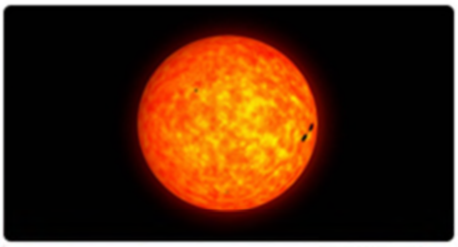
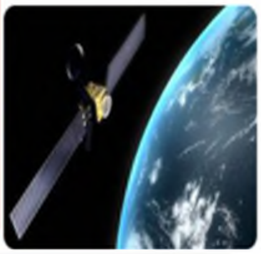
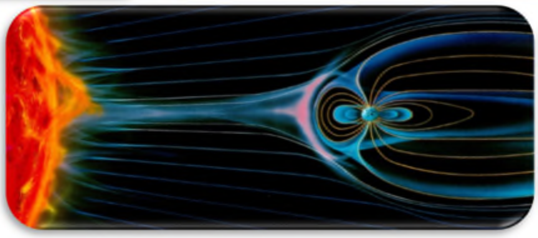
Submitted by
Abt Associates Inc.
6130 Executive Boulevard
Rockville, MD 20852

Customer Needs and Requirements for Space Weather Products and Services




Submitted to
National Oceanic and Atmospheric Administration
Space Weather Prediction Center

March 29, 2019

FINAL REPORT

Customer Needs and Requirements for Space Weather Products and Services

March 2019

Abt Associates Inc.
Rockville, MD

Written under contract for the
NOAA Office for Coastal Management
www.coast.noaa.gov

Abt Associates Inc.

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National Weather Service

NOAA's National Weather Service is the US Government official and definitive source of civilian space weather watches, warnings, and alerts to the general public, industry, and government agencies. The Space Weather Prediction Center provides real-time monitoring and forecasting of solar and geophysical events, which impact satellites, power grids, communications, navigation, and other technological systems.

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List of Acronyms and Abbreviations

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
4-D	four-dimensional (3-D + time)
ACE	Advanced Composition Explorer satellite
ADS-B	Automatic Dependent Surveillance-Broadcast
AE8/AE9	NASA models of the natural trapped radiation environment near the Earth
AMS	American Meteorological Society
ATC	Air Traffic Control
BPS	Bulk Power System (North America)
cm	centimeter
CME	Coronal Mass Ejection
ConOps	Concept of Operations (report on space weather information for aviation sector)
CPWG	Cross Polar Working Group
DSCOVR	Deep Space Climate Observatory
E-field	Geoelectric Field
EM	Emergency Management
EPRI	Electric Power Research Institute
ESD	Electrostatic Discharge
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FIR	Flight Information Region
G	Geomagnetic Storm NOAA Storm Scale
GEO	Geostationary Earth Orbit
GHz	Gigahertz
GIC	Geomagnetically Induced Current
GIS	Geographic Information Systems
GMD	Geomagnetic Disturbance
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HF	High Frequency (3–30 MHz)
IC	Internal Charging
ICAO	International Civil Aviation Organization
ISS	International Space Station
km	kilometer
Kp	Planetary Index, a 3-hour global index of geomagnetic activity
L1	GPS frequency at 1,575 MHz
L2	GPS frequency at 1,227.60 MHz
L3	GPS frequency at 1,381.05 MHz
L5	GPS frequency at 1,176.45 MHz
L-band	1–2 GHz frequency range of radio spectrum
LEO	Low Earth Orbit (satellite system)
MEO	Medium Earth Orbit
MeV	Mega (million) Electron Volts (unit of energy)
MHz	Megahertz (one million cycles per second)
MOSWOC	United Kingdom Met Office Space Weather Operations Centre
NASA	National Aeronautics and Space Administration
NCEI	Nation Centers for Environmental Information
NERC	North American Electric Reliability Corporation

NextGen	Next Generation Air Transportation System (FAA)
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NSWS	National Space Weather Strategy
NWS	National Weather Service
OPUS	Online Positioning User Service
OSTP	White House Office of Science and Technology Policy
OVATION	Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting
pfu	Particle Flux Unit (describes integral proton flux)
PNT	Position, Navigation, and Timing
POES	Polar Operational Environmental Satellites
R	Radio Blackout NOAA Storm Scale
S	Solar Radiation Storm NOAA Storm Scale
SATCOM	Satellite Communication
SBAS	Satellite-Based Augmentation Systems
SC	Surface Charging
SEAESRT	Spacecraft Environmental Anomalies Expert System – Real Time
SEASONS	Space Environment Applications, Systems, and Operations for National Security
SEE	Single Event Effect
SEESAW	Space Environment Engineering and Science Applications Workshop
SEP	Solar Energetic Particle
SIDC	Solar Influences Data Analysis Center (Royal Observatory of Belgium)
SIGMET	Significant Meteorological Information advisory
SOP	Standard Operating Procedure
SWAP	Space Weather Action Plan
SWORM	Space Weather Operations, Research, and Mitigation
SWPC	Space Weather Prediction Center
TEC	Total Electron Content
TID	Total Ionizing Dose
UCLA	University of California, Los Angeles
USAF	United States Air Force
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
UV	ultraviolet
VHF	Very High Frequency (30–300 MHz)
WFO	Weather Forecast Office (NWS)

Executive Summary

Space weather refers to disturbances originating from the Sun that can impact the Earth and near-Earth environment as well as assets in space. Space weather events have the ability to disrupt technology crucial to important industry sectors, including electric power, satellites, global navigation, aviation, and emergency management (EM), and thus affect the related services those sectors provide. While extreme space weather events with hugely disruptive impacts historically occur once or twice over a 30 to 50 year period, minor and moderate space weather events that still have the ability to impact industries occur far more frequently. As a result, stakeholders in these sectors require the information, products, and services to allow them to better understand the risks associated with space weather and to more effectively respond to future events and mitigate their impacts.

The focus of this study is to support the National Oceanic and Atmospheric Administration's (NOAA's) Space Weather Prediction Center (SWPC) with identifying and describing the different customers for space weather information products and services, and their evolving requests. SWPC provides stakeholders with specific information about conditions in the environment affected by space weather events, including historical conditions, real-time conditions, and forecasts. This role is similar to that of the National Weather Service (NWS) for terrestrial, meteorological weather. This study assesses the variety of uses and needs for SWPC space weather information across five sectors: (1) electric power, (2) satellites, (3) global navigation satellite systems (GNSS), (4) aviation, and (5) EM. Within most sectors, the uses and needs for space weather information are assessed across two user groups with distinct requirements for space weather products: engineers and operators. Within the EM sector, emergency managers define another distinct user group. For each of these different sectors and user groups, key customers and stakeholders were engaged to explore a range of relevant topics with a focus on clearly identifying pertinent product parameters and specifications for effectively applying and using space weather information.

Key Findings

Electric Power

Technological components used by the electric power sector can be susceptible to geomagnetic disturbances (GMDs) caused by space weather. GMDs can cause misoperation of protective relays, reactive power consumption, transformer heating, power imbalances, and loss of precision timing. These physical effects can have a multitude of impacts on the power grid, from reducing grid stability, to causing physical damage to the grid, and to creating blackouts.

As part of their efforts to prevent these effects, electric power utilities make use of SWPC products and services. Electric power utilities use both real-time data and forecasts. Real-time data help identify locations where there may be problems and provide situational awareness. Forecasts can help utilities monitor the evolution of a storm and perform mitigating actions. In addition, power utilities use SWPC alerts after an event to determine the cause of physical effects such as relay equipment misoperation, which can be attributed to space weather based on alerts and data review.

While stakeholders in the electric power sector find these products helpful, they identified several areas where products could be improved. One major area that stakeholders would like to see improved is the **granularity of SWPC scales and indexes**. Scales and indexes like the G-scale and the Kp-index are helpful for situational awareness, but the lack of granularity for space weather events beyond the current G5 value on the G-scale make it difficult for utilities to take action based on SWPC warnings and alerts. This is because utilities are only concerned about a subset of the most severe of these G5 events and are unconcerned with any events below G5. While stakeholders recognize that SWPC is unable to add granularity beyond G5 in the forecast timescale, SWPC could potentially do so for real-time conditions or historical events. The Kp-index would also be more useful for electric power stakeholders if it provided more localized descriptions of storm severity, rather than global descriptions, with a goal of producing a map that provides information on the expected level of activity for a given region.

Stakeholders also expressed the desire and perceived need for SWPC to move away from the G-scale and instead use the **geoelectric field (E-field)** as the basis for their description of the severity of space weather events. E-field forecasts are more useful for stakeholders than the G-scale because the G-scale does not map to geomagnetically induced currents (GICs), which ultimately cause space weather impacts on the electric power grid. However, if SWPC could forecast the geoelectric field, then customers could directly plug the geoelectric field values into their models to compute GIC flows based on configurations and determine potential impacts. SWPC has developed nowcast and short-term forecast geoelectric field products, but interviewees believe current SWPC customers would like access to longer-term forecasts, preferably with a 24-hour lead time, but recognize expanding the lead time in forecasts to even 3 to 6 hours would be an important improvement. Interviewees also requested, if possible, confidence intervals with E-field products, such as 1 V/km with +/-0.5 V/km, with emphasis on the V/km units. The interviewees understand there is uncertainty with the forecasts, but would like confidence intervals to provide a sense of the accuracy level. Interviewees also identified a key need for E-field data to be used within geographic information systems (GIS).

Stakeholders also identified improvements that they would like to see for the **usability of SWPC products**. Some interviewees have experienced problems downloading the National Aeronautics and Space Administration's (NASA's) Advanced Composition Explorer (ACE) and NASA/NOAA/United States Air Force's (USAF's) Deep Space Climate Observatory (DSCOVR) data for electric field forecast work, specifically noting intervals when the data were unavailable. The interviewees also noted challenges and limits in accessing data for historical space weather events. In particular, customers would like SWPC to develop a more flexible, easy-to-search and filter tool for these data, particularly magnetic field measurements, as a new product of considerable interest. They also suggested a product that consists of a list or ranked list of geomagnetic storms and associated links to access measurements for those events.

Satellites

Space weather has varying effects on satellites depending on their orbit. Satellites in geostationary Earth orbit (GEO) are used for telecommunications and weather and operate in a highly variable radiation environment, exposed to a dynamic radiation-belt environment and occasional bursts of protons from the sun. Satellites in medium Earth orbit (MEO) are used for navigation and communications and encounter a relatively harsh radiation environment passing through the outer Van Allen radiation belt. Satellites in low Earth orbit (LEO) are used for data communication and Earth resources imagery and operate within the Earth's inner magnetosphere where trapped radiation can also be a concern. Satellites in LEO are also affected by space weather events heating the upper atmosphere, which causes aerodynamic drag and lowers orbits.

To address these potential space weather impacts, some satellite engineers and operators use SWPC products and services for design evaluation and to support decision-making. Satellite engineers use statistical models as well as historical SWPC data [e.g., from the Geostationary Operational Environmental Satellite (GOES)] to create historical models to evaluate engineering specifications for future systems to ensure satellites are resilient against worst-case scenarios through redundancies, hardened components, shielding, or extra-generous design margins. Operators use daily reports, the Spacecraft Environmental Anomalies Expert System – Real Time (SEAESRT) model, post-belt indices, forecasts, and real-time data. They also use real-time information, alerts, and forecasts to determine mitigation actions, which can include actions like repositioning satellites, ensuring more staff are on-call, or taking no action for specific space weather events. Real-time data like SEAESRT are also used by operators to decide when it is safe to perform a vulnerable operation like maneuvering a satellite. However, the use of SWPC products for these purposes among satellite engineers and operators appears uneven.

