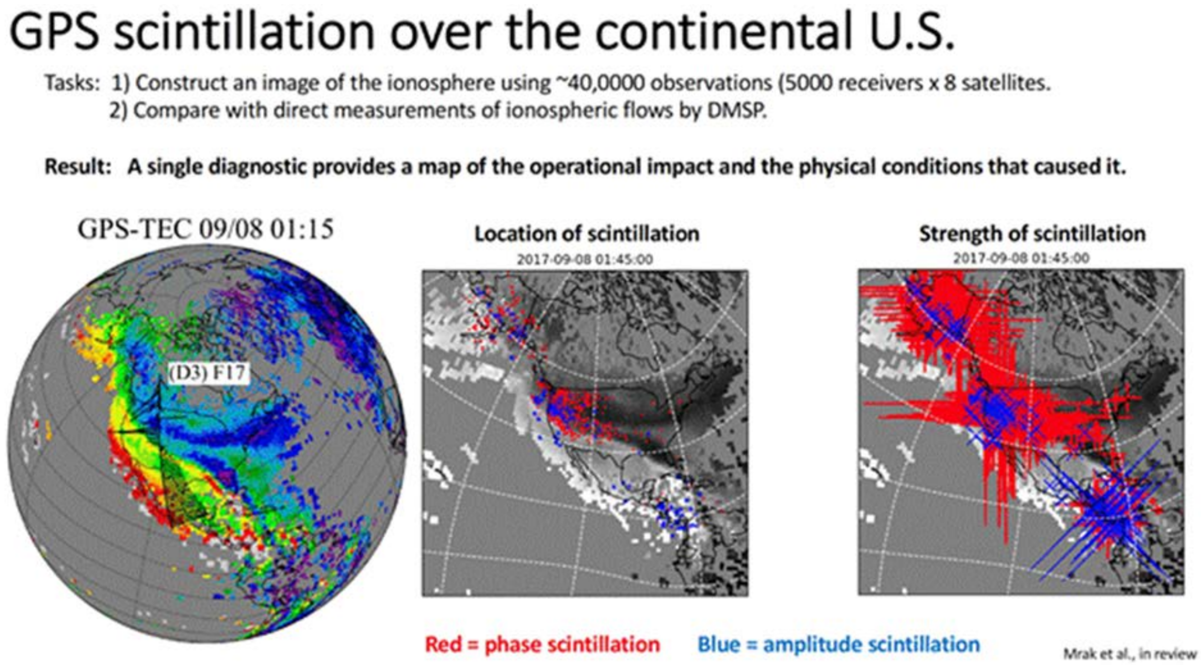

FIGURE 7.8 The plot on the left shows a DMSP (Defense Meteorological Satellites Program) track overlaid showing ionospheric flows overlaid onto a Global Positioning System (GPS) total electron content (TEC) map. The two right hand images show the associated location and strength of scintillation in the region of large TEC gradients associated with the divergent ionospheric flows shown in the DMSP data on the left. NOTE: See also S. Mrak, J. Semeter, Y. Nishimura, F.S. Rodrigues, A.J. Coster, and K. Groves, 2020, "Leveraging Geodetic GPS Receivers for Ionospheric Scintillation Science," *Radio Science* 55(11), and S. Mrak, 2020, "GNSS Remote Sensing of Space Weather at Mid-Latitudes: Ionospheric Irregularities and Source Analysis," October 2, Boston University Theses and Dissertations, https://doi.org/https://hdl.handle.net/2144/41499. SOURCE: Courtesy of Joshua Semeter, Boston University; left and bottom right images from the Earth and Space Science Open Archive (ESSOAr).

if communications to or from the satellite, with the ground, is required while in a scintillation region. This indicates that improving the system using commercial capabilities may be important.

Currently, AFRL is working with Los Alamos and Space and Missile Systems Center to explore the flow of data into a central repository. This would, ideally, be shared with the research community. The future architecture and the Space Force and Air Force division to be resolved. Issues with Arctic sensing and communications and cis-lunar space indicate the need to work together to meet goals.

New Technologies

Although there is a wealth of information available in the merging of ground-based observations for operations and research of space weather events, drivers, and impacts, the use of data mining will further enhance understanding. Existing data sets are ideal for this challenge. An example is shown in Figure 7.8.

In the burgeoning field of data science, the analytical strategies *are* the basic research. applications of artificial intelligence and machine learning, to space weather prediction can exploit a vast knowledge base that has been developed over the past 50 years in mathematics, statistics, signal processing, and information theory. By utilizing collaborative observations of ground and low-Earth orbiting sensors, an even larger perspective of the broader heliophysics system can be developed.

In the thesis shown in the presentation, the "LEO–Ground-based Collaborative" is "collaborative observations by sensors on the ground and in low-Earth orbit provide a projection of the broader heliophysics system. Collaborations among physicists, computer scientists, and engineers allow us to optimally exploit this projection for space weather operations." LEO-ground-based collaborations may have sampling that is generally non-uniform, incomplete, and heterogeneous, yet the data can provide detailed images that depict dramatic changes over time and space. The advantage of this data fusion is that space weather impacts can be mapped to a cause. There are opportunities for shared infrastructure (Earthscope, buoy networks), for shared data resources (earthquake monitoring and space weather), in addition to opportunities for fruitful new collaborations between academic disciplines in mathematics, statistics, computer science, physics, and electrical engineering. Potential collaborations among physicists, computer scientists, and engineers could enable ways to optimally exploit such a system for space weather operations.

In summary, a number of participants spoke to the importance of ground-based observations as a critical component of space weather measurements. Yet, as noted by one participant, the government has set an unfunded mandate for space weather, unlike other science mandates. Many of the ground-based networks of instrumentation are designed for research, and yet are used for monitoring operational space weather (e.g., GONG). The research part of GONG has been funded, but the operational component has not yet been supported. It was noted that monitoring and research are not separated and discovery science is not unrelated to operations. Therefore, it was argued that other ways of supporting and integrating ground-based instrumentation need to be identified, as well as identifying resources to support the transition to operations. Finally, it was observed that as sensor costs have decreased, their numbers have increased—making intercalibration more important.

SUPPORTING RESEARCH ARCHITECTURE

- Pete Riley, Predictive Science Inc., Chair
- Brian Gross, Environmental Modeling Center, NOAA Weather Service, "NWS Perspective"
- Monica Bobra, Stanford University, "Machine Learning"
- M. Leila Mays, Community Coordinated Modeling Center (CCMC), NASA Goddard Space Flight Center (GSFC), "Model Validation and R2O"
- Gabor Toth, University of Michigan, "Transitioning Research Models"

The "Architectural Framework Panel—Supporting R&A" session at the September workshop examined the needs for both continuity and for defining the necessary next steps in research supporting the space weather goals.[10]

Decades of experience integrating both internal and external research results and developing forecast code at the NWS provide invaluable examples for the Space Weather Prediction Center (SWPC), which is now also under the NWS administrative and operations umbrella. Future space weather reporting and forecasting has been developing in the direction of greater uses of models involving high-performance computing, and, in particular fluid dynamics simulations of the type used for weather and climate. Like the latter, approaches to space weather modeling are expected to include ensemble modeling, ensembles of models, and data assimilation. Similarly, many of these models are initially developed within the broader community of researchers, including methods of ingesting and preprocessing observations used as well as the source codes themselves.

The NWS has developed ways of working with the larger research community and agencies both foreign and domestic to foster collaboration and exchange, providing many lessons learned and mutual benefits including access to needed data sets. This includes the incorporation of a mutually agreed-upon set of metrics by which models are evaluated for both transitioning from research to applications, and for their ability to produce desired products. Weather forecasting has also demonstrated that Observing System Simulation Experiments (OSSEs) are important for improving model performance. In such tests, sensitivity

[10] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

to various assumptions and parameters is determined, which leads to narrowing down of measurement requirements and identification of ancillary research priorities. However, participants were also informed that one of the main issues in transitioning model upgrades into operations seems to be that the NWS runs too many modeling suites and NWS is in the process of analyzing ways to simplify/streamline their forecasting operations.

In the meantime, SWPC has been working toward an analogous framework that involves (1) maintaining operational observing platforms for their needs; (2) working with NASA to establish an R2O2R program to introduce and improve their forecast models; and (3) enhancing their services by producing regional and local forecasts for certain (mainly Geospace) products, including indices useful for decision-making purposes. Their current coupled space weather forecast model chain, which resulted from years of community model "challenges" and workshops, consists of WSA-ENLIL for solar and heliosphere domain products, the University of Michigan's Geospace model, CIRES's WAM-IPE (Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics), for vertical coupling between geospace conditions and the atmosphere, and a geo-electric field model from USGS.

Another rapidly expanding area utilizing state-of-the-art computing techniques and facilities falls under the broad categories of data science/data mining and artificial intelligence uses. Over the last decade the solar and space physics community has been accumulating both long-term data sets, sometimes from disparate sources, as well as high temporal- and spatial-resolution data sets with large data storage requirements and major data transfer/manipulation demands from both hardware and software sides.

