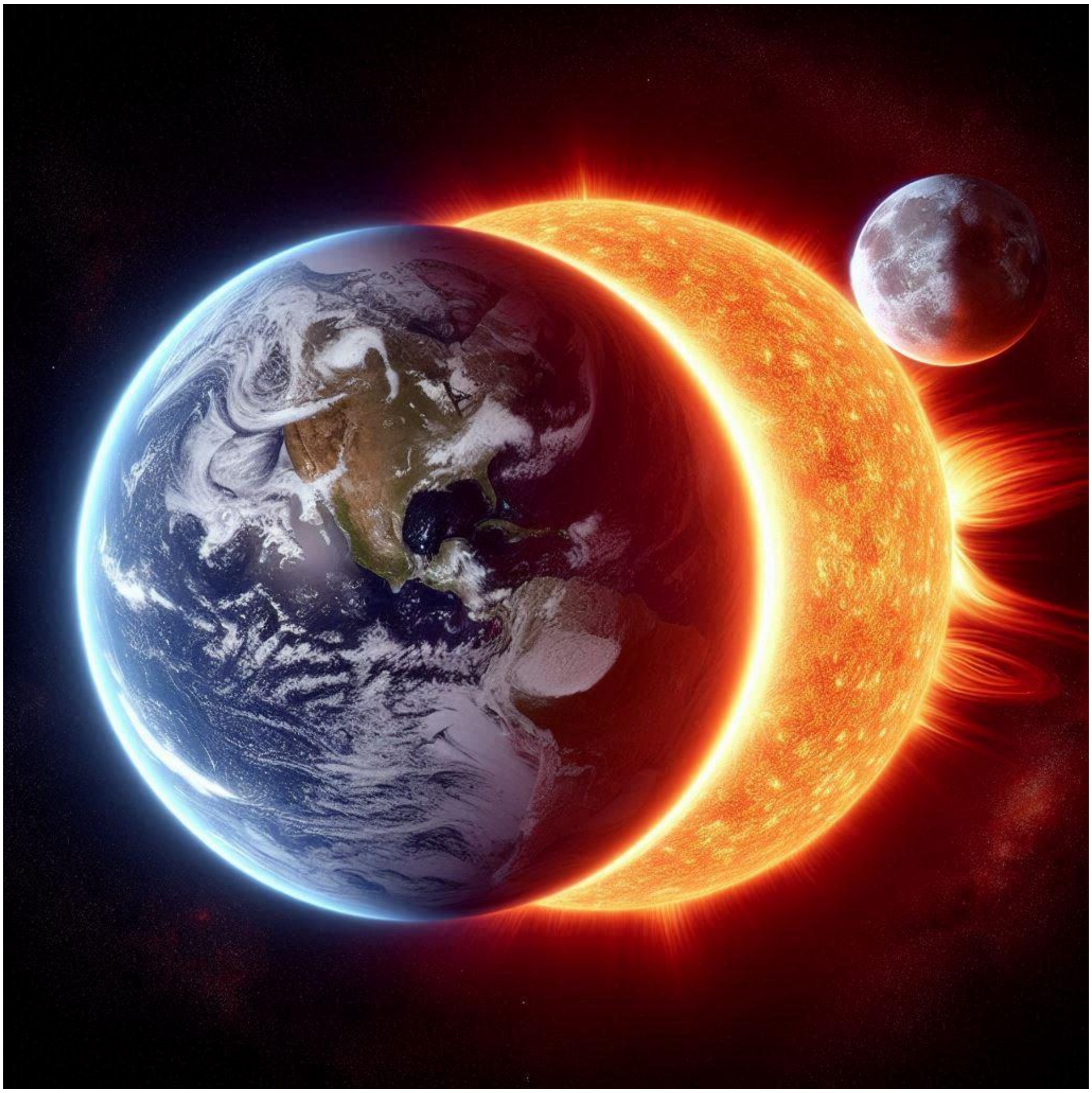
Results of the First National Survey of User Needs for Space Weather



Product of the Space Weather Advisory Group

September 26, 2024

In recognition and memory of Dr. Jennifer Gannon—a leading international space weather physicist who left us in her prime. Dr. Gannon was a key member of the SWAG and a significant contributor to this end user survey report.

Acknowledgements

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Executive Summary

In 2014, the Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee was chartered under the National Science and Technology Council (NSTC) to coordinate actions to address space weather risk. In October 2020, Congress passed the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act (PROSWIFT; P.L. 116-181; 51 USC 60601-60608). PROSWIFT directs the National Oceanic and Atmospheric Administration (NOAA), working with SWORM, to establish a Space Weather Advisory Group (SWAG). PROSWIFT tasked SWAG, among other things, to "conduct a comprehensive survey of the needs of users of space weather products to identify the space weather research, observations, forecasting, prediction, and modeling advances required to improve space weather products."

In conducting the user needs survey, SWAG built on the work presented in Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise (SWAG, 2023) and Customer Needs and Requirements for Space Weather Products and Services (Abt Survey Report, 2019), and in accordance with the survey considerations provisions outlined in the PROSWIFT Act [51 USC 60601(d)(3)(B)]:

[1] assess the adequacy of current Federal Government goals for lead time, accuracy, coverage, timeliness, data rate, and data quality for space weather observations and forecasting;

[2] identify options and methods to, in consultation with the academic community and the commercial space weather sector, improve the advancement of the goals;

[3] identify opportunities for collection of new data to address the needs of the space weather user community;

[4] identify methods to increase coordination of space weather research to operations and operations to research;

[5] identify opportunities for new technologies, research, and instrumentation to aid in research, understanding, monitoring, modeling, prediction, forecasting, and warning of space weather; and

[6] identify methods and technologies to improve preparedness for potential space weather phenomena.

The space weather end-user community is diverse and can be categorized in a variety of ways. SWAG divided the community into 10 industry sectors. In 2023, SWAG decided to conduct the user needs survey on 7 of the 10 sectors: electric power, aviation, human space flight (HSF), space traffic management and coordination (STM/C), emergency management (EM), research, and applications and users of global navigation satellite systems (GNSSs). The sectors identified and interviewed play important roles in national security, the economy, and society. SWAG developed a common set of questions that could be asked across all the sectors and sets of sector-specific questions. For most sectors, focus groups were used to collect the survey information. The GNSS sector is large and diverse, and thus the information will be collected over 2 or more years via an online survey followed by focus groups. The GNSS sector survey is ongoing and results are not presented in this report.

Focus group respondents were asked questions about their (1) current use of space weather observations, information, forecasts, and technological systems; (2) components or elements affected by space weather; (3) current and future risk and resilience activities; (4) future space weather requirements; and (5) unused or new types of measurements or observations that would enhance space weather risk mitigation.

This report's goal is to further the national space weather enterprise through articulating the needs of the user community. The report is organized by sector; each chapter summarizes the focus group discussions for a sector and draws findings and recommendations based on that information. SWAG members, as community representatives, did not participate as users in the survey, but as subject matter experts have thoughts on user needs. Therefore, some chapters include a section on thoughts, findings, and recommendations from SWAG.

Through the analysis of sector-wide surveys, SWAG identified 46 findings and 113 recommendations that, when implemented, will enable these critical sectors to better prepare for and become more resilient to the effects of space weather.

In compiling this report, SWAG recognized common themes that arose across multiple sectors. These common themes with summarized findings and recommendations are detailed in the final chapter of the report—Overarching Themes and Next Steps—and present an opportunity for common investment and consolidated action to address multiple recommendations across several sectors and are summarized below.

Summary of Overarching Themes

Overarching Theme 1. Regionalization and Impacts

The need for increased regionalization and granularity of forecast products and an indication of the potential impacts was identified as a need in the electric power, aviation, HSF, STM/C, and EM sectors. Regionalization means different things across the different sectors.

Examples include the need for more local measurements, products with longer lead time, and a better understanding and characterization of space weather effects on the local environment.

Overarching Theme 2. Education and Testbeds

The need for additional education was identified in the electric power, aviation, STM/C, EM, and research sectors. This includes broadening the educational base and workforce through developing programs for the application of non-traditional fields to space weather research and the need for space weather users and practitioners to increase awareness of space weather products and its effects through training, coursework, and testbeds and exercises.

Overarching Theme 3. Data Archives, Access (Latency), and Automation

Accessible data, including indices and proxies, that is rapidly populated (low latency) and well curated (with stated uncertainties and metadata) are key to developing actionable space weather products and informing both prompt operational decisions and long-term planning activities. The evolving need for rapid access to data for decision-making would be enabled through improved automation—reducing the need for humans in the loop.

Evolving computational approaches for modeling drive the need to ensure space weather data archives are machine readable and artificial intelligence (AI) and machine learning (ML) friendly. Additionally, there is a need for interoperability between historical data sets and recent data sets to enable seamless model development, validation, and verification. Lastly, the private sector is a growing source of unique and additive space weather relevant data. The sharing of private sector data would be further enhanced through collaboration with Federal agencies and lowering the barrier for participation by the private sector.

Summary of Sector-Specific Issues

Below is a summary of the issues covered in each of the sector-specific chapters.

Electric Power Sector

The electric power sector is among the most mature space weather user groups and was one of the first sectors to recognize that a severe event could result in significant societal and economic consequences, including long-term power disruption. Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. A priority among surveyed participants is the ability to perform measurement-based validation of geomagnetically induced current (GIC) models used for system and equipment vulnerability assessments and mitigation planning. The limited geographic coverage of the magnetometer network in North America leaves many planners reliant on estimated geomagnetic field data for their areas, reducing the quality and accuracy of validations. Another priority expressed by surveyed participants was the need for updated industry vulnerability assessment tools capable of more expansive analysis of system vulnerability to GIC.

Aviation Sector

The aviation sector, both commercial and corporate, is among the most mature space weather user groups and was among the first sectors to recognize that a severe event could result in significant societal and economic consequences, including disruptions to air space, navigation, routing, and crew operations. A priority among surveyed participants was the need for improved education, information dissemination, and policy development to address space weather risks effectively across the aviation sector. Another priority was the need for more accessible resources and clearer guidelines to enable better risk-informed decision-making and management. Surveyed participants emphasized the importance of using space weather information in aviation operations, even though there are no specific regulations mandating its use. Surveyed participants noted the need for radiation, navigation and communication measurements, modeling, and standardization across the aviation industry. Additionally, they highlighted concerns about health effects, data availability, and lack of resources for effectively incorporating space weather into flight planning, decision-making, and safety protocols.

Human Space Flight Sector

The HSF sector is defined as the activity that enables human travel through the atmosphere and throughout near-Earth and deep space. To our knowledge, this user needs survey is the first time the HSF sector has been surveyed about space weather needs. Overall, the discussion highlighted the need for improved radiation mitigation, information dissemination, education, and policy development to address space weather risks effectively across the HSF sector. Surveyed participants had a diverse set of perspectives and priorities regarding the current state and future directions of space weather observation, forecasting, and risk management. Participants emphasized the need for improved data quality, predictive capabilities, and regulatory frameworks to support safe and successful human spaceflight missions and space exploration activities. Highlighted topics of concern included radiation exposure, data availability, and lack of education and resources for understanding and incorporating space weather into flight planning and decision-making. Suggestions for improvement include better education and training tools, enhanced dissemination of information, and clearer guidelines for incorporating space weather into safety protocols.

Space Traffic Management and Coordination Sector

STM/C is a rapidly evolving sector that has not been previously surveyed. Until recently, the STM/C sector has been largely unregulated in terms of traffic management and deorbit requirements. Space weather-driven changes in the neutral density (ND) and resulting changes in atmospheric drag are the largest orbital perturbation for low-Earth orbit (LEO) satellites and the largest source of prediction error. Surveyed participants identified the need for near-term ND forecast improvements and model developments. There was no consensus on cadence, thresholds, and resolution required for ND forecasts. However, there was general agreement on the importance of 3-day forecasts for conjunction and collision avoidance. And for maneuvering and tracking, forecasts up to 7 days are needed for collision avoidance. Satellite operators need long-term solar cycle forecasts including 5-year predictions to plan satellite builds, launches, and mission profiles. Five-year forecasts would allow satellite operators to better plan missions to meet the Federal Communication Commission's (FCC) rule stipulating spacecraft, at altitudes below 2,000 km, de-orbit in under 5 years after the end of their mission. Surveyed participants recommended that uncertainty values, of both the model inputs and outputs, be provided with any ND model forecasts (and with any other space weather model prediction) so users can better assess model results and make their own reliability assessments of the information provided. Surveyed STM/C users desire observations and space weather forecasting akin to the current state of terrestrial weather forecasting, particularly with regard to ensemble modeling.

Emergency Management Sector

Space weather events pose unique challenges for emergency managers, including its unpredictability, potential for widespread impacts, and complexity in communicating risk to the public. The survey results identified specific challenges and barriers emergency managers face in integrating space weather considerations into emergency preparedness and response activities. Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. This primarily focused on regional specificity and impact communication at a level approachable by non-experts.

Research Sector

The research sector is the community that investigates new scientific and engineering approaches to advance space weather observations and forecasting. Research sector insights and perspectives can be grouped into two broad areas: a systems approach to space weather and education and workforce diversification. Surveyed participants identified a number of strategic and tactical gaps in advancing the research enterprise, including the spectral and spatial coverage of observations. Surveyed participants emphasized the need for system-level observations, constellation observations of the Sun-Earth system, and the ingestion of observations into current and next-generation models. Surveyed participants expressed the need for archives of observations and prior forecasts, and to conduct follow-up studies on how well past predictions performed. Participants stated that the current limited coverage of the Sun is an issue. Participants also noted that adopting a systems-based approach could close observational gaps. Surveyed participants identified the need to improve educational elements and expand diversity beyond traditional disciplines and communities to drive future success.

Path Forward

SWAG looks forward to engaging SWORM agencies and other relevant stakeholders on these findings and recommendations. These recommendations align with and augment many of the findings and recommendations identified in the SWAG 2023 Report. The successful implementation of the recommendations in this report and those identified in the SWAG 2023 Report will significantly advance and transform the national space weather enterprise, but will be impossible to accomplish without sufficient funding and sustained prioritization by Congress and the Federal executive branch.

Chapter 1
Introduction

The Recent Intense Space Weather Event: The Gannon Storm (May 2024)

As SWAG was preparing this report, a period of intense space weather events occurred that originated from two persistent active regions on the Sun. These regions evolved rapidly during the period of May 5–15, 2024 to create the most intense space weather event on Earth in the last 20 years, since the Halloween Storms of October–November 2003. The Gannon Storm had a number of intense flares (up to R3)[1] and coronal mass ejections (CME; resulting in G5 conditions), but with relatively limited solar energetic particle events. The responses to and impacts from the first G5 event in 20 years, discussed in detail below, showcased the progress the United States has made to become more space weather-ready. SWAG recognizes this significant progress and commends the advances made across the national space weather enterprise—largely due to 10 years of effort from SWORM. However, it is worth noting the stark differences between the Gannon Storm and events like the Carrington Event[2] and the fact that recent and significantly less intense space weather events have resulted in notable economic and technological losses. The findings and recommendations presented in this report, *Results of the First National Survey of User Needs for Space Weather*, will serve to inform next steps that will further transform the national space weather enterprise and enhance our national resilience across the sectors surveyed.

The Gannon Storm was an aggregation of many smaller events (see Figure 1.1A and B) and affected most sectors that are susceptible to space weather described in this report. Events within the Gannon Storm include 25 flares of M5 class or larger, including 17 X-class flares, that affected high frequency (HF) communications nearly instantaneously on the sunlit side of the planet. Most of these flares ejected some material into the solar wind, with much of it aimed towards Earth, resulting in several independent, smaller CMEs with eruption timelines and velocities such that they arrived within a relatively narrow time window. Their confluence resulted in an intense geomagnetic storm that caused a major heating event in the

1 See Appendix 1 for information on NOAA Space Weather Scales.

2 The most intense geomagnetic storm in recorded history, which peaked on September 1–2, 1859.

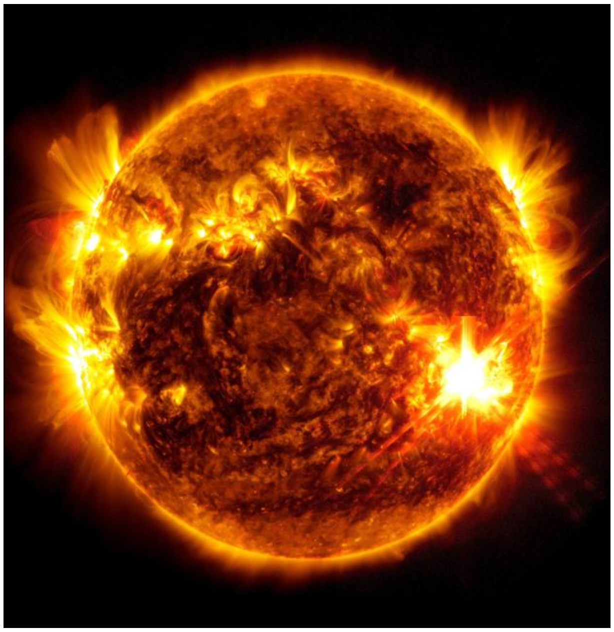

Figure 1.1A. Image from NASA's Solar Dynamics Observatory (SDO) of the Sun captured on 10 May 2024 at 9:23 pm EDT when the X5.8 solar flare peaked. (courtesy of NASA)

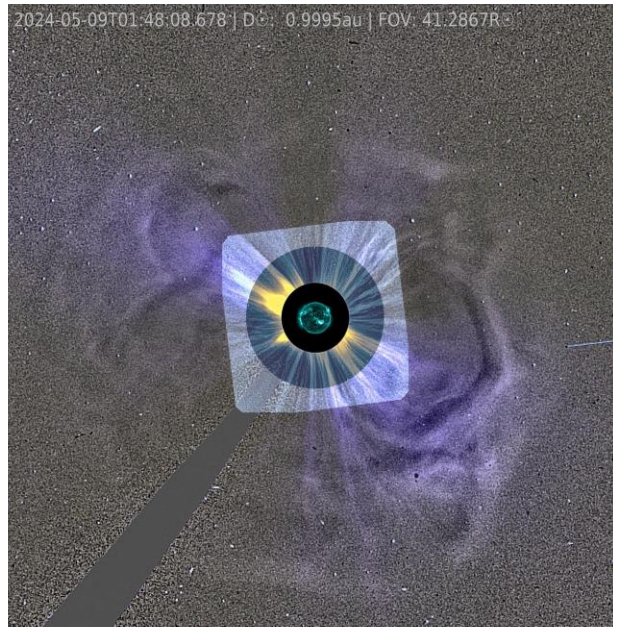

Figure 1.1.B. The observed structures in the solar and inner heliospheric associated with the events that went on to comprise the Gannon Storm of May 2024. Figure shows the composite images from different solar telescopes that detected the CMEs as they propagated from the Sun to the inner heliosphere.

thermosphere, adding an approximate 600 K temperature increase,[3] affecting LEO satellite positions with an increase in ND. For example, the KANOPUS-V 3 satellite, orbiting at ~486 km, lost a half km of altitude in 2 days[4] (Parker and Linares, 2024). GIC developed in the Earth's crust (surface), leading to higher risks of transformer outages. In the sections that follow, SWAG highlights the impacts of the Gannon Storm on the electric power, aviation, STM/C, and GNSS sectors.

Impacts of the Gannon Storm on the U.S. Electric Power Sector

Responding to early warnings from the NOAA Space Weather Prediction Center (SWPC) on May 10, power grid system operators in North America began implementing special operating

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3 Source: U.S. Space Force High Accuracy Satellite Drag Model (HASDM) storm time correction to the thermospheric temperature at the time of the G5 event. The correction was in addition to those associated with solar irradiance.

4 Parker and Linares, 2024, Satellite Drag Analysis During the May 2024 Gannon Geomagnetic Storm | Journal of Spacecraft and Rockets (aiaa.org)

procedures for resilience as early as 6 hours before onset of strong geomagnetic disturbances. Preparatory actions included limiting some equipment maintenance, posturing the system into more resilient configurations, and scheduling additional generation to be available if needed. CMEs began producing strong to extreme geomagnetic storm levels late on Friday afternoon, May 10, and dynamic conditions existed through May 12. System operators maintained a high level of awareness throughout the event using SWPC products and services and voice notifications.

The bulk power system remained stable throughout the Gannon Storm, though conditions for elevated levels of GIC were observed across North America (see Figure 1.2). GIC levels at a small number of power transformers exceeded thresholds, triggering operating actions to maintain system reliability and protect equipment. Likewise, some transformer oil temperatures reached limits resulting in additional monitoring. There were isolated incidents of unexpected transmission equipment tripping, including transmission lines and voltage support equipment, though none of these affected transmission service. Most observed impacts to power system equipment were in the U.S. Northeast, U.S. Mid-Atlantic, and Western Canada.

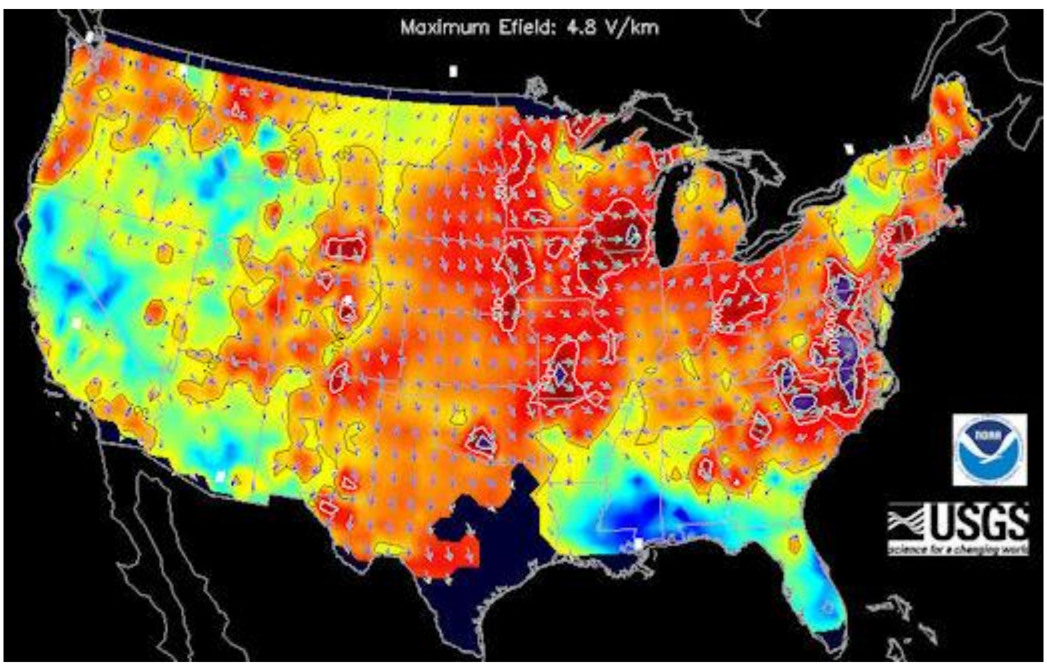

Figure 1.2. A snapshot of the geoelectric field modeled for the continental United States during the Gannon Storm. This is a measure of the induction hazard to artificial conductors, such as electrical power lines, that results from geomagnetic activity.

Over the past decade, the electric power sector has implemented mandatory requirements (regulations) for operating procedures related to geomagnetic disturbances (GMDs) and has developed a robust notification procedure with SWPC for rapidly disseminating space weather alerts and warnings to system operators. In addition, grid owners and operators use space weather information and models to periodically assess and mitigate risks to operations that could result from severe GMD events. These mechanisms were leading factors in effectively responding to the intense space weather in May and maintaining the reliable operation of the interconnected transmission system.

Impacts of the Gannon Storm on the Aviation Sector

Major United States air carriers deviated flight paths during the Gannon Storm due to risk of communications losses for high-altitude transatlantic routes between western Europe and eastern coast of North America and potential degradation or loss of navigation systems that rely on the Global Positioning System (GPS). On May 9–15, 2024, SWPC proactively advised the aviation sector of possible large geomagnetic storms in the coming days. On May 10, 2024, Federal Aviation Administration (FAA) Air Traffic Control issued an advisory to all carriers on the developing storm conditions and the potential for communication outages at higher latitudes and potential navigation (GPS) outages or degradations.

Coincidentally, a SWAG member was flying on United Flight 990 from San Francisco to Paris during the peak of the Gannon Storm (May 10–11) with an ARMAS (Automated Radiation Measurements for Aerospace Safety) radiation detector. Normally, this flight takes off from San Francisco, flies over the Hudson Bay, across Greenland, over Iceland and the UK, and lands in Paris. Typically, it flies at 38,000 to 40,000 feet in altitude and will reach latitudes on the order of 70 degrees north.

Just prior to boarding, the SWAG member noticed an increase in solar activity and asked a United Airlines staff member if there would be any changes in the flight due to space weather. The staff member indicated that they were going to deviate to a more southerly route, mainly because of the potential for communication outages. Instead of flying a great circle route, United 990 flew 40 to 43 degrees north latitude, across the continental United States, south of Nova Scotia, across the Atlantic Ocean, and into Paris. The flight altitudes ranged from about 34,000 feet to 36,000 feet and the maximum latitude was 51 degrees north, which occurred just outside of France.

During the G5 period of the Gannon Storm (see Figure 1.3), the flight was between Chicago and Nova Scotia. The Galactic Cosmic Ray (GCR) background (Figure 1.4), as measured with the ARMAS, was 6 micro sievert per hour. The dosage for the entire flight was 78 micro sievert.[5] This was less than would have been expected during a higher latitude flight. Because United 990 was

[5] Which included GCRs, a Solar Energetic Particle event, and excess dose from precipitating Van Allen belt particles.

flying a longer distance at lower altitudes and latitudes, one would have expected higher fuel consumption and a longer flight time (13 hours vs. 10.75 hours for the typical flight). However, due to strong tailwinds over the Atlantic Ocean, the United 990 flight did not take any longer than originally planned.

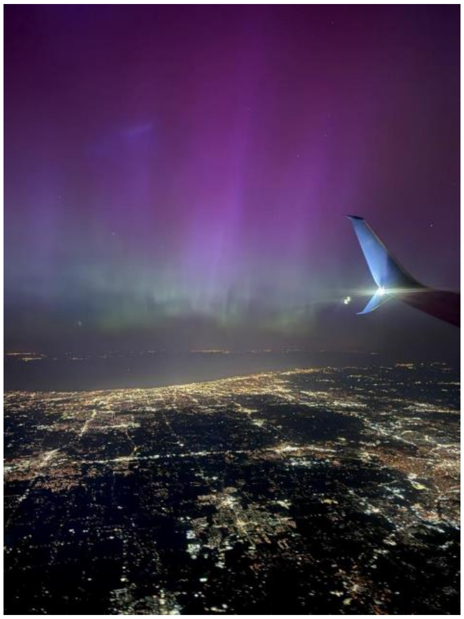

Figure 1.3. Photo of aurora taken from on a Minneapolis to Baltimore flight at the height of the storm. Photo credit: Ken Trombatore.

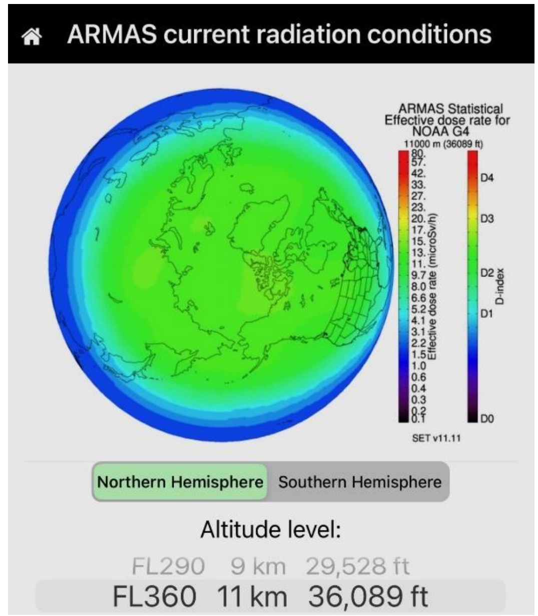

Figure 1.4. Modeled effective GCR radiation dose rate at aviation altitudes during the Gannon Storm.