Stakeholders identified several ways SWPC could improve its products. One major area is in improved product granularity through **products localized to orbits** and **increased precision for forecast products**. Spacecraft operators are treated as a single forecast group, which does not account for the variability of conditions and potential impacts of space weather in different orbits. In addition to forecasts specific to different satellite orbits, stakeholders believe data products also need to be tailored for each orbit. Customers suggested that SWPC build tools like SEAESRT for other orbits, and they suggested archiving SEAESRT data so that historical records can be used to develop and improve mitigation activities. Operators also requested increased granularity and precision for forecast products to improve planning efficiency. Increased confidence in the arrival time to Earth for coronal mass ejections (CMEs) will enhance operators' ability to take actions such as increasing staffing or delaying scheduled operations. Interviewees expressed a desire for forecasts that can predict 6 to 12 hours ahead of arrival. Users recognize that current models may not be able to improve arrival time predictions, so development of verification measures to capture the uncertainty in a warning could at least help users make decisions more confidently. Additionally, information about the earliest possible time a CME could hit Earth could improve confidence if the forecasted arrival time accuracy cannot be improved.

Interviewees also expressed a need for SWPC to develop **historical data products** to drive engineering activities and space weather mitigation efforts. Because interpreting forecasts without understanding historical data is challenging, stakeholders would like to be able to compare forecasts to the last few years of operational data. Much archived science data are not very accessible, but these historical data are used to associate past space weather events with past anomalies and service outages. Interviewees recommended better access to archived science data in such manner that system effects can be related to historical effects from space weather, which can then be used to calculate risk budgets for current and future systems. Interviewees also recommended that flux and fluence alerts include language referencing historical information.

Stakeholders also had a number of suggestions to **improve accessibility and usability** of SWPC products, including suggestions on desired **product presentation**. They recommended that SWPC establish a single place to retrieve, process, and visualize data for satellites. For GOES data, users recommended that SWPC provide more detailed data and develop plots and increased functionality that allows users to interact more with the data. Usability of forecasts should be augmented with the parallel generation of a simpler "non-technical" version that provides a contextual overview and outlook of potential space weather impacts. Similarly, they would like real-time information and forecasts to be placed in context and presented alongside data or summary statistics describing historical environmental conditions. Some interviewees suggested that SWPC look to the Met Office, the United Kingdom's national weather service, as an example of good technical reporting and visuals, particularly noting their color-coding scheme to indicate event likelihood.

Interviewees also identified a need for **education and outreach** to increase the standard of knowledge of space weather in the satellite sector, noting that currently most companies generally have only one or two people with the background and expertise to really understand what can be done with available space weather information. Improving space weather education levels in the sector will thus allow more users to interpret SWPC alerts and other products. In addition to education, interviewees discussed improving outreach by sharing information on a near real-time basis during large events using a product resembling a space weather Twitter or NWSChat tool.

Global Navigation Satellite Systems Users

Space weather can disrupt the transmission of broadcast GNSS signals, impacting GNSS users that rely on the signals for precise positioning, navigation, and timing. During geomagnetic storms, plasma density irregularities in the ionosphere increase, causing scintillation, which is characterized by rapid fluctuations in the amplitude and phase in trans-ionospheric radio signals. Scintillation can cause cycle slips and degrade the positioning accuracy in GNSS receivers. Additionally, solar radio bursts can impact GNSS signals and cause a loss of signal lock and positioning information.

GNSS users incorporate SWPC products to provide situational awareness, but there are relatively few GNSS-oriented products available from SWPC. Customers subscribe to SWPC alerts, but they primarily rely on products developed by commercial entities and in-house experts to understand space weather impacts and associated errors. These products often rely on SWPC data [e.g., estimates of the magnetic index (Kp)] as the starting point for their work.

To provide more support to GNSS users, stakeholders hope to see **improved precision and granularity of forecasts** from SWPC. Scintillation is one of the primary challenges for GNSS users, and stakeholders would like SWPC to develop warnings for scintillation with spatial and temporal granularity. Interviewees expressed the desire for an equatorial forecast and polar and auroral zone forecasts with spatial granularity of 100 km^2 on the order of 10 minutes. Positioning customers need to be able to better anticipate potential impacts of large geomagnetic storms and would like products like Geomagnetic Storm Watch and Warning products to be available on the continental scale and have a reliability of at least 90%. Users are also interested in being able to sign up for warnings and alerts based on geography to focus the information on their area of interest, and would like these products to be delivered with a list of potential impacts in order to help users interpret the meaning of warnings.

Stakeholders would also like SWPC products to improve in terms of **accessibility and usability**. GNSS interviewees suggested improvements to the SWPC website, which they currently find overwhelming for non-scientists. They recommended that users should be able to navigate easily to the correct information. They also believe there is a need for interpretive tools that can relate or lead SWPC customers to better understand the nature, severity, and timing of impacts they may experience. Interviewees also emphasized the value in a simple mechanism that users could use to report issues with data products.

Aviation

In the aviation sector, space weather poses a threat through communication, navigation, and radiation concerns. Space weather impacts aircraft communication systems when increases in radiation cause ionization in the ionosphere, leading to attenuation of high-frequency (HF; 3–30 MHz) radio waves, used to send and receive critical information during oceanic or remote area operations, rather than reflection. Similarly, ionospheric disturbances can disrupt GNSS signals, limiting navigation accuracy for flights relying on GNSS-based systems. Radiation also has the potential to threaten both airplane electronic equipment and the health of crew and passengers in flight.

The aviation community uses SWPC products for situational awareness and for engineering. Aviation customers use forecast products and alerts to assess if space weather will impact a particular flight through HF communication vulnerabilities and radiation increases. Where there are concerns, this information is also used to help develop rerouting options. They also use this information to develop procedures to operate with a loss in HF communications or precision navigation landing systems. Engineers use SWPC products and alerts for retrospective studies, and use historical characterization of the environment to assess the historical precedent for different phenomena with established or likely adverse impacts in order to project how frequent and severe space weather events could be in order to understand potential future disruptions.

To aid aviation stakeholders with their operational decisions, stakeholders need **improved forecast granularity and precision**. Users would like finer-resolution information on the hazards to support both planning and tactical decision-making. Interviewees also expressed a need for warnings with longer lead times in order to plan routes and aircraft flow. Ideally, the warning time could improve to two days before an event and describe the potential for space weather events to cause different communication technologies to be partially or totally compromised. However, accuracy at that timescale is not currently feasible. To help users assess whether or not to act on a forecast, interviewees also suggested SWPC provide product verification statistics or confidence intervals alongside forecasts. Interviewees also identified a need for scintillation forecasts to predict navigation interruptions.

To improve the usability of SWPC products, interviewees suggested improvements to **product language and presentation.** Interviewees emphasized the need for SWPC forecasts and warnings to be written in "aviator speak" for a lay person, with accompanying explanations. Similarly, users would prefer if SWPC focus on the expected impacts rather than the phenomenon that could cause the impacts. Interviewees identified several communication products that SWPC could look to for language and presentation, including the language used in terrestrial weather forecasts for aviation and the graphics used in hurricane forecasting products. SWPC product users would generally like to see more graphical products, such as graphical short-term forecasts. Interviewees also had suggestions to improve the SWPC website presentation, including providing all relevant information in one place, as well as links to allow users to self-educate.

Interviewees also recommended that SWPC develop more products for **post-event and historical data**. Experts would like SWPC to develop better reporting of solar radio bursts and provide in-depth reports about significant events and associated impacts. This product might consist of rapid, brief reports that describe the environmental and space weather conditions during the time of an anomaly. Engineers also expressed a need for historical information on scintillation.

Emergency Managers

Emergency managers are tasked with "All Hazards," meaning that they need to understand, prepare for, and effectively manage the entire range of hazards, including natural, industrial and technological accidents, and adversarial threats and terrorism. Since space weather is a natural hazard, the primary responsibility for emergency managers is to understand the hazard, assess the vulnerabilities, and quantify the risk they are willing to accept in order to plan investments in preventing, mitigating, and responding to associated potential impacts. EM stakeholders are primarily concerned with space weather impacts to satellites, communications, and power grids, but they also need to be aware of any systems that could potentially be impacted by space weather. However, there is a significant gap in knowledge in the field, with many emergency managers lacking understanding of space weather and its potential impacts.

The EM sector varies in its use of SWPC products. Many emergency managers do not subscribe to SWPC products, and some of those who do subscribe to products have a difficult time using the products and finding ways to make them applicable to their work. Some EM divisions receive SWPC alerts and repackage them for better understanding. Other more advanced EM divisions have conducted several in-house training sessions and have a daily space weather situational report similar to the Federal Emergency Management Agency (FEMA) daily outlook.

Stakeholders in the EM sector identified a need for **localized, plain language forecasts and alerts** that provide **earlier warnings** of space weather events. Emergency managers need to be alerted one to two days before an event with accurate information on strength and severity of the event. The existing SWPC observations and warnings also need to be localized because most emergency managers work in specific areas. Geographically refined forecasts and nowcasts could be provided in the form of a map; interviewees suggested that a simple box outlining the warning area would be more helpful than interpreting scales. For text-based forecasts and alerts, emergency managers need products to be written in less-technical language that clearly defines the potential impacts of a space weather event.

Emergency managers also expressed a need for SWPC to facilitate **education and communications** to help them better understand space weather and its impacts. Because of the gap in awareness about space weather, stakeholders expressed the need for a geographically relevant education initiative to better communicate the hazard and potential impacts. It would be helpful to have webinars that help emergency managers understand SWPC products and how to interpret and use the items listed on the EM dashboards. Emergency managers are also interested in developing space weather contacts with critical infrastructure representatives in order to understand vulnerability concerns and how emergency managers can provide support. This is an area where SWPC could provide facilitation and education support to emergency managers, as well as work with EM at the federal scale to develop guidance for state and local emergency managers. Similarly, emergency managers would like more contact with SWPC and clear pathways of communication at national and local scales to answer localized questions.

EM experts would also like SWPC to improve its website in terms of **accessibility and usability**. Interviewees identified tools that they would like to see developed based on NOAA-NWS tools they already use. Existing sophisticated systems like the NWSChat instant messaging program are highly regarded by emergency managers for communicating impacts and flooding information. The EM community would like a tool similar to this, especially during busy solar periods, which could be used to ask questions and report information. Interviewees also recommended adding a headline above the NOAA scales banner on the SWPC website that provides a high-level overview of an event's current status. They also recommended that SWPC create more stoplight charts, which are helpful for emergency managers and provide intuitive interpretations of information, specifically identifying what information users should pay attention to.

1 Introduction

Space weather refers to disturbances originating from the Sun that can impact the Earth and near-Earth environment as well as assets in space. Space weather events have the ability to disrupt technology that is crucial to important industry sectors, including electric power, satellites, global navigation, aviation, and emergency management (EM), and thus affect the related services those sectors provide. While extreme space weather events with hugely disruptive impacts historically occur once or twice over a 30 to 50 year period, minor and moderate space weather events that still have the ability to impact industries occur far more frequently. As a result, stakeholders in these sectors require the information, products, and services to allow them to better understand the risks associated with space weather and to more effectively respond to future events and mitigate their impacts.

The focus of this study is to support the National Oceanic and Atmospheric Administration's (NOAA's) Space Weather Prediction Center (SWPC) with identifying and describing the different customers for space weather information products and services and their evolving requirements and requests. SWPC provides stakeholders with specific information about the conditions in the environment affected by space weather events, including historical conditions, real-time conditions, and forecasts. This role is similar to that of the National Weather Service (NWS) for terrestrial, meteorological weather. This study assesses the variety of uses and needs for space weather information across five sectors: (1) electric power, (2) satellites, (3) global navigation satellite systems (GNSSs), (4) aviation, and (5) EM. Within most sectors, the uses and needs for space weather information are assessed across two user groups with distinct requirements for space weather products: engineers and operators. In general, operators support the provision and maintenance of real-time operational services. In contrast, engineers tend to focus on the design of the equipment and systems that provide those sources, often by developing benchmark events to help clarify performance/reliability thresholds. Within the EM sector, emergency managers define another distinct user group. Emergency managers may have a background in engineering or operations, but are charged with preparedness and response to hazards. For each of these different sectors and user groups, key customers and stakeholders were engaged to explore a range of relevant topics with a focus on clearly identifying pertinent product parameters and specifications for effectively applying and using space weather information. Table 1 presents the specific components of this study.

Table 1. Summary of key study objectives to identify and describe customer and user requirements for space weather products and services.