The field of machine learning and how it can be applied to learn more about solar activity from previous patterns of behavior is an area ripe for development, and can significantly benefit future space weather services. An open source community approach (e.g., SunPy[11]) is one example. The key requirements for machine learning techniques to aid in space weather prediction are (1) long-term, continuous, and consistent datasets; (2) easy access to these data; and (3) adequate and available computational resources to undertake these analyses.

Among the major challenges to machine learning's greater application in the field of space weather research and forecasting has been lack of infrastructure for efficiently manipulating and transferring large data sets, variations in merged data sets collected from different sources (e.g., intercalibration of observations), and sampling limitations (e.g., only a single imaging perspective or too sparse spatial coverage from in situ measurements). Potential solutions for these include (in order): co-locating analysis projects at the sites of the large data sets; availability of sponsored programs focused on improving data sets; and in the longer term deployment of more multi-perspective, multipoint observing systems for space weather monitoring.

NASA's CCMC is a repository for heliospheric models submitted by the research community for wider use, some of which can be applied for space weather purposes. It is thus a major enabler of community involvement in solar, heliospheric and geospace modeling development. The models hosted by the CCMC generally undergo a filtering process (Figure 7.9) to ensure they meet the goals set by the center: (1) to advance research, (2) to aid in mission planning and science, (3) to enable model validation through data comparisons, and (4) to archive useful models developed under sponsored research programs and the results of model runs at the CCMC. The submitted codes are not open source, and have generally been modified by collaborations with the developer to make them compatible with their practice of providing model runs requested "on demand" by the public.

CCMC also carries out some model validations specifically for NOAA SWPC, keeping a forecasting Scoreboard based on largely retrospective applications and pre-set metrics of performance. They are also active in organizing both domestic and international community workshops where techniques for space weather data-model comparisons, including those that have been developed and implemented at the CCMC,

[11] SunPy is a community-developed, free, and open-source solar data analysis environment for Python. See the SunPy website at https://sunpy.org and The SunPy Community, W.T. Barnes, M.G. Bobra, et al., 2020, "The SunPy Project: Open Source Development and Status of the Version 1.0 Core Package," *Astrophysical Journal* 890: 1. Another open source community library is SpacePy at https://spacepy.github.io/.

FIGURE 7.9 Space weather proving grounds, illustrating steps needed to transition research models to operations. SOURCE: M. Leila Mays, NASA, "Model Validation and R2O at CCMC," presentation to the workshop, September 11, 2020.

are discussed and lessons learned are shared. CCMC personnel also experiment with real-time runs of data-based space weather forecast models as demonstrations and support specific mission-related modeling campaigns. However, some participants at the workshop asserted that the CCMC was extremely under-resourced. It was said that additional investments would be needed to develop better models—both research and operational—and to enable model developers to be both better informed about the underlying concepts and requirements that make successful operational models, and to be better prepared to work with the CCMC on their model's ingestion.

One recently initiated program supported by NOAA and managed by NASA is focused on the long-standing need for transitioning research models to operations/applications. This research-to-operations (R2O) process has been tested at SWPC using models like SWA-ENLIL-cone model and the geospace element of the University of Michigan Space Weather Modeling Framework. The approximately 6-year collaboration between SWPC and the University of Michigan group followed the selection of their geospace model after a series of competitive model "challenges" set to the research community in a series of multi-agency-sponsored workshops.

Funding provided by NOAA enabled regular interactions to put the model into operation, including tailoring of its outputs to meet the SWPC customers' desire for local and regional information, such as dB/dt (the rate of change of the magnetic field) at the surface. The model is driven by the "real-time" in situ solar wind and interplanetary magnetic field information from L1 spacecraft, which must adhere to certain criteria in format and cadence to be compatible with the model code. The developers worked with SWPC toward providing products that could be compared with metrics and well as contextual visualizations for model output evaluations. The developers have continued to provide enhancements/improvements to the geospace model, in response to SWPC suggestions, such as the addition of a radiation belt model that utilizes the geospace model results. Other upgrades and coupled models are envisioned to be offered in the future, subject to support for these projects.

The session brought together experts representing the broad diversity of the current R2O environment. A state-of-the-art space weather modeling and forecasting enterprise is now taking shape as a part of the NWS, with SWPC bringing its own specialized experiences, tools, and customer needs to the organization. At the same time, NWS knowledge of how to manage an increasing demand for science-based services and grow connections to resources, provides a template and framework for SWPC.

The increased integration of scientific community research efforts, including needed data set preparations and interpretations, and potentially operational models, is necessary if the number and accuracy of products and forecasts is to grow. Participants stated that ongoing collaborations between SWPC and the CCMC at NASA GSFC are invaluable toward this goal. Themes emerging from discussions in this session included the following: (1) a need for more substantial model development and transitioning to operations/programs; (2) more strategic and streamlined planning and processes related to model ingestion and product generation; and (3) a closer interaction between developers and forecasters, and, in particular, helping scientific model developers understand the requirements for producing and successfully transitioning research models into operational tools.

8

Closing Observations

Organizers of this workshop were asked by the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF) to consider options for continuity and future enhancements of the U.S. space weather operational and research infrastructure. In developing the workshop agenda, organizers found it necessary to look broadly at the national and international landscape concerning space weather—policies, plans, and issues—while focusing more narrowly on the request of NOAA, the principal sponsor of the present workshop, to examine its Space Weather Follow-On (SWFO) and options to continue observations beyond SWFO. As the workshop activity neared conclusion, NASA and NSF, in consultation with NOAA, requested that the National Academies of Sciences, Engineering, and Medicine conduct a follow-on workshop that would focus on the research agenda and observations needed to improve understanding of the Sun-Earth system that generates space weather.

Space Weather observations have greatest value when incorporated into forecast models and impact assessments. These observations are central to positioning, navigation and timing applications, power grid management, and many other aspects of societal infrastructure that rely on continued delivery of space weather observations and forecasts. Continued support of space environment research and model development, and a reliable path for translation to operational tools are needed to ensure that appropriate capability continues to keep up with future needs. The evolving interagency research to operations–operations to research (R2O2R) process established by National Space Weather Strategy and Action Plan marks the beginning of such an enterprise, yet to be evaluated for its effectiveness and growth potential.

Participants at the workshop encouraged developers of future space architectures to leverage an emerging, diverse, and evolving commercial capability. Representatives of commercial enterprises expressed their readiness to acquire fundamental data and to ensure their continued availability, creating opportunities to convert these observations and model output to focused and tailored products required by society today.

The mission of NOAA's Space Weather Prediction Center, one of the National Weather Service's nine National Centers of Environmental Prediction, is to provide space weather products and services to meet the evolving needs of the nation. NASA and NSF contribute scientific knowledge and technical developments to this mission; the involvement of other agencies, such as the Department of Interior/U.S. Geological Survey and the Department of Defense, other branches of government, and the private sector—together with international partnerships and coordination—provide additional key elements.

The grand challenge for space weather services is to forecast conditions in Earth's space environment with skill, reliability, and timeliness—toward achieving the capability associated with terrestrial weather services. A frequently expressed view at the workshop was that meeting this challenge will require the cooperation and coordination of the government, academic, and private sectors as envisioned in the 2019 National Space Weather Strategy and Action Plan and codified in the 2020 Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act.

Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to organize a workshop that will consider options for continuity and future enhancements of the U.S. space weather operational and research infrastructure. A report of the workshop proceedings will follow. The workshop will:

1. Review current and planned U.S. and international space weather-related observational capabilities;
2. Discuss baseline space weather observational needs;
3. Identify programmatic and technological options to ensure continuity of the baseline, giving particular attention to options to extend the Space Weather Follow On (SWFO) program; and
4. Consider options for technology, instrument, and mission development to support in situ and remote sensing space weather observations from either ground- or space-based vantage points, the latter including L1, L5, L4, GEO, and LEO.

B

Poster Session at the November 9-11, 2020, Workshop

The workshop included a poster session to provide the community with an opportunity to discuss topics relevant to the workshop (a need, a capability, or a potential architecture). Posters were introduced in a pre-recorded, virtual "Lightning Round" (3 minutes per poster provided by the presenter). Links to the posters and to the video presentations were available to attendees throughout the workshop and are also included online.[1] Thirty-one posters were submitted. The title, author, links, and summary information about each of the posters is provided below, grouped into six categories.

- Solar and Interplanetary Missions (9)
- Geospace Missions (4)
- Models (5)
- Data Portals (2)
- Instruments/Facilities (5)
- Strategies/Architectures (6)

SOLAR AND INTERPLANETARY MISSIONS

Magnetic Explorer (MagEx): A Low-Cost Science Mission to L5
W. Dean Pesnell, NASA GSFC, https://vimeo.com/showcase/7518343/video/454811074

The Magnetic Explorer, or MagEx, is a low-cost science mission proposed to fly to the L5 Lagrange point. MagEx uses the latest CubeSat-derived technology for subsystems and four compact instruments. The instruments on MagEx will provide magnetograms, coronal images out to 3 solar radii, and in situ observations of the solar wind. The combination of MagEx observations with those near Earth will improve models of the solar and heliospheric magnetic field, eventually providing better predictions throughout the heliosphere.