In contrast, the return flight from Paris to San Francisco (United 984), occurred during a very quiet geomagnetic period. The flight took the great circular route from Paris over North Hudson Bay and into San Francisco at an altitude of 36,000 to 38,000 feet and about 70 degrees north latitude. The total flight exposure was 87 micro sievert, more than during the G5 event at lower latitudes.

The aviation sector, in general, is aware of space weather risks and has planned for a major event such as the Gannon Storm, which paid off during the Gannon Storm. The major United States carriers received early notifications that an event was possible and acted to mitigate the risk from the space weather storm.

Impacts of the Gannon Storm on the Space Traffic Management and Coordination Sector

On and before 1 May 2024, solar activity during the rapidly rising solar cycle 24 had deposited sufficient energy in Earth's thermosphere, where LEO satellites operate, to cause the climate there to be characterized as 'warm,' based on estimates from data gathered by NASA's TIMED satellite and geomagnetic storm indices. In less than 2 weeks the thermosphere went from warm to 'hot.' The primary culprit in this sudden heating was the solar active region associated with the Gannon Storm. Solar flares and CMEs from the Gannon Storm and others caused Earth's tenuous upper atmosphere to heat, expand, and produce density anomalies.

The resulting sudden ND expansion taxed the ability of LEO satellites to maintain orbits and payload pointing. Satellites from large constellations, such as Starlink, need to pass over points on Earth's surface in a specific sequence (phase) to support continuous communications services. When individual satellites experience local atmospheric density anomalies, autonomous orbit maintenance algorithms kick-in to maintain phase. Early on May 11, roughly 5,000 spacecraft suddenly began to maneuver to maintain altitude and phasing, and to avoid collisions (Parker and Linares, 2024). Other active satellites, another 5,000 or so, that were not part of the constellations also had to assess and respond—but this response required, in many cases, commands from satellite operators on the ground. Responding operators must avoid collisions with any maneuvering satellites and defunct objects, such as old rocket bodies, as well. All 10,000 satellites need to avoid the space debris that was set into altered motion by the geomagnetic storm. This altered motion reduces the amount of space debris in the long run, but requires enhanced collision avoidance efforts while storms are in progress. In general, the density enhancement near 450 km, where many spacecraft operate, was estimated to be a factor of five. Local enhancements near the auroral zones, where the bulk of Gannon Storm energy is deposited, were significantly higher, causing the thermosphere to bulge and dip in a manner similar to rough seas.

In such a dynamic and corrugated atmosphere, planned collision-avoidance actions (which are usually set several days in advance) quickly become obsolete. Parker and Linares (2024) note that the entire collision avoidance pipeline can be disrupted by a combination of natural storm-driven ND perturbations and the significant, semi-autonomous maneuvers generated by large spacecraft constellations. During extreme storms the collision avoidance pipeline may reach a point of needing a full restart. Such restarts are most successful after cessation of both geomagnetic storming and large-scale autonomous maneuvering. For the Gannon Storm, the data in Parker and Linares (2024) suggest that at least 2 days were needed for an effective restart.

Above 700 km in the high reaches of Earth's thermosphere, spacecraft operations are often assumed to be minimally affected by density anomalies. Nonetheless, NASA's Aura satellite, orbiting at ~695 km, experienced a loss of 90 m altitude during 11–13 May 2024. Further, a report from the European Space Agency (ESA)[6] and others[7] showed that ESA's two-satellite spacecraft constellation called Sentinel, whose mission is high-resolution imaging, saw the power used by the attitude control system to maintain spacecraft pointing increase by several times during the peak of the Gannon Storm. Within that disturbance interval the second largest solar flare of solar cycle 25 and a ground level enhancement of energetic particles also occurred. Significant effort will be needed to do a full root-cause analysis of each effect.

As much as the March 1989 geomagnetic storm acted as a catalyst for hardening the power grid against geomagnetic disturbances, the Gannon Storm should be a wake-up call for developing satellite-operator best practices and for improving ND forecasting.

Impacts of the Gannon Storm on the Global Navigation Satellite System Sector

Radio frequency (RF) signals that transit the upper atmosphere, such as signals from GNSS, are susceptible to changing ionospheric conditions. The Gannon Storm affected the ionosphere by significantly increasing the amount of plasma in it. During the Gannon Storm, large rapid changes in column ionospheric density over time and space occurred causing increased GNSS signal delay or degradation. This compromised end-user applications through increased error in timing and calculated positioning values, and in extreme cases, a complete loss of signal tracking.

Many end users' integrated systems contain GNSS dependent technology, which potentially introduces susceptibility to space weather events. While both the agriculture and high-frequency communication communities reported issues associated with the Gannon Storm. The most quantifiable economic loss, to date, was due to storm-induced GNSS degradation within precision agriculture.

The Gannon Storm occurred at the height of the planting season for many crops. Modern precision farming equipment is mostly autonomous through the use of autosteer and guidance systems, far exceeding the capabilities of manually steered equipment. These precision systems rely on sub-centimeter positioning accuracies to maximize the number of rows per field and placement of seeds. During the Gannon Storm, farmers across the United States and Canada

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[6] How To Survive a Solar Storm - Payload (payloadspace.com)

[7] ESA Earth Observation on X: "We can all relate to how much more difficult it is to keep our bike 🚴 straight on a windy day, while being pushed around. It's the same for satellites during a solar storm! During the most recent intense solar storm, @CopernicusEU #Sentinel2 AOCS (Attitude Orbit Control https://t.co/pTlW6uQtgN" / X

reported positioning errors from 10 to 30 feet resulting in a significant cumulative loss of planting area. The farmers had the choice of delaying planting, utilizing the precision systems with the large navigation errors, or attempting to manually steer the equipment using legacy visual guidance markers. Any of these options would reduce the overall yield. In the case of the Gannon Storm, the impact to some farmers was further compounded because of the rain delayed planting in the preceding days.

Figure 1.5. Photo of aurora borealis over a family farm in Minnesota associated with the Gannon Storm which disrupted and reduced GPS accuracy on precision farming equipment. Photo credit: Tiffany Graham. Source: [Did solar storm mess with your planter's accuracy? (farmprogress.com)]

Farmers also utilize GNSS-based technologies for logging geo-referenced data—such as plant growth, yield variation, and soil mapping—that can be used to plan various activities or address problems more efficiently. The loss of geo-referenced data was also reported by some farmers during the storm. This highlights that while space weather induced GNSS effects can be temporary, they can happen at a critical time or in conjunction with other adverse conditions, amplifying the consequences and extending their duration for the end users.

Looking Beyond the Gannon Storm

Even though various sectors were affected during the 2024 Gannon Storm, a decade of Federal space weather coordination through SWORM showcased an increased level of national preparedness. Good fortune also played a role. While this storm was intense, it lacked the extreme intensity of a Carrington-class event.[8] Despite our increased preparedness, the next space weather event could be Carrington-class and result in devastating consequences across multiple sectors and countries. Thus, as a Nation, with global infrastructure, we must continue to invest in resilience. This report provides findings and recommendations that if implemented will improve the Nation's ability to forecast and be more resilient to the next significant storm.

User Survey Background

In October 2020, Congress passed the PROSWIFT Act (PROSWIFT; P.L. 116-181; 51 USC 60601-60608) with bipartisan support and support across the national space weather enterprise, which comprises three sectors: the Federal Government, the commercial sector, and the academic sector. However, Congress has yet to sufficiently fund the roles and responsibilities and activities codified by PROSWIFT.

In 2014, the SWORM Subcommittee was chartered under the National Science and Technology Council (NSTC) to coordinate Federal actions to address space weather risk. SWORM is co-chaired by the White House Office of Science and Technology Policy, the Department of Commerce, and the Department of Homeland Security (DHS). It is composed of members from over 20 Federal departments and agencies, including the Office of Management and Budget (OMB) and the National Security Council. The establishment of SWORM was the first time the science, national security, and preparedness communities were seated at the same table to strategically address the risk of space weather across the Federal enterprise.

PROSWIFT defines the roles and responsibilities of the Federal departments and agencies, codifies SWORM, and directs NOAA, working with SWORM, to establish SWAG. In April 2021, NOAA chartered SWAG (see Appendix 2), which consists of five members each from academia, the commercial sector, and non-governmental end users (see Appendix 3).

PROSWIFT tasked SWAG, among other things, to "conduct a comprehensive survey of the needs of users of space weather products to identify the space weather research, observations, forecasting, prediction, and modeling advances required to improve space weather products." In carrying out the user-needs survey, SWAG communicated and coordinated with SWORM to ensure the needs of the Federal space weather stakeholders were sufficiently and appropriately addressed by the survey.

[8] The Carrington event was the most intense geomagnetic storm in recorded history, peaking on September 1–2, 1859. It created strong auroral displays, reported globally, and caused sparking and fires in telegraph stations.

Previous and Related Work

This survey and report focus on the national (United States) user's needs and was informed by initial SWAG engagements across the national space weather enterprise. The findings from these initial engagements can be found in Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise (SWAG 2023 Report). Despite the national focus of this user survey, SWAG recognizes space weather as a global risk that requires coordinated international engagement and investment. This is highlighted by Recommendations 25.1 through 25.4 in the SWAG 2023 Report.

Abt Associates Report

In 2019, with funding from NOAA SWPC, Abt Associates, Inc. conducted an "objective assessment of SWPC customers and users of real-time and forecast products." The report, Customer Needs and Requirements for Space Weather Products and Services (2019 Abt Survey Report), was developed to address actions in the 2015 National Space Weather Strategy and Action Plan. This report identifies and describes customers of space weather products and services and documents their requirements and needs. It also assesses uses of and needs for space weather information in five sectors: electric power, satellites, GNSS, aviation, and EM. Abt Associates engaged key customers and stakeholders across each sector to identify product parameters and specifications for effectively applying and using space weather information.

The primary tool for the 2019 Abt Survey Report's assessment was a series of interviews with 21 industry experts across the 5 sectors. Many of the experts surveyed were SWPC customers, who were knowledgeable about the uses and needs of space weather products and services from engineering, operations, and EM perspectives. The 2019 Abt Survey Report findings were summarized by sector and were organized within each sector into the following topical areas: outreach, technological vulnerabilities, use of SWPC products and services, product needs and attributes, and summary of user data product requests.

Space Weather Prediction Testbed

NOAA Testbeds are unique collaborative spaces where researchers and forecasters work together to improve weather products and services. Testbed projects shorten the transition from research to operations for forecasting tools and models. In the testbed environment, researchers and forecasters work side-by-side to integrate new observing systems into models, test and streamline data assimilation methods, test model improvements, and strategize about new developments for the benefit of the public.

NOAA conducts testbeds in 12 topical areas from aviation weather to coastal and ocean modeling to space weather prediction. NOAA generally hosts testbed exercises on a yearly basis. These exercises bring together forecasters, customers, regulators, internal and external research and development staff, and Federal partners to explore the capabilities, needs, and gaps of current NOAA weather services.

The Space Weather Prediction Testbed is a Research-to-Operations-to-Research (R2O2R) partnership led by NOAA SWPC. The testbed enables customers, researchers, and forecasters to engage collaboratively on improvements to observations, models, and forecast products and accelerates emerging concepts and new technologies for improving space weather prediction as well as to inform O2R (Operations to Research). Numerous partners (including NASA, the National Science Foundation [NSF], and the Department of Defense [DOD]) support SWPC's efforts to integrate these improvements into NOAA operations, ensuring the Nation benefits from these significant and coordinated investments in space weather.

SWPC has held two space weather testbed exercises to date. The first one focused on aviation (2022 Testbed Exercise for Aviation) and the second focused on space situational awareness (SWPC’s 2023 Satellite Environment Testbed Exercise). The physical testbed infrastructure is under development at SWPC in Boulder, CO.

User-Needs Survey Process

SWAG discussed possible approaches to the user-needs survey at its first meeting in December 2021 and completed the necessary clearance for the survey instrument through the Paperwork Reduction Act process in June 2023. SWAG completed the final focus group for this first round of the surveys in December 2023. Completing and delivering the results of these surveys in a meaningful way was a time intensive process due to the breadth and complexity of the user community and the drivers of the space weather risk.

In conducting the user needs survey, SWAG built on the work done in the SWAG 2023 Report, the 2019 Abt Survey Report, and in accordance with the survey considerations provisions outlined in the PROSWIFT Act (51 USC 60601(d)):

- [1] assess the adequacy of current Federal Government goals for lead time, accuracy, coverage, timeliness, data rate, and data quality for space weather observations and forecasting;
- [2] identify options and methods to, in consultation with the academic community and the commercial space weather sector, improve the advancement of the goals;

[3] identify opportunities for collection of new data to address the needs of the space weather user community;

[4] identify methods to increase coordination of space weather research to operations and operations to research;

[5] identify opportunities for new technologies, research, and instrumentation to aid in research, understanding, monitoring, modeling, prediction, forecasting, and warning of space weather; and

[6] identify methods and technologies to improve preparedness for potential space weather phenomena.

The space weather end-user community is diverse and can be categorized in a variety of ways. SWAG divided the community into 10 industry sectors. In 2023, SWAG decided to conduct the user needs survey on 7 of the 10 sectors (Table 1.1). SWAG developed a common set of questions that could be asked across all the sectors and sector-specific questions. The questions used by each sector are shown in Appendix 4.

For most sectors, focus groups were used to collect the survey information. The GNSS sector is large and diverse, and thus the information will be collected over 2 or more years via an online survey followed by focus groups. The GNSS sector survey is ongoing and the results are not presented in this report. Most focus groups were held virtually. However, the electric power and STM/C sectors held in-person and hybrid focus groups in conjunction with in-person community meetings. Focus group respondents were asked questions about their (1) current use of space weather observations, information, and forecasts, technological systems, (2) components or elements affected by space weather, (3) current and future risk and resilience activities, (4) future space weather requirements, and (5) unused or new types of measurements or observations that would enhance space weather risk mitigation. The questions and methodology for each sector were approved by OMB via the Paperwork Reduction Act process.

SWAG members chaired the focus groups and worked from a script so as to not inject their personal opinions or steer the discussion. The engagements were conducted under Chatham House Rules where the participants were free to use the information received, but neither the identity nor the affiliation of the speakers and participants were revealed.

Table 1.1. Space Weather Sectors Surveyed and Number of Participants (N).

Surveyed in 2023	**Plan to Survey in Next Round**
Electric Power (N=125)	Satellites
Aviation (N=12)	National Security
Human Space Flight (N=12)	Radio Frequency Applications (Communications and Radar)
Space Traffic Management/Coordination (N=16)	GNSS (continued)
Emergency Management (N=9)	Others To Be Determined
Research (N=30)	
GNSS (ongoing)	

Next Steps and Challenges for Phase 2

PROSWIFT states that user-needs surveys should be "reviewed and assessed not less than every 3 years." A lesson learned from conducting this First National Survey of User Needs is that SWAG understands the need for regular user engagement; however, SWAG needs sufficient resourcing to ensure the quality and utility of future in-depth surveys of user needs.

Use of this Report

This report is organized by sector and has 46 findings and 113 recommendations (Table 1.2) from across the user communities surveyed. Each chapter summarizes the focus group discussions and draws findings and recommendations based on that information. SWAG members, as community representatives, did not participate as users in the survey, but as subject matter experts have thoughts on user needs. Therefore, some chapters include a section on thoughts, findings, and recommendations from SWAG. Additionally, SWAG identified some common themes and needs identified in multiple sectors. These common themes with summarized findings and recommendations are identified in the final chapter of the report: Overarching Themes and Next Steps, and present an opportunity for common investment and consolidated action to address multiple recommendations across several sectors.

Lastly, the inclusion of SWORM in an individual recommendation implies SWORM will assist the lead organization to facilitate and coordinate efforts among agencies and the national space weather enterprise.

Table 1.2. Number of findings and recommendations by chapter.

Chapter	Number of Findings (Including SWAG Findings)	Number of Recommendations (Including SWAG Recommendations)
Electric Power	4	11
Aviation	8	22
Human Space Flight	7	20
Space Traffic Management and Coordination	13	30
Emergency Management	4	9
Research	7	15
Overarching	3	6

These recommendations align with and augment many of the findings and recommendations identified in the SWAG 2023 Report. Implementing these recommendations will significantly advance and transform the national space weather enterprise, but will be impossible to accomplish without sufficient funding and sustained prioritization by Congress and the Federal executive branch.

Chapter 2
Electric Power Sector

Summary

The electric power sector is among the most mature space weather user groups and was one of the first sectors to recognize that a severe event could result in significant societal and economic consequences, including long-term power disruption. The survey process for this sector benefited from broad participation, with over 125 participants from entities that own or operate components of the North American power grid. Respondents to the SWAG user-needs survey provided insights into current use of space weather information and end-use perspectives on future applications and priorities. Several established mechanisms are currently in place in North America to promote the use of space weather information and services by entities across the electric power sector.[9] These mechanisms include mandatory and enforceable reliability standards TPL-007 & EOP-010 approved by the Federal Energy Regulatory Commission, established alerting protocols to ensure all geographic areas are aware of impending severe space weather events, and industry groups for technical collaboration and knowledge sharing on mitigation techniques.

The electric power sector survey resulted in 4 findings and 11 recommendations that seek improvements in topics from data and information sharing to planning and reliability to grid modeling. Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. A priority among surveyed participants is the ability to perform measurement-based validation of GIC models used for system and equipment vulnerability assessments and mitigation planning. To perform validations, entities compare the measurements from GIC monitors attached to power grid equipment with the calculated GIC values from their models using local magnetic field observations as inputs.

The limited geographic coverage in North America from the existing network of magnetometers leaves many planners reliant on estimated geomagnetic field data for their areas, reducing the quality and accuracy of validations. Another priority expressed by surveyed participants was the need for updated industry vulnerability assessment tools capable of more expansive analysis of risk to the system from GIC. The Department of Energy (DOE), National Labs, and industry are in

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9 The electric power sector includes generation, transmission, and distribution.

the best position to collaboratively address the need for updated industry vulnerability assessment tools and training end users on their use.

Sector Background

The electric power sector has been aware of space weather impacts for over 30 years, with well-documented effects during large storms in certain areas. During that time there has been significant progress in understanding the geophysical drivers of the hazard and how design characteristics and configuration of the power infrastructure influences risk. This progress has been achieved through a combination of space weather and power engineering research, development of industry-standard software tools and equipment for planning and mitigation, and regulatory efforts that incorporate these advances. Given the advanced understanding of space weather in this sector, it is worthwhile to understand how well current tools are working, how the needs of power systems change with new infrastructure, and where there are opportunities to further reduce risk and improve the services that protect U.S. critical power infrastructure. Wide area blackouts of the power system, whether the result of severe space weather or other causes, can have devastating and long-lasting societal consequences (see Sidebar 2.1).

Sidebar 2.1 Texas Power Outage

A recent severe terrestrial weather event that illustrates an extreme cost in lives (over 200 deaths) and damages (estimated by Dallas Federal Reserve Bank to be $4.3B) associated with a major electricity supply disruption is the February 2021 cold weather outages in Texas and the South Central United States. Over a 24 hour period, the electric grid across much of Texas was unable to provide adequate supply due to significant failure of generating units from freezing conditions. More than 4.5 million people in Texas lost power during the event and were exposed to below-freezing temperatures for as long as four days. Frigid temperatures played a significant role in the devastating impact of this power outage event. However, it provides a recent example of the serious consequences and high societal costs of major grid disruptions and cascading disasters.

Source:
The February 2021 Cold Weather Outages in Texas and the South Central United States | FERC, NERC and Regional Entity Staff Report | Federal Energy Regulatory Commission

GMDs affect the power system by driving quasi-direct currents (quasi-DC), known as GIC, through transmission lines and grounded power transformers. GIC affects transformer performance and exposes the electric grid and equipment to various harmful impacts, such as unexpected tripping of critical equipment, system voltage collapse, and damage to large power transformers. GMD effects are far from uniform and depend on storm characteristics, Earth structure, and electrical system and component design.

When GIC is present, transformers may not produce normal 60-hz sine waves of alternating current (AC). Rather, the usual AC output is distorted with harmonics that not only affect the performance of the transformer but also propagate throughout the power system. The extent of harmonic production and transformer susceptibility varies considerably by transformer design, but in general the GMD-induced harmonics can increase reactive power consumption by the transformer, which can decrease system voltages. Voltage risk to the system is further threatened as the harmonic currents propagate throughout the system, where they can cause some switches and relays to trip on sensing an abnormal condition. When vital voltage support equipment is tripped—as occurred in March 1989 on the Hydro-Quebec power system—the system is in danger and operators may not be able to respond fast enough to prevent voltage collapse and blackout.

Another concern is that GIC could damage power transformers when abnormal magnetizing currents cause intense heating in internal structural components. This heating phenomenon and the transformer's vulnerability to it is highly dependent on transformer design characteristics, age, and condition. In susceptible transformers, GIC-related heating can shorten transformer life span or, in the extreme, lead to catastrophic failure in the transformer.

Prior User Engagement with the Electric Power Sector

The electric power sector has been a consistent user base for NOAA SWPC's operational products. The sector was surveyed during the 2019 Abt Survey report. The Abt report found users wanting (1) improved granularity of SWPC scales and indexes, (2) SWPC to move away from the G-scale and instead use the geoelectric (E-field), and (3) improved usability of SWPC products. This SWAG user survey aims to expand on the Abt effort, identifying how far this rapidly advancing sector has come since the previous survey. The survey also aims to broaden the inclusion of operators and planners from across the United States and Canada, including those from higher- and lower-hazard geophysical regions, a range of geomagnetic latitudes, and those with different approaches and attitudes.

Space Weather Impacts on the Electric Power Sector

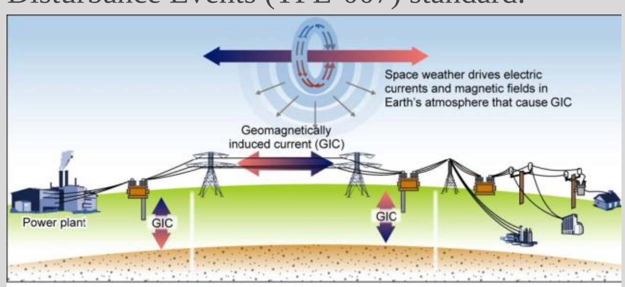
As discussed below in Sidebar 2.2, space weather primarily affects transformers used in long-distance (i.e., long haul) transmission systems. Because of the longer length of the lines used in these systems, they are subjected to a greater total geoelectric field induced at ground-level during a geomagnetic storm, which means they can experience larger GICs and therefore greater impacts, including increased reactive power consumption by the transformer and decreased system voltages. In addition, the specific characteristics of the transformers needed to transport power over long distances make the system more vulnerable to GICs. The North American power system is a complex and interconnected collection of companies and equipment. The transmission system is connected to distribution systems and generation facilities, and different power companies are connected to each other, which means that the effects of GIC do not stop at a single transformer—instead they propagate to neighboring systems, companies, and even across international boundaries.

Regulatory Environment in the Electric Power Sector

Owners and operators of the Bulk Power System (BPS) in the United States are subject to reliability standards approved by the Federal Energy Regulatory Commission (FERC). In 2014, FERC directed the North American Electric Reliability Corporation (NERC) to develop a set of reliability standards to address GMD caused by severe space weather.[10] Two reliability standards were developed by NERC and the North American electric power industry and approved by FERC to address GMD risks through operating procedures and periodic vulnerability assessments. The first reliability standard, EOP-010, has been in effect in the

Sidebar 2.2 Power Grid Definitions

Terrestrial and space weather events can result in widespread impact across the electric grid, leading to power outages or other electrical effects. Harmonics, for example, are a negative effect responsible for degrading power quality. Harmonics consist of multiple frequencies flowing on the grid system and can be caused by nonlinear electrical loads as well as space weather. GMDs, a type of space weather event caused by charged particles ejected from the Sun interacting with the Earth's atmosphere, cause GIC to flow through power lines and transformers that can result in equipment degradation and harmonics, triggering operational issues, voltage collapse, or even a grid blackout. To mitigate negative impacts from GMD events, planning coordinators within the power grid sector perform vulnerability assessments and plan corrective actions in accordance with the Transmission System Planned Performance for Geomagnetic Disturbance Events (TPL-007) standard.



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

Sources:
[Effects of Harmonics on Power Systems | EC&M (ecmweb.com)]
[Geomagnetic Disturbance Data (nerc.com)]
[TPL-007-2.pdf (nerc.com)]

10 NERC is the commission-approved Electric Reliability Organization with authorities established in the Energy Policy Act of 2005. These authorities include developing mandatory reliability standards for FERC approval and enforcing such approved standards.

United States since 2015 and requires grid operators to implement operating procedures to mitigate the effects of GMD.[11] Space weather alerts and warnings from NOAA SWPC are widely used by grid operators to trigger operating procedures. Requirements of the second reliability standard, TPL-007, started implementation in 2017 through a phased plan and became fully enforceable in January 2024. TPL-007 requires owners and operators of the BPS to assess the vulnerability of the power system and equipment to a 100-year benchmark GMD event and incorporate design or other corrective measures to prevent grid failure.[12]

Survey Process

The electric power sector held two survey focus groups, one for power grid operators and one for system planners and equipment experts. The focus groups were held in person and virtually at the NERC-Electric Power Research Institute (EPRI) GMD Workshop.[13] In total, 125 individuals participated in the sector's focus group sessions, including at least 1 representative from each Reliability Coordinator (RC),[14] who are responsible for the day-to-day operation of the North American grid.

Participation in the survey focus groups was open to all owners or operators of the North American electric grid. SWAG leveraged NERC's relationships with power grid owners and operators to obtain survey focus group participants. Because the survey was held in conjunction with a public meeting, there were also Federal scientists and academic researchers present. Notice of the GMD workshop and survey was widely distributed to the RCs and Transmission Operators registered with NERC along with power grid engineering staffs and subject matter experts.

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11 See FERC Order No. 797 available here: https://www.ferc.gov/sites/default/files/2020-04/E-18.pdf

12 See FERC Order No. 850 available here: https://www.ferc.gov/sites/default/files/2020-04/E-4_2.pdf

13 The GMD Workshop was held August 15–16, 2023 in St. Paul, MN. The agenda, presentations, and background materials are available online. https://www.nerc.com/pa/RAPA/GMD/Pages/GMD-Training.aspx

14 Reliability Coordinator (RC): The entity that is the highest level of authority who is responsible for the Reliable Operation of the Bulk Electric System, has the Wide Area view of the Bulk Electric System, and has the operating tools, processes and procedures, including the authority to prevent or mitigate emergency operating situations in both next-day analysis and real-time operations. https://nercipedia.com/glossary/reliability-coordinator/

Common Themes Among the Surveyed Groups

This section highlights common themes heard from surveyed participants, providing additional background and context for the subsequent findings and recommendations. In some cases, quotes from surveyed participants are used to highlight or illustrate specific points.

Information Sources and Uses (Including Alerts and Warnings)

The electric power sector uses space weather information from various sources to plan and operate the interconnected transmission system. Surveyed participants described how they currently use space weather information for situational awareness, operational planning, vulnerability assessment, and to satisfy mandatory and enforceable reliability standard requirements. Electric grid RCs receive alerts and warnings of expected GMDs from space weather forecasters and widely disseminate them. The alerts and warnings of severe space weather trigger operators to implement special GMD operating procedures designed to minimize the impact to the grid. In general, these procedures consist of (1) preparatory steps taken prior to the commencement of the GMD event based on SWPC's warning, and (2) operating actions taken during the GMD event based on observed GIC levels and system conditions. Warnings and forecasts of severe space weather are urgent and essential for the reliable operation of the power grid, and therefore NERC maintains a capability for SWPC to provide voice alerts and warnings directly to RCs via a hotline notification system. However, specific actions taken by operators vary. For example, one RC described their actions on receipt of a SWPC warning:

> The [...] Reliability Coordinator gets the alerts and warnings from SWPC. If the prediction is a Kp 7 or greater then they notify the transmission operators in our area… Our operators notify the engineering reliability section who starts monitoring the GIC current that is in the 500 kV transformers. We have almost twenty 500 kV Transformer neutrals monitored… if the GIC gets above a certain threshold, we have certain mitigating actions that we can take including switching lines out of service to redirect the current that our studies have shown [to] mitigate the current. We have recently installed a GIC blocker on the system and that is activated when we receive an alert of a K7 event.