Identify and Describe	Sectors and Application	User Groups	Parameters and Product Specifications
• Users of space weather products and services • User requests for space weather products and services	• Electric power • Satellite operations • Commercial aviation • GNSS-reliant industries • EM	• Engineering/ manufacturing • Operations • Emergency managers	• Desired forecast parameters including lead time, cadence, and uncertainty • Recommendations on the social science influence on the format and delivery of products and services • Preferred product formats • Interim user requirements for needs that scientific capabilities cannot deliver in the next 5–10 years

This report responds to the National Space Weather Strategy (NSWS) and Space Weather Action Plan (SWAP)[1] released in 2015 by the White House Office of Science and Technology Policy (OSTP). This plan details the activities, outcomes, and timelines to be undertaken by federal departments and agencies with the goal of developing a "Space Weather Ready Nation." This report addresses Sections 4.4.1 and 5.1.1 of the SWAP, in particular:

- "Improve operational impact forecasting and communications"
- "Improve understanding of user needs for space weather forecasting to establish lead-time and accuracy goal."

The goal of this study is to provide an objective assessment of SWPC customers and users of real-time and forecast products. The study is designed to provide a tractable and systematic framework that supports ongoing feedback and recommendations that can be documented over time. Because customers have dynamic vulnerabilities that change with technology, the synthesis of outreach described in this report provides a benchmark to assess and prioritize needs across sectors in the future. Findings are synthesized for and between sectors to identify how products are used and to identify products that could serve multiple sectors. These findings will also inform SWPC with immediate and future priorities.

1.1 Overview of SWPC Products and Services

Space weather consists of disturbances of the upper atmosphere and the near-Earth space environment driven by the magnetic activity of the sun, with major components consisting of solar flares, coronal mass ejections (CMEs), and solar energetic particles (SEPs). Solar flares are bursts of electromagnetic radiation from the sun that can impact the sunlit side (i.e., dayside) of the ionosphere through increased ionization, causing radio blackouts. CMEs are large bursts of magnetic field and plasma from the Sun's corona and can lead to geomagnetic storms. Solar flares and CMEs can also lead to the development of SEPs, which are high-energy particles that can make up radiation storms.

Because radio blackouts from solar flares, solar radiation storms from SEPs, and geomagnetic storms from CMEs have the potential to impact technology on Earth, NOAA provides the NOAA Space Weather Scales[2] as a resource to customers and the public to communicate current and future space weather conditions and possible impacts to systems, industries, and people (Table 2). The scales are characterized by the following three types of environmental disturbance events: Radio Blackouts (R), Solar Radiation Storms (S), and Geomagnetic Storms (G). The scales have levels numbered from 1 to 5 to convey the severity and possible effects at each level, as well as the frequency of event occurrence.

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[1] Executive Office of the President, National Science and Technology Council, *National Space Weather Action Plan* (2015).

[2] NOAA Space Weather Scales, available at https://www.swpc.noaa.gov/noaa-scales-explanation.

Table 2. Summary of the NOAA space weather scales.

Agent	Scale	Measure	Time to Earth	Impact
Flares	R	Mostly short-wavelength [ultraviolet (UV) and X-ray] radiation from flare	8 minutes	Radio blackouts on dayside, global positioning system (GPS) errors, and loss of lock
SEPs	S	Severity of the charged-particle radiation	10s of minutes–hours	Satellite damage and radiation exposure, and polar HF blackouts; increased radiation exposure to persons in aircraft at high latitudes
Geomagnetic Storms	G	Severity of the geomagnetic storm that arise from CMEs	15–96 hours	Possible bulk electric power grid voltage collapse, transformer damage, and general loss of system stability; satellite and radio communication disruptions due to scintillation; and satellite surface charging and drag in Low Earth Orbit (LEO)

SWPC also provides a range of alerts, warnings, watches, summaries, and forecasts that subscribers can receive as email alerts.[3] Notifications are issued for event-based activities and are based on observations. The subscription products consist of the following five categories:

- **X-ray Flux:** X-ray flux data are used to track solar activity and solar flares. Large solar x-ray flares can affect the Earth's ionosphere, which can block high-frequency (HF) radio transmission on the sunlit Earth side. SWPC issues alerts when solar flare intensity reaches the moderate threshold (R2) on the NOAA Radio Blackout Scale. Summary messages are issued post-event for all R2 and greater intensities. These messages describe the peak X-ray class and NOAA scale, timeframes, and source region.
- **Radio Burst:** Radio bursts refer to enhancements of solar radio emissions. SWPC issues alerts for two burst types – Type II (slow-drift) and Type IV (prolonged continuum).[4] These emissions are generally indicative of CMEs. SWPC also produces a daily summary of radio interference [245 megahertz (MHz) Radio Emission] and a summary of 100-cm radio bursts [e.g., frequency 10.7 centimeters (cm)].
- **Geomagnetic Storms:** Geomagnetic storms refer to large disturbances of the Earth's magnetosphere resulting from an exchange of energy from the solar wind into the space environment surrounding the Earth. Storms can be driven by CMEs or high-speed solar wind streams associated with coronal holes. The largest storms are driven by CMEs, which can take tens of hours to three–four days to arrive on the Earth. Geomagnetic storms can also produce large currents in the magnetosphere, and changes in radiation belts and in the ionosphere. Geomagnetic storming can be predicted through the analysis and modeling of the driving CME or the analysis and extrapolation of the high-speed solar wind stream. A watch is driven by the forecast of an impending storm, with lead times determined by the velocity of the CME. A warning is driven by upstream, in-situ solar wind observations and is issued minutes to several hours in advance of a geomagnetic storm. An alert is driven by ground-based magnetometer observations and is indicative of a storm threshold being reached.
- **Electron Flux:** Electron flux indicates the intensity of the outer electron radiation belt. Alerts are issued when energetic (> 2 MeV) electron flux levels exceed 1,000 pfu (particle flux unit: 1/cm^2/sec/steradian). Impacts of increases in electron flux include satellite deep dielectric charging at higher energies and surface charging at lower energies.

[3] The product description and subscription are available at https://www.swpc.noaa.gov/content/subscription-services.

[4] J.P. Wild, S.F. Smerd, and A.A. Weiss, "Solar Bursts," *Annual Review of Astronomy and Astrophysics* 1 (1963):291.

- **Proton Flux:** Solar radiation storms accelerate protons to very high velocities, with protons able to travel from the solar atmosphere to the Earth in as little as tens of minutes. SWPC provides two proton flux products based on proton energy levels: ≥ 10 MeV and ≥ 100 MeV. The ≥ 10 MeV products match the NOAA Solar Radiation Storm (S) thresholds of $10–10^5$ pfu from Geostationary Operational Environmental Satellite (GOES) satellite program observations and the ≥ 100 MeV products are based on a threshold of 1 pfu. Warnings for these two proton energies are issued based on expectations of flux-level thresholds, and specify the applicable condition of onset or persistence. Alerts are issued based on confirmation of ≥ 10 MeV and ≥ 100 MeV exceeding 10 pfu and 1 pfu thresholds, respectively. Summaries are issued once the proton flux has dropped below a given threshold; and specify the start, maximum flux, and end time for the event.

Additionally, SWPC produces weekly *Advisories,* which include Space Weather Outlooks with conditions during the past week and an outlook for the upcoming week; and weekly *Forecasts and Summaries,* with plain language weekly highlights and a 27-day outlook. SWPC also provides daily forecasts for 1, 2, and 3 days ahead, including (1) C, M, and X flare probability; (2) proton event probability; (3) global geomagnetic activity level (Kp/Ap); and (4) F10.7 cm radio flux. The SWPC website also provides links to forecasts, models, observations, and experimental products.

1.2 Approach

This study used an iterative approach to identifying experts, conducting outreach, following up on questions and discussions with stakeholders, and reviewing draft requirements with stakeholders. The primary research tool for this study was a series of interviews with 21 industry experts, many of whom are SWPC customers who are knowledgeable about the uses and needs of space weather products and services from engineering, operational, and EM perspectives. The project was initiated by conducting interviews with SWPC personnel with expertise across one or more of the five sectors. A conversational guide provided a visual overview of the topics in the study to guide the conversation. The guide was iteratively updated during the interview process (Figure 1). Initial conversations with SWPC were used to test the conversational guide and to learn about questions forecasters and developers have for specific user needs and perspectives.

The expert interviews began by walking through the conversational guide and reviewing specific SWPC products and services (e.g., the SWPC sector dashboards). Notes from the first interviews were reviewed for draft user needs and requests and for additional outreach questions and clarifications. Interviewees also provided additional insights on specific attributes and parameters for the sector requirements. Additional stakeholder outreach was conducted with existing and new stakeholders when expertise gaps were identified in the first round of outreach.

The interview findings are summarized by sector and are organized within each sector into the following five sections:

1. **Outreach Summary,** with a high-level overview and findings.
2. **Technological Vulnerabilities,** which varies in detail based on the sector but focuses on current industry vulnerabilities to space weather and how vulnerabilities are anticipated to change with new technology. This section also includes relevant existing mitigating activities. The purpose of assessing this is to understand how frequently these requirements need to be revisited based on how quickly they evolve.
3. **Use of SWPC Products and Services,** which focuses on how industries use SWPC products and how well needs are met.
4. **Product Needs and Attributes,** which includes the specific products and parameters that stakeholders discussed. These findings were typically confirmed several times with users in each sector.
5. **Summary of User Data Product Requests,** which provides a summary of all the user requests identified from the outreach summarized in the prior sections.

The requirements outlined in the Summary of User Data Product Requests section are organized to specifically support SWPC with addressing the SWAP goals of improving operational forecasting and communication, and improving the understanding of user needs for forecasting lead-time and accuracy.

Figure 1. Conversational guide for outreach with experts and customers.

1. Identify technological components affected by space weather.

- Review physical effects identified within each sector.
- How have these vulnerabilities changed or how/why are they changing?
- Rate of technology change and vulnerability assessment to inform the frequency that requirements should be reviewed.

2. Describe steps already undertaken to reduce vulnerabilities.

- Industry preference for engineering vs. operational actions?
- Relative effectiveness of engineering vs. operational actions?
- Relations between engineering and operational actions?
- Do current SWPC products and services support engineering vs. operational actions and how?

3. Determine actions that could be taken to further reduce these vulnerabilities.

- What additional actions could be taken by these sectors? In both the short-term (within the next 1–2 years) vs. longer term (within the next 5–10 years)?
- What may be limiting the sector’s ability to take these actions to reduce these vulnerabilities? Lack of education, lack of understanding, lack of resources?

4. Describe specific attributes of space weather information needed to further reduce these vulnerabilities.

- Current products: Incremental improvements that you are working toward or have discussed needing to make? Importance of these incremental improvements?
- New products that you are working on developing, a rough timeline for when they will be ready, what motivated their development, and what contributions they will make to reduce sector vulnerabilities?
- Barriers to do your job well?
- Lead time, cadence, and accuracy improvements of SWPC products that are needed?
- New products needed and how they will be used?

5. Describe potential improvements in how space weather information is communicated to increase its usability.

- Feedback from stakeholders on current content, format, and/or delivery? Includes alerts, products, and overall website user experience.
- How will improvements increase the number of SWPC customers and expand audience?

6. Describe desired format of space weather information.

- What do engineers and operators within this sector need? Why?
- Specific map or graphical products preferred over others?
- Any “exemplar” products or services for users within this sector for addressing vulnerabilities, either those associated with space weather or other hazards?

2 Electric Power Findings

We interviewed four experts from the electric power sector to elicit distinct perspectives on the use of the NOAA SWPC products and services, as well as potential enhancements and data gaps that future SWPC efforts could address. All four interviewees indicated familiarity and expertise with the engineering and operational aspects of space weather products and services (Table 3). Generally, power system engineers are responsible for developing equipment that can meet certain operating parameters; while system operators are responsible for using available equipment to maintain a reliable power supply and address operational constraints, such as variable supplies and the need to bring equipment offline for maintenance or repair. Because engineers and operators have distinct perspectives, we interviewed representatives of both groups to understand how they currently use SWPC data and forecasts and to identify data gaps and enhancements that would address their respective power sector needs.

Table 3. Space weather experts interviewed in the electric power sector by area of expertise.