Sub-L1 Monitors: Required Science Discoveries Before Operations
Noé Lugaz, University of New Hampshire, https://vimeo.com/showcase/7518343/video/454811604

To improve the lead time of accurate space weather forecast, it will be necessary in the near future to launch monitors closer to the Sun than L1. Various orbits and technological approaches are possible, but we do not

[1] Links to the presentations can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

currently know enough about the physical properties of interplanetary space weather drivers to determine which location is the optimal one. Therefore, we believe that a space weather research mission is necessary as a pathfinder for sub-L1 space weather monitors; it is possible to build, launch as a rideshare, and operate such a mission for a relatively low cost.

Evaluating Solar SAil Technology Readiness for NOAA Space Weather Missions

Patricia Mulligan, NOAA/MITRE, https://vimeo.com/showcase/7518343/video/454811514

Recent progress in solar sail development and flight testing suggests that solar sails will technology will soon be able to provide access to a point closer to the Sun than L1. The Solar Cruiser Mission, if selected for flight under the Heliophysics Announcement of Opportunity, would launch in 2024. Solar Cruiser's flight will test solar sail maneuvers for a mission profile with many similarities to that of a possible future NOAA mission profile at a point sub-L1.

MUSE - Multislit Solar Explorer

Mark Cheung, Lockheed Martin Solar & Astrophysics Laboratory, https://vimeo.com/showcase/7518343/video/454811410

The Multislit Solar Explorer (MUSE) is selected for a MIDEX Phase A Study. With an innovative 37-slit design, MUSE will take spectral rasters of active regions at 12sec cadence, 100x faster than existing EUV spectrographs. State-of-the-art numerical modeling (including of space weather events like flares and CMEs) is a key component of the MUSE science investigation. The measurement of coronal line intensities, doppler flows & non-thermal broadening will enable data-driven models of Earth-directed CMEs. MUSE will also place unprecedented observational constraints to discriminate between various driving mechanisms of space weather events and to rule out coronal heating theories.

The Benefits of the Pearl Necklace Concept

Douglas Biesecker, NOAA/SWPC, https://vimeo.com/showcase/7518343/video/454811117

The Pearl Necklace (aka String of Pearls) concept is a cost efficient method of achieving a 360° view of the Sun from the ecliptic plane. We take advantage of NOAA sending new operational spacecraft to L1 every 5 years, either by sharing launch costs or by utilizing the old NOAA spacecraft to drift in a heliocentric orbit. The poster demonstrates the payload needed to achieve specific forecasting improvements and briefly describes the benefits that would result.

Solaris: Revealing the Mysteries of the Sun's Poles & Improving Understanding for Space Weather Research

Don Hassler, Southwest Research Institute, https://vimeo.com/showcase/7518343/video/455957926

Solaris is an exciting, innovative & paradigm-breaking mission of discovery to explore the poles of the Sun. Solaris was selected for Phase A development as part of NASA's MIDEX program, and will be the first mission to image the Sun's poles from 75 degrees latitude, providing new insight into the workings of the solar dynamo and the solar cycle which are at the foundation of our understanding of space weather and space climate. From its solar polar vantage point, Solaris will provide "enabling" observations for space weather research and complement other high priority missions (such as PSP, DKIST, Lagrange and other assets). Just as our understanding of Jupiter & Saturn were revolutionized by polar observations from Juno and Cassini, our understanding of the Sun will be revolutionized by Solaris.

High Inclination Solar Mission (HISM): Observing the Sun from Above Using Solar Sails

Ken Kobayashi, NASA Marshall Space Flight Center, https://vimeo.com/showcase/7518343/video/456203847

The High Inclination Solar Mission (HISM) is a concept for an out-of-the-ecliptic mission for observing the Sun and the heliosphere. The mission profile is largely based on the Solar Polar Imager concept: initially spiraling in to a 0.48 AU ecliptic orbit, then increasing the orbital inclination at a rate of ~10 degrees per year, ultimately reaching a heliographic inclination of >75 degrees. The orbital profile is achieved using solar sails derived from the technology currently being developed for the Solar Cruiser mission, currently under development.

The Heliospheric Meteorology Mission: A Mission to DRIVE our Understanding of Heliospheric Variability

Scott Mcintosh, NCAR, https://vimeo.com/showcase/7518343/video/454811655

The Heliospheric Meteorology Mission (HMM) would sample the complete magnetic and thermodynamic state of the heliosphere inside 1AU using a distributed network of deep space hardened smallsats that encompass the Sun. The observations and in situ plasma measurements made by the fleet of HMM smallsats would be collected, and assimilated into current operational space weather models. The HMM mission concept naturally allows for research motivated technology development that can improve forecast skill.

Solar Cruiser: Enabling New Vistas for Heliophysics

Les Johnson, Marshall Space Flight Center, https://vimeo.com/showcase/7518343/video/454811366

NASA MSFC is developing the Solar Cruiser mission concept to mature solar sail technology for use in future space missions. Solar Cruiser is a pathfinder for missions that observe the solar environment from unique vantage points such as sub-L1 for advanced warning of solar storms, observations away from the Sun-Earth line (SEL), and high solar inclinations.

GEOSPACE MISSIONS

ARCS

Kristina A Lynch, Dartmouth College, https://vimeo.com/showcase/7518343/video/454811295

The Auroral Reconstruction CubeSwarm is a mission concept set up to explore ionospheric physics on scale sizes of auroral arcs. It uses a combination of a localized array of 32 ionospheric LEO CubeSats; a dedicated array of 32 ground-based imagery stations across Alaska; plasma tomography between the two arrays; and ionospheric modeling for using the data. Advances in low-resource spacecraft technology and in auroral imagery techniques can now enable truly multipoint studies of ionospheric system science.

The Solar-Terrestrial Observer for the Response of the Magnetosphere

David Sibeck, NASA/GSFC, https://vimeo.com/showcase/7518343/video/454811026

STORM is the first stand-alone mission to observe the big picture of space weather. STORM takes simultaneous solar wind measurements and global images to quantify the magnetospheric response including the magnetopause, auroral oval, ring current dynamics. STORM makes continuous observations on all relevant space weather time-scales.

Radiation Belt Monitoring from Geo-Transfer Orbit: The GTOSat CubeSat

Lauren Blum, University of Colorado, Boulder, https://vimeo.com/showcase/7518343/video/455886663

With the end of the Van Allen Probes mission in 2019, radiation belt monitoring is needed from geo-transfer orbit (GTO), to provide radial profiles of the outer radiation belt. The GTOSat CubeSat, currently under development and targeting a launch in late 2021, will provide energy and pitch angle resolved measurements of energetic electrons from GTO for both scientific purposes and low-latency space weather monitoring (through the TDRS network). This 6U CubeSat can pave the way for future SmallSats to be used for space weather applications and enable affordable constellation missions in the inner magnetosphere beyond low Earth orbit.

Tracking Space Weather in 3D with Polarized Images From PUNCH

Craig DeForest, Southwest Research Institute, https://vimeo.com/showcase/7518343/video/455886644

PUNCH is a NASA Small Explorer mission to understand how the solar corona gives rise to the ambient solar wind and transient events within it. PUNCH accomplishes its science with routine, high resolution, deep field, global 3D imaging of the entire outer corona and inner heliosphere from 1.25°-45° from the Sun. PUNCH 3D tracking of CME structure and trajectory overcomes the major outstanding forecasting problems of arrival prediction (to determine event probability and ETA) and of Bz direction (to determine geoeffectiveness). The baseline PUNCH mission has ~1 day latency but with additional ground passes the mission could be used on an operational-demonstration basis.

MODELS

Improving Short to Medium-Range Forecasting of CME Geo-Effectiveness: Technology Roadmap
Angelos Vourlidas, Johns Hopkins University Applied Physics Laboratory,
https://vimeo.com/showcase/7518343/video/454810868

The poster provides an example roadmap for improving short to medium forecasting (up to 7 days) of two key hazards associated with CMEs—SEP production and magnetic field structure. The roadmap is based on a wider systems strategy for addressing comprehensively the SpWx "problem" via concise R2O and O2R frameworks. The Space Weather Aggregated Network of Systems (SWANS) is an integrated web of SpWx stations and state-of-the-art modeling facilities to enable space situational awareness for end-users invested in spaceflight operations, infrastructure risk mitigation, and future human endeavors in space exploration while profoundly transforming Heliophysics research.

A Machine Learning Approach to Forecasting Proton Flux with Electron Flux
Jesse Torres, Lulu Zhao, Philip Chan, and Ming Zhang, Florida Institute of Technology,
https://vimeo.com/showcase/7518343/video/454811766

Because of their speed difference, near-relativistic electrons released from solar energetic particle events often arrive at Earth significantly earlier than protons of energies from tens to a few hundred MeV. Damages to human health and electronics on satellites caused by tens MeV protons are much more severe than those relativistic electrons. The earlier arrival of electrons can be used to forecast solar energetic proton radiation hazards (Posner, 2007). This project develops a machine-learning algorithm using electron intensity measurements and other solar and heliospheric observations to predict proton intensity tens half to one hour ahead of the time. The results show that the new algorithm scores better than the method using simple correlations of particle intensities.