Other operators reported similar use of space weather alerts and warnings for preparatory actions and system monitoring during the GMD event for operating actions. Surveyed participants indicated that it was reasonable to delay taking operating actions on the system until triggered by GIC monitors or system operating parameters (e.g., system voltages, equipment monitors). They explained that, unlike space weather alerts and warnings which have limited ability to predict the severity of power system impacts in specific locations, measured values coming from the grid provide actionable indication of system conditions. One participant noted that they have incorporated supervisory control and data acquisition (SCADA)/Energy Management Systems alarming based on GIC monitoring for operator awareness.

Many participants use SWPC alerts and warnings as well as grid-focused services and products, including SWPC's real-time geoelectric field maps. Surveyed participants acknowledged that it is standard practice for RCs and transmission operators to subscribe to SWPC services. Some surveyed participants also obtain information from other providers, including Natural Resources Canada (NR Can) and the commercial provider Solar Terrestrial Dispatch. Surveyed operators voiced the need for timely alerts from SWPC, noting that there were delays in the communication chain potentially due to the need for human intervention in notification paths.

One surveyed participant stated,

> I think what we've observed over the past couple of years now that we've had GIC monitoring, is there are times when we are observing deflection on our GIC instruments ahead of when the actual SWPC alerts are issued. And in some cases, we're seeing significant deflection. You know, in the February event, we saw it 90 minutes before the alert was released.

Another surveyed participate noted,

> I think there might be some space for, maybe some clarification, or better communication to the electric utility industry, with respect to the differences between warnings and alerts, for the varying Kp levels.

Local and regional GIC and magnetic field measurements are important in hazard mitigation and planning since impacts vary by system and location. Grid owners and operators use a wide range of data sources for situational awareness, including magnetic field data and GIC measurements. There were multiple mentions of the value of data access and data sharing between operators and the need for more local measurements and improved regional indices. Most surveyed participants indicated that their GMD Operating Procedures are initiated at the G3 (K7) levels. However, a surveyed participant in a low-latitude area indicated that they initiated actions at the G4/K8 level.

> My wish would be for more real-time GIC monitor sharing via [Inter-control Center Communications Protocol] ICCP through RCs, not just the SWPC Alert-based system. No different than congested lines, let's share info on actual GIC impacts.

These responses indicate that geographic granularity is useful to grid operators.

Planning and Reliability

Space weather information is used in long-term planning to promote reliability and resilience to severe GMD. All surveyed participants from planning entities[15] reported that they assess vulnerability of the grid to approved benchmarks for severe space weather as required by reliability standards. Industry uses the benchmark GMD events that were developed as part of the TPL-007 reliability standard and approved by FERC. The approved benchmarks include a 100-year GMD event, statistically derived from measured historical magnetic fields, and are specified in terms of geoelectric fields that can be used in industry's software tools for calculating GIC. The benchmarks include a peak geoelectric field magnitude for assessing GIC impacts to system voltage and a long-duration geoelectric field time series for assessing the heating effects in power transformers. Planners use the benchmark GMD events to perform GMD vulnerability assessments and must put mitigations in place to address identified vulnerabilities that could cause the system to fail. A surveyed participant familiar with research activities being performed by the participating utilities in EPRI projects stated that some utilities have also studied the potential system impacts to more severe GMD conditions than the established TPL-007 benchmarks. Recommendation R.14.1 from SWAG (2023) highlights the need for coordination and reconciliation of government and industry benchmarks to ensure the latest research and knowledge from industry and the space weather enterprise is applied and can be expressed in terms that are applicable to end users.

Harmonic currents are a key risk to the power system during GMD events.[16] Furthermore, harmonic currents generated in the transformer propagate far and wide throughout the power system, and can disrupt normal operation of frequency-sensitive devices such as relays and control equipment, as well as grounded capacitors and surge arrestors that provide voltage stability. Thus, a significant grid vulnerability can be summarized by the inability to control system voltages due to two conditions that are both attributed to GIC-related harmonics: the rapid tripping of critical voltage support equipment and, simultaneously, the excessive power consumption in transformers. When these or similar conditions extend over a wide area and

[15] Planning entities, a reference to the functions used by NERC for registering owners and operators of the electric grid in North America, are electric utilities and transmission organizations responsible for ensuring their portion or the interconnected transmission system is designed to meet reliability criteria.

[16] GIC flowing through a grounded power transformer affects magnetism in the transformer core, causing the normally smooth sinusoidal current and voltage waveforms to become distorted and spread across a range of harmonic frequencies. The presence of harmonic currents within the transformer can cause it to have excessive power consumption and also experience potentially damaging localized heating at internal transformer components.

affect enough transformers and critical equipment, the system is at risk of cascading failures (i.e., blackout).

Most surveyed participants noted that there is little guidance or training for assessing the impact of GIC-related harmonics on their systems:

> [Reliability Standard TPL-007] says that you have to consider the tripping of transmission facilities…due to harmonics during benchmark GMD events. It was kind of a technical gap of how to get there.
>
> I think at least from our perspective, we're looking forward to seeing more directions and recommendations on how to evaluate the harmonics that would end up tripping off circuits and reactive devices…

Modeling Space Weather and the Grid

Model validation using measurements of geomagnetic fields and GICs are a top priority among many survey participants to ensure vulnerability assessments are representative of realistic conditions and severe GMD events. Reliability standards require grid-planning entities to have access to GIC data and geomagnetic field data, which can then be used to compare actual GICs with model-derived GICs. Survey participants noted several challenges to performing validations, including the relatively quiet solar activity of the recent solar cycle; limited or unavailability of magnetometers or variometers near the system area; placement of GIC monitors on equipment that is located in an area not likely to see significant GIC due to the system topology; little experience with performing GIC validations; limited technical guidance and training; and difficulty in obtaining accurate technical information of grid equipment that can significantly affect the accuracy of GIC estimates, such as transformer winding resistances and substation grounding grid resistances.

For example, one participant noted:

> Because really the outcome is having that confidence in your models, making sure you're using the right Earth models. And, really the only way you can do that is by performing the validation studies.

When geomagnetic observatories or instruments are not near areas of the power grid (due to the limited spatial coverage in the United States), grid planners often resort to using estimates produced by NOAA SWPC. Survey participants expressed challenges with using these estimates because they are not readily usable or integrated into system planning tools, noting:

> Our transmission footprint extends [across multiple states in the midwest and central plains]. So, the closest [U.S. Geological Survey] USGS magnetometer observatories, I think that we pull data from, frankly are Boulder and Sitka.
>
> [We] have code to extract the SWPC-available JSON eField data to lay into our TPL-007-4 planning models. We do this to minimize scaling errors and to match actual operating conditions (power flow) with the snapshot eField, we then compare it to our actual GIC monitoring.
>
> We also have this present 1-D model versus the opportunity of using 3-D modeling. We have not valued that at this point, but I think that's something we should consider going forward.

Findings and Recommendations

The following findings and recommendations are a direct distillation of the engagements and responses from the surveyed participants. They are not ordered based on priority.

Finding 2.1. Validation of GIC models and vulnerability assessments using GIC and magnetic field measurements are a key priority to advance mitigation of the impacts from GIC. The industry has growing needs for space weather information to perform validation studies. The spatial coverage density for North American geomagnetic field data is not sufficient to meet industry needs for accurate validation studies. Additionally, some geoelectric field maps and estimate products are not in formats that support direct use in existing industry GIC tools, limiting application of the products.

> **Recommendation 2.1.1. NOAA, in collaboration with USGS, should support one or more existing (non-Federal) operational magnetometer arrays and assess priorities for new installations to provide increased public access to geomagnetic field data with adequate coverage, prioritizing areas of higher hazard.** This builds on findings and recommendations identified in the 2023 SWAG Report (SWAG, 2023): the recommendation to support real-time ground-based, operational magnetometers (see R.8.1. [2023]).
>
> **Recommendation 2.1.2. NOAA should collaborate with DOE and electric power industry software providers to integrate geoelectric field maps and estimates into standard electric power industry software used for GIC studies and GMD vulnerability assessments.**

Recommendation 2.1.3. NOAA, in collaboration with USGS, should invest in infrastructure to ingest magnetic field data from privately owned sensors into operational geoelectric field models to support industry needs.

Finding 2.2. The electric power industry finds existing space weather alerts and warnings to be useful for triggering preparatory actions prior to the onset of a GMD event. Notification procedures between SWPC and power grid operators are well established. Grid operators will delay taking operating actions on the system until triggered by GIC monitors or system operating parameters (e.g., system voltages or equipment monitors) because these metered values from the grid provide accurate and direct indication of system impacts. Enhancements to space weather alerts and warnings that improve the timeliness, accuracy, and spatial density of expected impacts will support grid operators in making more effective and actionable preparations.

Recommendation 2.2.1. DOE and industry should develop a process for direct sharing of real-time GIC data—for situational awareness—between operators through open access data models and cooperative agreements.

Recommendation 2.2.2. NOAA should continue to validate and evolve predictive models of the geoelectric field to improve forecasting capabilities and alert lead times.

Recommendation 2.2.3. NOAA should support the development of regional and local alerts through private sector partnerships.

Recommendation 2.2.4. NOAA, in collaboration with the electric power industry (particularly the power grid RCs), should identify and implement ways to minimize alert latencies, for example, through the use of automated tools that reduce human intervention in the communication path. Enabling industry-to-industry sharing of data is an initial first step.

Finding 2.3. Harmonic studies are an important component of assessing GIC risk. Reliability standard requirements in North America specify that system planners must evaluate harmonic impacts on the transmission system and equipment in their GMD vulnerability assessments. However, tools and guidelines for doing the detailed analyses of harmonic impacts are not widely disseminated and integrated into the tools used by industry to perform GMD vulnerability assessments.

Recommendation 2.3.1. DOE should lead a collaborative effort with the electric power sector to develop capabilities, guidance, and tools for incorporating GIC-related

harmonics in GMD vulnerability assessments and promote widespread adoption and use through standard system planning tools, training, and best practices.

Finding 2.4. Effective GIC mitigation is an interdisciplinary, cross-sector, and community-wide effort requiring increased collaboration between DOE, the National Labs, and the power industry. The power industry needs ongoing training on capabilities and limitations of space weather information and services, as well as information on advances and developments in engineering and vulnerability assessment tools. The SWPC Testbed and the NERC GMD workshops provide excellent venues for training and communication.

Recommendation 2.4.1. DOE, the National Labs, and power industry should collaborate to update vulnerability assessment tools and capabilities. This collaboration should involve the space weather and industry-focused development communities in reviewing and updating vulnerability assessment tools and capabilities using recent Earth conductivity data, harmonic assessment approaches, and model validation insights.

Recommendation 2.4.2. NOAA and USGS, in collaboration with the space weather commercial sector, should provide expanded training opportunities for the power industry on current capabilities for warnings, alerts, and geoelectric field estimates, including those from the commercial sector. Surveyed participants noted that they need clarification and better communication between SWPC and the electric power industry regarding the difference between warnings and alerts.

Recommendation 2.4.3. DHS and DOE should solicit sector representatives to participate with other infrastructure sectors and emergency managers to understand and mitigate risks from interdependencies.

Chapter 3
Aviation Sector

Summary

The aviation sector, both commercial and corporate,[17] is among the most mature space weather user groups and was among the first sectors to recognize that a severe event could result in significant societal and economic consequences, including disruptions to air space, navigation, routing, and crew operations. The survey process for this sector included 12 participants, 6 each from commercial and corporate aviation, representing a cross section of the aviation industry operating within domestic and international airspace.

U.S. aviation, both commercial and corporate, lacks a coordinated method by which the breadth of existing space weather information can be understood and made actionable. This sector also lacks the information required for tracking, reporting, and understanding radiation exposure at aviation altitudes. Accurate space weather forecasts 12 hours and beyond that are actionable by the aviation industry do not exist, but are needed. Aviation operations policy, procedures, and operational protocols do not mitigate space weather-related aviation hazards at an acceptable level. Aviation stakeholders are not uniformly aware of the threats from space weather and the existing tools that may be available to help mitigate such threats. Current tools provided by the government and the private sector are not fully aligned with industry needs.

The aviation sector survey resulted in 8 findings and 22 recommendations that cover topics from communications, navigation, and human health to policy and regulation development. Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. A priority among surveyed participants was the need for improved education, information dissemination, and policy development to address space weather risks effectively across the aviation sector. Participants recognized the importance of space weather awareness, and another priority was the need for more accessible resources and clearer guidelines to enable better informed decision-making and risk management. Surveyed participants emphasized the importance of using space weather information in aviation operations, even though there are no specific regulations mandating its use. Surveyed participants noted the need for navigation and communication measurements, modeling, and standardization across the aviation industry. Additionally, they highlighted

[17] Commercial and corporate aviation are terms representative of all aviation available to the public, including passenger airlines, private jets for hire, and jets operated by corporations for private use.

concerns about health effects, data availability, and lack of resources for effectively incorporating space weather into flight planning, decision-making, and safety protocols.

Sector Background

The aviation sector is defined as the industry that flies aerospace vehicles in the atmosphere as a business activity. Aviation is a major transportation component of the global economy. The United States is the world's largest airline passenger market (666 million in 2021), followed by China (440 million in 2021).[18] In 2021 there were 61 commercial air carriers[19] in the United States—including 5,800 aircraft—of which 18 were considered major carriers.[20] Operating revenues of all these carriers totaled $194 billion in 2021 and has surpassed $200 billion in 2024.[21] In addition, private and corporate jets in the United States account for 63% of the world's total private jet fleet (14,600)[22] and, in 2024, was a $44 billion market, i.e., about 17% the revenue of commercial carriers.[23]

Prior User Engagement with the Aviation Sector

The aviation sector was previously surveyed in the 2019 Abt Survey Report on use of SWPC products and services, as well as potential enhancements and data gaps future SWPC efforts could address. The Abt report found users wanted (1) improved forecast granularity and precision; (2) improvements to product language and presentation and (3) products for post-event and historical data with better reporting of solar radio bursts; and (4) more in-depth reports about significant events and associated impacts.

Space Weather Impacts on the Aviation Sector

As identified by the International Civil Aviation Organization (ICAO), space weather effects on the commercial aviation sector include HF radio communication effects, GNSS uncertainties from the surface to all altitudes, and exposure to a radiation environment for vehicles flying above 8 km or 26,000 ft (see Sidebar 3.1 and 3.2).

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18 Airline passengers by country, around the world | TheGlobalEconomy.com

19 Any person or business entity who undertakes directly by hire, lease, or other arrangement to engage in the carriage by aircraft of persons or property for compensation

20 Number of U.S. air carriers 2024 | Statista

21 Total operating revenues of the U.S. airline industry 2023 | Statista

22 Analysis reveals scale of private jet fleet in the USA | Business Airport International

23 Business Jet Market Size, Share, Trends | Growth Report [2032] (fortunebusinessinsights.com)

Regulatory Environments in Aviation Sector

U.S. aviation operators are governed by Federal regulations. The regulations that are primary to commercial and business aviation are 14 CFR Parts 121 and 135. These regulations, among other things, mandate that aircraft operators must be able to maintain operational control at all times; this includes the ability to communicate with their aircraft.

When operating in certain environments, contingencies must be available to mitigate hazards. When commercial airlines operate in the polar region, they are required to have the ability to mitigate hazards associated with increased solar activity. These include the mitigation of hazards and consequences, which include human health effects, aircraft navigation and communication disruptions with Air Traffic Control, and company operations.

Survey Process

Surveyed respondents were chosen from two groups: major commercial carriers and smaller corporate jet service providers.[24] Six participants were selected from major carriers that fly cross polar flights and thus can have more impacts from space weather. Six participants were selected from the corporate business jet community that have

Side Bar 3.1 Aviation System Impacts

ICAO has identified that the aviation sector relies on an array of systems that are vulnerable to space weather including effects to HF communications and GPS navigation, as well as crew and passenger health from radiation. Flights transiting the polar regions are particularly vulnerable to space weather impacts, and during space weather events, some airlines may choose to divert planes away from polar regions. Solar radiation storms at the S-3 level or above can negatively affect HF comms while flying over the poles, while radio blackouts at the R-3 to R-4 levels can also degrade HF communications and negatively affect aircraft that lack backup communications options. Fortunately, the aviation industry, particularly large commercial carriers, have built several layers of redundancy into their systems for pilots to switch to satellite communication if needed. However, increasing reliance on GPS and satellite systems means that degradation to those systems due to space weather events like geomagnetic storms can be problematic for navigation and communication. Solar storms can also affect human health with exposure to radiation while flying; airlines have different operating protocols for avoiding these risks, including diverting or deviating planes, although the most at-risk people are pilots/crew with long flying careers and fetuses less than 3 months of age.

Sources:
Manual on Space Weather Information in Support of International Air Navigation (Doc 10100) | ICAO Store
Space Weather Radiation Effects on High-Altitude/-Latitude Aircraft - Mertens - 2021 - Geophysical Monograph Series - Wiley Online Library

[24] Commercial and corporate aviation are terms representative of all aviation available to the public including passenger airlines, private jets for hire, as well as jets operated by corporations for private use.

a well-defined corporate safety management process. The participants consisted of pilots and flight operations professionals, and some of the respondents represented international carriers. Military aviation was not included in this survey. The two survey focus groups were held virtually.

Common Themes Among the Surveyed Groups

This section highlights common themes heard from surveyed participants providing additional background and context for the subsequent findings and recommendations. In some cases, quotes from surveyed participants are used to highlight or illustrate specific points.

Information Sources and Tools

Commercial and business jet pilots do not have a standard way to incorporate space weather information into the day-to-day facets of their respective operations. Information is disseminated via email alerts and integrated into flight planning and pre-flight discussions. The pilots surveyed had varying degrees of familiarity with space weather, with some individuals relying on apps as well as websites for receiving their information.

Sidebar 3.2 Aviation Space Event December 2023

On December 14, 2023, the aviation community was affected by the biggest solar flare since 2017. Solar flares are classified by the intensity of the peak flux (W/m^2); the smallest are B-class, followed by C, M, and X-class, which is the largest class (each class has a subscale from 1.0 to 9.9). This solar flare was classified as an X2.8, corresponding to an R3 on the space weather scale for radio blackouts. The flare, combined with a large radio burst, led to impacts across U.S. airspace. Multiple National Weather Service (NWS) Center Weather Service Units reported interference with aircraft radio communications, even at higher frequencies. Radio interference lasted for hours and, if effects had persisted, might have caused air traffic restrictions.

Sources:
Strongest Solar Flare of Solar Cycle 25 | NOAA / NWS Space Weather Prediction Center
NASA SVS | X-Class: A Guide to Solar Flares
Space Weather Radiation Effects on High-Altitude/-Latitude Aircraft - Mertens - 2021 - Geophysical Monograph Series - Wiley Online Library

> For example, one pilot said, “There's an app that I use for space weather. If I'm having a trip across the Atlantic or Pacific, I'll definitely look to see if there's any sort of solar flare activity. I don't necessarily change the routes I’m flying but I know that there's something going on in the system. It's not necessarily even incorporated in the typical weather briefing.”

Surveyed participants use data from a variety of sources. NOAA SWPC is the primary source of space weather observations, forecasts, and associated data. Other sources of information include UK Met Service, European Space Weather Network, ICAO Standards and Recommended Practices (SARPs), Oulu neutron monitor data, NASA’s NAIRAS model, university websites, and commercial apps and websites. Surveyed participants identified tools familiar and available to the space weather community from NOAA SWPC, UK Met Office Space Weather Operations Centre (MOSWOC), NASA's Goddard Space Flight Center Community Coordinated Modeling Center (CCMC) Langley Research Center (LaRC), the FAA Civil Aerospace Medical Institute (CAMI), and third-party commercial providers.

As one participant put it,

> We use everything that we can get our hands on. When we think about observations in the forecast, we use it as a forward-looking indicator. We sign up with a lot of alerts, warnings, watches, as well as the 12-hour around the clock forecast. We try to incorporate it into different educational platforms. We're also incorporating some of these advisories and products into real-time platforms graphically to build redundancy systems in the cockpit and on the ground for pre-flight planning.

Some pilots had limited awareness of commercial sources of information suggesting gaps in information dissemination. For example,

> We use NOAA's prediction center. We monitor other sites like the UK Met Office, but mainly it's about NOAA. Other sources of information, apart from NOAA, are Notice to Airmen (NOTAMs) received by email. But I must say that I've never seen a NOTAM with information about space weather.

Surveyed participants advocated for improved visualization of space weather data and its integration into existing flight planning tools. Suggestions included incorporating space weather alerts into briefing packets and flight planning apps, as well as including graphical representations of space weather impacts for efficient dissemination of information. Social media was proposed as a possible dissemination medium. Nevertheless, it is clear that visual tools provide clarity and efficiency just like the timeless adage "a picture is worth a thousand words." In particular, one participant said,

> We are working with our weather provider to facilitate graphical impact-based space weather products directly into the iPad. That would be very similar to terrestrial weather products that pilots globally instantly know how to recognize and react and make their best decisions for. This iPad [approach] has been a phenomenal resource. We think it is the future.

Use of color coding and graphical visualizations could enhance the understanding of impacts with forecasts and warnings. One pilot emphasized this:

> We are really good with pictures, so I would say maps showing you messages with the altitudes where you can tell me to fly a different altitude or fly a different route. And this is why, this is how much radiation on this route. Pilots love colors.

Tools must be easy to understand, readily accessible and, of course, fast. Operational control centers can be extremely fast-paced and present-day air traffic volumes require expeditious decision-making. Corporate, commercial, and business jet pilots often must make quick assessments and decisions.

Surveyed participants noted a need for data collection from stakeholders to quantify impacts and validate current concepts as well as drive the establishment of best practices, guidelines, and standards for operators. Interest in the utility of predictive AI was expressed along with the desire for graphics using 3D maps. For example, one participant noted,

> We're very interested in two things: (1) High prediction models and (2) characterizing the global radiation environment. We think tying those two together will provide a complete full spectrum look at space weather into the future.

Additional ideas included equipping airplanes with recording devices to monitor space weather impacts and emphasizing redundancy in space weather monitoring and response systems. One suggestion was,

> If we look at it from an operational point of view, I would have to say the models are not accurate enough, when you consider the large variations in the solar environment. I'm reluctant to put anything forward to be used by flight dispatch, on a real time basis, for operational decisions. I don't think we're quite there yet, though that's what's needed. The Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) program in the UK is all about getting radiation monitors on board aircraft. That data set, like every other data set that's gone before it, is to try and feed into the modeling efforts so that we can improve them.

As another pilot commented,

> I'd like to have my wish of recording devices in airplanes that actually record the bad stuff that space weather can do. So really, see how much radiation is there, how bad the HF is impacted or not and how bad the GNSS is impacted or not. And what the quality is of the comms. Real recordings in real airplanes for all.

Surveyed participants expressed a need for additional global operational centers in the EU and United States. For example, one said,

> As far as getting the information out, we think there's room for a couple different global control centers both in the EU and at the FAA. There's probably a greater need to understand where the information goes in real time, both on a federal level and then also on an individual airline level. Some of the things that we've come up with are global space weather routes based on FAA experts looking at mirror regions 1 through 4 of the maps of ionizing radiation and having preloaded space weather routes. What does that translate to besides lower latitude and lower altitude?

Risk Management

Surveyed participants were most concerned about the potential impact of space weather on human health, but also expressed concern about communication and navigation. Participants noted a lack of awareness regarding health risks and operational impacts indicating a need for further education and research.

For example, it was noted that

> Quantifying the impacts is still difficult. We need to have a process of gathering data from airline end users and actually try[ing] to quantify those impacts.

Participants reflected on efforts to mitigate risks. As one pilot noted,

> It's definitely not on most of our radar[s] as far as the dangers to human health. It's valuable to talk more about this and educate everybody so that they're at least aware of it. I think more studies and data would be warranted. It could be as simple as treating pilots as radiation workers and putting a little detector on everybody as we go to work. There are enough pilots out there that you'd get a lot of very good data very quickly if you tied flight hours and flight locations to those detectors. I think there's a lot of data out there that could be studied regarding this and you know maybe give us more information to make a better determination of what we should do going forward.

Radiation is a sensitive topic to many people. Flight crews and the flying public have significant concerns when it comes to possible exposure. The need for correlation between space weather events and health risks is an undertaking that will likely continue into the foreseeable future. It may be necessary to provide guidance based on the ALARA principle (as low as reasonably achievable). As research and data collection continue, guidance can continually adjust. The most important factor may be the consistent dissemination of information so as to alleviate the perception that health concerns are being ignored.

One business pilot noted,

> Canada recommends that you follow the ICRP limits, which are pretty low. And they say that if your employees involved in flight operations get one mSv or more from working, then you should have a monitoring program in place. There is dialogue about how they're going to move forward and bring in some regulation, but now it's voluntary and they say they use the term ALARA.

A specific example of overall operational risk was discussed in terms of what is typically the northernmost latitude for operations. The context of this discussion is the coupling of higher latitude routes to higher radiation exposure, potentially more frequent GNSS disruptions, and sometimes more communications interruptions. One respondent noted the latitude range:

> I would say for most of our [operations], probably around 65 or 70 [degrees North] would probably be a fairly northern route for us.

This tends to reflect an industry practice of using North Atlantic and North Pacific crossings and less frequent cross-polar routes. Surveyed participants sought clearer guidelines for decision-making in response to space weather events, especially regarding safety thresholds for phenomena and for flight restrictions. A common sentiment was,

> We need…more data to truly understand this and then we can more properly address it.

Sidebar 3.3 Aviation SMS

The aviation industry, like other sectors with safety management needs, uses a Safety Management System (SMS). The aviation SMS is a top-down organizational tool for risk management and is used by civil aviation authorities, the International Civil Aviation Organization, the Joint Planning and Development Office, and other aviation services. SMS consists of four components: safety policy, safety risk management, safety assurance, safety promotion. These components are leveraged in a centralized SMS which provides resources, information, and frameworks for safety risk management decision making and management to the FAA and service providers.

Sources:
https://www.faa.gov/about/initiatives/sms/explained
https://www.faa.gov/about/initiatives/sms/explained/components

Surveyed participants suggested integrating space weather into existing Safety Management Systems (SMS; see sidebar 3.3).[25] They advocated for incorporating SMS protocols with approved

[25] SMS is the formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls. It includes systematic procedures, practices, and policies for the management of safety risk as directed by FAA Order 8000.369.

documents to address space weather risks and ensure operational safety. This was emphasized by a participant noting,

> If we are treating the issues within our Safety Management System, space weather will have an equal treatment. We can use the processes we have in place to deal with an expected event for risk management for space weather.

Surveyed participants identified space weather risks including potential disruptions to and impacts on GNSS-based navigation systems, communication infrastructure, and personnel safety from radiation exposure. The importance of the risks was captured in the quote:

> If we have a major event affecting our operation, the ultimate [consequence] would be not being able to fly.

Due to the increasing reliance on satellite communication and navigation, concerns were raised regarding space weather impacts on satellite-based technologies and the need for robust backup systems. One of the corporate jet pilots noted issues with coms flying over the ocean for about 45 minutes around 10 degrees West longitude. Another comment was made regarding quantifying the risk so appropriate action can be taken:

> If this is a once a year type of event that is moderate in nature, not off the chart type events, how much concern do we really need to have?

Surveyed participants generally perceived space weather risks as low, but acknowledged the need for more data and research to fully understand potential impacts. Similar to volcanic ash events, when they occur the impact can be significant.

Surveyed participants noted a lack of specific policies or procedures for mitigating space weather risks within their organizations and are taking steps to improve their policies. For example, it was explained,

> We are looking at radiation, communications, and [the] impact[s] on the aircraft itself. We are doing an operational risk assessment to see if there is anything we can see right now. We don’t have the reporting to connect a failed system to a solar storm. So, at the moment, it’s just more a recommendation or best practice.

Common thresholds and procedures, developed by corporate operations groups, are needed to activate flight protocols during severe and extreme space weather events, including flight planning restrictions and coordination with relevant authorities. Education and awareness-building are crucial components of any mitigation strategy.