Space weather expert	Area of expertise		
	Engineer	Operator	EM
Interviewee 1	●	●	
Interviewee 2	●	●	
Interviewee 3	●	●	
Interviewee 4	●	●	

2.1 Outreach Summary

The electric power system's vulnerability to space weather is well-recognized based on impacts from notable past events (e.g., Canadian impacts in the 1989 storm), stakeholders' involvement or awareness with the Geomagnetic Disturbance (GMD) Task Force, and reliability standards development for TPL-007-01 and -02.[5, 6] Electric power sector stakeholders currently utilize SWPC warnings and alerts, real-time data, and forecasts. However, they identified several areas for potential improvement, including improving the granularity and extending the range of values addressed with SWPC scales, developing indices of geoelectric field products (e.g., E-field intensities), extending the lead time for forecasts, and improving the usability of other SWPC data products, especially historical data products.

2.2 Technological Vulnerabilities

Space weather events can affect the strength and shape of the Earth's geoelectric field (E-field) and geomagnetically induced currents (GICs). These impacts are particularly noteworthy for the electric power sector because of tolerances inherent in the existing infrastructure. In our interviews, power sector stakeholders were asked to describe the potential physical effects of space weather on technological components of the power sector to better understand how SWPC products are currently used and the need and desire for future enhancements.

Table 4 summarizes potential physical effects of space weather on power sector components and possible mitigating responses. Potential physical effects of space weather events include (mis)operation of protective relays, increased reactive power consumption, transformer overheating, power imbalances, generator heating, and the loss of precision timing. All physical effects and impacts to the electric power sector are related to space weather impacts to the E-field, except for the loss of precision timing.

[5] Federal Energy Regulatory Commission, Order No. 830, "Reliability Standard for Transmission System Planned Performance for Geomagnetic Disturbance Events," *Federal Register* 81, no. 190 (September 30, 2016): 67120, https://www.gpo.gov/fdsys/pkg/FR-2016-09-30/pdf/2016-23441.pdf.

[6] North American Electric Reliability Corporation, "Petition of the North American Electric Reliability Corporation for Approval of Proposed Reliability Standard TPL-007-2," *NERC Filings to FERC*, Docket No. RM18-8-000 (January 22, 2018).

Table 4. Potential impacts of space weather events in the electric power sector and mitigating responses.

Physical Effect of space Weather Events	Potential power sector impact	Response
(Mis)operation of protective relays	Improper functioning of relay systems that are designed to protect the grid by detecting electrical aberrations (e.g., faults, surges, over/under voltages), and then isolating the impacted area from the rest of the network. Relays trip equipment that provide reactive power and are the cause of blackouts.	None currently; stakeholders identified the need to address a gap in understanding harmonic propagation through the system.
Reactive power consumption	Reduction in amount of reactive power flowing through the grid due to the increased consumption of reactive power by transformers. This hazard is an exclusive function of GICs and is recognized to be one of the greatest threats.	Addressed by operators primarily through actions like reducing transmission flow, redispatching generation, or emergency procedures, but engineers also perform vulnerability assessments.
Transformer overheating	Power from direct current components induced by GICs results in heat being dissipated within the core of a distribution transformer. Heating of internal transformer components can cause transformer energy loss, accelerated asset aging, and potentially cause transformer damage. [7]	Largely addressed with engineering solutions. Engineers assess GIC current and transformer thermal models to make design decisions.
Power imbalances	Difference in real-time supply and demand for power stemming from transformer overheating.	Must be managed by operators to maintain grid stability, but operators are not well-positioned to manage at this current time.
Loss of precision timing	When GNSS timing signals are lost, substation clocks will continue to operate and remain accurate for several hours. Potential impacts could occur if the impacts extend beyond the capacity of backup systems.	Although the industry is increasingly relying on GPS timing, it will not take a system down.

In addition to their experience and independent research efforts, electric power sector stakeholders' knowledge of the sector's technological vulnerabilities to space weather has improved in response to regulatory actions. Specifically, the North American Electric Reliability Corporation (NERC), the regulatory authority charged with developing and enforcing Reliability Standards for the electric power sector, has mandated the sector undergo a major vulnerability assessment to address potential impacts of GMD

[7] K.F. Forbes and O.C. St. Cyr, "The Challenge Posed by Geomagnetic Activity to Electric Power Reliability: Evidence From England and Wales," *Space Weather* 15, no 10 (October 2017): 1413 – 1430, https://doi.org/10.1002/2017SW001668

(i.e., space weather) events on the reliability of the North American Bulk Power System (BPS). These mandates are expressed collectively in Reliability Standards EOP-010-1 and TPL-007-02. Reliability Standard EOP-010-1 (Geomagnetic Disturbance Operations) requires owners and operators of the BPS to develop and implement operational procedures to mitigate the effects of GMDs.[8] Reliability Standard TPL-007-2 (Transmission System Planned Performance for Geomagnetic Disturbance Events) requires owners and operators to conduct initial and ongoing assessments of the potential impact of a defined benchmark GMD event on BPS equipment and systems.[9] While these studies are scheduled to be completed by 2020, lessons learned and preliminary results have been shared within the sector.

2.3 Use of SWPC Products and Services

Electric power sector stakeholders currently utilize SWPC products for engineering and operations. Electric power sector customers work closely with SWPC, providing guidance with respect to desired components and outputs for SWPC models. SWPC responds to this feedback and works to provide sector stakeholders with their requested observation, forecast, and modeling data and variables.

Engineers use real-time SWPC data for planning studies and system vulnerability assessments. The results of these assessments influence system design decisions and shape the guidance engineers provide to the system operators. Further, SWPC alerts help engineers determine the potential cause of physical effects such as relay equipment misoperation by clarifying if a space weather event may have contributed to an observed impact.

SWPC products used for operations include warnings and alerts, real-time data, and forecasts. SWPC warnings and alerts provide situational awareness and allow operators to react to eminent events by positioning the system's infrastructure to help mitigate potential impacts such as reactive power loss and voltage collapse. Real-time SWPC data are also used by operators and engineers to help identify locations where problems could develop (e.g., voltage depression during high geoelectric fields) and improve situational awareness. Real-time data can also improve confidence by providing the evidence needed to validate an operator taking mitigating actions while enhancing the speed for diagnosing the potential source of the problem. Because the intensity of space weather storms may vary over many days, forecasts are important for monitoring the evolution of a storm and for tailoring mitigating actions. Finally, SWPC forecasts are important as the lead time they provide expands the range of options that can be considered and implemented for posturing a system.

2.4 Potential SWPC Product Needs and Enhancements

G-Scale

While SWPC products that incorporate scales and indexes (e.g., G-scale and Kp-index) are used by those in the electric power sector, most interviewed stakeholders expressed challenges and a desire for revision and enhancement related to the granularity of the scales and indices. One recommendation addressed the construction of SWPC's G-scale, currently a five-level system that indicates the potential severity of geomagnetic activity associated with space weather. In our interviews, electric power stakeholders indicated that they only see actionable impacts, and thus are focused exclusively on "extreme" space weather events (e.g., G5 value) of the scale. However, the electric power sector understands that not all events at the G5 level are impactful. As a result, there was expressed interest in more granularity for events that currently receive a G5-level designation in order for products utilizing the G-scale to be effectively applied by operators in the electric power sector.

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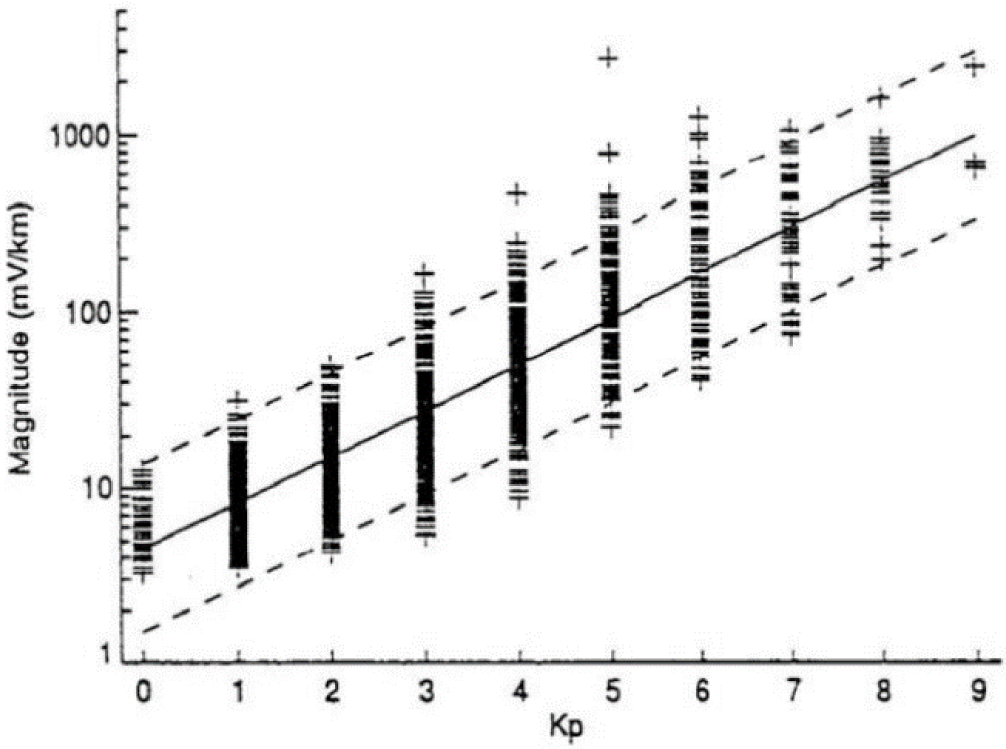
[8] Federal Energy Regulatory Commission, Order No. 797-A, "Reliability Standard for Geomagnetic Disturbance Operations", *Federal Register* 79, no. 122 (June 25, 2014): 35911, https://www.gpo.gov/fdsys/pkg/FR-2014-06-25/pdf/2014-14849.pdf.

[9] North American Electric Reliability Corporation, "Petition of the North American Electric Reliability Corporation for Approval of Proposed Reliability Standard TPL-007-2," *NERC Filings to FERC*, Docket No. RM18-8-000 (January 22, 2018).

While recognizing advantages this additional granularity could provide, SWPC currently lacks the ability to address this with its forecast products because of data needs. There are very few G5 events to analyze, which makes it difficult to develop and forecast additional levels beyond G5. However, SWPC could potentially add granularity for nowcast or hindcast products.

Values on the G-scale map to the Kp-index, the three-hour global geomagnetic activity index, and stakeholders identified the Kp-index as a SWPC product that could be improved. Specifically, interviewees noted that while the Kp-index provides a reasonable description for scientific purposes, it lacks the precision needed for power systems because the values are not available at a sub-global scale. Customers would like to see more localized descriptions of storm severity, especially where severity is expected to be strongest, with a goal of producing a map that provides information on the expected level of activity for a given region. SWPC is currently working with customers on this localized description. Additionally, there are currently 28 Kp values (e.g., scale of 0 to 9 expressed in thirds of a unit),[10] but the scale could be more useful for forecasting if the values were replaced with a few qualitative descriptions, such as quiescent, small, medium, and large. Kp-values for space weather events vary widely across locations (Figure 2) [11] and lead to wide variation in the E-field, so electric power utilities would also like SWPC to provide statistics alongside Kp-warnings that characterize how the anticipated Kp-value has translated to different E-fields in the past, effectively providing a regional adjustment index based on the historical record of observed values.

Figure 2. E-field values calculated for North American observatories show the variability of peak E field values as a function of Kp.



Geoelectric Field

Stakeholders also expressed the desire and perceived need for SWPC to move away from the G-scale and instead use the geoelectric field (E-field) as the basis for their description of the severity of space weather events. E-field forecasts are more useful for stakeholders than the G-scale because the G-scale does not map

[10] Kp-value description from “Geomagnetic kp and ap Indices,” NCEI Solar-Terrestrial Physics Data (STP), NOAA National Centers for Environmental Information, https://www.ngdc.noaa.gov/stp/GEOMAG/kp_ap.html.