Quantitative 3D Modeling from the Sun to the Local Interstellar Medium (LISM): Solar Wind (SW), Magnetic Field (MF), and Energetic Particles
Devrie S. Intriligator, Director/Carmel Research Center, Inc.,
https://vimeo.com/showcase/7518343/video/454811162

The Sun's dynamic influence in space weather shows large variations in longitude, latitude, and radii throughout the heliosphere, heliosheath, and Local Interstellar Medium (LISM). Full 3D modeling and observations of space weather are crucial and provide key insights. Asymmetries prove the importance of full 3D space weather models. Space weather shocks and magnetic fields can adversely affect space travelers' health. Near Earth and even in the outer solar system they can modulate, at Voyagers 1 and 2 in 1977-2017, incoming heavy cosmic ray data and cause human brain damage and other health effects. Studying these space weather events may help provide better understanding of Parker observations at the Sun and remote astrophysical data beyond the LISM.

Physics-Based SWx Modeling with Machine Learning
Tamas Gombosi, University of Michigan, https://vimeo.com/showcase/7518343/video/455886684

The team is developing interpretable hybrid physics-driven and data-driven approaches to data analysis and modeling frameworks to make significant progress in physical understanding of space physics phenomena and in space weather predictions of solar eruptions and their terrestrial impacts. This work is an extension of our Space Weather Modeling Framework that is available for community use at the CCMC and is running operationally at NOAA SWPC.

Robust Ionospheric Data Assimilation Using Multi-Instrument Tomography
Cathryn Mitchell, University of Bath, https://vimeo.com/showcase/7518343/video/455886619

A large space-weather event would degrade the quality and quantity of ionospheric observations and hence our ability to specify the 3D time dependent electron density in the ionosphere—the key parameter needed to predict the performance of multiple navigation, communications and surveillance systems. This presentation proposes the parallel use of IDA4D as the primary algorithm for ionospheric specification throughout a major space weather event, with MIDAS as the independent algorithm to confirm reliability of the real-time resulting ionospheric specification.

DATA PORTALS

Radiation Data and Tools for a Space Weather-Ready Satellite Infrastructure

Janet Green, Space Hazards Applications, LLC, https://vimeo.com/showcase/7518343/video/454811201

Space radiation can damage satellite components causing on-orbit anomalies that are a risk to the reliable operation of the rapidly growing fleet of satellites. This poster describes an effort to develop tools that bring together the necessary physics, engineering, and software components to make anomaly monitoring and attribution feasible and routine for end users. It discusses the data required to support that endeavor into the future and emphasize the need for data that can be easily integrated into global retrospective and real time radiation environments.

SWx TREC's Space Weather Data Portal and Model Staging Platform

Jenny Knuth and Greg Lucas, CU Boulder, SWx TREC, LASP, https://vimeo.com/showcase/7518343/video/454811256

The Space Weather Technology, Research, and Education Center (SWx TREC) at the University of Colorado has developed a new Space Weather Data Portal to provide easy access to space weather data housed in a wide variety of formats from many different institutes. The Data Portal eases the previously complex task of finding and displaying data for education, forecaster training, and research. SWx TREC has also developed a new Model Staging Platform to run models and analyze data in the Cloud. The Staging Platform lowers the barriers to entry for getting research models into operational centers.

INSTRUMENTS/FACILITIES

Center for Geospace Storms

Slava Merkin, JHU/APL, https://vimeo.com/showcase/7518343/video/454811703

The poster presents an overview of a Center for Geospace Storms (CGS)—one of the NASA DRIVE Science Centers currently in Phase 1. The CGS vision is to transform the understanding and predictability of space weather. CGS plans to achieve this vision by developing a new model that will include and treat all critical regions of storm-time geospace, including coupling with the lower atmosphere, while resolving critical mesoscale processes. The objectives are, in short: 1. INNOVATE community modeling capabilities. 2. EMPOWER the models with data. 3. DISCOVER how storm-time geospace works.

Center for Solar-Terrestrial Research

Andrew J. Gerrard, New Jersey Institute of Technology-Center for Solar-Terrestrial Research, https://vimeo.com/showcase/7518343/video/454810843

The Center for Solar-Terrestrial Research (CSTR) at the New Jersey Institute of Technology (NJIT) is an international leader in ground- and space-based solar and terrestrial physics, with an interest in understanding the effects of the Sun on the geospace environment. This poster presents some of its major facilities, including the Big Bear Solar Observatory (BBSO), the Expanded Owens Valley Solar Array (EOVSA), the Polar Engineering Development Center (PEDC), and our work on spacecraft instrumentation, namely the RBSPICE instrument on the NASA Van Allen Probes Mission.

The Automated Radiation Measurements for Aerospace Safety (ARMAS) Program

W. Kent Tobiska, Space Environment Technologies, https://vimeo.com/showcase/7518343/video/454811732

This poster discusses decision-aid tools for managing aviation radiation exposure risks using state-of-art scientific methods and data. Objectives of ARMAS include: Assemble and organize historical knowledge of the aerospace-relevant radiation environment, with metrics; Demonstrate monitoring of current epoch, real-time "weather" of atmospheric radiation; Provide exposure risk management forecast capabilities to international, national, commercial entities and the public.

Nested Optical Networks: A New Tool for Space Weather Research

Asti Bhatt, SRI International, https://vimeo.com/showcase/7518343/video/454810984

Space weather characterization requires understanding impact from the Sun and the lower atmospheric forces on the terrestrial ionosphere-thermosphere system. The MANGO-NATION project supported by NSF DASI program uses large-scale optical networks to investigate the relative influences of these forces. An optical network of imagers measuring atomic oxygen 557.7 nm wavelength along with 3 Fabry-Perot Interferometers measuring both 557.7 and 630 nm in the south-western US is planned to be nested inside an existing network of 630 nm imagers across the continental US. The planned configuration is optimally suited to understand thermospheric influence on lower atmospheric forces affecting space weather.

NRL Space Science Division Sensors to Meet the Needs for Future SWx Research and Operational Forecasting

Christoph Englert, US Naval Research Laboratory,
https://vimeo.com/showcase/7518343/video/456203892

US Naval Research Laboratory Space Science Division has established sensor heritage to meet the needs for future SWx research and operational forecasting. Innovative, miniaturized sensors have been developed.

STRATEGIES/ARCHITECTURES

Architectures for Space Weather Magnetographs

Neal Hurlburt, Lockheed Martin Advanced Technology Center,
https://vimeo.com/showcase/7518343/video/454811554

As we move to the next generation of space weather observing systems, a key driver is the optimal architecture for photospheric (and possibly chromospheric or coronal) magnetic field measurements. Using existing operational observing systems as the starting point for our comparison, the poster projects what the next generation of ground- and space-based systems will offer, and compare estimates for their total cost of ownership, system performance, reliability and operational efficiency. It concludes that space-based instruments are the best solution, not only due to the well-established fact of their superior data quality, but also to the lesser understood role they play in providing a more cost effective, more flexible and more operationally efficient solution.

A Chapman Conference on Space Weather: Recommendations for the Community

Anthony J. Mannucci, Jet Propulsion Laboratory, California Institute of Technology,
https://vimeo.com/showcase/7518343/video/454810905

Recommendations are presented that arose from the Chapman Conference on "Chapman on Scientific Challenges Pertaining to Space Weather Forecasting Including Extremes," held in February 2019 in Pasadena, California. The first recommendation is that the community develop robust methods of determining the observations needed to achieve specific predictive capabilities. The second recommendation is that the community develop new, possibly disruptive approaches to space weather prediction. Adapting the approaches used by terrestrial weather prediction will be of limited effectiveness for space weather.

LEO Space Domain Science—Are We Doing Enough?

Jeff Thayer, University of Colorado, https://vimeo.com/showcase/7518343/video/455886659

We are now at the cusp of a new revolution where societal expansion and economic growth will increasingly depend on how we wisely utilize space—particularly in low-Earth orbit (LEO). This will require greater fidelity in forecasting and nowcasting of the LEO space environment and convergent research across the many disciplines involved in the LEO space domain. This poster introduces the concept of LEO weather stations and demonstrates the utility of common spacecraft measurements for improved characterization of the LEO environment and more accurate predictions.

Ionosphere Thermosphere Space Weather: Observations, Infrastructure, and Architecture Needs
Timothy Fuller-Rowell, CIRES University of Colorado and NOAA Space Weather Prediction Center, https://vimeo.com/showcase/7518343/video/455910451

This poster reports on a study to review satellite observations in the thermosphere and ionosphere (T-I) required to support space weather (SW) services provided by NOAA in the coming years. The observations are either of the parameters themselves that directly impact SW applications, such as plasma irregularities or neutral density, or a parameter in a physical model that drives the impact, such as solar EUV radiation, auroral precipitation, plasma drift, neutral composition, or winds. The SW impacts in the T-I include disruption of radio wave propagation from plasma irregularities, including GNSS positioning, navigation, and timing, and HF communications, and satellite drag, orbit prediction in low-Earth orbit, and space traffic management from neutral density. The study reviewed potential satellite orbits and observation methods, and we would appreciate feedback from the community on the recommendation.