Simulation and Exercises

Participants suggested incorporating space weather scenarios into simulator training and developing emergency response plans for space weather events. Industry-level exercises would be of significant benefit. Precedence for scenario-based exercise has been set as there have been annual volcanic ash simulations carried out for two major world regions (Europe and Russia).

In-house simulations and exercises are intermittently conducted to enhance risk mitigation strategies and preparedness for future space weather events. One pilot noted the objectives of these exercises is to understand backup systems in case of communication or GPS navigation failures.

Safety Management

SMS, an industry practice, is an accepted means to delineate mitigation strategies for aviation hazards. Current tools provided by the government and the private sector are not fully aligned with industry needs and the FAA has a role to play in setting limits and thresholds for operations during space weather events. Having dispatch centers provide information to the pilots is important to reduce the pilot workload.

SMS and risk management have become infused in all aspects of aviation. Current understanding of risks can be for a specific flight or at enterprise level. Clearly defining specific risks is paramount. Incorporating space weather into SMS requires severity assessment of risks and developing and utilizing best practices, guidelines, or standards. This was highlighted by one pilot who said,

> IS-BAO (International Standard for Business Aircraft Operations) is a safety management system standard that has developed protocols, and BASC (International Business Aviation Safety Consortium) companies/organizations have SMS protocols. It’s helpful to lean on those organizations and to include as a recommendation for companies looking to achieve the highest levels of these certifications to monitor their personnel's radiation exposure.

Education

A common theme from all participants was the need for more space weather education applicable to the aviation industry. Education aids used for aviation must be translatable to an operational environment and easily understandable, e.g., color-coded information for radiation hazards and GPS navigation error.

One pilot noted,

> There definitely needs to be, at some level, some sort of education, whether it's hitting the corporate pilot road show, the conference road show, and explaining these things at different conferences to groups for people to take back to their organizations. There has to be more education before just jumping in and reading forecasts and weather alerts.

Airline and corporate operations function by policy and procedure. The theoretical aspects should be made easy to absorb for the operational mind. The commercial operators noted that pilot curriculums should include space weather, similar to training elements of terrestrial weather.

One pilot emphasized this point,

> I'm almost embarrassed at the lack of knowledge…some kind of educational tool to just make people aware of the risks of space weather. Something that I could bring back to our department and get every pilot convinced that this is a risk to consider prior to each flight. And make them want to check what's going on in space weather that particular day. At the most basic level, an educational tool to get 'buy in' that this is a risk that is applicable to all of us.

It was suggested that space weather topics for pilot training programs be included with academic institutions. For example, one pilot said,

> Some of the places to start would be an American elite flight university [as well as] schools that not only have professional pilot programs, but also have space studies programs. And also, a med school and a law school. Having a collaborative effort at the university level would be ideal. Specifically, those pilots who want to get a high-altitude endorsement, which is a pilot qualification above flight level 25,000 [feet mean sea level].

Education, combined with best practices, guidelines, and standards is a cornerstone of aviation operations. Training, procedures, doctrines, education, presentation, and communication of information should be standardized. Ease-of-use, simplicity, and visual aids were mentioned as important for educational material. Participants expressed a need for more educational resources to better understand space weather and its implications as noted in this quote,

> Flight dispatchers have a lot of training in the weather, but not in understanding space weather phenomena. [They need] a tool that would give [them] some view into what is available now, what are the consequences of space weather phenomena, and how that may interfere with the aircraft systems or else [cause] issues with passengers and crew.

Regulations and Policies

Surveyed participants noted a lack of specific regulations requiring consideration of space weather in flight operations.

> At the ICAO meeting last week, [there was] no discussion of an enforcement mechanism. Everyone does what they like, guidance is there but it's disregarded. Operators should continue to make the crews aware of space weather; to develop operational procedures for managing flights in areas impacted by space weather for example using technical nowcast. And the manufacturers…should also do their part. That's what the recommendations are at this stage.

Regulations do not mandate the use of space weather information. Its use is irregular; some companies integrate it into their business continuity plans. From the responses it appeared the commercial operators were more aware of regulatory language, though it seemed to be more guidance and best practices than actual legal requirements that might normally be associated with flight operations. As one might expect, the FAA and the European Union Aviation Safety Agency (EASA) were primary sources of regulations. There were also references to International Commission on Radiological Protection (ICRP) limits. Commercial operators may be more attuned due to the safety regulations applied to polar flights, which began at the turn of the century.

Participants mentioned the need for separation of communication, navigation, and exposure health effects of space weather events in aviation action plans. Operational limits for radiation exposure, whether self-imposed or regulated, were discussed and pregnancy was an area of focus. One commercial pilot noted,

> The most sensitive group of pilots among us [are those] in the first trimester of pregnancy, they're incredibly vulnerable. We know that 0.36 millisieverts and more increases the risk of miscarriage. We educate them to … know their occupational exposure [and identify] things to look for, so when they talk to their doctor, they'll have a better occupational understanding of radiation markers.

Findings and Recommendations

The following findings and recommendations are a direct distillation of the engagements and responses from the surveyed participants' input. They are not organized in priority order.

Finding 3.1. There is a lack of a framework for clear and common best practices, guidelines, and standards related to policies, education, and training across the aviation industry. Domestic and international aviation, both commercial and corporate, use diverse sources for space weather information; NOAA SWPC is the primary information source. However, the sources are not typically associated with actionable decision aids that can be tied to best practices, guidelines, and standards. The industry lacks clearly defined, actionable policies that directly support pilot and flight operations responses to space weather events. The industry also lacks uniform educational curricula that would enable a broad, common knowledge of the causes, risks, and mitigations for the adverse effects of space weather.

> **Recommendation 3.1.1. DOT, FAA, NIST, and NOAA should coordinate with other agencies or entities, including ICAO, International Organization for Standardization (ISO), or World Meteorological Organization (WMO), to create industry-wide best practices, guidelines, or standards related to space weather effects on aviation.** This would include documents that define, quantify, and identify space weather risks to avionics and health affecting communication and navigation systems, as well as radiation exposure.

> **Recommendation 3.1.2. FAA should develop appropriate policies and regulations based on best practices, guidelines, or standards that enable the aviation industry to respond safely and effectively to space weather conditions.**

> **Recommendation 3.1.3. SWORM agencies should coordinate with relevant entities, including aviation professional associations, academia, and commercial organizations, to develop appropriate curricula on the causes of space weather and informational sources for its effects on aviation, risks to aviation, and hazard mitigation pathways.**

> **Recommendation 3.1.4. SWPC, in collaboration with the aviation industry, academia, and commercial space weather organizations, should establish regular testbed training exercises, including simulations, focused on aviation.** These exercises should use space weather scenarios to identify and train the community in emergency response plans for space weather events.

Finding 3.2. There is a lack of measurements, reporting, limits, education, and hazard mitigation pathways for radiation exposure across the aviation industry. U.S. and International aviation, both commercial and corporate, lack the information required for tracking, reporting, and understanding radiation exposure at aviation altitudes. There is an overall lack of understanding of the radiation environment. Without proper education and awareness, this can lead to misinformation or incorrect action among crew and the flying public.

Recommendation 3.2.1. NWS, in collaboration with NASA, NSF, and FAA, should conduct or acquire ionizing radiation measurements at all relevant aviation altitudes and make them available for use by the aviation community. Measurements could be acquired via dosimeter badges on flight personnel, instrumenting individual or fleet/commercial/business aircraft, or purchasing data commercially.

Recommendation 3.2.2. FAA, in collaboration with SWPC and NASA, should develop public-facing educational materials that clearly explain the elements of human exposure to radiation when flying at altitudes normally used by commercial and corporate aviation.

Recommendation 3.2.3. FAA, NASA, and NOAA, in coordination with industry and academia, should expand their data reporting and data collection mechanisms to the aviation community to obtain scientific measurements that can validate existing models, such as FAA Civil Aviation Research Institute (CARI) and NASA Nowcast of Atmospheric Ionizing Radiation for Aerospace Safety (NAIRAS). This will provide the aviation industry a better understanding of the impact on human health from radiation exposure at flight altitudes with assimilative modeling.

Recommendation 3.2.4. FAA, informed by qualified organizations such as the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP), should establish practicable limits and regulatory guidance for crew and passenger radiation exposure limits based on scientific measurements and validated modeling. Policies and regulations should be structured within the framework of SMS, which is already embedded within the aviation community. Limits should be readily identifiable, easily monitored, and structured under the ALARA principle (as low as reasonably achievable).

Recommendation 3.2.5. SWORM agencies should coordinate radiation research findings from agencies, academia, industry, and entities such as ICAO, ISO, and WMO to disseminate best practices, guidelines, and standards on a global scale. International radiation exposure procedures should be harmonized across the industry.

Finding 3.3. There is a lack of navigation and communication measurements, modeling, and standardization across the aviation industry. U.S. and international aviation, both commercial and business, lack best practices, guidelines, and standards for the impact on navigation and communication generated by space weather. These provide the basis for decision-aids and tools that help the aviation industry manage space weather risks to navigation and communication.

Recommendation 3.3.1. DOT, FAA, and DOD, in collaboration with DOC, should conduct or acquire measurements related to navigational information, including GNSS uncertainties that vary during space weather events, from the ground to aviation altitudes, and make them available for common use by the aviation community.

Recommendation 3.3.2. DHS, FCC, NTIA, DOT, and FAA should conduct or acquire measurements related to communication information, including HF propagation and UHF uncertainties that vary during space weather events, from the ground to aviation altitudes, and make them available for common use by the aviation community.

Recommendation 3.3.3. FAA, NASA, and SWPC, in collaboration with academia and industry, should continue to improve and validate existing ionosphere models, enable new and additional measurements of the ionosphere, and support the development of data assimilative modeling for the navigation and communications environments.

Recommendation 3.3.4. Relevant SWORM agencies should promulgate internationally recognizable best practices, guidelines, or standards developed by entities such as ICAO, ISO, and WMO for mitigating navigation and communications interruption hazards for use by aviation operators.

Finding 3.4. Aviation industry needs accurate forecasts with longer lead times beyond 12 hours. Nowcast capabilities only provide actionable information for a few hours, yet operational systems require forecasts beyond 24 hours to plan for contingencies.

Recommendation 3.4.1. NOAA Office of Ocean Atmospheric Research (OAR),[26] NASA, and NSF should oversee expanded scientific data collection in time and space, as well as coordinate expanded fundamental and applied research to develop accurate, operational space weather forecasts beyond 12 hours.

Finding 3.5. There is a lack of threat awareness, protocols, planning tools, and oversight across the aviation industry. Aviation stakeholders are not uniformly aware of the space weather risks to aviation, and they are not fully aware of existing tools that may be available to help mitigate such risks. The existing SMS for aviation does not adequately consider space weather risks and mitigations. There are no regulations or policies, much less best practices, guidelines, and/or

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[26] In the report *Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise* (April 2023), SWAG recommended that NOAA create and fund an applied research program office for space weather within NOAA OAR to coordinate, facilitate, promote, and transition applied research across the national space weather enterprise.

standard operational protocols that Air Navigation Service Providers (ANSPs) or Air Traffic Units have to help them mitigate disruptions from significant space weather events. Current aviation industry planning tools for adverse space weather mitigation, provided by either the government or the private sector, are not fully aligned with industry needs.

> **Recommendation 3.5.1. FAA, in collaboration with the aviation industry and NOAA, should develop a thorough space weather threat analysis that can become the framework for an SMS.** It should include space weather hazards as risks with impacts to human health due to radiation exposure, navigation disruption due to GNSS inaccuracies, and communication disruption due to losses in HF and UHF propagation.

> **Recommendation 3.5.2. FAA, in collaboration with the aviation industry, NOAA, and NASA, should develop regulations and policies that address mitigation strategies and solutions to space weather-related disruptions.**

> **Recommendation 3.5.3. FAA, in collaboration with the aviation industry, should set limits and thresholds as part of an SMS to identify hazards and mitigation strategies.** The Air Traffic Management system should direct dispatch centers to provide relevant space weather information to pilots and implement Recommendation 3.5.2.

> **Recommendation 3.5.4. FAA, in collaboration with the aviation industry, should direct the use of tools that incorporate space weather conditions and alerts into briefing packets and flight planning applications. These products should include color-coded, graphical representations of space weather impacts on aviation decision points for ease of pilot use.** The Air Traffic Management system should utilize global control centers for efficient dissemination of information.

> **Recommendation 3.5.5. FAA and DOT, in collaboration with relevant SWORM agencies, should develop a suitable oversight process that ensures all facets of the aviation sector are able to utilize mitigation strategies and solutions for space weather-related disruptions. Elements of these would include: awareness of all current tools available to industry; awareness of developments within the scientific community that may assist operators; and assignment of responsibility for coordinating issues related to space weather within the industry.**

SWAG Findings and Recommendations

This section lists findings and associated recommendations SWAG identified that were not explicitly expressed by surveyed participants, yet are natural extensions of ideas expressed in the survey sessions.

Finding SWAG 3.1. The aviation industry needs to identify or create an organization best suited to develop policies related to mitigation of space weather hazards for aviation. Current expectations for U.S. operators default to FAA but, for many issues, FAA may not be the best suited. NASA HPD, NSF AGS, NOAA OAR, IATA, ICAO, ICRP, and ISO as well as other professional organizations may be better positioned to take action on some of the recommended actions.

> **Recommendation SWAG 3.1.1. SWORM agencies should coordinate an analysis to identify an organization best suited to enable mitigation strategies and provide actionable solutions for space weather-related disruptions to aviation. SWORM agencies should provide leadership in encouraging broad space weather enterprise collaborations.**

Finding SWAG 3.2. There is a need for continuing space weather enterprise engagement across the aviation industry. An organized process for engaging the diverse space weather community from agencies, academia, and industry to address aviation-related issues has not yet fully emerged. The SWPC 2022 Testbed Exercise for Aviation is one excellent example of an enterprise-wide engagement, but standards and tools development outside of the testbed environment can also be pointed to as important activities. The current SWAG effort is a step in the right direction, as are other advisory bodies related to space weather phenomena. Progress that has been made recently in collecting the breadth of space weather advisory inputs may recede if a conscious effort is not made to implement and expand on this work.

> **Recommendation SWAG 3.2.1. SWORM agencies should create suitable processes across agencies, academia, and industry that ensure all facets of how space weather affects the aviation sector can be utilized to provide fundamental knowledge, quality measurements, validated models, and actionable solutions through user-friendly tools for space weather-related disruptions.**

Finding SWAG 3.3. There is a need for using guidelines from the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) to define the status of aviation crew members as workers in an enhanced radiation environment. The bulk of the discussion in this survey centered on the human health component of crew members working in a high radiation environment. There has not been a sufficient dialogue on this topic, unlike other communities such as nuclear power plant operators or the radiation medical community. The aviation sector should clearly acknowledge the issue of crew members working in a high radiation environment and develop the guidelines, education, and regulatory framework to support work in this environment.

Recommendation SWAG 3.3.1. SWORM agencies should create a suitable process across the national space weather enterprise that ensures discussion and resolution to the issue of crew members working in an enhanced radiation environment, which may require risk assessment and mitigation of identified hazards.

Chapter 4
Human Space Flight Sector

Summary

The HSF sector includes activities that enable human travel through the atmosphere into near Earth as well as deep space. To our knowledge this user needs survey is the first time the HSF Sector has been surveyed about space weather needs. Two focus groups were held virtually consisting of a total of 12 participants from U.S. Government and commercial space launch organizations, including scientists, operations flight teams, and former astronauts. The commercial HSF group focused on launch from domestic airspace into orbital space flight, including suborbital and orbital capabilities.

Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. Overall, the discussion highlighted the need for improved radiation mitigation, information dissemination, and policy development to address space weather risks effectively across the HSF sector.

Surveyed participants emphasized the importance of using space weather information in space flight operations, even though there are no specific regulations mandating its use. They highlighted the need for more educational resources and improved information dissemination methods to better understand and mitigate the impacts of space weather. Mitigation procedures and risk assessment protocols are in place with a continuous effort to enhance preparedness through simulations and exercises. Overall, surveyed participants acknowledged the severity of the risks associated with space weather and advocated for proactive measures to address them effectively.

The human space flight survey resulted in 7 findings and 20 recommendations that cover topics from radiation measurements, modeling, and tools to the regulatory environment. Surveyed participants had a diverse set of perspectives and priorities regarding the current state and future directions of space weather observation, forecasting, and risk management. Participants emphasized the need for improved data quality, predictive capabilities, and regulatory frameworks to support safe and successful human spaceflight missions and space exploration activities. Highlighted topics of concern included radiation exposure, data availability, and lack of education and resources for understanding and incorporating space weather into flight planning and decision-making. Suggestions for improvement included better education and training tools,

enhanced dissemination of information, and clearer guidelines for incorporating space weather into safety protocols.

Sector Background

The United States leads the world's human space activity, whether it be through NASA missions to the International Space Station (ISS) or private sector flights of passengers into the stratosphere (20–30 km), to the Von Karman line (100 km), or into LEO. The HSF sector includes activities that enable human travel through the atmosphere into near Earth as well as deep space.

Prior User Engagement with the HSF Sector

The HSF Sector was not surveyed in the 2019 Abt Survey Report. To our knowledge this user needs survey is the first time the HSF sector has been surveyed about space weather needs, which are growing as humans seek to explore further and develop the necessary infrastructure and architecture for further space exploration.

Space Weather Effects on HSF Sector

Space weather effects on HSF include exposure to an enhanced radiation environment on vehicles and humans above 8 km (26,000 ft.). Space vehicles in LEO can experience atmospheric drag, surface charging, and debris or micrometeoroid environments. Space weather effects on atmospheric drag and vehicle surface charging are also covered in the STM/C chapter.

Regulatory Environment in the HSF sector

Operators of human space flight activities are governed by Federal regulations 14 CFR Parts 450 and 460. 14 CFR Part 450 prescribes requirements for obtaining and maintaining a license to launch and/or reenter a vehicle while maintaining safety of the activity for the public. 14 CFR Part 460 establishes training and environmental requirements for crew of a vehicle, whose operator is licensed, as well as informing crew and participants of risks in space flight launch, operations, and landing.

Survey Process

The respondents for the HSF sector were a subset of individuals working in HSF. They included scientists, operations flight teams, and former astronauts cognizant about safety issues related to HSF operations. Two focus groups were held virtually consisting of 12 participants. Nine were from the U.S. Government (civil) and 3 from commercial space launch organizations that operate in the United States. Respondents were from organizations that had well-defined safety management processes.

The government focus group included most of the relevant HSF NASA centers and a supporting NOAA organization. The commercial HSF group focused on launch from domestic airspace into orbital space flight, including suborbital and orbital capabilities.

Common Themes Among the Surveyed Groups

This section highlights common themes heard from surveyed participants, providing additional background and context for the subsequent findings and recommendations. In some cases, quotes from surveyed participants are used to highlight or illustrate specific points.

Information Sources, Uses, and Tools

Space weather information from measurements and modeling techniques is needed to enhance space weather monitoring and risk mitigation for HSF. Surveyed participants highlighted the importance of solar monitoring, high-energy radiation detection, and multi-altitude orbit predictions. Participants were concerned about space weather impact on spacecraft and the need for associated products to inform actions associated with single event effects, orbital regime changes in a spacecraft's trajectory, the debris environment, and loss of satellite communications—in particular due to the South Atlantic anomaly.

Commercial HSF companies use space weather observations to forecast potential radiation exposure for astronauts or spaceflight participants. These companies use the information to help with planning and then monitor space weather products throughout launch day. They also monitor watches and warnings before and during extravehicular activity (EVA). One participant noted,

> We use the space weather observations to forecast potential exposure for future astronauts or spaceflight participants. For our flights, we receive the information as early as possible prior to flight to help with planning and then we continue to monitor prediction and forecast up until launch day. Once the mission takes place, we record the dose and integrate that into medical records for the spaceflight participants as well as the flight crew. We do that for space flights and we also do that for proficiency flights as we're training our pilots.

Biomedical engineers and astronauts both look at radiation issues for crew health monitoring, which was underscored by survey respondents who said,

> So, looking at mission planning in the long range and also short range mission planning, we're interested not only in potential EVA activity but also immediate dose management. We're very interested in fluctuations and transients, as early and as high resolution as possible. We are also interested in immediate dose management for helping our crew shelter for real time.
>
> In our human flight program we definitely have decision making limits and thresholds. We're still navigating the messaging a little bit on what this means, particularly because [the reason some astronauts retired early is that they exceeded their estimated dose limits.] They were still qualified for flight for every other reason other than radiation risks.

Surveyed participants also discussed how space weather affects their operations, decision-making processes, and risk assessments. Topics included radiation exposure limits, operational thresholds, and the need for better risk mitigation strategies. The importance of using the experience of prior missions was emphasized.

Availability of data for use in operations was an issue for the human space flight community. For example, one participant expressed the desire for a tool that performs modeling and forecasting where they could enter data on altitude, duration, and astronaut weight to predict individual dose exposure.

Surveyed participants also discussed how future missions to Mars might be affected by space weather, including vehicles in the Martian and near-Martian environment. For example, one said,

> Space weather observations for our flight projects are helpful, having near real-time, real-time, or recent information. That helps us if we have a spacecraft anomaly if something's gone wrong. We look at space weather typically the week or two leading up to critical events such as orbit insertion or planning on Mars.

Surveyed participants use a combination of sources, including SWPC, private companies, international data sources, and academic research for space weather information. As one participant noted,

> We do use NOAA’s SWPC website to look 3 days in advance as a backup for our primary source of information, which is a private company. So, we look as far out as possible in terms of prediction.

There is interest in expanding and aggregating data sources to produce more comprehensive and accurate space weather information throughout the solar system, especially as Moon, Mars, and asteroid belt missions occur. For example, one person noted,

> We use NOAA SWPC synoptic flare and sunspot prediction capability. The map basically looks at individual active regions because we need to know connectivity to Mars, not necessarily Earth. And GOES real time data is what's happening on our side of the Sun, which may or may not be relevant to Mars. We use STEREO beacon information if we need images of CMEs and understand where they're going and qualitatively how big they are. Also NSOs GONG data to try to look on the other side of the Sun.

Surveyed participants also noted that there is utilization of NASA CCMC tools which tend to collect data from many sources as well.

Surveyed participants use multiple products from Federal Government and commercial sources. NASA's Space Radiation Analysis Group (SRAG) is working with NASA's RadWorks team to develop tools for mission planning, to better understand the space environment, and to aid in scheduling crew time. Space weather events can affect the debris environment in space and the ability to track it. Some NASA teams use the F10.7 solar flux, both the actual measurements and the future predictions to model the evolution of the debris environment. This solar proxy is used in models of the thermospheric ND. Variability of ND affects the drag on micrometeoroids and debris, causing changes in the reentry timing into Earth's lower atmosphere. Micrometeoroids, in the centimeter to millimeter size regime, are a primary concern in LEO and are modulated by dynamic space weather and present a challenge for operations.

Commercial HSF sector participants receive information from SWPC. However, surveyed participants noted that there are commercial products available for radiation monitoring and for other space weather products and services.

Participants expressed varying levels of satisfaction with the current quality, accuracy, and latency of space weather observations and forecasts. There was support for NOAA SWPC's use of common color-coding on the NOAA scales, but it was suggested that there is room for improvements. For example, one respondent requested color coding for radiation safety.

Comments related to the quality of data included,

> ... for real time operations, I want a higher time resolution for the changes in dose rate as they're happening rather than summing over minutes, whether or not that's possible with the current telemetry right now is a different issue.

Survey participants noted that the debris environment is important for HSF. For micrometeoroids, a primary concern was understanding the behavior and risk of the centimeter to millimeter size regime in lower orbit. The micrometeoroid (natural) and debris (human-induced) environments are usually aggregated with the topic of space weather since they represent hazards to space missions and their flux rates as well as behavior can vary dramatically with space weather effects. The forces acting on these two populations of small particles include the drag force from the atmosphere, electrodynamic forces, and solar radiation pressure. Each of these can affect the behavior of these populations and, thus, the hazard level they pose for space systems. While all objects in LEO are affected by these forces to one degree or another, the very small particles pose a particular problem because they are numerous, too small to be tracked, and yet they can cause surface damage on vehicles that lead to loss of mission capabilities, or potentially mission failure. For example,

> [The] Orbital Debris Program Office is really concerned about the millimeter size debris not because millimeter size causes small damage—it could still damage the spacecraft—the problem is its number. There's a huge number of millimeter size objects in low Earth orbit. And, so, centimeter size debris, millimeter size differ, just in terms of their sheer numbers. Just to give you an understanding, the ISS has been hit many, many times by millimeter size debris. We've documented I would probably say hundreds of impact sites on the ISS. Now the ISS is heavily armored. And it only causes damage if it hits on the wrong place. But for smaller spacecraft, they tend to be more sensitive and more susceptible than the ISS.

A number of topics were raised by surveyed participants related to the future needs for space weather information sources, uses, and tools, including forecasting the next solar cycle to improve LEO debris lifetime estimations. Other needs include an automated real-time flare location product and the solar energetic particle (SEP) spectrum at 1 AU outside of the magnetosphere. Improvements are needed for specific inputs for models such as the cutoff rigidity variation with magnetic activity from solar wind plasma and IMF interaction; the Dst index of the magnetospheric ring current is an often used indicator of the strength of geomagnetic storms and needs forecasting improvement. Better proton pitch angle distributions—which are important for characterizing the radiation environment at the beginning of a storm, through its peak, and after it subsides—are needed as are heavy ion data. For coronagraph measurements, latency was identified as an issue. Neutron monitor data is a continual priority as it is used for inferring the relativistic proton spectrum during a CME. Some participants commented on the need for better prediction capabilities with respect to phenomena like CMEs. In particular, having real-time information was strongly supported, as for example:

> If we can make some changes at SWPC, [one] is that they have the ability to provide a real-time flare location product that is automated. The GOES instrument has that capability because it has multiple diodes. They've just released that on a non-real time basis—on a 2-day delay. That's great for research, but right now we're waiting for the human forecast.

> The neutron monitor data could use some funding to continue to develop the real time [observational] availability. And any new satellite [measurements] that could extend beyond the energy range of 500 MeV for protons would be great … from the experimental side.

Surveyed participants wanted improved space weather forecasts including enhanced predictive capabilities, more detailed and customized information, and automated delivery of forecasts. For example, it was noted,

> Many of the SEP models, the energetic particle models, they're important for human space flight as triggered information [for models]—the ones that trigger based on flare information. We can get that so much faster if we have automated flare detection. Our understanding is that NOAA is reluctant to put this out because they always want a human to verify their information. They don't want to put something out automatically … it could go out with disclaimers so that people can use these to drive models for triggered events.

Surveyed participants emphasized the importance of real-time data for improving temporal resolution. One said,

> What could we use that we don't have right now? For observations, I would say increased time frequency for increased frequency of data. Actionable information are things like the rate of dose rate change. So, as you see [dose rate] curves start to climb quickly, you know … getting updates every 15 minutes it's pretty useless if you want to know real-time or every 5 minutes.

This is especially important for monitoring astronaut radiation exposure during spacewalks, for forecasting potential exposure for future space flight participants, and for monitoring spacecraft anomalies. Forecasting and predicting with lead times of +3 days for a launch date and +2 weeks for flight readiness review was of high interest. For example,

> The sooner we get the info the better, based on the complexity of planning the mission and all the different cogs that are involved. Having some ability to understand what a [launch] slip might mean or what one day would be in terms of [changes to] radiation exposure and interference with comm versus another day [would be useful] in terms of selecting launch windows. We're relatively live with our launch window, but if we could have [even just a one-day lead on] prediction, [or better yet] two or three days, [it] would be very helpful for us.

Surveyed participants expressed a desire for continual model development, model improvements, and consistent developer involvement. Surveyed participants noted the need for automated CME parameters, 3D modeling, and Mars-specific models. Participants also wanted enhanced measurements to develop and validate the models. There was an interest in additional solar measurements to improve accuracy. There was consensus among surveyed participants on the need for improved real-time information, higher frequency data, and better monitoring of specific space weather phenomena such as the shape and dynamics of the South Atlantic anomaly. A participant noted,

> There are so many assumptions you have to make. The more of those we can eliminate, like where the [South Atlantic anomaly] boundaries are, would be awesome.