[11] D.H. Boteler, “Assessment of Geomagnetic Hazard to Power Systems in Canada,” *Natural Hazards* 23, no 2–3 (March 2001):101–120, https://doi.org/10.1023/A:1011194414259.

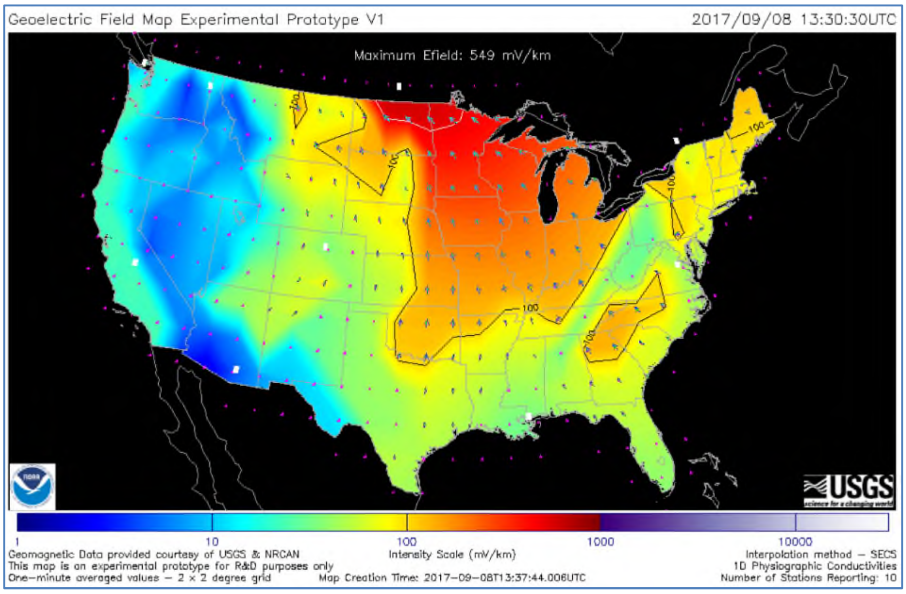
to GICs, which ultimately cause space weather impacts on the electric power grid. However, if SWPC could forecast the geoelectric field, then customers could directly plug the geoelectric field into their models to compute GIC flows based on configurations and determine potential impacts. This transition to the E-field from the G-scale would allow electric system operators to make better proactive decisions, transitioning away from reactive decision-making after observing impacts. Industry users could also use the E-field to calculate the expected current and measure it in the system in real-time, and report back to SWPC the deviation between expected and measured values. E-field products would ideally be more localized than existing G-scale and Kp-index products.

SWPC and its customers have discussed the need for local geoelectric field information for some time. In response, SWPC has made progress developing nowcast and short-term forecast geoelectric field products. However, the interviewees believe current SWPC customers would like access to longer-term forecasts, preferably with a 24-hour lead time, but recognize expanding the lead time in forecasts to even 3 to 6 hours would be an important improvement. Stakeholders did note predicted E-field intensities with a 10-minute lead time can be used to inform short-term, regional warnings that can motivate mitigating actions, particularly where the projected E-field value is expected to exceed 10 V/km. Similarly, the interviewees requested that nowcast products be updated to provide a snapshot of the E-field every minute to every five minutes.

Interviewees also requested, if possible, confidence intervals with SWPC products, such as 1 V/km with +/- 0.5 V/km, with emphasis on the V/km units. The interviewees understand there is uncertainty with the forecasts, but would like confidence intervals to provide a sense of the accuracy level. SWPC does not yet provide confidence intervals, largely due to limitations with the physical models. Addressing this request might also require transitioning from the one-dimensional (1-D) conductivity models to more advanced three-dimensional (3-D) conductivity models. To date, this effort has involved using real-time data and conducting targeted validation efforts (Figure 3). Several customers using this new map are providing feedback to SWPC for recommendations on how to visualize the data in their control rooms. Once the data are available, SWPC can verify and validate comparisons to assess the accuracy of the results. Furthermore, the Electric Power Research Institute (EPRI) is researching the granularity in E-fields and assessing the localized enhancement. Improvements in resolution will lead to improved modeling results, and SWPC and customers have discussed a quarter degree as the appropriate level of granularity, although not all experts agree that this fine of a scale is appropriate. Higher resolution requires more grid points to be modeled; a sensitivity study[12] considered the impact of an increase in resolution from 2 degrees to 0.5, and this continues to be an area of active research.

[12] Christopher Balch, "Geoelectric Field Maps: Progress on NOAA's Operational Near Real-Time Geoelectric Field Estimation Capability" (presentation, Space Weather Workshop, Westminster, CO, April 16–20, 2018), https://cpaess.ucar.edu/sites/default/files/documents/sww-2018-presentations/Balch_Chris_04.pdf.

Figure 3: SWPC experimental 1-D geoelectric field map product, released October 2017.



Stakeholders also expressed that the usability of geoelectric field information could be improved with more flexible data delivery in their in-house-mapping platforms. Customers identified a key need for E-field data to be used within geographic information systems (GIS) and for the GIS data to include details on the projected contour of the E-field. Electric system operators typically have their own maps with information about the network, voltage, generators, and other systems, and would prefer to overlay E-field information on top of their in-house models, which would be possible with E-field GIS data. System operators would like to be able to embed SWPC data directly into their tools. However, because utilities have different levels of advancements with some lacking a GIC interface in their control rooms, the interviewees recommended being able to provide these data through a combination of tabular displays and GIS data products to address anticipated varying needs and capabilities to integrate E-field data. Further, flexibility in the format of the available data would address the comment from several interviewees that end users likely want to be able to control the visualization of these data, such as changing the SWPC default color scale or using a gradient color scheme.

Additional Data Products

Stakeholders expressed a desire for additional new products and noted issues to address with some existing data products. For example, some interviewees have experienced problems downloading NASA's ACE and NASA/NOAA/USAF's DSCOVR data for electric field forecast work, specifically noting intervals when the data were unavailable. The interviewees also noted challenges and limits in accessing data for historical space weather events. Currently, stakeholders rely on resources from Intermagnet or Natural Resources Canada to examine a historical event, and these resources require users to specify the event, its time frame, and its geographic location. Customers would like SWPC to develop a more flexible, easy-to-search, and filter tool for these data, particularly magnetic field measurements, as a new product of considerable interest. Mentioned examples of potential data filters included G-scale, peak geoelectric field, peak rate of change of the magnetic field (dB/dt), and geographical location. Output from this tool would ideally contain geomagnetic and corresponding geoelectric fields and data confidence indices, and follow established data format standards (e.g., match the NERC Section 1600 data request format).[13]

[13] North American Electric Reliability Corporation, "Request for Data or Information – Protection System Misoperation Data Collection" (August 2014), Table 1, https://www.nerc.com/pa/RAPA/ProctectionSystemMisoperations/PRC-004-3%20Section%201600%20Data%20Request_20140729.pdf.

Stakeholders also suggested that SWPC could provide historical event data through a product that consists of a list or ranked list of geomagnetic storms, and associated links to access the measurements. Providing data for significant historical events for different analysis scenarios would be beneficial because there will be variability across the spectrum in a real event and observed data could help inform ongoing extreme event analyses that are critical within the electric power sector.

2.5 Summary of User Data Product Requests

The four interviewees identified seven user requests for the electric power sector. These experts were knowledgeable about the uses and needs of space weather products and services from engineering and operational perspectives; therefore we do not distinguish the user requests by these perspectives.

Request 1: More granularity on geomagnetic storm intensities. Interviewees identified a need for additional levels and details for space weather events that satisfy current G5 and Kp-9 classification criteria, ideally for nowcast, hindcast, and forecast products.

Request 2: More localized descriptions of geomagnetic storm severity. Interviewees would like to see a clear indication of spatial variability and an emphasis on identifying anticipated areas of greatest severity.

Request 3: Improve forecast lead time. Interviewees believe that increased forecast lead time will allow operators to better understand the best course of action. For E-field intensities, interviewees noted that a 10-minute lead time can inform short-term, regional warnings, which can motivate mitigating actions, particularly where the projected E-field value is expected to exceed 10 V/km. For geoelectric field products, interviewees believe expanding the lead time to 3 to 6 hours would improve operations.

Request 4: Warnings of impending events with more accurate estimates of their potential severity. Knowing that Kp-values lead to wide windows of E-fields, users suggest SWPC provide statistics alongside Kp-warnings to characterize how the anticipated Kp-value has translated to different E-fields in the past.

Request 5: SWPC products include confidence intervals. Interviewees acknowledge uncertainty in forecasts, but suggest that confidence intervals could provide a sense of the accuracy level. At this time, SWPC does not provide confidence intervals due to limitations with the physical models.

Request 6: Flexible data delivery. Interviewees would like to access underlying data to provide customized displays or other visuals, and to incorporate SWPC data directly into their systems tools, such as utility maps with information about the network, voltage, generators, and other systems.

Request 7: Searchable, easy-to-navigate list of historical events. Interviewees expressed interest in a tool that allows users to search historical events of interest and their magnitudes with data filters and downloadable output. Potential query filters include G-scale, peak geoelectric field, peak dB/dt, and geographical location (e.g., rectangle with latitude/longitude coordinates or predefined sizes and locations). Output might include a brief list of storms that fit user-specified criteria, and include links to where additional data on all of these storms can be found and downloaded.

3 Satellite Findings

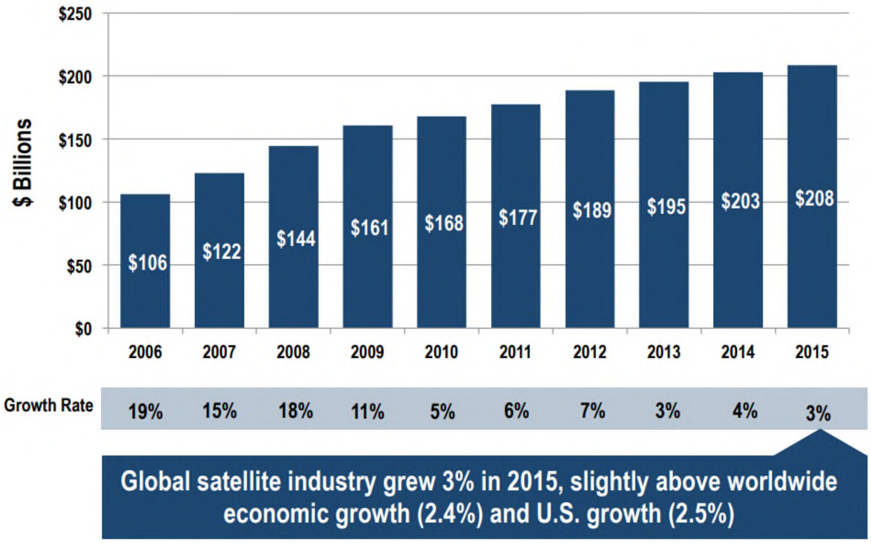
We targeted a diverse set of experts across the satellite sector, recognizing that some commercial providers may not want to share their vulnerabilities or issues with the public or the government. Of the four experts interviewed, two had engineering expertise and three had operational expertise (Table 5).

Table 5. Space weather experts interviewed in the satellite sector by area of expertise.

Space weather expert	Area of expertise		
	Engineering	Operational	EM
Interviewee 1		•	
Interviewee 2	•	•	
Interviewee 3	•		
Interviewee 4		•	

The satellite sector consists of a broad range of SWPC customers and corresponding services, including, among others, navigation, weather, television, and the internet, with the potential for this list to expand through technological development and provide other services. Technology continues to evolve, with new services in satellite internet and imaging; over the last 10 years, the total industry revenue doubled to an annual value of roughly $200 billion (Figure 4).[14] SWPC provides customers with knowledge of environmental conditions to inform engineering design and mitigating operations. This includes the distribution of data from NOAA's GOES satellite program. SWPC also coordinates with other agencies and research institutes regarding observatory operations and maintenance, model development, and new technology.[15] One challenge SWPC faces with the satellite sector is the heterogeneity among users across characteristics, including performance characteristics, level of active management of space resources, risk tolerance, and orbit characteristics of satellites. SWPC faces further challenges in that many customer needs are unachievable today due to limitations in existing scientific capabilities. Therefore, we focused our expert interviews on identifying specific near-term user needs for satellite products and services.