Space Science at AFOSR
Julie Moses, AFOSR, https://vimeo.com/showcase/7518343/video/454811244

This poster gives some basic information about AFOSR, some information about space science at AFOSR such as number of PIs and the size of the budget. It includes a slide detailing the areas of space science that are funded. The last two slides on the poster feature two important transitions from AFOSR to space weather operations, the GAIM model And the ADAPT model.

Cosmic Rays Variation in the Natural Environment, and the Effects on Our Technology
Madhulika Guhathakurta and Dennis Wingomguhathakurta, NASA and Skycorp Incorporated

Today there is a rare confluence of space weather and our technical progress that bears reexamination in order to better quantify risk to the public from space weather variability. Solar cycle 24 has been the lowest in a century along with two deep solar minimums, resulting the highest Galactic Cosmic Ray (GCR) flux in our modern technical era. Additionally, the terrestrial bipolar magnetic field is rapidly decreasing, leading to a reduced geomagnetic rigidity constant which further increases GCR penetration into the biosphere. These factors coincide with dramatic advances in semiconductor technology that is increasing their susceptibility to these extraterrestrial influences and here we quantify all these factors.

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Workshop Agendas

PART I: VIRTUAL WORKSHOP: JUNE 16-17, 2020

All Sessions Shown in Mountain Daylight Time (-1 PDT; +2 EDT)

June 16, 2020

8:15 am Welcome and Introductory Remarks from the Co-Chairs
Janet Luhmann, University of California, Berkeley
Mary Hudson, NCAR/HAO and Dartmouth College

8:30 Workshop Objectives and Review of U.S. and European SpaceWx Plans
Tammy Dickinson, Science Matters Consulting, Session Chair

8:40 Discussions with Agency Sponsors (~15 min each)

- NOAA (Elsayed Talaat, NESDIS)
- NASA (Jim Spann, HPD)
- NSF (Mike Wiltberger, GEO/AGS-Geospace)
- Q&A

9:40 U.S. National Plans (10-15 min per speaker)

- Space Weather Operations, Research, and Mitigation (SWORM)—Mike Bonadonna, OFCM
- National Space Weather Strategy and Action Plan (NSWSAP)—Bill Murtagh, NOAA SWPC
- EMP R&D Priorities—Adam Balkcum, Office of Science and Technology Policy
- Q&A

NOTE: Links to the presentations and posters can be found at https://www.nationalacademies.org/spacewx-phaseI-presentations.

Break—30 min

11:00 ESA's Space Weather Network Plans (including L5)
- Juha-Pekka Luntama, Head of Space Weather, Space Situational Programme Office, European Space Agency, ESOC
- Q&A

11:25 DoD Perspectives
- Rachel Hock-Mysliwiec, Air Force Research Laboratory
- Q&A

Brunch/Lunch—40 min

12:30 pm National Priorities
Bill Murtagh, NOAA SWPC, Session Chair

12:40 Human Spaceflight/Human Exploration (Moon/Mars)
John Allen, Program Executive for Crew Health and Safety, NASA

1:00 Power Grid, Reliability Standards
Joe McClelland, Director, Office of Energy, Federal Energy Regulatory Commission

1:20 Space Traffic Management and Space Situational Awareness
Kevin O'Connell, Director, Office of Space Commerce, Department of Commerce

1:40 Roundtable Discussions with Session Presenters

2:00 Current and Planned Operational Requirements
- Doug Biesecker, NOAA SWPC
- Q&A

2:25 Break—15 min

Sectors and Applications—I
VADM Conrad Lautenbacher, CEO, GeoOptics, Session Chair

2:40 Electric Power
Mark Olson, Senior Engineer and Manager, Reliability Assessments at North American Electric Reliability Corporation

3:00 Satellite Operations
Steve Jolly, Director and Chief Engineer, Commercial Civil Space, Lockheed Martin Space Systems

3:20 Commercial Aviation
Mike Stills, Aviation Subject Expert; Director, Flight Dispatch (Network Operations)

3:40 Roundtable Discussions with Session Presenters

4:00 Japan's SpaceWx Plans (7:00 am on June 17 in Tokyo) 30 min total

- Mamoru Ishii, Director, National Institute of Information and Communications Technology, Space Weather Forecast Center, Japan.
- Q&A

4:30 Adjourn for the Day

June 17, 2020

8:00 am Plans for the Day
Janet Luhmann and Mary Hudson, Co-Chairs

8:15 Sectors and Applications—II
VADM Conrad Lautenbacher, CEO, GeoOptics, Session Chair

8:20 Human Exploration and Radiation—Eddie Semones, Space Radiation Analysis Group, NASA Johnson Space Center

8:40 Space Weather Effects on Communications—Mark MacAlester, Department of Homeland Security, Headquarters

9:00 PNT-Reliant Industries—Susan Skone, University of Calgary, Canada

9:20 Arctic—Bob McCoy, Director, Geophysical Institute, University of Alaska

9:40 Roundtable Discussions with Sectors and Applications Presenters

10:00 Break/Breakfast/Bruch/Lunch

11:00 Sessions on Strategic Knowledge and Observation Gaps Solar and Heliospheric Physics
Janet Luhmann, University of California, Berkeley, Session Chair

11:10 Solar Polar and Far Side Measurements—Todd Hoeksema, Stanford University

11:30 IMF Bz at L1—Pete Riley, PSI, Inc.

11:50 L5 Measurements—Mark Gibbs, UK Met Office

12:10 pm L4 Measurements—Nat Gopalswamy, NASA Goddard Space Flight Center

12:30 Solar Cycle—Lisa Upton, NCAR/HAO

12:50 Roundtable Discussions with Session Presenters

1:10 Break

1:30 Geospace—Mary Hudson, NCAR/HAO and Dartmouth College, Session Chair

1:40 Inner Magnetosphere Measurements—Drew Turner, Johns Hopkins University Applied Physics Laboratory (JHU/APL)

2:00 Low Altitude Measurements Gaps—Particles (POES/DMSP)—Delores Knipp, University of Colorado, Boulder

2:20 Low Altitude Measurements Gaps—Fields—Brian Anderson, JHU/APL

2:40 Ionosphere Measurement Gaps—Tim Fuller-Rowell, CIRES

3:00 Thermosphere Measurement Gaps, Satellite Drag—Eric Sutton, University of Colorado, Boulder

3:20 Roundtable Discussions with Presenters

3:40 Committee and Invitees Review Workshop and Discuss Interim Activities and Plans for the September 10-11, 2020, Workshop (likely virtual)

PART 2—VIRTUAL: SEPTEMBER 9-11, 2020

All Sessions Shown in Eastern Daylight Time

September 9, 2020

10:00 am Welcome/Introductory Remarks
Mary Hudson and Janet Luhmann, Organizing Committee Co-Chairs

10:15 Workshop Objectives for Phase II and Update on U.S. SpaceWx Plans (15 min each)

Tammy Dickinson, Science Matters Consulting, Session Chair

10:20 Agency Presentations—I (~15 min each)

- NOAA (Elsayed Talaat)
- NASA (Nicky Fox)
- NSF (Mike Wiltberger, GEO/AGS-Geospace)

11:10 National and International Plans (~15 min each)

- Space Weather Operations, Research, and Mitigation (SWORM)—Louis Uccellini, National Weather Service
- U.S. Air Force Plans—Lt Col Omar A. Nava, Headquarters, Air Force Weather
- Discussion of Pending Congressional Legislation to Promote Space Weather Research, Observations, and Forecasting—Jeff O'Neil, Legislative Director, Rep. Ed Perlmutter, D-CO (to be reconfirmed closer to date)
- Collaboration on Space Weather—David Turner, Acting Director, Office of Space and Advanced Technology, U.S. State Department

12:10 pm Roundtable Discussions of Morning Session Presentations

12:50 Break/Lunch/Brunch

1:45 National Priorities

Bill Murtagh, NOAA SWPC, Session Chair – 15 min per person

1:50 Nicole Kinsman, Alaska Regional Advisor, NOAA/NOS/National Geodetic Survey

2:05 Mitigating the Effects of Geomagnetic Storms on the Nation's Bulk Power System
Mark Lauby, Senior Vice President and Chief Engineer, North American Electric Reliability Corporation

2:20 Space Weather in NASA's Exploration Campaign
Steve Clarke, Deputy AA, Aeronautics Research Mission Directorate, NASA

2:35 Roundtable Discussions on Afternoon Sessions

3:15 Break

3:40 Poster Lightning Round—Ron Turner

5:10 Adjourn for Day

September 10, 2020

10:00 am Recap/Plans for Day 2
Janet Luhmann and Mary Hudson

10:15 Agency Presentations—II (~25 min total)
Steve Volz, NOAA Assistant Administrator for Satellite and Information Services

10:40 The Impact of Space Weather on Space Traffic Management in the NewSpace Era
Ted Muelhaupt, Principal Director, Center for Orbital and Reentry Debris Studies, The Aerospace Corporation (25 min, including discussion)

11:05 Break/Breakfast/Bruch

11:45 Keynote Address: "Space Weather: An Emergency Manager's Perspective"
W. Craig Fugate, Federal Emergency Management Agency, Former Administrator

12:30 pm Space-Based Architectural Framework Panel (~15 min each)