Automation

Surveyed participants need improved space weather forecasts including enhanced predictive capabilities, more detailed and customized information, and automated delivery of forecasts. It was noted,

> More autonomy, in terms of [disseminating] information would be ideal for us. That is still controlled on the back end by all of the people who are doing all the forecasting and predicting, but we now have the ability to get the information much quicker.

Surveyed participants want quicker, automated SWPC alerts and bulletins. For example, participants highlighted the production and limitations of ASCII text bulletins even though they are universally accessible. Enhancing automation of measurements, data collection, and data transfer to other machines was also emphasized.

> Machine-to-machine communications…was something that came out of the [NOAA SWPC] satellite testbed experiment. The satellite operators are not really interested in interacting with humans, or having humans interact with the data. They want the data directly with no intervention. And they'll make decisions about what they think is quality and acceptable data to use in their decision-making process.
>
> Another development on the horizon is the ability for us to produce direct to machine coded messages that are more digestible than just ASCII text, which is painful to ingest.

Surveyed participants noted the importance of estimating long-range solar cycle climatology. As one participant commented,

> We'd like to know going out into the future how the solar cycles are going to behave, because, for instance, if a mission is starting to plan today, they're going to be planning a mission that will go into the next solar cycle. They also want to

> understand after their mission is done, since they need to get it out [i.e., deorbit] in 25 years[27] so that's another solar cycle or two.

Surveyed participants were also interested in how long-term planning applied to the climatology of the micrometeoroid natural environment. A participant noted that,

> Meteoroids, meteorite streams you could consider as part of space weather and orbital debris for that matter. It's certainly an environmental issue, but as far as purely solar activity, I think the only place we have a good overlap is how to fix the atmosphere and [its] effects [on] drag of objects in Earth orbit.

Participants were asked whether climatological and statistical data and models reflecting historical conditions were more important than event models. One responded with,

> If we have a bad day, we're assuming it's a Carrington [event] and just activating our full protection measures. Boy, would it sure be helpful if we knew we didn't have to treat every solar particle event as your century's worst case.

Measurements of total accumulated dose and dose rates, including those at high-latitudes, at operational orbital altitudes, and across the radiation energy spectrum, were priorities among the surveyed participants. These quantities are a highly variable component of space weather. A comment highlighted this:

> Right now, that's one of the trailing [or lagging] factors—accumulated dose for crew—and it's not very well measured; it's fairly well estimated but it would sure make a difference to have eyes on it rather than to have to estimate it all the time.

Several participants expressed a desire for increased monitoring and products for operations in and around the Moon and Mars. Measuring the flux of albedo neutrons in the lunar environment was of great interest. Additionally, the discussion of Mars' needs included:

> …model development for space weather [at] Mars. We have so much for Earth, but we need to do it for Mars. We need to validate it with the data we already have on Mars. We have a collaboration with the Maven team where we brought in real time Maven [flare] data and particles and fields. We're going to try to get the community to think about how you can use this data—to maybe adapt your Earth model for Mars, or make a whole new model. But real time means it can be up to 2 days, but this still allows people to get a proof of concept going, so that if you did have a data stream, or if you had an onboard model or something, you could see if it performed well.

[27] FCC adopted a new rule in 2022 to mitigate the growing space debris problem by requiring satellite operators proposing new launches to LEO to dispose of their satellites in 5 years.

In terms of Mars modeling, a suggestion was made to concentrate on poorly modeled cases as a pathway for future improvements.

> You might want to focus on those events that were poorly modeled and validated. Understand what the issues were so that you could maybe improve the model or at least understand where the model has weaknesses so that when you have a future event, you're better prepared.

Surveyed participants were willing to utilize data from research missions along with real-time data for operational purposes. This supports the evolution of data usage that transitions research observations onto operational platforms in later stages of an instrument's life cycle (Research to Operations, R2O). The reverse direction is also true, where models have value when they can evolve with data from operational environments (Operations to Research, O2R), i.e., responsive model development. Utilizing both research and operational data can help fill model gaps. Participants were supportive of adding space weather instruments to flight vehicles when possible. This path supports radiation tracking, as one participant noted,

> The ability to track [a] radiation number on an annual basis when the [astronauts and] pilots are going through their flight physical would be the ideal outcome.

When modeling crew dose rates, one would want to be able to take into account the characteristics of the vehicle and mitigation (e.g., shielding). Surveyed participants discussed the need for instrumentation on vehicles that fly unique trajectories, e.g., suborbital flights and highly elliptical flights.

> One thing we haven't brought up is suborbital flights. We talked about LEO, but we haven't talked about a flight that would go highly elliptical, like Inspiration. What did they experience in terms of radiation? It goes back to that modeling - if you could just input some numbers and get an answer, which is very difficult, I know, but for multi-altitude orbits I think we're going to need to do that.

Addressing Space Weather Risk

Surveyed participants discussed risk management processes, simulation activities, and the need for standardized data outputs. A starting point in the conversation was worst-case design. The discussion highlighted that it was often required to design for worst-case scenarios due to lack of knowledge. Participants noted the importance of data for justifying less conservative designs and reducing uncertainty. One person said,

> Doing the worst case always means we have to use the historical data and so if we design the spacecraft, we have some risk we can tolerate. More data will … help

> our understanding of the risk posture we are taking [and] will be useful for human missions or for robotic missions.

Another person added,

> We try to avoid the risk associated with space weather … by designing our spacecraft for a worst-case environment, by assuming very bad space weather.

A participant noted that one way risk is reduced for their operations is to instrument the flight. For example,

> We get forecast information starting 6 days prior to flight. We retain that in a very specific record associated with the flight. We instrument the flight. We receive the actual dose and then also retain that as an element of the records of the folks that are flying, in addition to a long-term view of different levels of exposure that we've seen during flights.

Participants agreed that revisiting troublesome space weather cases to better understand the problems is useful for risk reduction. The participants noted that testbeds add value to identify what is helpful to reduce risk and agreed that international partnerships for data sharing are important and growing. Surveyed participants identified establishment of self-certified flight rules relative to radiation exposure, using real-time risk assessment that is based on available data, as a goal. For example,

> What comes out of the [14 CFR] Part 460 rule making could have a huge effect on the commercial companies in what manner they go about trying to discuss radiation effects on humans. And I don't think we know that answer yet. It could have a huge effect right now. [14 CFR] Part 450 is a pretty difficult regulation to comply with because you have to prove that you're meeting their standard. And the companies have objected to that and made comments and I've talked to the GAO about it but in the end that's the way the FAA put it out. It'll be modified of course, but many have wanted to go towards the airline type of model. You know, more certifying and then the FAA checking. But I think there's a real risk to human space flight, for spaceflight participants, depending on what comes out of this [14 CFR] Part 460.

Participants noted a role for the FAA as well,

> And then the other part I think that we're probably missing is there is an insurance requirement by the FAA. So commercial companies have to have insurance. And that has its own rulemaking committee to say if that should be revised. Typically, when you're doing high risk operations that could have long term consequences, you mitigate those with proper insurance; there is a set of insurance regulations.

One participant tied risk to legal liability, particularly in the radiation topic,

> The only thing preventing a lawsuit is having a very firm radiation safety program that points to industry standards, acknowledges the risk, owns it, and calculates it.

The surveyed participants noted the importance of engaging with commercial and agency human space flight communities to evaluate tools, data, and models. One quote highlighted this:

> Launches are governed by so many factors that have nothing to do with the solar radiation conditions. I'm working backwards in a sense. They launch when they're going to launch. And then I put together what the radiation conditions are—where the crew members are on ISS during their stay makes a huge difference in the dose that they're getting. I have to reconstruct where they were and then work backwards with instruments, partial data sets, instruments that are in the right place and then probably good location information and do a boatload of modeling and come out with best estimates, and all that's packaged together and lives with a dose report that goes out to the astronauts afterwards.

The value of measurements was stressed:

> It seems to me that having good independent measurements of the environment would be extremely valuable. As far as determining what the actual exposure has been to a given space person, independence of measurements is probably an important aspect of that.

An interesting discussion was when risk was tied to economics for commercial HSF. As a participant said,

> I see the risk associated with profitability. At the end of the day in this commercial world that we're in, survivability is based on getting to profit. In our world where we're at a relatively low risk for radiation exposure, in the suborbital space, every single dollar of that would go towards instrumentation or analysis needs to be justifiable with a significant ROI. So, having equipment that is not a significant capital expenditure, being able to develop operational concepts that don't require a significant amount of bandwidth from people who are doing all the processing. And then, the value of the data needs to be proven. So, I think economics is a big consideration when we're talking about survivability in this space.

Surveyed participants highlighted educational activities as an important, ongoing need. This includes the need for a better understanding of what space weather is, how it can affect HSF, and what are steps that can be taken now and in the future to address the risk.

Regulatory

Commercial HSF participants were particularly interested in the current regulatory environment of the sector. Several participants are involved in rulemaking groups that have been stood up under the auspices of 14 CFR Part 460—HSF Requirements.

The commercial HSF community strongly urged self-regulation for non-NASA space flight participants. An analogy of self-regulation in the diving industry was noted,

> I think the perfect solution is for us to become self-regulating. If we were able to pull that off the same way that recreational diving has done it with really strong adoption of PADI and NAUI standards, if we can do that for space radiation safety then we don't have to inherit the DOE and OSHA package of radiation safety regs which can be kind of stifling.

Surveyed participants highlighted gaps in regulations and the need for performance-based standards for spaceflight participants' safety. As another participant added,

> Human orbital space flight safety for non-NASA space flight participants is a complete regulatory hole. Our approach is to make it so the FAA doesn't own it, they just do launch and re-entry. The Department of Commerce's Office of Space Commerce [OSC] could own it, but they don't. They're just getting their legs up. It's OSHA…but that arguably would only apply to your employee astronauts and not necessarily to the flight participants. It's a gap. Our strategy is for it to be OSHA acknowledging, but have NASA push for supplementary regulations that aren't quite as flight prohibitive.

Participants discussed the regulatory landscape governing space weather monitoring and its effect on human spaceflight safety. Surveyed participants stressed that one should be required to monitor their radiation environment. It was noted,

> My understanding is that the tools we are developing have not necessarily been driven by policy per se, rather our space radiation community has identified this as a source of information to help to understand and protect crew risk when it comes to missions, EVAs, longer duration trips, for example Mars transit, things like that. I don't believe at this point we have a policy driving the use of the space weather tool[s] for crew health and safety.

This viewpoint was seconded by another participant, who said,

> It'd be nice to have a policy that would help in terms of monitoring. I think that one of the challenges is that we're relying on satellites with instrumentation that are not necessarily in the same area as the spacecraft that we're dealing with and

> so we have to assume things about the spacecraft based on other information. If there were a policy that said you will monitor your radiation environment that would be helpful.

Surveyed participants noted that industry-wide recommendations on prediction, guidelines, and standards were important, in particular instrumentation or analysis needs to be justifiable with return on investment. Another way of looking at the issue was that development of tools should be driven by community needs as a complement to regulatory requirements. It was suggested that adherence to standard practices for orbital debris, in particular, should occur with regulatory enforcement by the FAA and FCC. This was highlighted by a participant who said,

> For many years the U.S. government has had standard practices for orbital debris. Those are starting to be enforced by the FAA and the FCC about removing their objects from space. It has also been adopted by the U.N. Committee on Peaceful Uses of Outer Space (COPUOS). Similar rules and a lot of other countries are putting them in place also. So there is regulation. There are also the NASA guidelines that's supposed to apply to all NASA missions. These are the U.S. government guidelines but they're starting to make their way into the regulatory process.

Findings and Recommendations

The following findings and recommendations are a direct distillation of the engagements and responses from the survey participants' input. They are not organized in priority order.

Finding 4.1. Radiation measurements, modeling, and tools are a priority for commercial HSF. Commercial organizations that operate HSF put a priority on the radiation environment; however, there is a lack of sufficient radiation environment measurements, modeling, and available tools. Investment in instrumentation and analysis that improves radiation environment specification will significantly enable addressing the space weather risk to HSF.

> **Recommendation 4.1.1. NASA and NOAA, in collaboration with OSC, DOE, DOD, industry, and academia, should conduct or acquire ionizing radiation measurements, including dose and dose rate changes with high time resolution, at all relevant flight altitudes (suborbital, LEO, Moon, Mars, and deep space).** These measurements should be made available for common use by the HSF community. Possible methods of acquiring measurements include requiring dosimeter badges on flight personnel, instrumenting spacecraft, or purchasing data commercially.

Recommendation 4.1.2. NASA and NOAA, in collaboration with OSC, FAA, DOE, DOD, industry, and academia, should continue to improve and validate existing radiation models. These models extend from Earth's atmosphere, through the Van Allen Radiation Belts, to the Moon, Mars, and asteroid belt. This should include integration of measurements identified in R4.1.1. and should support the development of data assimilative models to characterize all radiation environments.

Recommendation 4.1.3. OSC, NOAA, NASA, FAA, DOE, and DOD, in collaboration with industry and academia, should coordinate to develop tools that can be used to specify the local radiation environment based on HSF systems and locations.

Recommendation 4.1.4. OSC, NOAA, NASA, FAA, DOE, and DOD, in collaboration with industry and academia, should improve accuracy of radiation dose measurements for astronauts and private mission crews through improved monitoring and modeling of dynamic regions such as the South Atlantic anomaly. Dependence on worst-case scenarios and models mean that astronauts may prematurely be "dosed out" of future flight opportunities because models estimate higher doses than were actually received. Possible methods of acquiring measurements include extending the measurement capability in LEO and ISS missions, making existing LEO mission data available to the research community, or purchasing data commercially.

Finding 4.2. There is a lack of sufficient lunar and Martian space weather tools. There is a growing focus on HSF activities directed at lunar and Martian operations, but commercial and government organizations lack the basic space weather information required for operating safely in these environments.

Recommendation 4.2.1. NASA and NOAA, in collaboration with NSF, industry, and academia (and informed by the 2024 Heliophysics Decadal Survey), should acquire particle and field measurements at and near the Moon, Mars, and other relevant locations, and make them available for common use by the community. Possible methods for acquiring measurements include extending the measurement capability in Commercial Lunar Payload Services (CLPS) missions; making existing CLPS, other lunar, and Mars mission data available to the research community; or purchasing data commercially.

Recommendation 4.2.2. NASA and NOAA, in collaboration with NSF, industry, and academia, should continue to improve and validate existing models of lunar and Martian radiation environments.

Recommendation 4.2.3. NOAA and NASA, in collaboration with industry, should support the development of real-time, automated flare location products and CME forecasts throughout the solar system.

Recommendation 4.2.4. NOAA should develop space weather indices or scales that are relevant for HSF environments.

Finding 4.3. There is a lack of sufficient operational radiation, atmosphere density, particle, and micrometeoroid/debris measurements and models for long-term planning and mission design. Commercial and government organizations that work with HSF activities need space weather information that can inform long-term planning mission design practices in all relevant environments. Model and sensor development should cover LEO environments and highly elliptical orbits (e.g., the Inspiration4 Mission).

Recommendation 4.3.1. OSC, NOAA, NASA, DOE, and DOD should develop onboard sensor suites of particles and field detectors in support of both public and private sector missions. Currently, because of limited data availability and low confidence in current models, spacecraft and mission design is limited to worst-case scenarios.

Recommendation 4.3.2. NOAA, NASA, and NSF should consider the support of existing ground-based neutron monitor networks in its prioritization of ground-based measurements. These data can provide a better specification of the particle environment for humans in space. Additional sensors may be needed to measure heavy ions and neutron monitor data for use in model validation.

Recommendation 4.3.3. SWPC, in collaboration with OSC and NASA, should support the collection, validation, and timely distribution of radiation, atmosphere density, particle, and micrometeoroid/debris measurements, including those by the commercial sector, and support the development of models.

Recommendation 4.3.4. NOAA, NSF, and NASA should fund the development of models and tools that improve the accuracy of forecasting and predictions for a launch date plus 3 days and for flight readiness reviews at least 2 weeks out. Ideally, these models would be integrated into a software platform or dashboard where key parameters are entered, e.g., altitude, geographical location, and geomagnetic conditions, to estimate the expected radiation dose.

Recommendation 4.3.5. NOAA, in collaboration with NSF, NASA, industry, and academia, should develop climatology models specific to lunar and Martian environments to enable long-term planning and mission design.

Finding 4.4. Human space flight sector needs a strategic approach to advance the regulatory environment. Commercial and government organizations that support HSF activities find the regulatory environment is almost non-existent. Overall, the HSF sector understands the importance of regulatory guidance, particularly as it relates to radiation exposure. The commercial HSF sector is willing to self-regulate and is heavily invested in a successful outcome. While they acknowledge the benefits of eventual regulations, there are financial and innovation considerations that should be evaluated. Some participants saw benefit in industry-wide recommendations on prediction, guidelines, and standards which the industry could then use to regulate itself. Commercial participants were less enthusiastic about the performance-based regulations that the FAA uses in other areas, implying that an overly burdensome regulatory regime could stifle innovation in this sector.

Recommendation 4.4.1. SWORM, with inputs from FAA, NASA, OSC, NIOSH, and OSHA, and in collaboration with industry and academia, should improve the language of 14 CFR Part 460—Human Space Flight Requirements. In particular, there is no mention of radiation exposure as a hazard and how to mitigate it. This is a space weather enterprise wide topic and should be addressed with the concurrence of all stakeholders.

Recommendation 4.4.2. SWORM should determine an appropriate method for establishing policy and regulatory guidance for crew and passenger radiation exposure.

SWAG Recommendations

Below, SWAG identifies findings and associated recommendations that were not explicitly expressed by surveyed participants, yet are natural extensions of ideas expressed in the survey sessions.

Finding SWAG 4.1. There is a need for a gap analysis of agency, regulatory, and industry capability and responsibility for human spaceflight. This type of analysis has not been thoroughly conducted whereby actions can be identified for tasking to the most appropriate entity. Current expectations for commercial and government organizations that operate HSF activities default to the FAA but, for many issues, this agency may not be the best suited. NASA HPD, NSF AGS, NOAA OAR, IATA, ICAO, ICRP, and ISO as well as other professional organizations may be better positioned to act on some of the recommendations.

Recommendation SWAG 4.1.1. NASA should fund a targeted gap analysis across agencies, academia, and industry to inform strategies and actions that will ensure all facets of the HSF sector are able to identify mitigation strategies and provide actionable solutions for space weather-related disruptions.

Finding SWAG 4.2. There is a need for continuing space weather enterprise engagement. An organized process for engaging the diverse space weather community from agencies, academia, and industry to address HSF related issues has not yet fully emerged. The current SWAG effort and the SWPC Testbeds are examples of a step in the right direction, as are other advisory bodies related to space weather phenomena.

Recommendation SWAG 4.2.1. SWORM agencies should fund a follow-on review across agencies, academia, and industry to determine progress on space weather effects related to HSF are being mitigated, and whether the stakeholders are providing fundamental knowledge, quality measurements, validated models, and actionable solutions through user-friendly tools for space weather related disruptions. The SWPC Testbed might be a good venue for organizing that review.

Finding SWAG 4.3. There is a lack of sufficient micrometeoroid and debris measurements and modeling. Micrometeoroid and orbital debris (MMOD) are modulated by dynamic space weather, and these phenomena aggravate the operational environment. Commercial and agency organizations that work with HSF activities lack the information required for tracking, reporting, and understanding of MMOD in the millimeter to centimeter size range at flight altitudes. There is an overall understanding of the MMOD environment among the expert communities, and the topic was addressed in several subtopic discussions. However, it was continually noted that there is a lack of sufficient measurements and modeling capability for how space weather affects particles of this size.

Recommendation SWAG 4.3.1. NASA and NOAA, in collaboration with OSC, DOE, DOD, industry, and academia, should conduct or acquire measurements of MMOD in the millimeter to centimeter size range at LEO and make them available for use by the HSF sector. Possible methods of acquiring measurements include sampling ISS micro craters from MMOD or purchasing data commercially.

Recommendation SWAG 4.3.2. NASA and NOAA, in collaboration with OSC, FAA, DOE, DOD, industry, and academia, should continue to improve and validate existing MMOD models for LEO that extend in time out to 25 years or two solar cycles. MMOD is modulated by dynamic space weather and these phenomena aggravate the operational environment. More measurements can be used to support the model development of this environment and improved forecasts of solar flux F10.7 to two solar cycles will also support modeling improvements.

Recommendation SWAG 4.3.3. NASA and NOAA, in collaboration with NSF, industry, and academia, should continue to improve and validate existing models of lunar and Martian dust environments.

Chapter 5
Space Traffic Management/Coordination Sector

Summary

Space weather events can heat the upper atmosphere, resulting in atmospheric expansion that can cause aerodynamic drag on LEO satellites. This affects the ability to manage and coordinate space traffic. To prevent loss of altitude, these satellites require extra maneuvering, tracking, and conjunction avoidance efforts during space weather events. Space weather-driven changes in ND and resulting changes in atmospheric drag are the largest orbital perturbation for LEO satellites and the largest source of prediction error.

STM/C is a rapidly evolving sector that has not been previously surveyed. Until recently, the STM/C sector has been largely unregulated in terms of traffic management and deorbit requirements.

The survey process for this sector included 16 participants from 4 sub-sectors: satellite owners/operators; satellite tracking and maneuvering; data acquisition/data providers; and service and product development. All participants were U.S.-based non-government entities. This survey process benefited from many users participating in the SWPC 2023 Satellite Environment Tested Exercise; there, many surveyed participants were exposed to SWPC terminology, operations, and products for the first time.

The STM/C sector survey resulted in 15 findings and 33 recommendations that seek improvements in topics from planning and model development to product acquisition and availability. Surveyed participants need near-term ND forecast improvements and model developments. With the broad participant pool, there was no consensus on cadence, thresholds, and resolution required for ND forecasts. For large constellations, with semi-autonomous or autonomous maneuvering capabilities, up to 3-day forecasts are needed. For ground-commanded maneuvering and tracking, forecasts up to 7 days are needed for collision avoidance. Satellite operators need long-term solar cycle forecasts including 5-year predictions to plan satellite builds, launches, and mission profiles. Five-year forecasts would allow satellite operators to better plan missions to meet the FCC’s rule stipulating spacecraft, at altitudes below 2,000 km, de-orbit in under 5 years after the end of their mission.

Surveyed participants recommended that uncertainty values, of both the model inputs and outputs, be provided with any ND model forecasts (and with any other space weather model prediction) so users can better assess model results and make their own reliability assessments

of the information provided. Surveyed STM/C users desire observations and space weather forecasting akin to the current state of terrestrial weather forecasting, particularly with regard to ensemble modeling. Terrestrial weather forecasting benefits from substantially more observations and sufficiently developed models to support ensemble forecasting. The path to meeting these needs and desires include:

[1] Increasing observations from large satellite constellations and specific instruments fielded or data purchased by NOAA, and novel uses of related observations such as GNSS observations of ionospheric total electron content.

[2] A baseline ND model that is well documented in terms of assumptions and dependencies. This will require significant comparison and validation, likely done in collaborative testbeds and proving grounds. Such a model will need to be two-way coupled so that thermospheric and ionospheric data can be assimilated for use in forecasts.

[3] Development and use of data assimilation machine learning techniques and enabling the use of reduced order models.

[4] Ongoing user engagement and education regarding space weather effects and model updates.

Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector.

Sector Background

The STM/C sector is a developing area of national importance. In mid-1957 there were no artificial satellites. By the mid-1960s DOD was actively monitoring LEO and was supported by a small cadre of space environment support services personnel. Operationally relevant research increased, demonstrated by Jacchia's (1965) publication of the first in a series of static diffusion models of the upper atmosphere. In 1985, the U.S. Space Command was tasked to take over from North American Aerospace Defense Command (NORAD) the maintenance of a catalog of all artificial objects in Earth orbit. With the number of resident space objects rapidly growing, the International Academy of Astronautics defined a global space traffic management system in 2006. Rapid advances in satellite technology and decreasing launch costs during the last decade have supported an extraordinary proliferation of new private sector satellite operators in the LEO environment. These operators provide essential services worldwide in communication, weather forecasting, urban planning, environmental monitoring, etc. In 2018, Space Policy Directive-3 designated the Department of Commerce (DOC) as the United States lead civilian agency for providing basic space situational awareness data services to civil and commercial space operators. Rapid growth in the number of spacecraft and constellations of satellites in LEO has raised concerns globally about potential collisions and the consequences of increased orbital debris (e.g., Inter-Agency Space Debris Coordination Committee, 2020). Anticipating forecast needs for the LEO environment and in response to an ICAO call for space weather aviation support, NOAA's SWPC developed a physics-based Whole Atmosphere Model (WAM), which transitioned to operations in July 2021 (updated July 2023). In 2022, on behalf of DOC, NOAA's Office of Space Commerce (OSC) began developing the Traffic Coordination System for Space (TraCSS). (See Sidebar 5.1) The FCC adopted a new rule in 2022 to mitigate the growing space debris problem by requiring satellite operators proposing new launches to LEO to dispose of their satellites in 5 years. In 2023, NASA estimated that the space economy had expanded by more than 60% in the last decade and was valued at ~ $400 billion. As of mid-March 2024, there were ~8,250 satellites in LEO.

Sidebar 5.1 Traffic Coordination System for Space

The Traffic Coordination System for Space (TraCSS) is a policy initiated in 2018 and currently in development within NOAA's Office of Space Commerce (OSC). TraCSS will be used to disseminate space situational awareness (SSA) data, products, and services to space operators from the public and private sectors. Consisting of a data repository, application services, and modeling, simulation, and other R&D environments, the TraCSS user portal will consolidate data sources from across Federal and commercial sensors and satellites for use by stakeholders. The research and development component of TraCSS will be managed by NASA and will focus on better understanding how the space environment impacts SSA, space weather and orbital debris, as well as how forecasts and predictions can improve.

Sources:
Traffic Coordination System for Space (TraCSS) – Office of Space Commerce
DalBello Testimony for Senate Commerce Hearing 12.13.pdf

Prior User Engagement with the STM/C Sector

STM/C as a sector has not been previously surveyed. However, satellite operators, responding to questions about the broad space sector in the 2017 Abt Report (Social and Economic Impacts of Space Weather in the United States), identified concerns about LEO satellite loss-of-altitude, disruption in communication links, and spacecraft charging. These concerns were generally reiterated in the 2019 Abt Survey Report, which found satellite operations seek products for more localized orbits with increased precision, historical data products, improved accessibility and usability and enhanced products presentation, and more education and outreach. In addition, the National Institute of Standards and Technology (DOC Boulder Laboratories) published a 2019 workshop report with recommendations from critical members of industry, academia, and the Federal Government on key technology, measurement, and modeling barriers to deploying and safely operating commercial space technology.

Satellite operators will be surveyed as a sector in a future user needs survey.

Space Weather Impacts on Spacecraft

Satellites operating in LEO are subject to various space weather effects:

- Unanticipated orbit changes (including deorbiting) or spacecraft pointing deviations due to increased drag from atmospheric expansions;
- Spacecraft differential surface charging;[28]
- Charging of sensitive electronic components within the satellite due to penetrating high-energy radiation from the inner radiation belt;[29]
- Communication degradation from solar radio bursts that reduce the signal-to-noise ratio in received signal; and
- Loss of ephemeris or precision pointing capability from degradation of GNSS signals,[30] commonly referred to as signal scintillation.

Regulatory Environment in the STM/C Sector

Until recently, the STM/C sector has been largely unregulated in terms of traffic management and deorbit requirements. The most relevant guidelines were NASA's 25-year deorbit guideline and United Nations Office for Outer Space Affairs (United Nations Office for Outer Space Affairs, 2021) Guideline A.4, which provided general recommendations about disposition of LEO

[28] Spacecraft differential surface charging refers to the phenomenon where different parts of a spacecraft's surface become charged to varying degrees when exposed to space environments. This charging occurs due to interactions with charged particles, such as electrons and ions, which are highly enhanced during space weather events. Differential surface charging poses serious risks to spacecraft systems because if these voltage imbalances become too large, they can lead to electrical discharges, which might damage sensitive electronics or affect spacecraft operations.