Figure 4. Global Satellite Industry Revenues (in $ billions).



[14] The Tauri Group, "State of the Satellite Industry Report," Satellite Industry Association, June 2016, https://www.sia.org/wp-content/uploads/2016/06/SSIR16-Pdf-Copy-for-Website-Compressed.pdf.

[15] These include the United Kingdom (UK) Met Office Space Weather Operations Centre (MOSWOC), the Royal Observatory of Belgium Solar Influences Data Analysis Center (SIDC), and others.

3.1 Outreach Summary

In addition to identifying experts by engineer and operator, we also considered orbit, service application, and upcoming satellite technologies. The three orbits of focus include geostationary Earth orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO), further defined in Table 6. Service application refers to the risk tolerance that users are willing to accept, and largely depends on the ultimate end-user purpose. For example, one application might have advanced redundancy and error checking, allowing systems to remain operational during harsh environmental conditions. On the other hand, there are satellite industry users that are more "start-up" or "one-of-a-kind" operations that lack the maturity or business revenue to support the redundancy and efficient error checking and diagnostics seen in some more mature operations. Likewise, low orbit flights are lauded for cost savings and use commercial parts, and therefore may be more prone to taking failure risks. However, the engineering stakeholders interviewed work for more sophisticated satellite companies and emphasized that they do not design satellites to be susceptible to a certain level of acceptable risk. They design satellites to be robust against the highest level of risks currently identified. Instead, satellites typically experience risks not previously identified such as susceptibility of a new part that was never considered.

Table 6. Orbital class descriptions and end-user application.

Orbit	Altitude (km)	Use
LEO	200–2,000	Data communication, high-resolution Earth resources imagery [from the International Space Station (ISS)]
MEO	2,000–30,000	Navigation (GPS and other global navigation satellite systems (GNSS) and communications satellites
GEO	36,786	Telecommunications, weather (GOES)

The satellite community has hosted a number of workshops on topics related to identifying needs for engineers and operators. In 2017, the Space Environment Engineering and Science Applications Workshop (SEESAW) was held to discuss needs for long-term design, anomaly resolution, and real-time forecast alerts. Short roadmap summaries of engineering actions to address industry needs across surface charging, internal charge, total dose, single-event effects, and nowcasts/forecasts from the workgroup are still pending as of February 2019.[16] Another relevant conference is the Space Environment Applications, Systems, and Operations for National Security (SEASONS),[17] which focuses on the operational impacts of space weather. These recent activities across industry demonstrate the differences in priorities between operators and the scientific community. For example, while the scientific community is focused on magnetopause crossings, GEO satellite operators no longer use magnetometers for attitude determination because the magnetic field at GEO is highly variable. Nevertheless, the magnetopause location is known to be important for radiation belt losses and for specifying the level of space weather disturbance in the magnetosphere and ionosphere, both of which are important for operational considerations.

3.2 Technological Vulnerabilities

Satellite customers with assets in various orbits – GEO, MEO, and LEO – operate in regions of near-Earth space where the principal effects and impacts of the environment vary distinctly (Figure 5; Table 6 summarizes the typical use of satellites in each orbit class).

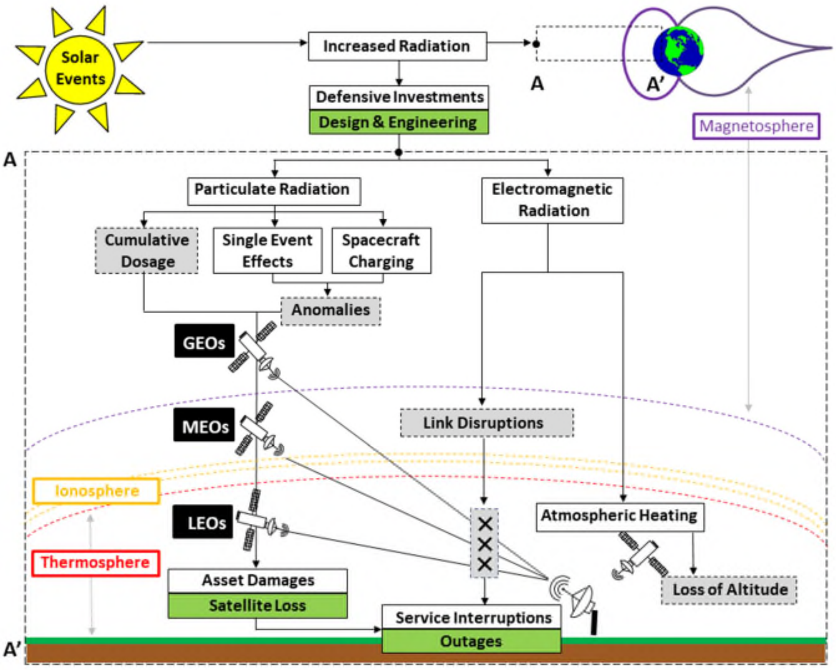
In GEO, satellites operate in a highly variable radiation environment, exposed to a changing radiation belt environment and occasional bursts of protons from the Sun. Satellites in MEO encounter a relatively harsh radiation environment passing through the outer radiation belt. These environments demand substantial defensive investments in the form of hardened components, shielding, or extra-generous design margins to protect the integrity of satellites from high cumulative radiation dosages and from anomalous satellite

[16] P. O'Brien, "Metrics for Addressing Satellite Operator Needs," (presentation, International CCMC-LWS Working Meeting, Cape Canaveral, FL, April 3, 2017).

[17] SEASONS conference: http://seasons.jhuapl.edu/.

behaviors resulting from surface- and deep-dielectric charging. LEO satellites operate within the Earth's inner magnetosphere where trapped radiation can similarly be a concern that requires defensive investments. Additionally, space weather events can heat the upper atmosphere, resulting in atmospheric expansion that can cause aerodynamic drag on LEO satellites. To prevent loss of altitude, these satellites require extra maneuvering, tracking, and conjunction avoidance efforts during space weather events.

Figure 5. Overview of Earth satellite orbit types and location relative to the thermosphere, ionosphere, and magnetosphere.[18]



Four primary operational space environment hazards affect all Earth orbit types[19,20, 21, 22]:

- **Total Ionizing Dose (TID):** Deposited dose from electron or proton ionization, where the total dose is the cumulative ionizing radiation that an electronic device receives over time. The time frame of concern is the total mission life, during which many high dose-rate events may occur. TID results in device degradation and reduced performance at the circuit or system level.
- **Single Event Effects (SEEs):** Caused by a single, energetic particle. Energetic protons and heavy ions from cosmic rays deposit a charge inside integrated circuits, and can cause electronics to latch-up or burn out.

[18] NOAA SWPC, *Social and Economic Impacts of Space Weather in the United States* (2017), https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf.

[19] J.C. Green, J. Likar, and Yuri Shprits, "Impact of space weather on the satellite industry," *Space Weather* 15 (2017): 804-818, doi:10.1002/2017SW001646.

[20] C. Balch, "Geoelectric Field Maps: Progress on NOAA's Operational Near Real-Time Geoelectric Field Estimation Capability" (presentation, Space Weather Workshop, Westminster, CO, April 16–20, 2018), https://cpaess.ucar.edu/sites/default/files/documents/sww-2018-presentations/Balch_Chris_04.pdf.

[21] P. O'Brien, "Metrics for Addressing Satellite Operator Needs" (presentation, International CCMC-LWS Working Meeting, Cape Canaveral, FL, April 3, 2017).

[22] J. Likar, "Space Environments & Effects Engineering User Experiences" (presentation, SEESAW Conference, Boulder, CO, September 5, 2017).

- **Internal Charging (IC)** leading to **Electrostatic Discharge (ESD):** Radiation belt electrons penetrate a spacecraft's outer structure to deposit a charge in spacecraft dielectrics (circuit boards or cable insulators), leading to electrical breakdown.
- **Surface Charging (SC):** Charged particles collect on satellite surfaces and produce high voltages, leading to damaging arcs and electromagnetic interference.

In addition, spacecraft in LEO experience risks due to proximity of the Earth's atmosphere, including corrosive atomic oxygen and orbit-affecting atmospheric drag, as mentioned above.

Satellites are generally robustly engineered with redundancies built-in to avoid interruptions to services, and are typically operated to ensure sensitive or vital actions are not performed during an incoming space weather event or that there is an element of redundancy to minimize the potential for service interruptions to the end user. Satellite operators vary in the level of mitigating actions they take in response to space weather events and generally fall into three categories: (1) direct satellite action, (2) staffing actions, and (3) no action. A small set of satellite operators are quick to take ***direct satellite action***, which might include repositioning the satellite antennae. Operators in this group are generally motivated as the result of past experiences with severe, high-probability impact events and the nature of their clients' needs. These operators are often reluctant to discuss their experience with space weather mitigation, largely because they do not want to publicize their vulnerability to space weather. This group tends to be proactive to space weather because (1) they have experienced impacts stemming from a past design error; and (2) they cannot replace their vulnerable assets for several years given the high cost to design, build, and launch a new satellite. Following an anomaly and impact, this user group will often assess the space environment and review National Centers for Environmental Information (NCEI) data for details of the event. While this group represents an engaged user base, it is typically small and transient because the vulnerable spacecraft is eventually replaced.

A second, larger group of satellite operators takes ***staffing actions*** during space weather events, such as activating on-call plans to ensure the best staff are available in the event of space weather impacts or that there is redundancy in staffing to avoid a personnel gap. Finally, a large group of satellite operators take ***no action*** during space weather events. This could be because their satellites are sufficiently robust to adverse space weather conditions; alternatively, the recent mild conditions may have promoted a false sense of security for these operators. This group may also reflect a reactive posture because of a combination of financial, technical, and professional experience constraints that leave them best equipped to respond to any issues that arise versus taking mitigating action.

The recent growth in small cube-satellite and micro-satellite companies has helped shift the technological vulnerabilities for GEO satellites. Specifically, these smaller, cheaper-to-produce satellites are increasingly being used as a way to increase the number of satellites in orbit and therefore rapidly refresh satellites. This approach is replacing the prior approach of using fewer large, expensive satellites with mission lifespans of 10 or more years for GEO. These cube-satellites use fewer radiation-hardened parts and are more susceptible to failure from space weather, but industries accept this risk because constellations are designed for relatively rapid turnover and have a relatively low launch cost per vehicle.

At the same time, satellites' space weather vulnerability is changing with a transition in the technology used to raise satellites to their final orbits. In this case, the technological shift involves a move away from the use of rockets to use of ion engines energized by electric power from on-board solar arrays. This approach has cost-saving benefits from reduced fuel use and lower launch mass. However, raising satellites using ion engines is much slower than with rockets, with transferring to higher orbits often taking months instead of days with rockets to reach final orbits. As this technology becomes more routinely used, satellites on their way to GEO increase the amount of time spent in much harsher environments, like MEO. This would increase the satellite fleet's overall vulnerability to space weather. The data from NOAA's Polar Operational Environmental Satellites (POES) vehicle may be useful to understanding this vulnerability to some extent.

3.3 Use of SWPC Products and Services

SWPC provides the satellite sector with specific information about the conditions in the space weather environment, including historical conditions, real-time conditions, and a small set of forecasts. SWPC does not provide products and services tailored to a company's particular satellite, unique instrument, or material. To the extent such services are desired, private vendors use SWPC's data and work with end users to develop and provide these tailored products. More generally, the use of SWPC products among satellite stakeholders appears uneven based on our interviews. Some users appear to be highly reliant on SWPC products and services to understand the environment their satellites are operating in and the causes of any anomalies; however, other users are largely unconcerned with space weather and do not use any SWPC products. Stakeholders who use SWPC products are generally pleased with and have used SWPC data and products for many years.