Topics to include data buys, resiliency, distributed versus single measurements, and availability of real time measurements to NOAA

Harlan Spence, University of New Hampshire, Session Chair

Session Keynote: Space Weather Observing Architectures: A Systems View
Dan Baker, University of Colorado, Boulder, and Laboratory for Atmospheric and Space Physics

- VADM (ret) Conrad C. Lautenbacher, GeoOptics—Leveraging the Commercial Sector

- Justin Kasper, Director of R&D at BWX Technologies—Solar Wind Particle Measurements
- Jerry Goldstein, Southwest Research Institute—ENA and EUV Imaging
- Robyn Millan, Dartmouth College—Distributed LCAS, CubeSats
- David Malaspina, University of Colorado, Boulder—Fields and Waves Measurements

2:50 Roundtable Discussions

3:30 Break

3:50 Ground-Based Measurements Panel

Topics to include data buys, resiliency, distributed versus single point measurements

Introductory Remarks by Anthea Coster, MIT Haystack Observatory, Session Chair

- ONR Marine Meteorology and Space—Daniel Eleuterio
- Canadian Space Weather Forecasts Centre—David Boteler, Head

4:50 Recap/Plans for Day 3 – Janet Luhmann and Mary Hudson

5:10 Adjourn for the Day

September 11, 2020

10:00 a.m. Ground-based Measurements Panel — Continued from Day 2

Topics to include data buys, resiliency, distributed vs. single point measurements

Anthea Coster, MIT Haystack Observatory, Session Chair

- Michael Starks, Air Force Research Laboratory (VLF and RF Propagation)
- Valentin Pillet, Director NSO (including NSO Synoptic Programs, DKIST)
- Tim Bastian, National Radio Astronomy Observatory (including solar radio)
- Josh Semeter, Boston University (including Ionosondes, Optical, GNSS)
- Jenn Gannon, Computational Physics, Inc. (including Ground-Based Magnetometers)

11:50 Roundtable Discussion

12:30 pm Break/Brunch/Lunch

1:15 Architectural Framework Panel—Supporting R&A

Opening Remarks by Session Chair Pete Riley, PSI, Inc.

- Modeling, Ensemble Modeling and Data Assimilation, and OSSEs—Brian Gross, Director, NOAA Environmental Modeling

- Machine Learning in Heliophysics—Monica Bobra, Stanford University
- Techniques for Data-Model Comparison—Leila Mays, Deputy Director, CCMC
- Transitioning Research Models to Operations—Gabor Toth, University of Michigan

2:40 Roundtable Discussion

3:10 Break

3:20 Summary of Panel-Led Discussions, Prioritization and Value to Society
Group Discussion and Q&A with all Participants

4:00 Workshop Adjourns
Committee Continues Discussion in Closed Session

5:30 Committee Closed Session Meeting Adjourns

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Acronyms and Abbreviations

3D	three dimensional
ACE	Advanced Composition Explorer
ACSWA	American Commercial Space Weather Association
ADAPT	Air Force Data Assimilative Photospheric flux Transport
AFRL	Air Force Research Laboratory
AMPERE	Active Magnetosphere Polar Electrodynamics Response Experiment
ARMAS	Automated Radiation Measurement for Aviation Safety
BBSO	Big Bear Solar Observatory
CCMC	Community Coordinated Modeling Center (NASA)
CCOR	compact coronagraph
CIRES	Cooperative Institute for Research in Environmental Sciences
CME	coronal mass ejection
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CSA	Canadian Space Agency
CSFC	Canadian Space Weather Observations and Forecasts Centre
CWDP	commercial weather data program
D3S	Distributed Space Weather Sensor System
DASI	Distributed Array of Small Instruments
DKIST	Daniel K. Inouye Solar Telescope
DMSP	Defense Meteorological Satellites Program
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DSCOVR	Deep Space Climate Observatory
EMP	electromagnetic pulse

EO	Executive Order
EOP	Executive Office of the President
EOVSA	Expanded Owens Valley Solar Array
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUV	extreme ultraviolet
EXIS	Extreme Ultraviolet and X-ray Irradiance Sensors
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GCR	galactic cosmic ray
GDC	Geospace Dynamics Constellation
GEO	geostationary orbit
GIC	geomagnetically induced current
GMD	geomagnetic disturbance
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb and Disk
GONG	Global Oscillations Network Group
GOX	GPS occultation experiment
GPS	Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
GSFC	Goddard Space Flight Center (NASA)
HAF	Hakamada-Akasofu-Fry (solar wind model)
HAO	High-Altitude Observatory
HEMP	high-altitude electromagnetic pulse
HERMES	Heliophysics Environmental and Radiation Measurement Experiment Suite
HPD	Heliophysics Division
ICME	interplanetary mass ejection
ICON	Ionospheric Connection Explorer
ICSWIAS	International Committee for Space Weather Impacts to Aviation Safety
IDA	Institute for Defense Analyses
IDIQ	Indefinite Delivery Indefinite Quantity
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMAP	Interstellar Mapping and Acceleration Probe
IoT	Internet of Things
ISEP	Integrated Solar Energetic Proton Event Alert/Warning System
ISES	International Space Environment Service
ISRO	Indian Space Agency
ISS	International Space Station
ISTO	Ionospheric Scintillation TEC Observatory
IVM	ion velocity meter
JAXA	Japan Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
KMA	Korea Meteorological Administration

LANL	Los Alamos National Laboratory
LASCO	Large Angle and Spectrometric Coronagraph
LASP	Laboratory for Atmospheric and Space Physics
LEO	low Earth orbit
LWS	Living With a Star
MAG	magnetometer
Metop	Meteorological Operational satellite
MHD	magneto hydro-dynamics
MIDEX	Medium-Class Explorer
MLSO	Mauna Loa Solar Observatory
MOU	memorandum of understanding
NAPA	National Academy of Public Administration
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEI	National Center for Environmental Information
NCEP	National Centers for Environmental Prediction, NOAA
NERC	North American Electric Reliability Corporation
NESDIS	National Satellite Data and Information Service (NOAA)
NEXION	Next Generation Ionosonde
NEXT	Iridium 2nd Generation Satellite Constellation
ngGONG	Next Generation Global Oscillations Network Group
ngRH	Next Generation Radioheliograph
NGDC	National Geophysical Data Center, NOAA
NICT	National Institute of Information and Communications Technology (Japan)
NOAA	National Oceanic and Atmospheric Administration
NOP	Refers to the N, O, and P satellites in the fourth generation of the GOES satellite system
NORAD	North American Aerospace Defense Command
NRAO	National Radio Astronomy Observatory
NRCan	Natural Resources Canada
NSF	National Science Foundation
NSO	National Solar Observatory
NSOSA	NOAA Satellite Observing System Architecture
NSPO	National Space Organisation (Taiwan)
NSTC	National Science and Technology Council
NSWAP	National Space Weather Action Plan
NSWP	National Space Weather Program
NSWS	National Space Weather Strategy
NSW-SAP	National Space Weather Strategy and Action Plan
NWS	National Weather Service (NOAA)
O2R	operations to research
OADR	open architecture data repository
OES	Bureau of Oceans and International Environmental and Scientific Affairs (Department of State)
ONR	Office of Naval Research
OSC	Office of Space Commerce (Department of Commerce)
OSTP	Office of Science and Technology Policy
PLASMAG	Plasma-Magnetometer (PlasMag)

PNT	positioning, navigation, and timing
POES	Polar-orbiting Environmental Satellite
PPP	Presidential Policy Directive
PROBA	Project for Onboard Autonomy
PROSWIFT	Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow
PUNCH	Polarimeter to Unify the Corona and Heliosphere
R2O	research to operations
R2O2R	research to operations-operations to research
R&D	research and development
RF	radio frequency
RO	radio occultation
RSTN	Radio Solar Telescope Network
RSTU	Refers to the R, S, T, and U satellites in the latest generation of the GOES satellite system
SDO	Solar Dynamics Observatory
SECHHI	Sun-Earth Connection Coronal and Heliospheric Investigation
SEISS	Space Environment In-Situ Suite
SEM	Space Environmental Monitor
SEON	Solar Electro-Optical Network
SEP	solar energetic particle
SHOES	Solar-Heliospheric Optical Environment Satellites
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SOON	Solar Optical Observing Network
SpaceWOC	Space Weather Operations Center (USAF)
SPD	space policy directive
SPE	solar particle event
SRAG	Space Radiation Group (NASA)
SRB	solar radio burst
SSA	space situational awareness
STEREO	Solar Terrestrial Relations Observatory
STM	space traffic management
SuperDARN	Super Dual Auroral Radar Network
SUVI	Solar Ultraviolet Imager
SWC	Space Weather Center
SWEP	Severe Weather Emergency Plan
SWFO	Space Weather Forecast Office
SWGC	Space Weather as a Global Challenge
SWIS	Solar Wind Instrument Suite
SWORM	Space Weather Operations, Research, and Mitigation
SWPC	Space Weather Prediction Center (NOAA)
SWRI	Southwest Research Institute
SWXC	global space weather center
SXI	Solar X-ray Imager
TEC	total electron content
TGRS	Tri-GNSS Radio-Occultation System
THEMIS	Time History of Events and Macroscale Interactions during Substorms Mission