[29] Similar to differential surface charging, during a space weather event, high-energy particles can penetrate the spacecraft surface and deposit accumulation of electrical charge on sensitive components. Charging of sensitive electronics can lead to potential risks such as single event latch-up, single event upset, etc.—all of which can disrupt the normal operation of satellite systems, potentially leading to mission failures or degraded performance.

[30] Spacecraft ephemeris data includes information such as the positions, velocities, and trajectories at specific points in time. Loss of ephemeris at any time can have significant implications for satellite navigation and execute maneuvers effectively.

satellites at end of mission. In September 2022, the FCC promulgated new requirements for satellite operators in LEO to dispose of their satellites within 5 years of mission completion.

Recent events underscore the critical need for operational improvements, which will require coordination across this sector (See Sidebar 5.2 and discussion in Chapter 1 related to STM/C).

Sidebar 5.2 Starlink Constellation Loss

On February 3, 2022, SpaceX's Starlink constellation lost 38 of its 49 satellites shortly after launch. This loss was partially attributed to unexpectedly high atmospheric drag induced by several geomagnetic storms related to a solar eruption on January 29, 2022. Subsequent analysis by the research community revealed that the incident was driven by a significant increase in neutral density at an altitude of 200-400 km. This heightened density likely contributed to the satellite failures. In response to these findings, experts have emphasized the importance of improving space weather nowcasting and forecasting capabilities for conditions in LEO. This information is crucial for launch controllers, space traffic managers, and satellite operators to mitigate risks and ensure the success of future missions.

Sources:
Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022 - Fang - 2022 - Space Weather - Wiley Online Library
The Thermosphere Is a Drag: The 2022 Starlink Incident and the Threat of Geomagnetic Storms to Low Earth Orbit Space Operations - Berger - 2023 - Space Weather - Wiley Online Library
Starlink Satellite Losses During the February 2022 Geomagnetic Storm Event: Science, Technical and Economic Consequences, Policy, and Mitigation: Space Weather (wiley.com)

Survey Process

Sixteen participants from four sub-sectors—satellite owners/operators; satellite tracking and maneuvering; data acquisition/data providers; and service and product development—engaged in the survey. All participants were U.S.-based non-government entities. From these participants, two focus groups were created with eight participants in each group.

The first focus group's participants were a subset of individuals attending SWPC's 2023 Satellite Environment Testbed Exercise. This survey session was arranged as a hybrid event with in-person and virtual participants. The second focus group's participants were a combination of testbed exercise participants who had conflicts during the first session and representatives from similar organizations who did not or could not attend the testbed exercise. The second focus group was held virtually.

Common Themes Among the Surveyed Groups

This section highlights common themes heard from surveyed participants providing additional background and context for the subsequent findings and recommendations. In some cases, quotes from surveyed participants are used to highlight or illustrate specific points.

Neutral Density Data

Information about ND was the primary concern voiced by surveyed participants. While sources of ND information include SWPC's latest version of the Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (WAM-IPE) Forecast System (WFS), there is significant use of other sources including some models created in the 1970s and 1980s, as well as newer international models. Some users run commercial or international models or their own ND models. Many of these models rely on heritage solar and geomagnetic indices such as F10.7 and Kp, although newer indices and physical measurements are being included in developing models. Other users derive ND from their spacecraft ephemeris data. Some commercial participants are consolidating or repurposing ND information to create new products The owner/operator and tracking communities desire model consistency and standardized inputs for mission planning, analyzing possible satellite conjunctions, and maneuver decisions.

A few surveyed participants were long-term users of SWPC's alerts, advisories, warnings, and scales; however, many participants were not familiar with SWPC's models and forecast products for LEO and the broader satellite environment. Some participants reported using data sources from several nations to build a more holistic, situationally aware view of the LEO environment. Based on experience or lessons from the 2023 Satellite Environment Testbed Exercise, participants recognized that the LEO environment is subject to strong and sometimes abrupt external forcing and that forecasting is subject to data-sparse conditions. Specific to the ND environment, surveyed participants want alerts about sudden changes in current conditions or in the 24-hour forecasts. Furthermore, participants noted the current NOAA scales are not well-suited to current operational needs.

Participants highlighted the importance of ND observations and predictive models of the space environment and space weather events. Observations and models are used for operational orbit determination, assessment of platform pointing stability, conjunction assessments, deorbit considerations, and general mission planning. Relevant environmental information includes indices and proxies, observations, real-time ND specifications, and predictions with various lead times depending on the needs of the user. Users recommended that all ND information be fully documented, available in machine-readable format, and have associated uncertainty descriptors.

Neutral Density Models

Relating specifically to ND models, some operators were using externally established empirical or climatological models driven by proxies and indices as mentioned above. Such models are high-heritage, inexpensive, and computationally light weight. The latter characteristic supports on-orbit processing and autonomous operations. A high-accuracy, data-informed empirical model was developed by DOD in recent decades. It ingests observations mostly acquired by DOD. On the computationally intensive end of the spectrum are full-physics models with data assimilation capabilities.

New data-informed and physics-based ND models are at various stages of development and validation. For all models, data sparsity and data latency remain as challenges for model initialization**,** validation, real-time assimilation, and operational use. Some participants were supportive of data sharing, but expressed caution about how to characterize their data uncertainties and terms of use of the data. With the onset of solar cycle 25, some owner/operators reported more collaborations with research institutions and (selective) data sharing.

The forecast horizon for constellation operators with semi-autonomous operations is generally shorter than for those making decisions about commanded maneuvers. Users are considering ND reduced-order models (ROMs) as useful quick turn-around tools for forecasts. In essence, ROMs are machine-learned versions of more complex models. As a light weight model-of-a-model, they can emulate a more computationally intensive model and adapt output based on new observations, which is desirable for operational applications.

Many surveyed participants discussed the need for accessible archives of past ND data, indices, and model outputs. With a standardized ND database, stakeholders could use historical data to inform models, leading to a future convergence towards commonality in model output desired by the community. There was some desire for a standardized model with known parameters and baseline assumptions. Additionally, autonomous operations require simple inputs. Participants suggested this need could be met with the aforementioned ROMs, along with an ambitious goal of having an ensemble of validated models with associated uncertainties.

Other Relevant Data and Information

Surveyed participants also discussed the value of other types of information that can affect satellite orbit control and overall STM/C. Specifically, information about: 1) the LEO charging and radiation environments for hardware anomaly resolution; 2) solar radio noise and bursts for communication anomaly resolution; and 3) the atomic oxygen environment for on-orbit materials degradation assessment. The latter concern has previously been addressed by operating environmental standards set by national space agencies. However, operations in new orbital regimes, such as very low-Earth orbit (VLEO), and variable neutral composition in Solar Cycle 25 have raised new concerns for mission planners.

Beyond the often-mentioned issues of drag, attitude control, and collision avoidance, surveyed participants voiced concerns about space weather impacts on communication links and GNSS signals. One surveyed participant (an operator) reported ground-to-satellite communications degradation attributed to a solar radio burst, apparently associated with an M-class flare in November 2023 (with anomaly resolution still ongoing as of the survey date). The loss of communication during critical commanding related to collision-avoidance maneuvers could adversely affect STM/C. Another surveyed participant reported that development of new commercial products and services is based on GNSS observations of orbital states. These products would not exist without GNSS.

> We are starting to do our own data simulation things. If we remove GNSS data, we cannot do any simulation at this point. It's [GNSS access and reliability] crucial for that.

Many surveyed participants reported that the SWPC 2023 Satellite Environment Testbed exercise was a significant awareness raising event for those operating in the LEO environment. Most respondents reported their first engagement in a table-top exercise related to the LEO environment occurred during the exercise. None of the participants had previously developed or engaged in table-top exercises to explore the impacts of severe storms on direct operations nor possible cascading effects related to communication or data loss (e.g., degradation of GNSS signals). Surveyed participants generally praised SWPC's efforts in advancing space weather forecasting and in the 2023 Satellite Environment Testbed Exercise.

Findings and Recommendations

The following findings and recommendations are a direct distillation of the engagements and responses from the surveyed participants' input. The findings and recommendations below are organized into four categories: Product Acquisition and Availability, Development and Validation, Dissemination and Other STM/C Concerns, and SWAG's Strategic Planning and Model Development Concerns. They are not organized in priority order.

Product Acquisition and Availability

Finding 5.1. A framework is needed to acquire, validate, and share inferred ND values. Surveyed participants noted the need for low-latency (i.e., hours time frame) ND observations in VLEO to LEO at approximately 100–400 km. Because ND values are generally inferred from indirect means including motions of objects in LEO, they are rarely available in real time to general users. If a framework for validating and sharing inferred ND values is developed, some large constellation operators are willing to share data related to ND inference.

Recommendation 5.1.1. NOAA, working with the commercial sector, should invest in data collection and promote information sharing that informs ND estimates. NOAA, in collaboration with the national space weather enterprise, should develop parameters and means (e.g., legal agreements and embargo periods) for information sharing. This should include the comparison, validation, and archiving of data.

Recommendation 5.1.2. NOAA Office of Space Weather Observations (SWO) and SWPC, working with the broader national space weather enterprise, should develop new observations, paths for acquiring ND information from satellite constellations, and new forecasting capabilities for the lower thermosphere (VLEO to LEO).

Finding 5.2. Environmental input parameters need to be maintained and archived for ND models. Improved orbit prediction requires next-generation, data-driven models that utilize accessible and well-maintained, long-term databases of proxies (e.g., F10.7) and indices (e.g., Kp). For some users, the transition to the next generation of data-driven forecasts will take time and long-term databases are important for bridging the gap between present and future models. Ultimately, surveyed participants want to move from indices and proxies to more direct observations and measurements.

Recommendation 5.2.1. NOAA National Centers for Environmental Information (NCEI) and SWPC should maintain and expand archives of indices and proxies. The archives should be in accessible, interoperable, machine-readable databases with modern change- and outage-notification protocols. Data hosting organizations should ensure data are usable and preserve metadata data information, error and uncertainty notations are standardized, and users are notified of disruptions or changes to data access from server maintenance and changes in archive address or location, etc.

Recommendation 5.2.2. NASA, NOAA, and DOD should improve cross-agency investment for transitioning measurements to operational products. As part of the R2O process, NASA and NOAA should continue to invest in transitioning direct science measurements (e.g., solar extreme ultraviolet radiation and nitric oxide emission that cool the thermosphere) to operational data to underpin prediction and modeling. Validation should be conducted in appropriate testbeds or proving grounds and published in peer-reviewed journals. NOAA and DOD should ensure the operational pipelines are capable of using these measurements.

Finding 5.3. STM/C users need usable data and actionable ND model outputs and products. Current ND data are inadequate for use by operators and developers. Specifically, the lack of standard machine-readable formats, full documentation, and calculated uncertainties are major impediments to users for accurate orbital prediction. Uncertainties are not currently available for data or model products.

Recommendation 5.3.1. NCEI and SWPC should work with users via focus groups, testbed exercises, and workshops to determine format and documentation requirements for ND model outputs and products.

Recommendation 5.3.2. SWPC, in collaboration with providers and user communities, should include and document uncertainties associated with all ND-related products. SWPC, working with data-providers, the research community, and commercial partners, should document uncertainties in proxies, indices, observations, and ND model output. These uncertainty estimates should accompany all archived and published ND model outputs and products.

Finding 5.4. Users need accessible long-term ND databases for model validation. Service providers and product developers expressed needs for low-latency data, archival databases, and consistent data access in support of their efforts to expand services and develop models for ND forecasts. Satellite constellation operators, service providers, and product developers need well-documented, interoperable, continuously accessible, and machine-readable databases of archived ND forecasts to support validation efforts.

Recommendation 5.4.1. NCEI and SWPC should determine the cause of latency in data and model output availability and develop and implement a plan to address it. While the agencies may be aware of many of the factors affecting data latency and model output availability, regular status checks on data availability and assessment of current latency should be done.

Recommendation 5.4.2 NOAA, NCEI, and SWPC should develop and implement a sustainable plan for archiving ND model output in a database that is accessible, interoperable, machine-readable with modern change- and outage-notification protocols.

Development and Validation

Finding 5.5. Users need near-term ND forecast improvements and model development. Surveyed participants did not reach consensus on which features and capabilities of ND forecasts should be improved first. One participant reported interest in 10-km resolution for ND model output. Another mentioned a desire for neutral wind in addition to ND values. There was general agreement that regional forecasts could be quickly improved for high latitudes, where energy deposition is particularly intense during intense storms. There was interest in improved ND forecasts for VLEO, and ND variation for the regime above 650 km during severe to extreme space weather events.

Recommendation 5.5.1. SWPC should continue and extend its engagement with the STM/C user community to determine needs for forecast cadence, resolution, and latitude requirements for ND forecasting, thresholds for alerts and warnings, and need for neutral winds values.

Recommendation 5.5.2. As part of the O2R process, NOAA SWO, SWPC, NASA, NSF, and DOD should work with satellite owners/operators across all altitude regimes to facilitate data acquisition and sharing to improve ND nowcasting and forecasting. This includes providing timely feedback to data providers about utility and suitability of potential data sources. This recommendation should be implemented under auspices of the December 2023, NASA, NOAA, NSF and DOD memorandum of agreement (QUAD agency agreement) outlining how the agencies will better coordinate broader R2O2R activities.

Recommendation 5.5.3. SWPC and academic and commercial model developers should strive for two-way coupling in their models. Doing so would allow data assimilation of both ionospheric plasma and thermospheric ND observations to improve forecasting. As an example, the WAM-IPE model is currently one-way coupled with information from the thermospheric state feeding into the ionospheric state. Only ionospheric data is currently assimilated into the model. Only after WAM-IPE is two-way coupled will it achieve its full potential as a forecast model that assimilates thermospheric data in support of STM/C needs.

Recommendation 5.5.4. NASA and NSF, in collaboration with industry, should invest in science and machine learning of ROMs and data assimilation to support on-orbit LEO constellation operations. ROMs—machine-learned, lighter-weight versions of more complex models—will only be as good as the models they try to emulate, thus investment in data-informed and physics-based models and their validation is prerequisite to successful implementation of ROMs.

Finding 5.6. STM/C users need improved long-range ND forecasts and model development for conjunction assessments. There was a general desire for improving and extending forecasts to 3 days. Extending forecasts from daily to multi-day is crucial for conjunction assessments and collision avoidance. Large-constellation satellite owners and operators were interested in forecasts with timelines of up to 3 days, while maneuver-and-tracking users have additional interest in forecasts extending to 7 days for collision avoidance applications. Many participants were aware that the lack of solar and geomagnetic measurements and forecasting capabilities posed significant challenges to extending the current forecast horizon beyond 2 days.

> **Recommendation 5.6.1. NASA, NOAA, NSF, and DOD should support research and development for extending ND forecasts out to 7 days to meet the needs of the STM/C community, in particular service providers such as OSC TraCCS and commercial product developers.**

> **Recommendation 5.6.2. NASA, NOAA, NSF, and DOD should develop and deploy priority operational instrumentation that will enable multi-day forecasts.** International collaborations should be encouraged. This builds off Finding 24 and associated recommendations (R24.1-3) and recommendations 25.1 and 25.3 from SWAG (2023).

> **Recommendation 5.6.3. NOAA and the research community should develop ensemble modeling and data assimilation capabilities that parallel those of terrestrial weather forecasting.** Surveyed participants generally agreed that ensemble ND modeling is an important long-term goal that will support uncertainty quantification and probabilistic forecasting. A useful first step to jumpstart the process could be a mini-workshop within the annual Space Weather Workshop or a meeting convened by SWAG, SWORM, or the Space Weather Roundtable to assess the state-of-the-art.

Finding 5.7. Users need ongoing updates of solar cycle evolution, including 5-year predictions, through model development for forecast improvements. In the era of large-constellation satellite development, satellite operators need 5-year predictions of solar cycle evolution to plan satellite builds, launches, and mission profiles to meet the new FCC rule for deorbit of spacecraft 5 years after end of mission.

> **Recommendation 5.7.1. NASA, NSF, and NOAA should fund research in solar cycle forecasting that supports long-term planning of LEO missions.** Such funding should be augmented with international collaborations and co-funding as identified in Recommendations 25.1 and 25.2 in SWAG (2023).

Finding 5.8. Users need regularly scheduled ND model validation as a key component of R2O development and operational maintenance. In addition to proxy and measurement validation, ND model data assimilation and validation are significant concerns for the STM/C sector. Users need transparent, well-documented, systematic methods for validation and multi-model comparisons with standard model interfaces. Validating data-driven empirical models and full-physics data assimilative models is a crucial first step in producing light-weight models and ROMs needed by autonomously operating on-orbit systems and other users.

Recommendation 5.8.1. The NOAA Office of Atmospheric Research (OAR), in collaboration with SWPC, should develop and publish systematic validations of WAM-IPE as part of a continuing R2O process and operational maintenance. NOAA OAR, in its space-weather applied research role identified in Recommendation 2.1 and 2.3 in SWAG (2023), should expand on proving ground activities established by SWPC and NASA CCMC via their Architecture for Collaborative Evaluation activities.

Recommendation 5.8.2. Relevant SWORM agencies should provide adequate funding for validation of ND models intended for R2O development and operations. A validation framework should accompany the Readiness-Level-4[31] Transition Plan[32]. For ND models, the validation framework could be informed by standards developed by the ISO Space Environment Working Group 4, procedures aligned with Committee on Space Research (COSPAR) International Space Weather Action Team (ISWAT), and peer review done by the international community.

Recommendation 5.8.3. As the SWPC Testbed becomes fully operational, NOAA should ensure that sufficient resources are available to use the Testbed for validation of ND data sets and models. When fully resourced, the Testbed should include R2O activities as well as user engagement events.

Dissemination and Other STM/C Concerns

Finding 5.9. STM/C users need clarity on ND model update cadence and notifications of abrupt changes in ND forecasts via alerts, advisories, and other products. Similar to the electric power sector's interest in abrupt or significant changes in the G-scale, users asked for more clarity regarding frequency and content of WAM-IPE updates based on the SWPC Nowcast Concept of Operations (ConOps). From SWPC's web page descriptions, some survey participants could not determine whether model output is being continuously updated and posted to the SWPC website in near-real time versus updated only after scheduled model runs. Further, some users stated

[31] NOAA SWPC Readiness Levels - Expanded Definitions.pdf

[32] Transition Plans Support – Office of Research Transition and Application (noaa.gov)

that notices of abrupt changes in forecasts (1–24 hr horizon) should be issued in the form ND-change alerts and advisories or other products.

> **Recommendation 5.9.1. SWPC should expand dissemination of ND alerts, forecasts, and products.** In coordination with the user community, the SWPC Nowcast ConOps resource should include alerts of abrupt forecast changes. They should also expand the description of the relationship between WAM-IPE model runs and published nowcasts and forecasts. This should be done as part of continued engagement between SWPC and the user community.

> **Recommendation 5.9.2. SWPC should conduct regular testbed exercises and focus groups meetings to determine and further refine specific user requirements that could not be discerned in a 2-hour user needs survey session.** Surveyed participants generally praised SWPC's 2023 Satellite Environment Testbed Exercise.

Finding 5.10. Surveyed participants need clarity about how space weather information is being used in the OSC's TraCCS. Concerns arose about whether and how uncertainties in atmospheric density would be included in the TraCCS conjunction risk assessment parameters. Some surveyed participants noted that the comments section of the existing DOD conjunction data messages contain information about the sensitivity of the density forecast, as well as sensitivity of the position and velocity vectors of the two spacecraft using the density model run by DOD. Other surveyed participants stated that uncertainty information related to ND observations and forecast products is important for risk reduction. For both owners and operators, and tracking and maneuvering services, such information flows into covariance estimates used in collision assessment and avoidance.

> **Recommendation 5.10.1. OSC should clarify to the broad STM/C community how actual and forecasted changes in ND will feed into conjunction risk assessment algorithms.**

> **Recommendation 5.10.2. When TraCCS becomes operational, OSC in collaboration with SWO and SWPC should evaluate and quantify the influence of ND changes on conjunction risk assessments.**

Finding 5.11. Beyond ND information, satellite constellation operators and product developers need energetic charged particle data and related information about the VLEO and LEO charging, radiation, and radio communication environments for operations and anomaly resolution. Energetic charged particle measurements from large numbers of orbiting spacecraft would provide more accurate estimates of the local environment, enabling more detailed characterization of spacecraft susceptibilities to space weather. Additionally, these data support anomaly analysis. Surveyed participants emphasized the need for on-orbit energetic charged particle measurements. At least one satellite owner and operator was willing to share the on-orbit data and information they collect with SWPC to improve models. Other owners and operators were interested in hosting payloads to collect and share data with SWPC.

Recommendation 5.11.1. SWORM should coordinate with STM/C stakeholders[33] and invest in information sharing that supports real-time charging and radiation-environment characterization and prediction across the broad LEO regime. The new Space Information Sharing and Analysis Center (ISAC) could play an active and collaborative role in this effort, engaging often with SWPC and academia to ensure that members are informed about space weather effects that could lead to anomalous conditions or be misinterpreted as intentional signal interference. This builds on Recommendation 19.1 to enhance the distribution of space weather products (SWAG, 2023).

Recommendation 5.11.2. SWPC, in collaboration with STM/C stakeholders, should conduct regular testbed training exercises, including simulations, focused on STM/C. These activities should use scenarios to build awareness across the community on the broad impacts and interdependencies associated with space weather events.

Recommendation 5.11.3. OAR should collaborate with the academic and commercial sectors to develop and produce compact charging sensors that would address both on-orbit environment characterization and research needs. Only a single respondent mentioned an awareness of available or flown operational/research compact charging sensors. This lack of awareness indicates a greater need to communicate available technology to the community.

Recommendation 5.11.4. SWPC, and relevant SWORM agencies, should collaborate with satellite owners and operators in VLEO and LEO to determine if SWPC products developed to meet ICAO requirements[34] can be extended to address needs in VLEO and LEO.

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[33] STM/C stakeholders comprise STM/C industry, academia, government, and commercial space weather organizations.

[34] 2019 Manual on Space Weather Information in Support of International Air Navigation (ICAO DOC 1Doc 10100)

Finding 5.12. STM/C users need reliable information on GNSS signal disruption associated with space weather. STM/C increasingly relies on GNSS signals and data for autonomous control and location of spacecraft for overall space traffic management and for orbit stability during early phase operations. Surveyed participants noted that newer constellations have GNSS support and the capability for platform cross-talk to facilitate autonomous operations, which could represent an evolution in space weather needs. GNSS signal disruption or interference could come from natural (e.g., space weather) or technological (both unintentional and intentional) sources, and distinguishing these sources (with attribution) is important.

> **Recommendation 5.12.1. SWPC should determine if products developed to meet ICAO requirements[35] can be extended to address needs related to GNSS signal disruption.**
>
> **Recommendation 5.12.2. Relevant SWORM agencies should coordinate with STM/C users to promote information sharing that supports real-time radio communications characterization and prediction across the VLEO to LEO regime.** The Space ISAC could play an active and collaborative role in this effort, which builds on Recommendation 19.1 to enhance the distribution of space weather products (SWAG, 2023) and Recommendation 5.11.1 above.

SWAG Recommendations

Below, SWAG identifies findings and associated recommendations that were not explicitly expressed by surveyed participants, yet are natural extensions of ideas expressed in the survey sessions.

Further Strategic Planning and Model Development Concerns

Finding SWAG 5.1. There is a need for an ND forecast strategy. The STM/C surveyed participants noted the importance of improved ND data for orbit determination. Despite the importance of this rapidly growing sector and the consequences of poor ND forecasts to satellite operations, the 2024 SWORM Implementation Plan of the National Space Weather Strategy and Action Plan does not address the critical need for thermospheric density specification identified in Finding 24 and associated recommendations of the SWAG (2023) report.

> **Recommendation SWAG 5.1.1. SWORM should develop a strategy for observing, modeling, and forecasting thermospheric ND for space traffic management and coordination.**

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[35] Ibid.

Chapter 6
Emergency Management Sector

Summary

Space weather events pose unique challenges for emergency managers, including their unpredictability, potential for widespread impacts, and complexity in communicating risk to the public. The EM sector organized two virtual focus groups: one for local EM officials and another for State officials. Nine emergency managers participated in the focus groups. By interviewing emergency managers, SWAG identified specific challenges and barriers emergency managers face in integrating space weather considerations into emergency preparedness and response activities. This information can inform the development of strategies to overcome these challenges and enhance resilience.

The emergency management sector survey resulted in 4 findings and 8 recommendations that cover topics from education to needed forecasts and tools. Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable resilience across the sector. This primarily focused on regional specificity and impact communication at a level approachable by non-experts.

Sector Background

EM involves planning, coordinating, and implementing measures to mitigate, prepare for, respond to, and recover from disasters and emergencies of all kinds, including those caused by space weather events. EM operates at various levels of government, each with its own responsibilities and authorities. The levels of EM in the United States typically include:

- Federal: At the Federal level, emergency management is primarily the responsibility of several government agencies, including the Federal Emergency Management Agency (FEMA), which is part of DHS. FEMA coordinates the Federal Government's response to disasters and emergencies, provides assistance to State and local governments, and oversees disaster preparedness, mitigation, response, and recovery efforts nationwide.
- State: Each State in the United States has its own EM agency or department responsible for coordinating emergency preparedness and response activities within the State. State EM agencies work closely with FEMA and other Federal agencies—as well as with local governments, nonprofit organizations, and private sector partners—

to develop statewide emergency plans, conduct training and exercises, and manage disaster response and recovery operations.

- Local: EM at the local level is typically the responsibility of county or municipal governments. Local EM agencies or offices are responsible for coordinating emergency preparedness and response efforts within their jurisdictions, including developing local emergency plans, conducting training and exercises, and coordinating with other local agencies, community organizations, and businesses. Local emergency managers often serve as the primary point of contact for residents during emergencies and disasters.
- Tribal Nations: Tribal nations in the United States have their own emergency management programs and agencies, which are responsible for coordinating emergency preparedness and response efforts within Tribal lands. Tribal EM agencies work closely with Federal, State, and local partners to address the unique needs and challenges of Tribal communities during emergencies and disasters.
- Private Sector and Nonprofit Organizations: In addition to government agencies, private sector companies and nonprofit organizations play important roles in EM in the United States. Private sector partners, such as utilities, transportation companies, and healthcare providers, contribute resources and expertise to emergency preparedness and response efforts, while nonprofit organizations, such as the American Red Cross and volunteer groups like CERT (Community Emergency Response Teams), provide assistance and support to communities affected by disasters.

EM and space weather intersect in the realm of disaster preparedness and response. Emergency managers' awareness of space weather hazards and their preparedness to address them varies widely. Interviews provide an opportunity to gauge the level of knowledge and understanding of space weather risks, as well as existing plans and procedures to mitigate these risks. This information is essential for identifying gaps in awareness and preparedness and developing targeted interventions to address them.

Prior User Engagement with the Emergency Management Sector

The emergency management sector was previously surveyed in the 2019 Abt Survey Report. This report found users wanting (1) localized, plain language forecasts and alerts that provide earlier warnings, (2) SWPC to facilitate education and communications to help them better understand space weather and its impacts, and (3) SWPC to improve its website in terms of accessibility and usability.

Space Weather Impacts on the Emergency Management Sector

The EM sector is primarily concerned with space weather effects on satellites, communications, and power grids. Losses or disruption to these infrastructure and the services they provide can challenge communities and emergency managers' roles in addressing such challenges.

Regulatory Environment in the Emergency Management Sector

There are no explicit regulatory requirements for the EM sector to use space weather observations, information, or forecasts. However, the Robert T. Stafford Disaster Relief and Emergency Assistance Act (the Stafford Act; 42 USC 5165) provides authority to the President to declare a national emergency in response to a disaster, such as a consequential space weather event. This declaration allows the President to access funds and disaster relief assistance set aside by Congress. In response to this Act, 44 CFR Part 201 was created to provide the regulatory framework through which the Administrator of FEMA can assist State, local, and Tribal governments in the preparedness for, response to, and recovery from disasters.

At the Federal level, Executive Order (EO) 13744 and EO 13865 required FEMA to develop a Federal operating concept to respond to notification of, and protect against, impending space weather events and for all Federal agencies that support National Essential Functions to ensure that their all-hazards preparedness planning sufficiently addresses GMDs through mitigation, response, and recovery, as directed by national preparedness policy.