SWPC products used by satellite operators include daily reports, the SEAESRT model, post-belt indices, forecasts, and real-time data. Satellite stakeholders specifically referenced the usefulness of daily reports and the SEAESRT model. They find SEAESRT to be a user friendly and relevant tool for operators that assigns degrees of urgency to relevant information about hazards to GEO satellites. Operators interviewed noted using real-time SWPC data to provide input to operations teams on space weather conditions; and when it is safe or unsafe to perform a vulnerable activity, such as maneuvering a satellite. Operators may also reach out to SWPC for after-the-fact situational awareness to understand the cause of an anomaly as soon as possible (i.e., if it is likely a satellite or potentially a space weather issue) and to quickly address the issue.

Operators also noted using SWPC forecasts, with the caveat they cannot use forecasts alone; forecasts must be considered with historical contexts. Products that provide forecasts along with historical contexts are not readily available from SWPC, however, which requires operators to understand thresholds and continuously assess space environment data when and after an anomaly occurs. Satellite operators use long-term historical measurements from NOAA's SWPC and NCEI for statistical analysis as part of spacecraft performance in orbit over time. In the event of spacecraft anomalies, satellite operators then use a different set of space weather information as part of the investigation and determination of the root cause.

SWPC products used by satellite engineers include statistical models and historical observational data. Engineers use standard AE8/AE9 statistical models (NASA models of the natural trapped radiation environmental near the Earth), which were developed using large datasets with decades of radiation environment measurements from a number of satellites.[23] Additionally, to help with radiation assurance, engineers use archived GOES data from NCEI and storm of the decade and century information from SWPC. Engineers also use GOES-R data, which includes full-response function and full details about sensor designs.

Overall, technology continues to change across the satellite industry, affecting the use of and needs for SWPC products. In general, customers use SWPC data to fine-tune engineering specifications for future systems by updating the knowledge about worst-case conditions. They use in-situ data to carry out post-event analysis following an anomaly to determine if space weather could potentially be the cause. These anomaly assessments will be further informed by GOES-R series data when it becomes operational in the near future, including Sun imaging and space environment measures.[24]

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[23] G.P. Ginet et al., "AE9, AP9 and SPM: New Models for Specifying the Trapped Energetic Particle and Space Plasma Environment," *Space Science Reviews* 179, no. 1–4 (March 9, 2013): 579–615, https://doi.org/10.1007/s11214-013-9964-y.

[24] See the GOES-R Series instrument overview at https://www.goes-r.gov/spacesegment/instruments.html.

3.4 Product Needs and Attributes

Localized Products

One major area stakeholders would like to see improvements in is to have products localized to orbits and to longitudes. Satellite stakeholders noted the need for information from the less well-sampled orbits like LEO and MEO. Information at non-GEO orbits is challenging to gather because there is much more variability and no in-situ sensors like those on GOES. While POES provide a reasonably good picture in LEO, the data resources and data flow from POES are not very good and real-time processing is not available. Because POES is constantly in motion, NOAA provides belt index updates once daily (10:00 UTC) for the previous day[25]; however, users would like to see more frequent updates. Awareness of space weather within the radiation belt is important for stakeholders because electrical launching missions can take 180 days to get into position from launch, hence the spacecrafts now will experience much longer exposure in variable environments and radiation belts than was previously the case with rocket-based launches. The space weather conditions of interest include the possibility of ESD, SEE, and solar panel degradation; and specifically, what causes said threats. This includes electron populations at both low and high energy and high-energy protons that can damage solar panels. Users discussed the value of a flexible online tool to visualize these data and select time periods and specifically identified real-time radiation belt forecasts that show electron fluxes across the whole magnetosphere.

Currently, spacecraft operators are treated as a single forecast group, which does not account for the variability of conditions and impacts of space weather in different orbits. For example, compared to GEO spacecrafts, LEO spacecrafts experience greater impacts by the inner radiation belt. Users recommend SWPC consider the development of better impact models that can inform improved engineering and manufacturing for satellites in different orbits. In addition to forecasts specific to satellite orbits, users recommend that a 4-D (3-D + time) model of the space environment would provide the capability to reconstruct satellite environments and satellite exposure since launch-related exposure varies for satellites in different orbits. This is especially relevant for electric orbit raising, with its relatively longer times to reach final orbit and could help customers better manage their assets through a projected lifespan.

Finally, stakeholders suggested that SWPC collect real-time data to fill in 3-D space and build tools like SEAESRT for other orbits besides GEO. For a given satellite location, users would then be able to custom develop a display similar to SEAESRT that estimates the current and past environment.

Forecast Granularity and Precision

Some operators discussed the need for increased granularity and precision for forecast products to improve planning efficiency. Currently, not all operators use forecast and warning products for planning and rescheduling. Instead, they simply react to forecasts with enhanced vigilance and situational awareness. In order to actually perform planning and take action based on forecasts, operators need forecasts with more precise predictions for the arrival time to Earth of space weather events. Increased confidence in the arrival time for these events will enhance operators' abilities to take actions such as increasing staffing or delaying scheduled operations. Operators currently find it difficult to justify action with a wide and unreliable forecast window, referencing a need of Earth arrival lead times of 6 to 12 hours to be able to adequately prepare. Further, recognizing the challenge of predicting the occurrence of a space weather event, users said it would be valuable to receive "*All Clear*" statements once an event has ended. Likewise, it would be helpful to receive assurance that the weather will be clear for predetermined periods (e.g., 12-hours) to increase the confidence that a scheduled work task will not be interrupted. Recognizing that it is currently infeasible to forecast an arrival time for a CME with accuracy that will be operationally useful, stakeholders recommend forecasts with information on the earliest possible arrival time. For example, a message along these lines could say, "*Impacts from the anticipated space weather event are expected no earlier than XX*."

Stakeholders also recommended that SWPC develop success scores to capture uncertainty in forecasts and warnings, where success is determined by assessing the accuracy of a warning compared to the actual arrival

[25] POES Radiation Belt Indices available here: https://satdat.ngdc.noaa.gov/sem/poes/data/belt_indices/

time and strength of the realized event. Users recognize that a forecast like an estimate of CME arrival time cannot be improved with current models and detectors, so a success score would provide a mechanism to inform certainty and help inform the need for mitigating actions. Operators could also perform their own tracking to compare mitigating activities over time to inform future response and understanding of cost effectiveness.

Stakeholders also expressed a need for precise ionospheric products. Users identified the need for information on frequencies expected to experience signal affecting scintillation in the ionosphere by predicted signal-to-noise, and fade by geographic region and future time and date. This would allow users to attribute a particular space weather event to a statistical model of the likelihood of effects within specific geographic regions, allowing optimization of how future operations in a region would be implemented. An example of the geographic scale described is, "*Over South America or Australia, between X and X time of day, expect these XX impacts, lasting for YY duration because of a space weather event*." Customers also suggest that this information could be useful as a hindcast, in addition to a forecast, to help with live operational planning.

Historical Data Products

Because interpreting forecasts without understanding historical data is challenging, stakeholders would like to be able compare forecasts to the last few years of operational data. The closest existing SWPC product is the space weather scales 1-in-10-year event. SWPC product users identified the need for longer-term historical information to allow operators to be more aggressive in their mitigations. If operators know the odds of failure are high in the next 24 hours based on historical conditions, they will be much more likely to make their system safe or postpone planned activities that are potentially vulnerable to space weather. Based on currently available products, operators are unable to make these decisions. Operators rarely shut down operations or go offline because of a forecast since the connections between the environment and anomalies are too tenuous. Much archived science data are not very accessible, but these historical data are used to associate past space weather events with past anomalies and service outages. Because these data are not currently very accessible through SWPC, it is difficult for operators to make these associations and understand if mitigation expenses are worthwhile or to know how much money would have been saved with better precision.

Users recommended better access to archived science data in a manner that system effects can be related to historical effects from space weather, which can then be used to calculate risk budgets for current and future systems. For example, relevant historical data for a spacecraft might include information on the radiation environment for a particular date. Specifically, while SEAESRT provides real-time information, the data are not archived. Customers recommend archiving this information to allow for a time-series display, retrieval, and comparison to variables such as the internal charging hazard for given times of observed anomalies. Central to this was a desire for a user-interface that would support selection of various available data for user-defined time periods (see below for additional details). Users also discussed the need for continuous data, which may be impaired by discontinued science missions or disruptions to service. This ultimately impacts the number of days that any physical model can be run in advance.

Further, for commercial satellite customers, it is often meaningless to provide products with fluxes and fluences because these are not actionable numbers. Instead, these stakeholders recommend that these products include language referencing historical information such as, "*This flux of XX electrons exceeds 98.6% of all days your asset has spent on orbit*." However, all information is relatively meaningless without knowledge of a given system's thresholds. Operators and engineers therefore must know how this information relates to their design requirements and equipment thresholds.

Data Accessibility and Usability

Satellite engineers and operators described several needs and recommendations for SWPC to improve accessibility and interpretation of products and services. Several stakeholders described challenges with locating data accessed regularly (e.g., daily fluence),[26] specifically following reorganization of the SWPC website. This can result in customers spending significant time performing calculations. Stakeholders recommend that if SWPC decides to redesign the website to enhance the functionality of any design, they include end users to obtain their input prior to the redesign. Accessibility can also be improved with the establishment of a single place to retrieve, process, and visualize the data. For example, this would be especially useful in post-event analysis and investigation of anomalies to learn about space weather for future systems. Such a data portal or data visualization service might serve as a gateway to NCEI data or other SWPC data sources.

Stakeholders also expressed the need for more detailed GOES data. GOES data are a major part of the radiation environment specifications that engineers use to design satellites. Stakeholders recommended that NOAA engage with the user community to better understand the detailed calibration of their sensors. Specifically, the GOES operational calibrations do not always provide the level of information needed by customers and data products produced in real-time for operators. NOAA has started to address this with GOES-R and now publishes the full-sensor response function and design details about sensor designs.

Stakeholders would also like to see GOES data become more interactive, with the addition of plots and increased functionality. Users believe the upcoming GOES-R series instruments will provide much more data and will require new products to support visualization and data downloads. Specifically, users would like to see an online browser tool that will allow them to select a time period for data to access and flexibility to view the data in combination with other data (e.g., turn GOES measurements on/off, overlay time series from other sources). While text products are useful, the ability for users to see the data and compare the data with the knowledge of system vulnerabilities supports industry decision-making. Access to these data online would prevent users from spending hours processing data before viewing. In addition to time-series plot functionality, users suggested the ability to input longitude and zoom in and out in time to look at the hazards, as well as to make marks on the plots. While the quantities that operators look to first in anomaly diagnosis are provided on the SWPC plot, users are limited by the inability to see historical information easily.

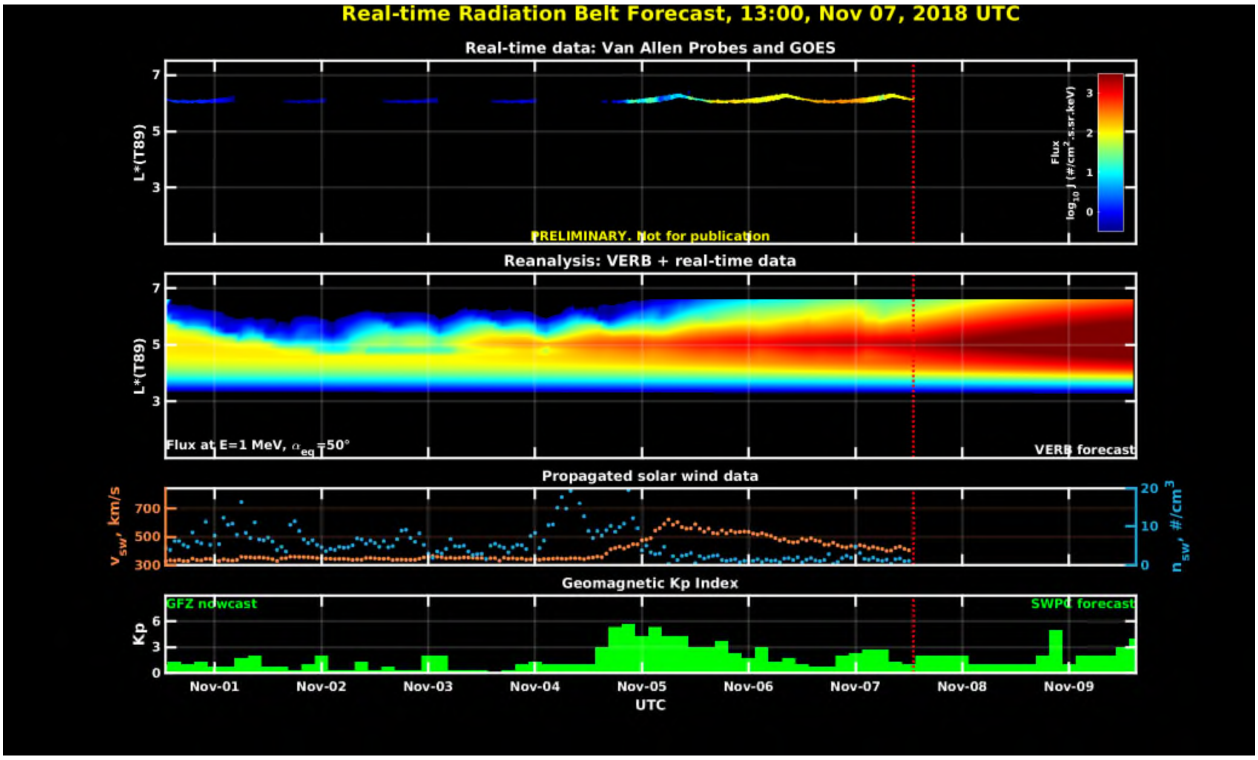
Another need to update the user experience is the three-day environment plots that have Kp, electron, and proton data to be modified to be live and dynamic, with scaling out to possibly five years. Users can currently acquire this information by downloading it from other websites and plotting and merging several years of data. However, SWPC could plot this information as a new product.