THIRA	Threat and Hazard Identification and Risk Assessment
TRACERS	Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites
ULF	ultralow frequency
UN	United Nations
USAF	U.S. Air Force
USGS	U.S. Geological Survey
VLF	very low frequency
WAM-IPE	Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics
WOC	Weather Operations Center
WSA	Wang-Sheeley-Arge Model

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Biographies of Committee Members and Staff

MARY K. HUDSON, *Co-Chair*, is the Eleanor and A. Kelvin Smith Professor Emerita of Physics at Dartmouth College and Senior Research Associate NCAR. She also served for 8 years as chair of Physics and Astronomy at Dartmouth. Dr. Hudson was one of the principal investigators (PIs) with the Center for Integrated Space Weather Modeling, where researchers studied the weather patterns that originate from a solar eruption, following the energy and mass transfer through the interplanetary medium, all the way to Earth's ionosphere. Current areas of investigation include the evolution of the radiation belts; how the ionized particle outflow known as the solar wind and the magnetic field of the Sun interact with the magnetic field of Earth, producing electrical currents in the ionosphere; and the effects of solar cosmic rays on radio communications near Earth's poles. She is a co-investigator on NASA's Van Allen Probes Mission. Dr. Hudson is a fellow of the American Geophysical Union (AGU), recipient of the 2017 Fleming Medal, and recipient of the AGU Macelwane Award. Dr. Hudson has served on Heliophysics Subcommittee of the NASA Advisory Council. Dr. Hudson received her Ph.D. in physics from the University of California, Los Angeles. Dr. Hudson previously served as co-chair of the National Academies of Sciences, Engineering, and Medicine's Standing Committee on Solar and Space Physics and as a member of the Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics).

JANET G. LUHMANN, *Co-Chair*, is a senior fellow at the Space Sciences Laboratory at the University of California, Berkeley. Her current research includes the use of spacecraft observations and models to investigate the connections between the Sun and heliospheric conditions, and the solar wind interactions with the planets. Dr. Luhmann is the current PI for the IMPACT Investigation on NASA's STEREO mission, and a deputy PI for the MAVEN mission. A fellow of the AGU, Dr. Luhmann was also the recipient of the 2007 John Adam Fleming Medal, awarded by the AGU for "original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, space physics, and related sciences." She received her Ph.D. from the University of Maryland, College Park. Dr. Luhmann has served on numerous committees for the National Academies, including the Committee on PI-led Missions: Lessons Learned, Committee on Solar and Space Physics (including as chair), Space Studies Board, and the Committee on Solar-Terrestrial Research. She is currently serving on the Committee for the Review of Progress Toward Implementing the Decadal Survey - Solar and Space Physics: A Science for a Technological Society.

DANIEL N. BAKER is director of the Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder. He is Distinguished Professor of Planetary and Space Physics, Professor of

Astrophysical and Planetary Sciences, and Professor of Physics at the university. He was group leader for Space Plasma Physics at Los Alamos National Laboratory (1980-87) and was division chief at NASA's Goddard Space Flight Center (1987-1994). Dr. Baker presently holds the Moog-Broad Reach Endowed Chair of Space Sciences at University of Colorado, Boulder. He was a member of the 2006 Decadal Review of the U.S. National Space Weather Program and chaired the National Academies Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics). He has edited nine books and published over 800 papers in the refereed literature. In addition to his election to the National Academy of Engineering, Dr. Baker's honors include being awarded the 2010 AIAA James Van Allen Space Environments Medal. In 2015, Dr. Baker was chosen as the Vikram A. Sarabhai Professor of the Indian Physical Research Laboratory. He also received in 2015 the Shen Kuo Medal of the International Association of Geomagnetism and Aeronomy (IAGA) for his interdisciplinary leadership in space and Earth sciences. He was chosen in 2016 as winner of the Colorado Governor's Award for High-Impact Research related to his space weather research. Dr. Baker was the recipient of the 2018 William Bowie Medal of the AGU for outstanding geoscience research. He also is the recipient of the 2019 Hannes Alfven Medal of the European Geosciences Union. Dr. Baker received his Ph.D. working under Prof. James A. Van Allen and subsequently worked with Prof. Edward C. Stone as a research fellow in the Department of Physics at the California Institute of Technology. Dr. Baker has served on numerous committees for the National Academies, including the Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics) as chair, the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions, and the Committee on Solar and Space Physics as chair, and the Space Studies Board.

ANTHEA J. COSTER is a principal research scientist at the MIT's Haystack Observatory. Her research interests include physics of the ionosphere, magnetosphere, and thermosphere; space weather and geomagnetic storm time effects; coupling between the lower and upper atmosphere; GPS positioning and measurement accuracy; radio wave propagation effects; and meteor detection and analysis. She is a co-PI on the National Science Foundation (NSF)-supported Millstone Hill Geospace facility award and a PI/co-PI on a numerous projects involving the use of GPS to probe the atmosphere, including investigations of the plasmaspheric boundary layer, stratospheric warming, and the ionosphere over the Antarctic. Dr. Coster and her co-workers developed the first real-time ionospheric monitoring system based on GPS in 1991. She has been involved with measuring atmospheric disturbances over short baselines (GPS networks smaller than 100 km) for the U.S. Federal Aviation Administration, and has coordinated meteor research using the ALTAIR dual-frequency radar for NASA. She received her Ph.D. in space physics and astronomy from Rice University. Dr. Coster previously served on the National Academies U.S. National Committee for the International Union of Radio Science.

TAMARA L. DICKINSON is president of Science Matters Consulting. She previously served as principal assistant director for Environment and Energy at the White House Office of Science and Technology Policy (OSTP). Dr. Dickinson served as OSTP's assistant director for Disaster Resilience and Space Science, addressing issues related to disasters (natural and man-made), NASA space science programs, space weather, and general Earth science. Dr. Dickinson served at OSTP on a detail from the U.S. Geological Survey (USGS) where she previously served as the program coordinator for the National Geological and Geophysical Data Preservation Program and Geology Lab Program. Prior to joining USGS, she held several positions at the National Research Council. Dr. Dickinson has held research positions at NASA Johnson and Goddard Space Centers and the Smithsonian Institution Natural History Museum where she focused on the origin and evolution of lunar materials and meteorites. Dr. Dickinson was awarded the National Academies Individual Service Award in 2002, the Bureau of Land Management Sustainable Development Award in 2004, and the Department of Interior Superior Service Award in 2008. She has an asteroid (Asteroid 1981 EU22 Tammydickinson) named in honor of her research and program management work. Dr. Dickinson is a fellow of the Geological Society of America. Dr. Dickinson earned her B.A. from the University of Northern Iowa and M.S. and Ph.D. from the University of New Mexico.

MARK GIBBS serves as the head of Space Weather for the UK Met Office where he has worked for nearly 30 years as a meteorologist. During that time he has undertaken a range of roles including flying on the Met Office's atmospheric research aircraft and also developing a health forecasting capability. Since late 2010, he has led the development of space weather forecasting within the Met Office. This work has led to the creation of a manned 24x7x365 Space Weather Operation Centre within the Met Office, only the third center globally to be fully operational. Work is currently focusing on understanding the particular user requirements of the sectors vulnerable to space weather and understanding how you communicate effectively with the public on such a high impact/low probability event. In his role as head of Space Weather he is also a member of the UK's Space Environment Impacts Expert Group; the UK representative on the International Space Environment Services organization; a member of the UN COPUOS, Science & Technology Sub-Committee, Expert Group on Space Weather; and an advisor of the International Civil Aviation Organization Met Panel Working Group on Meteorological Information and Service Development, Space Weather Sub-group.

JANELLE V. JENNIGES, MAJ. USAF, is chief, Space Weather Integration, Weather Strategic Plans at Interagency Division, Directorate of Weather, HQ U.S. Air Force. Her previous positions include the following: assistant professor of space physics, Air Force Institute of Technology-Graduate School of Engineering and Management, Wright-Patterson AFB; and flight commander, Space Weather Operations Center, 2nd Weather Squadron, Air Force Weather Agency, Offutt AFB. Her research covers a wide range of topics in space physics, including the improved specification of ionospheric space weather models, the structure of the high-latitude electric fields, and the transition of cutting-edge research to operational forecast products. She received her Ph.D. in physics in 2015 from Utah State University. In 2005, then Lt. Jenniges received the Air Force's Cadet of the Year award.

CONRAD C. LAUTENBACHER, JR., VADM USN (Ret.) is the chief executive officer of GeoOptics, Inc., which is also a member of the American Commercial Space Weather Association. Dr. Lautenbacher retired as Vice Admiral from the U.S. Navy, where he was Commander of the U.S. Third Fleet. Admiral Lautenbacher also served as Deputy Chief of Naval Operations in charge of programs and budget. After leaving the Navy he served as Under Secretary of Commerce for Oceans and Atmosphere and as the eighth Administrator of the National Oceanic and Atmospheric Administration (NOAA), 2001-2008. Before joining NOAA, Dr. Lautenbacher formed his own management consultant business, and worked principally for Technology, Strategies & Alliances Inc. He also has been president and CEO of the Consortium for Oceanographic Research and Education (CORE), a nonprofit organization of institutions of higher learning with a mission to increase basic knowledge and public support across the spectrum of ocean sciences. Dr. Lautenbacher is a graduate of the U.S. Naval Academy and holds M.S. and Ph.D. degrees in applied mathematics from Harvard University. From 2001-2008 he was an ex-officio member of the NRC Government-University-Industry Research Roundtable.