Pursuant to these policies, FEMA published the Federal Operating Concept for Impending Space Weather Events. This incident annex outlines the necessary actions Federal departments and agencies should take to prepare for, and respond to, a notification of an impending space weather event.

Survey Process

The EM sector organized two focus groups—one for local EM officials and another for State officials. These sessions were conducted virtually with a total of nine EM participants. Participants were solicited from two emergency management organizations: the International Association of Emergency Managers (IAEM) that represents local emergency managers, and the National Association of Emergency Managers (NEMA) that represents State, U.S. territories, and the District of Columbia Emergency Management Agencies. Participants received the survey questions and a Space Weather Fact Sheet in advance. To provide context and set the stage for the EM community, each session began with a 30-minute briefing on space weather by Mr. Bill

Murtagh from NOAA SWPC followed by a question and answer session. The focus groups then proceeded with a roundtable discussion of the survey questions.

Common Themes Among the Surveyed Groups

This section highlights common themes heard from surveyed participants providing additional background and context for the subsequent findings and recommendations.

Observations, Information, and Forecasts for EM

EM sector participants are familiar with products and services from SWPC, although their usage varies from "checking the website everyday" to only looking when alerted to a potential storm through the FEMA daily brief or open source reporting (e.g., newspapers and TV). Some participants rely solely on NOAA for space weather information, while others subscribe to alerts from different sources, including commercial entities and international governments.

Surveyed participants find the information on SWPC's website helpful, but noted that it can be too technical for the EM community to readily understand. Participants had a general understanding of the NOAA Space Weather Scales, but raised concerns regarding the correlation between the scales' magnitude and impact, hindering actionable decision-making and communication to community partners. Some participants noted that having geographic-specific information or products would be helpful. Participants highlighted that there are no regulatory or policy requirements for EM sector participants (i.e., State and local) to use space weather observations, information, or forecasts.

Surveyed participants expressed a need for forecast products with greater lead time, specificity to their region, and indication of impact. Participants desire communication methods that provide graphical representation and simplified language suitable for non-experts, potentially at a sixth-grade level. Participants stated that available information and tools—such as technology, products, and services—need improvements. Emergency managers need to be able to digest the information quickly, and they need greater awareness as to what tools, products, or services are available. Emergency managers also need to know how the information can be used to support decisions. Surveyed participants suggested collaborations between SWPC and FEMA regional offices to provide information in briefings for States or local EM programs.

EM sector participants had a general understanding of their systems' vulnerabilities to space weather events, but knowledge of mitigation strategies varied. Participants identified energy, communications, water, pipelines, financial systems, and GPS as critical infrastructure areas of concern. Participants noted limited testing opportunities due to infrequent significant space weather events and highlighted the need for more education and training for emergency managers. Such training should address the impact of space weather as well as discuss the underlying science to better enable emergency managers to interpret information from the space weather community.

Risk Reduction and Resilience Activities

Surveyed participants noted that space weather is included in all-hazards and mitigation plans, although the prioritization and understanding of the risk varies. Participants expressed a need for comprehensive threat assessments, including identifying susceptible infrastructure and systems and describing potential consequences. Participants noted their inability to comprehensively understand the threat or risk from space weather, and consequently how to prioritize space weather in relation to other risks. Surveyed participants emphasized the importance of national-level leadership for measures to build resilience against space weather. Participants noted the risk mitigation measures they have taken are generally limited to large-scale power and communication outages. Participants emphasized the value of learning from past space weather incidents, highlighting the importance of reviewing formal After-Action Reports (AARs). They cited examples such as the 2003 Halloween solar storms and the 1989 Hydro Quebec Blackout as valuable case studies. Participants also advocated for scenario-based planning and targeted space weather exercises to enhance preparedness.

Surveyed participants agreed on the importance of warnings, advisories, and alerts from SWPC for making informed decisions. They stressed the limited time to disseminate quality information to the public effectively and emphasized the need for region-specific, impactful, and easily understandable information.

Finding and Recommendations:

The following findings and recommendations are a direct distillation of the engagements and responses from the surveyed participants. They are not ordered based on priority.

Finding 6.1. There is not consistent or sufficiently broad awareness of space weather and its effects across the emergency management community. The EM community (at all levels, e.g., Federal and State through local) needs more consistent education and awareness regarding what space weather is and its impacts.

> **Recommendation 6.1.1. FEMA's Preparing the Nation for Space Weather Events Independent Study Course (IS-0066) should be incorporated into EM required training and education.** The course covers the lessons necessary to strengthen understanding of

space weather events, the potential impacts from those events, and the roles of the Federal, local, and jurisdictional emergency managers in preparing for and mitigating such impacts.

Recommendation 6.1.2. Space weather can be a national security event with significant consequences. Therefore, Congress or OMB should consider requiring IS-0066 training to receive EM grants.

Recommendation 6.1.3. FEMA, in collaboration with SWPC, should develop tabletop exercise packages for local, State, and Tribal governments. Exercises should address impacts of space weather events.

Recommendation 6.1.4. FEMA, in collaboration with the National Security Council Staff, should incorporate space weather into the FEMA National Exercise Program schedule.

Finding 6.2. Emergency managers need more information on the impacts of space weather, including cascading impacts, across the broad set of national critical functions or infrastructure services.

Recommendation 6.2.1. NOAA should develop forecasts that include the impacts of space weather events on critical infrastructure similar to what they are doing for terrestrial weather events.

Recommendation 6.2.2. NOAA, in collaboration with the commercial sector, should produce visualizations similar to the USGS/NOAA near-real time geoelectric field mapping product.

Finding 6.3. Emergency managers need space weather forecasts linked to regional space weather effects, including infrastructure, system, and service dependencies.

Recommendation 6.3.1. NOAA and the commercial sector should cooperate to develop regionalized products for emergency management.

Recommendation 6.3.2. NOAA, in collaboration with the commercial sector, should develop more regionalized forecasts with impact- and geographic-specific space weather information. NOAA may need to involve social science experts to assist in determining what data, models, and research they need to implement this recommendation.

Finding 6.4. Emergency managers need to be able to better understand what they need to do during the response phase of a space weather event.

> **Recommendation 6.4.1. FEMA in collaboration with SWPC should work with local, State, and Tribal emergency managers to evolve emergency management tool kits to address the impacts of space weather within their community.** This should include coordination of EM functions with infrastructure service providers across their region, and planning and exercising for space weather response and recovery.

Chapter 7
Research Sector

Summary

The research sector is the community that investigates new scientific and engineering approaches to advance space weather observations and forecasting. The research sector has not previously been surveyed despite its importance. Since a significant portion of the SWAG members are researchers, it seemed like a logical time to survey the needs of this sector. The research sector held one in-person focus group at the 2023 Space Weather Workshop in Boulder, CO and three virtual focus groups for each of the early-, mid-, and leadership or late-career groups across the Federal, private, and university components of the research sector.

Research sector insights and perspectives can be grouped into two broad areas: a systems approach to space weather education and workforce diversification. There is widespread and extensive use of ground- and space-based observational capabilities across the research sector. Surveyed participants identified a number of strategic and tactical gaps in advancing the research enterprise, including the spectral and spatial coverage of observations. Surveyed participants emphasized the need for system-level observations, constellation observations of the Sun-Earth system, and the ingestion of observations into current and next-generation models. Surveyed participants expressed the need for archives of observations and prior forecasts, and to conduct follow-up studies on how well past predictions performed. Participants noted that the current limited coverage of the Sun is an issue. Participants noted that adopting a system science approach could close such observational gaps.

The research sector survey resulted in 6 findings and 12 recommendations that cover topics from planning and investment, including a systems-based approach, to observational capabilities, to education and workforce diversification. Surveyed participants noted the need to improve educational elements and expand diversity beyond traditional disciplines and communities to drive future success. Education and outreach is important for the future of space weather research not only to ensure we have the necessary skilled workforce, but also to educate the public on the importance of space weather since public interest and support are necessary to ensure sufficient funding for space weather research. Funding can play a role in diversity of the field as well.

Surveyed participants identified opportunities for improvements in the space weather enterprise to further meet their needs and enable advancement across the space weather research sector.

Sector Background

The research sector is the community that investigates new scientific and engineering approaches to advance space weather observations and forecasting. The research sector has unique observation and resource needs, utilizes the latest scientific and technological advances to develop new nowcasting and forecasting models and techniques, and develops new measurement techniques and hardware. Large portions of the broader U.S. space weather research community (composed of solar, heliospheric, thermospheric, magnetospheric, and Earth-system sub-domain scientists) do not work directly with the space weather operations and end-user communities. The research community is challenging to survey because of the many sub-disciplines involved and their disparate needs and requirements. For example, ground-based assets are often used for space weather research of the Sun, thermosphere and ionosphere, while space-based observations are often used for space weather research of the heliosphere and magnetosphere. The research community leads the development of next-generation forecast capabilities and continually incorporates technological advances as they occur, increasing the need to regularly survey this community.

Advances in technology and spacecraft launch capacity have increased the need for improved space weather forecasts and mitigation across multiple time scales and spatial domains.[36] This drives the need to increase space weather funding for fundamental and applied research, including activities to address modeling and observational gaps in space weather operations. These activities, including technology objectives, should be prioritized to address space weather forecast needs and ensure effective use of taxpayer dollars. To ensure a healthy and functional research sector, sufficient and enduring funding and an overall and regular prioritization process is required, and sustained international collaborations are essential.

Prior User Engagement with the Research Sector

The research sector has not previously been surveyed despite its importance. Since a significant portion of the SWAG members are researchers, it seemed like a logical time to survey the needs of this sector.

Survey Process

The research sector held one in-person focus group at the 2023 Space Weather Workshop in Boulder, CO and three virtual focus groups for each of the early-, mid-, and leadership or late-career groups reflecting roughly 10-year increments post-highest degree, across the Federal,

[36] See Chapter 5 on Space Traffic Management and Coordination.

private, and university components of the research sector. SWAG engaged leaders of research entities across the country to nominate individuals from their institutions and groups to participate in the survey. Each focus group was limited to 10–12 individuals, selected on a first-come-first-served basis. Survey participants were a diverse set of researchers from a wide range of U.S. organizations with a focus on space weather research, or applied research, including nowcasting and forecasting. There was an approximate balance between ionospheric, magnetospheric, heliospheric, and solar focused participants. In total there were 30 participants.

Common Themes Among the Surveyed Groups

This section highlights common themes identified from surveyed participants and provides additional background and context for the subsequent findings and recommendations. In some cases, quotes from surveyed participants are used to highlight or illustrate specific points.

A Systems Approach to Space Weather Research[37]

There is widespread and extensive use of ground- and space-based observational capabilities across the research sector. Participants stated they rely on ground-based ionospheric and solar magnetograph networks and their space-based equivalents with important supporting context provided by extreme-ultraviolet imagers and white-light coronagraphs. Similarly, community coordinated modeling efforts are used across the space weather research system.

Surveyed participants identified a number of strategic and tactical gaps in advancing the research enterprise, including the spectral and spatial coverage of observations. These gaps limit the conception, validation, and verification of physical numerical models. Surveyed participants emphasized the need for system-level observations, constellation observations of the Sun-Earth system, and the ingestion of observations into current and next-generation models. Participants were concerned about the operational fragility and limited sources of coronagraphic observation. Similarly, the lack of a system-wide data repository for observational data is an impediment to advancing research. Finally, in-situ data from LEO satellites could be used to improve models.

Data on the impact space weather has on infrastructure, such as satellites, communications, and power grid, is limited, often because such information is proprietary and may pose a security or business risk. One participant stated:

> We have a lot of geophysical data, but we are really starving for impact data.

[37] Systems science is an interdisciplinary approach that focuses on the study of complex systems and the interactions within and across them, providing a framework for studying the interconnectedness and complexity inherent to real-world systems.

Additionally, to test new forecast capabilities and mitigations, surveyed participants expressed the need for archives, not only of observations but also prior forecasts, and to conduct follow-up studies on how well past predictions performed.

Surveyed participants identified the need to adopt a systems approach to the research sector. One participant said:

> On the modeling side, I would say that space weather is driven on both sides by the Sun and Earth's lower atmosphere. You need better representation of the solar driver and lower atmosphere driver and how they connect. That's what we're talking about, developing a whole geospace model that can consider all of this, the self-consistent interactions with the system.

Such an interdisciplinary perspective enables researchers and practitioners to address a wide range of complex challenges by understanding the systemic nature of the phenomena they are studying. Systems science requires a holistic observational strategy, where the entire system rather (than a single component of the system) is optimized to improve nowcasting and forecasting. This analysis needs to be conducted across the entire space weather environment with observations of the Sun, Earth (including the thermosphere and magnetosphere), and the interplanetary medium with an eye towards the inevitable expansion to Mars and other planetary bodies as the latter become targets for human exploration.

The participants mentioned the current limited coverage of the Sun is an issue. One participant said,

> All space weather variability is driven by solar photosphere magnetic fields. Currently we only observe magnetic fields for ~1/3 of the solar global surface. The data gap of ~2/3 of the solar surface greatly hinders the community's ability to forecast solar wind, CME, and extreme ultraviolet on time scales greater than 1 to 3 days accurately.

Another said,

> Limited vantage point of the sun should be tackled so the technologies would be advanced with the added surface coverage of the Sun's magnetic field.

A third participant indicated that polar observations of the Sun are one of the most critical missing components for prediction of solar wind, noting the incorporation of direct polar field observations will significantly improve the prediction of space weather. Such an approach would not only require new observational strategies, e.g., using constellations of spacecraft around the

Sun, but also the expansion of ground station and communication capacity to have these observations available for ingestion and timely assimilation in next-generation models.

Survey participants indicated that adopting a system science approach would drive conversations around technology development and prioritization necessary to quickly close known observational gaps. The 2021 NASA *Space Weather Science and Observational Gap Analysis Report* provided a ranked list of high priority space weather gaps and is largely consistent with the feedback from this user needs survey, and would further benefit from the recommendations herein. The priorities identified in the report, combined with the forthcoming 2024 Heliophysics Decadal Survey and this user needs survey, can form the basis for and inform the development of a National Space Weather Roadmap to close the identified observational and modeling gaps in a structured and strategic way.

Education and Workforce Diversification

Surveyed participants noted the need to improve educational elements and expand diversity beyond traditional disciplines and communities to drive future success. These include:

- Increase and improve outreach to the U.S. taxpayer on the importance of space weather;
- Increase resources for and sources of, space weather education to reach and engage non-traditional communities with complementary skills such as those in the fields of meteorology, computer science, and other fields; this will require improving open data access; and
- Reduce barriers to enter the space weather workforce, e.g., not requiring doctoral degrees and placing stronger emphasis on the spectrum of relevant abilities in the space weather community such as assessing, and communicating associated risks.

One participant pointed out

> Heliophysics or space weather is a perfect area to teach in general physics, these are simple examples you can actually give.

Education and outreach is important for the future of space weather research not only to ensure we have the necessary skilled workforce, but also to educate the public on the importance of space weather since public interest and support are necessary to ensure sufficient funding for space weather research. Funding can play a role in diversity of the field as well. One participant said

> You mentioned the diversity of people. I think that falls into lack of stability. It makes it harder for people who don't have a support network to be able to go through their Ph.D. or a postdoc" and "If you don't have a healthy funding budget for a field, it breeds not just instability, but people wanting to peel off to have better, higher-paying jobs...

Findings and Recommendations

The following set of findings and recommendations are a direct distillation of the engagements and the response from the surveyed participants. They are not ordered based on priority.

Planning and Investment

Finding 7.1. The national space weather enterprise needs to take a strategic, systems-based approach to develop and implement a comprehensive, structured, and stratified roadmap for optimizing U.S. and international investments in space weather research with the goal of addressing observations and modeling gaps necessary to meet current and future needs of space weather stakeholder (e.g., infrastructure owners and operators and humans traveling to Mars). There are several distinct efforts ongoing across the community (e.g., the 2024 Heliophysics Decadal Survey, the One NOAA strategy); however, there is a lack of clearly delineated pathways, timelines, and milestones to achieve research objectives and enable their strategic transition to operations. This should start with the development of an observing system simulation experiment (OSSE).[38]

> **Recommendation 7.1.1. NASA, NOAA, NSF, USGS, and DOD should develop, in consultation with the research community (Federal, commercial, and academic), a framework based on OSSE analysis to prioritize space weather observations.** An OSSE should be used to determine existing gaps, including the degree and location of ground-based and space-based coverage that, if filled, could enhance the space weather forecasts. This framework should serve as the baseline tool for prioritizing future observations for the enterprise.

> **Recommendation 7.1.2. SWORM should create a coordinated implementation plan for observations, research, and development that uses the OSSE (R.7.1.1) as a basis to prioritize investments in space weather research and operations to meet existing and future user needs.** This plan should be informed by all relevant sources such as the 2024

[38] OSSEs are simulation experiments that involve adding or removing observations in a controlled environment to evaluate how well the observing system contributes to improving the accuracy of model forecasts. See the 2023 SWAG report.

Heliophysics Decadal Survey, individual agency plans, this user survey needs report, and other relevant reports. The resulting plan should prioritize activities, specify timelines, and identify agency's responsibilities and funding profiles for successful and timely implementation. Furthermore, the plan should serve as a baseline for all future agency planning and Heliophysics Decadal Surveys.

Finding 7.2. Focusing on the full R2O and O2R cycle is critical to improve space weather nowcasting, forecasting, and mitigation. Improved techniques for forecasting, nowcasting, and measurements are underdeveloped, are at risk of not reaching full maturity, and cannot be implemented without intentional and sustained investment in R2O and O2R infrastructure and process.

Recommendation 7.2.1. NOAA, NASA, NSF, USGS, and DOD should improve coordination across the entire R2O-O2R pipeline, include development standards and consistent procedures for testing, nowcasting, and forecasting capabilities in the implementation of the pipeline, and ensure operational needs are fed back into the research pipeline. They should ensure effective bidirectional communication and information flow between space weather end users and researchers, and ensure sufficient implementation of the later phases (e.g., transition to operations) when the proof-of-concept has been demonstrated. Additionally, this includes expanding current functional and operational testbed capabilities, educating the research community on the common forecast procedures and processes, participating in international standards development, and expanding end-user participation in testing.

Finding 7.3. Users need reliable data access to historical and ongoing critical observations, and improved spatial and temporal resolution of key parameters, to sustain and advance R&D programs and prediction capabilities. These key historical measurements include F10.7, geophysical indices, magnetograph flux maps, and sunspot number. These are essential for model development, verification, and validation. Furthermore, necessary metadata, data quality flags, and measurement error should be included. The associated infrastructure for these data sets need to scale as measurements advance to ensure reliable access.

Recommendation 7.3.1. NASA, NOAA, NSF, USGS, DOE, and DOD should ensure the continuity of key long-term, historical space, ground, and airborne network and sensor data through ensuring existing and new observations have the appropriate level of redundancy and capability to sustain these multi-decadal data sets in perpetuity. This should include data sets and records such as standard geomagnetic indices sunspot numbers, solar synoptic charts, the F10.7 solar radio flux, coronal imaging, photospheric magnetic flux maps, ionosondes, total electron content receivers, and neutron monitor data.

Recommendation 7.3.2. NASA, NOAA, DOD, DOE, NSF, and the commercial sector should collaborate to ensure access to ancillary data is included as part of observational data sets. Ancillary data includes housekeeping data, associated metadata, and alternate uses of data (e.g., the use of Iridium satellite avionics magnetometer data by the NSF AMPERE project for continuous observations of the Birkeland currents). These additional data can inform mitigation of and preparedness for the effects of space weather nowcasting and forecasting. NASA, NOAA, and DOD should encourage commercial LEO and geostationary Earth orbit spacecraft operators to make their data available, potentially via data buys, following best practices and standards.

Recommendation 7.3.3. NASA, NOAA, NSF, DOE, and DOD should ensure that archived data is comprehensive, cross-referenced, well documented, well calibrated, interoperable, and accessible by artificial intelligence and machine learning (AI/ML) techniques. The resulting archive, or archives, should have user-friendly interfaces with a set of common data and calibration standards (e.g., the development of data standards to improve cross-calibration of magnetograph data).

Recommendation 7.3.4. NOAA, NASA, NSF, USGS, and DOD should augment infrastructure and instrumentation capabilities to obtain real-time or near-real-time observations. Improving the latency of data access from ground-based measurements is of particular and broad interest, with the ultimate goal of automating the data pipeline.

Finding 7.4. Users need next-generation computational resources and data analysis techniques for advancing space weather research and applications. Research utilizing "big data" techniques, including machine learning and artificial intelligence, requires significant expansion of computational capacity across agencies and availability to individual researchers.

Recommendation 7.4.1. NASA, NOAA, NSF, and DOE should expand investment in, and use of, new computing architectures and resources. Capabilities and resources should include distributed/cloud computing, High-Performance Computing (HPC), machine learning, artificial intelligence, and algorithm development to enhance accuracy and reduce computational time. Specifically, the intersection of AI/ML with fundamental heliophysics and space physics research should be emphasized. They should increase opportunities for cross-disciplinary education and training in cutting-edge space weather research and capabilities.

Observational Capabilities

Finding 7.5. Users need improved spatial and temporal observations to enhance space weather forecasting. The growth of constellations and space accessibility provides an opportunity to improve space-based observations and associated ground infrastructure. Beyond the need to address the operational frailty of existing ground-based observing systems (e.g., GONG or the coronagraphs at the Mauna Loa Solar Observatory), there is a need to reimagine, constitute, and revitalize ground-based facilities that would improve infrastructure cost and data reliability. The need for an expanded and comprehensive ground- and space-based network of magnetographic, spectrographic, and coronagraphic instruments to advance space weather forecasting was specifically expressed by the users and should be considered in a systems based approach (Finding 7.1).

> **Recommendation 7.5.1. NOAA, NASA, NSF, USGS, and DOD, in collaboration with commercial providers, should utilize current and future ground-, air-, and space-based sensors, along with improved downlink and associated ground infrastructure, to increase the resolution and coverage of key space weather, solar, space physics, and geophysical data.** Trade studies, informed by OSSEs (see Recommendation 7.1.1), need to be conducted to evaluate the best approach and configurations for these measurements. They should include international cooperation to further enable ground-based and space-based measurements. The end-to-end system infrastructure required for increased observation capabilities (resolutions and coverage) should be assessed and expanded including increased downlink capacity. Next-generation sensor development should focus on miniaturization and reduction of size, weight, and power to be hosted or deployed on fleets of diverse platforms and rideshare opportunities.

> **Recommendation 7.5.2. NASA, NOAA, and DOD should work with commercial providers and the research community to develop robust platforms to reduce risk and cost, and prioritize increased reliability, availability of space-based systems.** A specific area of improvement is the flexibility of interfaces on available platforms or sensors to enable expanded hosting opportunities.

Education and Workforce Diversification

Finding 7.6. Education and outreach is important for the future of space weather research not only to ensure we have the necessary skilled workforce, but also to educate the public on the importance of space weather since public interest and support are necessary to ensure sufficient funding for space weather research. The emphasis on improved educational support addresses the need of cross-disciplinary expertise to advance the state of space weather research. However, the lack of support throughout the career lifecycle can result in the loss of newly trained space weather and cross-disciplinary workforce.

Recommendation 7.6.1. NSF, NASA, and other relevant SWORM agencies should prioritize grants and other funding mechanisms that promote and broaden participation in space weather-related science, technology, and engineering starting at the undergraduate level.

Recommendation 7.6.2. NSF, NASA, NOAA, and other SWORM agencies should develop programs to increase the range of perspectives, experience, and education across the space weather community through cross-training and the integration of non-traditional and applied sciences, engineering, and mathematics to advance the state of space weather research.

Recommendation 7.6.3. NSF, NASA, NOAA, and other SWORM agencies should develop programs, public outreach, and engagements to educate the public on the importance of space weather and broaden public awareness and interest in space weather science and risks.

Recommendation 7.6.4. SWORM agencies should coordinate across the national space weather enterprise to sustain human capital and ensure the long-term health of the community by supporting professionals throughout their careers.

SWAG Findings and Recommendations:

Finding SWAG 7.1. Non-Keplerian[39] observations can improve forecast lead time and accuracy. This was identified in the 2021 Space Weather Science and Observation Gap Analysis for NASA, and should be considered in the systems approach discussed in Finding 7.1. To accomplish this, several areas of development will be required including next-generation propulsion systems (e.g., solar sails and nuclear propulsion) and miniaturization of high-heritage imaging and in-situ instrumentation.

[39] A non-Keplerian orbit is an orbit that is affected by a propulsive or perturbing acceleration in addition to the gravitational attraction of the primary body.

Recommendation SWAG 7.1.1. NASA should develop and demonstrate pointing-stabilized alternative propulsion methods and satellite buses to explore, and station keep at, positions along the Sun-Earth line, off the Sun-Earth line, and out of the ecliptic plane. The propulsion methods should be appropriate to enable their use at non-Lagrangian points along the Sun-Earth line, off the Sun-Earth line, and out of the ecliptic plane. Development efforts should include next-generation power and propulsion systems, improved ground systems, communication relays, and autonomous controls.

Chapter 8
Global Navigation Satellite System Sector

Due to the breadth and complexity of the GNSS sector, the survey is ongoing. Thus, this chapter focuses on describing the GNSS sector end users and the methodology underlying the ongoing survey.

Sector Background

GNSS, such as the United States' GPS, provides invaluable positioning, navigation, and timing to a wide variety of applications. It is estimated since its inception in the 1980s, GPS alone has $1.4 trillion in economic benefits. (RTI International Report, 2019). Today, GPS use has become highly integrated into our everyday lives and it would be difficult to identify any application that does not rely on GPS timing or positioning to some extent. The loss or degradation of GPS, even temporarily, can have significant safety, security, and financial consequences to stakeholders including private citizens, commercial companies, and government organizations.

Prior User Engagement with the GNSS Sector

There have been a variety of surveys that have focused on different aspects of GNSS technology and our society's reliance on it. However, there has only been one survey that focused on the social and economic effects of Space Weather events on GNSS technology. The 2017 Abt Report performed a limited survey of four sectors, which included the GNSS sector. As part of the survey, four experts with knowledge of GPS and space weather were interviewed. They highlighted the complexities associated with determining the extent of effects. The survey also provided a summary list of impact mechanisms and associated physical effects. However, the 2019 Abt Survey Report did not engage end users of various applications.

Space Weather Impacts on the GNSS Sector

GNSS technology relies on the transmission of radio frequencies that are susceptible to degradation or blockage as they pass through the upper atmosphere known as the ionosphere. Space weather events that induce structural changes in the ionosphere may range from 10s of km to 1000s of km. While only the most severe space weather events are likely to result in a complete loss of lock for an extended time, moderate space weather events are likely to degrade GPS with varying effects on technology systems and end users.

Regulatory Environment in the GNSS Sector

GNSS systems are owned and operated at a governmental level (e.g., GPS—USA, Galileo—EU), and the regulations are more focused on sustainability, resilience, and modernization. In 2021, The U.S. Space-Based Positioning, Navigation, and Timing Policy was established to "[T]o maintain United States leadership in the service provision, and responsible use of global navigation satellite systems, including GPS and foreign systems."

Survey Process

GNSS has become highly integrated in our daily lives. This translates to a variety of applications and user communities. The first step in the survey was to break down the GNSS sector into technologies that either rely on precision timing or precise navigation. Within each of these areas, specific communities were identified. Table 8.1 lists the community groups within the precision timing and navigation areas. Each one of the communities listed is made up of several individual application groups. For example, Land Usage includes construction, land survey, precision agriculture, mining and drilling exploration, and water supply management. Of the nine communities listed in Table 8.1, five were selected to survey in year 1 (Bold entries in Table 8.1).

Table 8.1. Breakdown of community groups within either the precision timing or navigation areas. 1: Communities surveyed in year 1. 2: Communities to potentially survey in subsequent years.