WILLIAM MURTAGH currently serves as the program coordinator for the NOAA Space Weather Prediction Center (SWPC) in Boulder, Colorado. He is NOAA's space weather lead in coordinating preparedness and response efforts with industry, emergency managers, and government officials around the world. He also serves as the National Weather Service lead in the National Science and Technology Council (NSTC) interagency committee to develop and implement actions in the 2019 National Space Weather Strategy and Action Plan. In November 2016, he completed a 26-month assignment in the White House OSTP as the assistant director for Space Weather. In his position at OSTP, he oversaw the development and implementation of the 2015 National Space Weather Strategy and National Space Weather Action Plan and coordinated efforts to develop Executive Order 13744 (2016), "Coordinating Efforts to Prepare the Nation for Space Weather Events." He regularly briefs the White House, Congress, and other government leadership on space weather and its effects on critical infrastructure. He is also a key contributor in U.S. government efforts to advance international cooperation in space weather-related activities. Before joining

NOAA, he was a weather forecaster in the U.S/ Air Force. He coordinated and provided meteorological support for national security interests around the world. He transferred to the SWPC in 1997 as a space weather forecaster and liaison between NOAA and the U.S. Air Force. He joined NOAA in 2003 after retiring from the Air Force with 23 years of military service.

MARK A. OLSON is senior engineer of Reliability Performance Analysis, North American Electric Reliability Corporation (NERC), where he works on geomagnetic disturbance mitigation. The mission of NERC is to ensure the reliability of the Bulk-Power System in North America; understanding the effects of geomagnetic disturbances (GMD) on bulk power systems and the ability of the industry to mitigate their effects are important to managing system reliability. Prior to joining NERC, Mr. Olson was an officer in the U.S. Navy where he served in various positions related to the operations and management of surface ships and naval personnel. He has a master's degree in electrical engineering from the Naval Postgraduate School and a bachelor's degree from the U.S. Naval Academy.

LARRY J. PAXTON is a member of the principal professional staff at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) and chief scientist of Geospace. Dr. Paxton is the PI on seven instruments that have flown in space. His research interests include space science, space technology, satellite- and ground-based mission design, the implications of global climate change for the stability of nations; and innovation. He is particularly interested in new instruments that characterize the geospace environment. He has published over 260 papers on these subjects. He is an academician member of the International Academy of Astronautics and the past president of the AGU's Space Physics and Aeronomy section (2016-2018). His awards include JHU/APL Publication of the Year Awards; JHU/APL Government Purpose Invention of the Year Nominee; and Best Paper–7th IAA Symposium on Small Satellites for Earth Observation. Other recent relevant experience includes JHU's Global Water Institute and the JHU Earth Environment Sustainability and Health Institute as well as the NASA Heliophysics Roadmap Committee; NSF Aeronomy Review Panel and NSF Aeronomy Committee of Visitors; chair of IAA Commission 4 and Small Satellite Program Committee. He earned his Ph.D. in astrophysical, planetary, and atmospheric sciences from the University of Colorado, Boulder. He has served on several committees of the National Academies, including the Committee on the Effects of Solar Variability on Earth's Climate: A Workshop, and the Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics) Panel on Atmosphere-Ionosphere-Magnetosphere Interactions. He is currently serving on the Space Studies Board.

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PETE RILEY is vice president, chief financial officer, and senior research scientist at Predictive Science Inc. (PSI). He is particularly interested in three-dimensional, time-dependent MHD simulations of large-scale heliospheric processes, including solar wind streams and coronal mass ejections. His expertise lies primarily in developing, testing, and running massively parallel computer codes, which are run on a range of parallel architectures, from small clusters to large supercomputers, such as NSF's Ranger and NASA's Pleiades. He also analyzes a variety of solar and interplanetary datasets, and is a member of the STEREO, Ulysses, and ACE plasma instrument teams. He is also a member of the Solar Probe and Solar Orbiter magnetometer instrument teams. In 1998, he was awarded a group achievement award for his contribution to the Advanced Composition Explorer mission and co-won the 2006 SAIC RDT&E Group performance award. He has published over 60 papers in the field of space physics, and particularly in the area of heliospheric physics. He was an editor, and subsequently chief editor, for *Reviews of Geophysics*, and, before that, an associate editor with *Geophysical Research Letters*. Previously, he served as chair for NSF's SHINE (Solar, Heliospheric, and Interplanetary Environment) steering committee, and he is currently serving on NSF's Space Weather Benchmarks steering committee, a follow-on to the NSF Space Weather Benchmarks Phase I study. Additionally, he chairs the 2019 Induced Geo-Electric Fields working group and is also co-lead of the real-time forecasting validation planning group for the CCMC's IMF Bz, which in turn, is part of the IMF Bz at L1 working team, also co-lead by him. Currently, he is a PI for a number of projects supported by NASA, NOAA, NSF, and the Department of Defense. He received his Ph.D. in space physics and astronomy in 1994 from Rice University.

RONALD E. TURNER is a distinguished analyst with Analytic Services (ANSER), Inc., which in 2004 became the parent institution of the Homeland Security Institute, the only federally funded research and development center dedicated to the Department of Homeland Security. Dr. Turner is an internationally recognized expert in radiation risk management for astronauts, particularly in response to solar storms. For 9 years, he was the ANSER point of contact to the NASA Institute for Advanced Concepts (NIAC), an independent institute charged with creating a vision of future space opportunities to lead NASA into the 21st century, and he is currently the senior science advisor to the new NASA Innovative Advanced Concepts Program. He was a participating scientist on the Mars Odyssey program. He is on the advisory council to the National Space Biomedical Research Institute Center for Acute Radiation Research. He served on an National Academies committee looking at precursor measurements necessary to support human operations on the surface of Mars (2002). He was chair of the Human Health and Support Technologies panel of the NASA Capabilities Technology Roadmap Review in 2005. He supported a report on Space Physics Support to NASA's Exploration Vision. He earned his Ph.D. in physics from the Ohio State University. He has served on several National Academies committees, including the Committee on Solar and Space Physics, the Committee to Review NASA's Evidence Reports on Human Health Risks, and the Committee for the Evaluation of Radiation Shielding for Space Exploration.

Staff

COLLEEN N. HARTMAN, joined the National Academies of Sciences, Engineering, and Medicine in 2018, as Director for both the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB). After beginning her government career as a presidential management intern under Ronald Reagan, Dr. Hartman worked on Capitol Hill for House Science and Technology Committee Chairman Don Fuqua, as a senior engineer building spacecraft at NASA Goddard, and as a senior policy analyst at the White House. She has served as Planetary Division Director, Deputy Associate Administrator and Acting Associate Administrator at NASA's Science Mission Directorate, as Deputy Assistant Administrator at NOAA, and as Deputy Center Director and Director of Science and Exploration at NASA's Goddard Space Flight Center. Dr. Hartman has built and launched scientific balloon payloads, overseen the development of hardware for a variety of Earth-observing spacecraft, and served as NASA program manager for dozens of missions, the most successful of which was the Cosmic Background Explorer (COBE). Data from the COBE spacecraft gained two NASA-sponsored scientists the Nobel Prize in physics in 2006. She also played a pivotal role in developing innovative approaches to powering space probes destined for the solar system's farthest reaches. While at NASA Headquarters, she spearheaded the selection process for the New Horizons probe to Pluto. She helped gain administration and congressional approval for an entirely new class of funded missions that are competitively selected, called "New Frontiers," to explore the planets, asteroids, and comets in the Solar System. She has several master's degrees and a Ph.D. in physics. Dr. Hartman has received numerous awards, including two prestigious Presidential Rank Awards.

ARTHUR CHARO has been a senior program officer with the SSB since 1995. For most of this time, he has worked with the board's Committee on Earth Science and Applications from Space and the Committee on Solar and Space Physics. He has directed studies resulting in some 38 reports, notably inaugural NRC "decadal surveys" in solar and space physics (2002) and Earth science and applications from space (2007). He also served as the study director for the second NRC decadal survey in solar and space physics (2012) and the second Earth science decadal (2018). Dr. Charo received his Ph.D. in experimental atomic and molecular physics in 1981 from Duke University and was a post-doctoral fellow in Chemical Physics at Harvard University from 1982-1985. He then pursued his interests in national security and arms control as a Fellow, from 1985-1988, at Harvard University's Center for Science and International Affairs. From 1988-1995, he worked as a senior analyst and study director in the International Security and Space Program in the Congressional Office of Technology Assessment. In addition to contributing to SSB reports, he is the author of research papers in the field of molecular spectroscopy; reports on arms control and space policy; and the monograph, *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990). Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was a 1988-1989 American Association for the Advancement of Science (AAAS) Congressional Science Fellow, sponsored by the American Institute of Physics.

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