Precise Timing Communities	Positioning/Navigation (PN) Communities
Finance[2]	Transportation[2]
Communication Networks[1]	Public Safety & Services[1]
Social Services[2]	Data Markets[2]
Manufacturing[1]	Land Usage[1]
Distribution[1]	

The number one challenge for surveying the GNSS sector is the identification of end users that understand both the specific technology systems, its susceptibility to GNSS degradation/outage, and the net effects on the community. The GNSS sector survey was a two-step process involving an online survey and virtual focus groups. The purpose of the online multiple-choice survey was to determine the general perception among the end users to the relative susceptibility of the application and technology systems to space weather events. It also provided information on the general level of understanding of space weather in the end user community as well as potentially identifying individuals for the focus groups. The survey questions were a combination of baseline and sector-specific questions.

The GNSS sector survey is still in process. The online survey was open for approximately 4 months. It was publicized through the National Space-Based Positioning, Navigation, and Timing Advisory Group meeting, the Institute of Navigation (ION) GPS membership email, and several community-specific association newsletters. However, the responses were limited in number. The next step is to move on to a focus group. This process will continue in 2024 and potentially beyond.

Through this process, it has become clear that a much higher level of effort is required to identify and contact GPS end users in the various communities, if a comprehensive understanding of their needs are to be achieved.

Results of the GNSS survey will be published in a future User Needs Survey Report.

Chapter 9
Overarching Themes and Next Steps

Several themes arose across all or several sectors. These themes are discussed in this chapter. Together, these themes present an opportunity for consolidated action and investment that can address multiple recommendations across several sectors. These overarching themes are not ranked by highest priority. They are presented in order in which they appear in the report. Similarly, the mapped recommendations within each theme appear in the order of appearance within the report. While the overarching recommendations, developed by SWAG and informed by the relevant sector recommendations, present an opportunity for common investment, they are not necessarily a higher priority than other sector-specific findings or recommendations. The inclusion of SWORM in an individual recommendation implies SWORM will assist the lead organization to facilitate and coordinate efforts among agencies and the national space weather enterprise.

Overarching Theme 1. Regionalization and Impacts

The need for increased regionalization of forecast products and an indication of the potential impacts was identified as a need in the electric power, aviation, HSF, STM/C, and EM sectors. Regionalization means different things across the different sectors. For example,

- Electric power grid owners and operators need more local measurements and a better understanding of ground conductivity on a regional basis;
- The STM/C sector needs near-term ND forecast improvements that include greater lead time and specificity to their atmospheric and orbital regions, with indications of impact and a specific focus on regional forecasts for high latitudes, where energy deposition is particularly intense during intense storms; and
- Emergency managers need forecast products with greater lead time, specificity to their region, and indication of impact.

The relevant recommendations in this report include:

- Electric Power: **R2.2.3**
- Aviation: **R3.2.1, R3.3.1, R3.3.2, and R3.4.1**
- HSF: **R4.1.1, R4.1.3, and R4.1.4**
- STM/C: **R5.5.1 and R5.5.2**
- EM: **R6.2.1, R6.2.2, R6.3.1, R6.3.2, and R6.4.1**

Recommendation Overarching 1.1. SWORM, through its member agencies, should take a consolidated, enterprise-wide, risk-informed, systems-based approach (using OSSEs) to identify and implement the most impactful and cost effective investments in observations, data, and modeling that enable more regionalization and specificity for forecast products and associated impacts.

Recommendation Overarching 1.2. NOAA, in collaboration with SWORM agencies, should use this report as a starting point to engage across sectors to further identify and prioritize forecasts and products that need longer lead times and specificity (accuracy, parameterization, resolution, etc.).

Overarching Theme 2. Education and Testbeds

The need for additional education was identified in the electric power, aviation, HSF, STM/C, EM, and research sectors. This includes a broadening of the educational base through developing programs for the application of non-traditional fields to space weather research and the need for space weather users and practitioners to increase awareness of space weather products and its effects through training, coursework, and testbeds and exercises.

For example,

- The aviation sector identified the need for pilot curriculums to include space weather, similar to training elements of terrestrial weather;
- The EM sector identified the need for more education and training for emergency managers, including addressing the impact of space weather and the underlying science to better enable emergency managers to interpret information from the space weather community; and
- The research sector identified the need for more education and outreach to ensure access to the necessary skilled workforce, and also to educate the public on the importance of space weather since public interest and support are necessary to ensure sufficient funding for space weather research.

The electric power sector did not explicitly identify the need for additional education; however, it is one of the most mature user sectors and has participated in broad efforts to build space weather awareness across the user community through regulation and other means. The STM/C sector couched its needs in terms of testbed training exercises and simulations.

The relevant recommendations in this report include:

- Electric Power: **R2.3.1**
- Aviation: **R3.1.4, R3.2.2**
- STM/C: **R5.2.2, R5.3.1, R5.9.2, R5.11.2**
- EM: **R6.1.1**
- Research: **R7.6.1-3**

Recommendation Overarching 2.1. SWORM, through its member agencies, should coordinate to expand programs and opportunities for broadening the range of disciplines that contribute to advancing space weather-related science, engineering, and technology starting with vocational and undergraduate education.

Recommendation Overarching 2.2. NOAA and SWORM agencies should collaborate to develop a regular cadence of testbeds and exercises for each sector (and cross-sector where appropriate) to advance sector understanding of and preparedness for space weather events and use of products. Additionally, these should serve as an opportunity to better understand sector needs and advance operations-to-research activities. Summaries and other products from testbeds and exercises should be made public, where possible.

Overarching Theme 3. Data Archives, Access (Latency), and Automation

Accessible data, including indices and proxies, that are rapidly populated (low latency) and well curated (with stated uncertainties and metadata) are key to developing actionable space weather products and informing both prompt operational decisions and long-term planning activities. The evolving need for rapid access to data for decision-making would be enabled through improved automation—reducing the need for humans in the loop.

Evolving computational approaches for modeling drive the need to ensure space weather data archives are machine readable and AI/ML friendly. Additionally, there is a need for interoperability between historical data sets and recent data sets to enable seamless model development, validation, and verification. Lastly, the private sector is a growing source of unique and additive space weather relevant data. The sharing of private sector data would be further enhanced through collaboration with the Federal agencies and lowering the barrier for participation by the private sector.

For example,

- The electric power sector identified the need for NOAA to collaborate with the power grid Reliability Coordinators to identify and implement ways to minimize alert latencies through leveraging capabilities that include automation tools to reduce human intervention in the communication path;
- The HSF sector identified the need for NOAA and NASA to collaborate with industry to support the development of real-time, automated flare location products and CME forecasts throughout the solar system;
- The STM/C sector identified the need for NOAA to work with the private sector to promote information sharing that informs ND models and the need to maintain environmental input parameters archives for ND models; and
- The research sector identified the need for a multitude of Federal agencies to ensure the continuity of key long-term, historical space, ground, and airborne network and sensor data through sustaining multi-decadal data sets in perpetuity.

The relevant recommendations in this report include:

- Electric Power: **R2.1.1, R2.2.1, R2.2.4**
- HSF: **R4.2.3**
- STM/C: **R5.1.1, R5.2.1, R5.3.2, R5.4.1-2**
- Research: **R7.3.1-4**

Recommendation Overarching 3.1. SWORM agencies should coordinate, and engage relevant user sectors, to evolve and enhance space weather data archives (including indices, metadata, and uncertainties) to reduce latency, increase interoperability and machine readability, ensure uptime and access, and enable AI/ML usability.

Recommendation Overarching 3.2. NOAA should facilitate and coordinate the automation of forecasting tools and dissemination of products to increase speed of delivery and decision through minimizing human intervention in the delivery process.

Next Steps

This report’s goal is to further the national space weather enterprise through articulating the needs of the user community. The sectors identified and interviewed play important roles in national security, the economy, and society. Through the analysis of sector-wide surveys, SWAG identified 46 findings and 113 recommendations that, when implemented, will enable these critical sectors to better prepare for and become more resilient to the effects of space weather.

SWAG looks forward to engaging SWORM agencies and other relevant stakeholders on these findings and recommendations. These recommendations align with and augment many of the findings and recommendations identified in the SWAG 2023 Report. The successful implementation of the recommendations in this report and those identified in the SWAG 2023 Report will significantly advance and transform the national space weather enterprise, but will be impossible to accomplish without sufficient funding and sustained prioritization by Congress and the Federal executive branch.

SWAG welcomes input from SWORM on specific sectors to be surveyed in the next round and recommendations on additional focus areas of interest within the sectors already surveyed. SWAG understands the need for regular user engagement; however, SWAG needs sufficient resourcing to ensure the quality and utility of future in-depth surveys of user needs. SWAG looks forward to advising SWORM on the implementation of these findings and recommendations pursuant to 51 USC 60601(d).

A Final Thought

Improving space weather resilience depends on human capital and an effective workforce. Over the course of the past 3 years, SWAG has interacted with many people in space weather research and end-user communities. Some of those conversations have illuminated a continuing challenge within the science communities related to instilling and maintaining a healthy and collaborative culture. It is imperative that the Nation address challenges in developing and sustaining human capital that systematically impede progress across the space weather enterprise.

The enterprise should strive for a culture that combats hostility and harassment, and promotes a safe workplace for everyone, including at conferences and workshops. A safe workplace is one in which, among other things, no one is subject to hostility, and personal and professional development is fostered, mental health is valued, and respectful communication is expected. Establishing a sense of community will advance the space weather enterprise and promote a supportive culture by and for individual community members.

Based on the state of the profession, the next cohort of SWAG, in coordination with SWORM, should identify best practices to apply across the space weather enterprise and propose concrete steps to improve the workplace environment for everyone. SWAG should particularly focus on successfully demonstrated practices of other disciplines that can be incorporated into the space weather enterprise.

Fostering an inclusive culture that does not tolerate harassment will create a strong foundation for the next generation, enabling them to focus on advancing the space weather enterprise towards a more resilient workforce, infrastructure, economy, and Nation.

APPENDIX 1.
NOAA Space Weather Scales

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

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

Scale	Descriptor	Effect	Physical measure	Average Frequency
Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

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

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

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

URL: *https://www.spaceweather.gov/noaa-scales-explanation* December 11, 2023

APPENDIX 2:
Space Weather Advisory Group Charter

U.S. DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

SPACE WEATHER ADVISORY GROUP

CHARTER

1. Committee's Official Designation. The committee shall be known as the Space Weather Advisory Group (hereinafter the "SWAG").

2. Authority. The Administrator of the National Oceanic and Atmospheric Administration (NOAA) is required to establish the SWAG pursuant to the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act of 2020 (Public Law 116-181) and in consultation with other relevant Federal agencies. The SWAG shall function as an advisory body in accordance with the Federal Advisory Committee Act (FACA), as amended, 5 U.S.C. App.

3. Objectives and Scope of Activities. The SWAG shall advise the Space Weather Interagency Working Group (hereinafter the "interagency working group") established by the National Science and Technology Council pursuant to Section 60601(c) of title 51, United States Code. This advice will inform the interests and work of the interagency working group.

4. Description of Duties. The advisory group shall advise the interagency working group on the following:
a. Facilitating advances in the space weather enterprise of the United States;
b. Improving the ability of the United States to prepare for, mitigate, respond to, and recover from space weather phenomena;
c. Enabling the coordination and facilitation of research to operations and operations to research, as described in section 60604(d) of title 51, United States Code; and
d. Developing and implementing the integrated strategy under section 60602 of title 51, United States Code, including subsequent updates and reevaluations.

The SWAG shall also conduct a comprehensive survey of the needs of users of space weather products to identify the space weather research, observations, forecasting, prediction, and modeling advances required to improve space weather products, as required by section 60601(d)(3) of title 51, United States Code. Not later than 30 days after the completion of the survey, the advisory group shall provide to the Committee on Science, Space, and Technology of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate a briefing on the results of the survey. Within 30 days of the briefing to Congress, the advisory group shall make the results of the survey publicly available. The advisory group shall review and assess the survey not less than every 3 years and update, resubmit, and republish the survey.

5. Agency or Official to Whom the Committee Reports. The SWAG shall report to the interagency working group, in coordination with the Designated Federal Officer (DFO).

6. Support. The National Oceanic and Atmospheric Administration (NOAA) shall make available to the SWAG such information, personnel, and administrative services as may be reasonably required to accomplish the duties of the SWAG, subject to the availability of appropriations. NOAA will also provide a DFO for the SWAG.

7. Estimated Annual Operating Costs and Staff Years.

a. The estimated annual operating costs, to include travel, meetings, and possible contracting support, is initially estimated to be $60,000 and 0.5 full-time equivalent (FTE) staff support per annum.
b. Members of the SWAG will not be compensated for their services, but may upon request be allowed travel and per diem expenses as authorized by 5 U.S.C. § 5701 et seq.

8. Designated Federal Officer. The Administrator of NOAA will designate a full-time or permanent part-time employee, appointed in accordance with Department of Commerce procedures, to serve as the Designated Federal Officer (DFO). The DFO will approve or call all of the SWAG meetings and subcommittee meetings; prepare and approve all meeting agendas; attend all the SWAG and subcommittee meetings; adjourn any meeting when the DFO determines adjournment to be in the public interest; and chair meetings when directed to do so by the Administrator of NOAA.

9. Estimated Number and Frequency of Meetings. The SWAG will meet approximately 3 times each year, which may be conducted in person or by teleconference, webinar, or other means. Additional meetings may be called as appropriate, with approval by the Administrator of NOAA. Members are expected to attend all meetings. If a member should miss more than 2 consecutive meetings without the permission of the Chair, that individual's membership will be reviewed by the interagency working group.

10. Duration. Continuing.

11. Termination. Pursuant to section 60601(d)(4) of title 51, United States Code, section 14 of the FACA, as amended, 5 U.S.C. App., shall not apply to the advisory group. The charter shall terminate 4 years from the date of its filing with the appropriate U.S. Senate and House of Representatives Committees unless earlier terminated or renewed by proper authority.

12. Membership and Designation.
a. The advisory group shall be composed of not more than 15 members appointed by the interagency working group, of whom—
i. 5 members shall be representatives of the academic community;
ii. 5 members shall be representatives of the commercial space weather sector; and
iii. 5 members shall be nongovernmental representatives of the space weather end user community.

Members should be chosen to provide an appropriate range of views that represent the span of the space weather community and end-user sectors.

b. Not later than 30 days after the date on which the last member of the advisory group is appointed under subparagraph (a), the Administrator of NOAA shall appoint 1 member as the Chair of the SWAG.
c. The length of the term of each member of the advisory group shall be 3 years beginning on the date on which the member is appointed.
i. Term Limits.
1. In general. A member of the advisory group may not serve on the advisory group for more than 2 consecutive terms.
2. Chair. A member of the advisory group may not serve as the Chair of the advisory group for more than 2 terms, regardless of whether the terms are consecutive.
d. Members shall serve in a representative capacity, expressing the views and interests of the respective space weather community and/or end-user sector; they are, therefore, not Special Government Employees. As such, members are not subject to the ethics rules applicable to Government employees, except that they must not misuse Government resources or their affiliation with the Committee for personal purposes.
e. Members will be selected on a clear, standardized basis, in accordance with applicable Department of Commerce guidance.
f. Members shall not reference or otherwise utilize their membership on the SWAG in connection with public statements made in their personal capacities without a disclaimer that the views expressed are their own and do not represent the views of the SWAG, NOAA, the Department of Commerce, or the interagency working group.

13. Subcommittees. NOAA may establish such subcommittees, task forces, and working groups consisting of SWAG members—as may be necessary subject to the provisions of FACA, the FACA implementing regulations, and applicable Department of Commerce guidance. Subcommittees and other subgroups of the SWAG must report back to the parent committee (SWAG) and must not provide advice or work products directly to NOAA, the Department of Commerce, or the interagency working group.

14. Record-keeping. The records of the SWAG, formally and informally established subcommittees, or other subgroups of the committee, shall be handled in accordance with General Records Schedule 6.2 or other approved agency records disposition schedule. These records shall be available for public inspection and copying, subject to the Freedom of Information Act, 5 U.S.C. § 552.

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Filing Date

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APPENDIX 3: Space Weather Advisory Group Membership

End Users:

- Tamara Dickinson, President, Science Matters Consulting, LLC., Washington, DC (Chair)
- Rebecca Bishop, Principal Scientist, The Aerospace Corporation., El Segundo, CA
- Craig Fugate, Senior Advisor, Bent Ear Solutions, Former FEMA Administrator, Gainesville, FL
- Mark Olson, Senior Engineer and Manager, Reliability Assessments, North American Electric Reliability Corporation, Atlanta, GA
- Michael Stills, Senior Director, System Operations Control National Airlines, Orlando FL, Former Director of Flight Dispatch, United Airlines, Chicago, IL

Commercial Providers:

- Nicole Duncan, Strategic Planning Manager, Space and Mission Systems, BAE Systems Inc., Boulder, CO
- Jennifer Gannon,[40] VP of Research and Development, Computational Physics Inc., Lafayette, CO
- Seth Jonas, Principal, Lockheed Martin, Bethesda, MD
- Conrad Lautenbacher, Executive Chairman, GeoOptics Inc., Dunwoody, GA
- Kent Tobiska, President, Space Environment Technologies, Pacific Palisades, CA

Academia:

- Heather Elliott, Staff Scientist, Southwest Research Institute, San Antonio, TX
- Tamas Gombosi, Distinguished Professor, University of Michigan, Ann Arbor, MI
- George Ho, Senior Program Manager, Southwest Research Institute, San Antonio, TX (December 2023 - present); Chief Scientist (Instrumentation), Johns Hopkins University Applied Physics Laboratory, Laurel, MD (until December 2023)
- Delores Knipp, Research Professor, University of Colorado, Boulder, CO
- Scott McIntosh, Vice President, Space Operations, Lynker Inc. (August 2024 - present); Deputy Director, National Centers for Atmospheric Research (until August 2024), Boulder, CO

[40] Passed away on May 2, 2024, prior to the report release.

APPENDIX 4:
Focus Group Questions[41]

Power Grid Sector

Current and future use of and need for space weather observations, information and forecasts

1. How familiar are you with space weather products and services?
2. How do you consider space weather conditions in planning and operating the power system and equipment?
3. What space weather information do you use?
4. Where and how do you get the space weather information?
5. How satisfied are you with the quality and utility of current space weather observations, products, and services?
6. Based on your experience with current space weather products and services, what feedback do you have for providers to help them meet your needs? [Examples if needed: content, format, data time resolution, regional granularity, and/or delivery, map or graphical products, exemplar products or services for users to address risk and improve resilience of the grid, either associated with space weather or other hazards]
7. What do engineers and operators within the power grid sector need in future space weather information? [Ask for an explanation of the need]

Sources for space weather information

8. How do you use other environment or system data (e.g., GIC data, geomagnetic field variation) or information to support engineering design or operating actions? [Prompts, if needed:
    - How do you monitor, archive and use measurements of GIC in any equipment?
    - How do you monitor, archive and use electrical system waveform harmonic distortion?
    - How do you monitor, archive and use geomagnetic field variation?
    - How do you monitor, archive and use Earth-surface impedance in the vicinity of your systems? If so, how do you use the data?
    - What other parameters do you monitor and use to protect equipment from the effects of GIC?
    - What modeling is used to determine GIC flows in your facilities based on the space weather forecast information?
    - How do you monitor, archive and use other parameters as part of your operating mitigations or engineering mitigations to reduce the risk of GMD events?
9. How long is the information and/or data kept?

[41] OMB approved the SWAG Focus Group Questions on June 27, 2023. OMB Control Number History (reginfo.gov)

10. Can this information be shared outside of the application, company, or community?

Technological systems, components, or elements affected by space weather

11. How has space weather affected your systems and components?
Examples: Power transformers, Voltage support equipment, Relays, circuit breakers, and other protection and control equipment (including components using GPS-timing), Communications networks used for grid operations or emergencies, Generator fuel supplies, other systems or components that could be affected by space weather and impact grid operations
    - Based on how space weather has affected your systems, what are the requirements for your systems and components?
12. Are there any new technologies, research, instruments, and models that are needed to address space weather in the power sector?

Risk reduction and resilience activities

13. How is space weather information used in operating procedures to reduce risk and improve resilience?
14. How is space weather information used for engineering designs that have been adopted to reduce risk and improve resilience?
15. What improvements or additional space weather products are needed to assist in increasing the resilience of the power system? Please consider both short-term (within next 1-2 years) and longer term (within 5-10 years).
16. What may be limiting the power sector's ability to take actions to reduce risk and improve resilience?
17. How could better education and training improve the sector's ability to take action?

Last Question

18. Are there any other things that we have not asked about that you wish to share?

Aviation Sector

Current use of space weather observations, information and forecasts

1. How do you use space weather observations, information or forecasts or other information such as advisories or alerts?
2. What are your sources for space weather information?
    - How do you use the NOAA Space Weather Prediction Center website as a source for space weather information?
    - How do you use information from commercial space weather sources?
3. What regulations and/or policies require you to use space weather observations, information, or forecasts?

Future need for space weather observations, information and forecasts

4. What educational tools, formats, or vehicles would best assist the aviation sector to better understand space weather?

5. How do you foresee enhancements or changes to current information dissemination?

Technological systems, components, or elements affected by space weather

6. How do you assess the specific impact of space weather on communication, navigation, and human health?
7. What are the specific limits and thresholds for decision making?
8. How should Safety Management System (SMS) protocols be incorporated into space weather products and notifications?

Current and future risk reduction and resilience activities

9. What are the current risks to your enterprise or operation from space weather?
10. On a scale from 1 to 5 where 1 is inconvenient and 5 is severe, how would you assess the risks to personnel/equipment safety, economic, and operations?
11. Which policies or procedures do you have to mitigate the risks associated with space weather?
12. What kinds of simulations or exercises do you perform to enhance risk mitigation of future events?
13. What are new or other sources of space weather information do you require to mitigate risks?

Last Question

14. Are there any other things that we have not asked about that you wish to share?

Human Spaceflight Sector

Current and future use of and need for space weather observations, information and forecasts

1. How do you use space weather observations, information or forecasts, or other information such as advisories or alerts?
    - What are your sources for space weather information? [Examples if needed: international, commercial, agency, and academic space weather sources]
    - Probe: How does your enterprise use the NOAA Space Weather Prediction Center website as a source for space weather information?
    - How are you seeking to expand your sources for information?
2. How satisfied are you with the current quality of the current space weather observations for your uses?
3. What regulations and/or policies require you to use space weather observations, information, or forecasts?
4. How are your operations affected by space weather?
    - What are the decision-making limits and thresholds?
    - [If human health and equipment are mentioned] How do you assess the impact of space weather on human health and equipment functionality?
5. How can forecasts be improved to meet your needs?

Technological systems, components, or elements affected by space weather

6. Which measurements or observations would enhance monitoring of space weather?
7. What modeling information would improve space weather risk mitigation for you?
8. How would you use research, instrumentation, or modeling activities itself to obtain that information or look to other sources?

Risk reduction and resilience activities

9. What are the risks related to personnel/equipment safety, economic viability, or operational resilience?
10. How does your risk management process account for space weather?
11. Which simulations or activities do you perform to mitigate risk of future events?
12. What different or new sources of space weather information do you need to mitigate risks?

Last Question

13. Are there any other things that we have not asked about that you wish to share?

Space Traffic Management/Coordination Sector

Current use of space weather observations, information and forecasts

1. Which environmental conditions and parameters are important for your operations?
2. How do you consider space weather information in STM decisions?
3. How does your system monitor for relevant space weather conditions?
4. What are your sources for space weather information?
    - Probe: How does your enterprise use the NOAA Space Weather Prediction Center website as a source for space weather information?
5. What other new or non-traditional sources of space weather data could be used for the STM sector?
6. Are you satisfied with the current quality and utility of space weather observations?

Future needs for space weather observations, information and forecasts

7. What space weather forecasts, lead-times, and products are needed to implement future operations?
8. What type of information related to neutral density/drag issues and space/upper atmosphere conditions would be useful for operational mitigations, or technical mitigations?
    - What spatial and temporal resolution is needed?

Technological systems, components, or elements affected by space weather

9. How does space weather affect common and specialized activities? [Examples: Launch operations, Tracking, Guidance-Navigation & Control (GNC), Station-keeping, Collision Avoidance and Debris Awareness, De-orbit and Re-entry, Specialized or newer/developing capabilities, Autonomous Operations, Orbit-Raising, Rendezvous)
10. What are current or planned collaborations with the environmental research communities to improve resilience?

Current and future risk reduction and resilience activities:

11. What technological mitigation is used to reduce vulnerabilities or risk?
12. What kinds of tabletop exercises have you developed and implemented to explore space weather sensitivities to severe or extreme geomagnetic storms?
13. Which specific altitude or latitude regimes are more problematic for your operations?
14. How do any of your reduction/resilience activities rely on GNSS data availability?
15. How can operations be modified to compensate for periods of predicted or known space environment variations?
    - What are the limiting factors to the proposed operation modifications? (e.g., lead-time, max operation mode duration, 24/7 in-person monitoring, etc.)
16. Are there known barriers or challenges to implementing the proposed mitigations?
17. What operating system improvements are required to compensate for neutral density or wind perturbations?

Last Question

18. Are there any other things that we have not asked about that you wish to share?

Emergency Management Sector

Current space weather observations, information, and forecasts used

1. How do you account for space weather in all-hazards planning?
2. What are the regulatory or policy requirements for you to use space weather observations, information, or forecasts?

Future space weather information required (communication methods, observations, and forecast products)

3. How do you use the NOAA Space Weather Prediction Center's observations, information, and forecasts products and subscriptions?
    - Which ones are most useful?
    - What changes or additional information or products would you like to see?
4. What other sources of space weather do you use?
5. What space weather related information are you missing?

Current technological systems or components affected by space weather

6. How familiar are you with space weather effects on technological systems?
7. What operational impacts does your organization anticipate on (not inclusive):
    - Information Technology systems (i.e. business networks)
    - Operational Technology systems (i.e. Industrial Control Systems)
    - Public Safety Radio systems

- Auxiliary communications systems
- Critical Infrastructure your organization relies upon
- Critical Infrastructure your community and customers rely upon

8. What education, training, and resources are being used to understand the space weather threat to technology and operations?

Risk reduction and resilience activities

9. What policies or procedures to mitigate the risks from space weather are included in your organization's emergency or risk management planning?
10. What lessons can you share to help develop a best practices guide for other emergency managers to use?
11. For risk and/or consequence management specifically, what additional information do you need to improve decision making?

Last Question

12. Are there any other things that we have not asked about that you wish to share?

Research Sector

Current use of space weather observations, information and forecasts

1. What facet of space weather do you research?
2. What are the sources of your information?
3. What are the gaps in information?
4. Are current data archives and curation methods adequate for your research activities?
5. Are there other sources of space weather information that are not readily available to users, but (in your opinion) could be broadly used?
    - What would be required to transition those to wider availability?

Future use and needs, and which systems are affected by space weather

6. What advances in capability (observations, models, or forecasts) would improve understanding of space weather causes?
7. What advances in capability (observations, models, or forecasts) would improve understanding of space weather effects?
8. What (software or hardware) infrastructure might be required to produce information to improve understanding of space weather causes and effects?
9. What educational tools, formats, or platforms would best assist in the communication of space weather information?

Next generation technologies, research, instrument and models to address space weather

10. Are there particular technologies that should be accelerated to reduce the risk of space weather effects?

11. How should future space weather capabilities be coordinated to reduce duplication of effort and enhance collaboration?
12. How can next-generation capabilities be integrated to rapidly improve numerical models and space weather forecasts?
13. What next-generation capabilities should be prioritized?
    - how might that best be accomplished?
14. What educational materials or approaches might be employed to improve scientific understanding and participation across the space weather research community?
15. What educational materials or approaches might be employed to improve diversity in the space weather research community?

Last Question

16. Are there any other things that we have not asked about that you wish to share?

GNSS Sector

To determine the effect of space weather on GPS end users, the information gathered in the survey addresses the following fundamental questions:

1. What is the threshold of GNSS outage or degradation that will adversely affect an individual community/application?
2. Can space weather events exceed that threshold?

The GNSS sector specific questions were included within Topic 2 (Technology Systems), Topic 3 (Current Risk Reduction/Resilience), and Topic 5 (Future Risk Reduction/Resilience).

The GNSS sector user survey was conducted via online survey. The survey was directed to individuals in specific positioning, navigation, and timing communities.