For product needs identified above for other orbits, specifically the real-time radiation belt forecast with electron fluxes across the magnetosphere (including the electrical orbit-raising trajectory), users specifically identified the need for 2-D representations of high-energy and lower-energy electrons, with particular reference to the radiation belt. Figure 6 presents an example plot generated by the University of California, Los Angeles (UCLA)[27] that stakeholders recommend, though it currently contains only high-energy electrons. This two-day radiation belt forecast of 1 MeV electrons compiles data from the Van Allen probe, ACE, and GOES data (the three-day Kp forecast obtained from SWPC).

[26] M. Bodeau, “Recent End User Experience with High Energy GOES Electron Data” (presentation, SEESAW Conference, Boulder, CO, September 5, 2017).

[27] http://rbm.epss.ucla.edu/realtime-forecast/.

Figure 6. UCLA real-time radiation belt forecast provides a two-day forecast of 1-MeV electrons using the data-assimilative VERB code, Van Allen Probe, and GOES data.



Product Presentation

Interviewees also commented that the presentation of SWPC products has been steadily becoming more useful. Some interviewees suggested that SWPC look to the Met Office, the UK's NWS equivalent, as an example of good technical reporting and visuals. The Met Office technical forecast graphics include a synoptic map of the Sun's surface and annotated features and provides an indication of flare likelihood. The product also includes a wrapper or envelope for spacecraft operators that are color-coded as green, yellow, or amber, with the coding aimed at a specific sector of satellite users. A second wrapper is also provided for each sector twice daily. The Met Office also provides access to forecasts located on their server, which is driven by a database engine that generates a distinct webpage by sector. The database is populated by forecasters and refreshed every five minutes. Finally, stakeholders discussed the value of the Met Office with customer process alignments to ensure the office is up-to-date on how industry operates and to confirm mutual understanding and agreement of alert definitions. The alerts are coded by colors of blue, purple, and red to indicate various likelihoods of extreme space weather (Table 7).[28]

[28] E. Haggerty, "Satellite Orbits and SpaceWx Influences" (presentation, UCL IRDR Eighth Annual Conference, London, UK, June 20, 2018).

Table 7. Situational advice structure developed by Met Office user to facilitate decision-making in extreme space weather events.

Space Weather Advice	Forecaster Issue Criterion	Spacecraft Operator Actions and Constraints
Blue	Situation **likely** to result in an extreme space weather event.	Consider the upcoming schedule of operations, disposition of personnel, and ground segment maintenance. May make non-service affecting changes and perform preparatory work, such as the refinement of on-call and work rosters, in mitigation of the space weather situation worsening. Service User informed.
Purple	Situation **expected** to result in an extreme space weather event.	Schedule of operations may be actively altered; the aim is to preserve assets and be prepositioned for a post-event stance that allows the most advantageous recovery. Service User advised when provision is primarily at risk from space weather effects and secondarily when system diversity mitigating other threat types have been depleted necessarily to address the now larger space weather threat.
Red	Situation **is now** an extreme space weather event.	Operator will take action to preserve assets and only implement service continuation actions that are zero risk to assets during the space weather event. Consult with Service User to capture prioritization changes. Forecaster is in direct contact with operator supporting risk management decisions during ongoing situation and recovery.

Stakeholder Education and Outreach

Consistent with the other sectors in this study, satellite stakeholders spoke about the need to raise the standard of knowledge through education rather than "watering down" the services to the detriment of more sophisticated users. Specific areas of education discussed include:

- Describing SWPC alerts and how to interpret them.
- Explaining the importance of staffing expertise or training employees with space weather awareness and monitoring.
- Supplying statistical descriptions of solar activity lulls and long-term averages.
- Providing varied education curriculum based on users (GEO, MEO, LEO).
- Training operators on when to act and mitigate. Specifically, stakeholders suggested that companies could then internally assess the effectiveness of response and mitigation activities performed or lack of preparation and response.

To help users interpret alerts, interviewees specifically discussed defining the meaning of the size of a solar radiation S1 or geomagnetic G1 storm, which will vary for operators at GEO, MEO, and LEO. For GEO, longitudinal location is also important for interpreting space weather information.

Satellite experts offered to support SWPC and others in this education endeavor. Users described that generally only one or two people within a company have the background and expertise to really understand what can be done with the space weather information available. Training and sharing user experiences is needed, as well as boiling down what they want based on their past experiences. For example, at a recent SEESAW,[29] engineering participants were asked to think about different need categories and presented with

[29] https://cpaess.ucar.edu/meetings/2017/seesaw-presentations.

these questions: (1) What do you need for environmental models?, (2) What do you need for design and effects tools?, (3) What do you need for quick-look anomaly analysis tools?, (4) What do you need for deep-dive analysis tools, and (5) What do you need for in-situ observation? Questions like these can help SWPC understand what stakeholders require.

In addition to education, operators discussed sharing information during large events using a product resembling a space weather Twitter or NWSChat tool. The objective would be to share information on a near real-time basis, which several are already doing informally. In this case, SWPC or a similar entity could facilitate a space weather conference room for several trusted expert operators to share details on what is being observed and to interact with science staff.

3.5 Summary of User Data Product Requests

The four interviewees identified 11 distinct data product requests for the satellite sector. These experts were knowledgeable about the uses and needs of space weather products and services from engineering and operational perspectives; therefore, we do not distinguish the user requests by these perspectives.

Request 1: Provide data products for MEO and LEO. Users would like products and tools that provide data for MEO and LEO, as many products can do for GEO. They would like forecasts specific to each orbit as well.

Request 2: Improve forecast lead time. Interviewees believe that increased forecast lead time will allow operators to make planning decisions based on forecasts. Operators need lead times spanning 6 to 12 hours before anticipated impacts from a space weather event to adequately prepare. Recognizing that it is currently infeasible to forecast an arrival time for a CME with accuracy that will be operationally useful, stakeholders recommend CME forecasts with information on the earliest possible arrival time. For example, a message along these lines could say, "*Impacts from the anticipated space weather event are expected no earlier than XX*."

Request 3: Develop measures of uncertainty for forecasts. Stakeholders also recommend that SWPC develop verification measures to capture uncertainty in forecasts and warnings by assessing the accuracy of a warning compared to the actual arrival time and strength. Users recognize that a forecast such as an estimate of CME arrival time cannot be improved with current models and detectors, so verification measures would provide a mechanism to help inform the forecast's certainty.

Request 4: Provide longer-term historical information. Historical information will allow operators to make decisions based on past experience and will allow engineers to design satellites to withstand severe space weather events. Interviewees recommended better access to archived science data in a manner so that system effects can be related to historical effects from space weather. Similarly, interviewees recommend archiving SEAESRT data to allow for a time-series display and comparison to variables such as the internal charging hazard for given times of observed anomalies.

Request 5: Establish a data portal or data visualization service. Interviewees described challenges with locating data accessed regularly, such as daily fluence, specifically following reorganization of the SWPC website, and recommended the establishment of a single place to retrieve, process, and visualize the data with a user portal to guide selection of specific variables for discrete time periods.

Request 6: Provide more detailed and interactive GOES data. Engineers need more detailed GOES data for radiation environment specifications. Stakeholders recommend that NOAA engage with the user community to better understand the detailed calibration of their sensors. Stakeholders would also like to see GOES data become more interactive with the addition of plots and increased functionality.

Request 7: Provide dynamic three-day environment plots. Interviewees recommend that SWPC modify three-day environment plots that have Kp, electron, and proton data to be live and dynamic, with scaling out to possibly five years.

Request 8: Create 2-D representations of high-energy and lower-energy electrons. Users have specifically identified the need for 2-D representations of high-energy and lower-energy electrons with particular reference to the radiation belt.

Request 9: Improve product presentation. Interviewees suggest that SWPC improve product presentation through visuals like technical forecast graphics with color coding. Interviewees specifically pointed to the formatting of graphics produced by the Met Office as a benchmark for effective communication products.

Request 10: Conduct stakeholder outreach and education. Interviewees believe there is a need for education in order to increase the standard of knowledge among industry stakeholders. Stakeholders could be trained on alerts and how to interpret them and when to act and mitigate.

Request 11: Develop an information-sharing tool. Interviewees recommend sharing information during large events using a product resembling a space weather Twitter or NWSChat tool. The objective would be to share information on a near real-time basis.

4 Global Navigation Satellite System Findings

We targeted a diverse set of experts across the GNSS sector, recognizing some commercial providers may not want to share perspectives on their vulnerabilities or issues with the public or the government. We interviewed five experts, three of whom had both engineering and operational expertise and one each with just engineering or operational expertise (Table 8). There are three general types of GNSS customers: (1) those involved with precise positioning activities (e.g., surveying, minerals extraction), (2) navigation, and (3) timing. Vulnerabilities to space weather among GNSS users vary according to a number of characteristics, including customer type, position where the activity is being undertaken/planned (i.e., latitude), and the participants' general understanding of space weather. As a result, the use of SWPC products vary widely in this group. SWPC faces challenges in providing products to GNSS customers because large uncertainties exist in estimating the severity of the impact on these customers, and differences in the relative need for spatial and temporal precision to support planning and operating decisions. This challenge is amplified by having many GNSS end users relying on equipment providers and/or commercial third parties using and integrating information from SWPC and others to support operations and decision-making. This creates a situation where the end customer may be unaware of their vulnerability to space weather. However, considering these users, results draw a clear conclusion that there is a role for SWPC to continue working to improve and enhance the spatial and temporal precision of its current global data and communication products. This additional information will in turn help users improve their general situational awareness of the potential impacts of space weather events and implement planning and mitigating activities that could limit operational delays linked to poor equipment performance and/or delays in critical services.

Table 8. Space weather experts interviewed in the GNSS sector by area of expertise.

Space weather expert	Area of expertise		
	Engineering	Operational	EM
Interviewee 1	●	●	
Interviewee 2	●	●	
Interviewee 3		●	
Interviewee 4	●		
Interviewee 5	●	●	

4.1 Outreach Summary

GNSS customers use GNSS for precision positioning, navigation, and timing (PNT); and rely on different types of receivers. These include single-, dual-, multi-, and hybrid-frequency receivers as well as multi-constellation capable receivers. Most GNSS users rely on single-frequency receivers, the most abundant type, which have accuracies on the order of meters. Single-frequency GNSS supports the positioning services available through most smart phones and automobile navigation systems. Single-frequency receivers are more susceptible to space weather impacts than other receiver frequencies. Dual-frequency GNSS receivers are essential for precise position and timing service and are widely used in the precision positioning associated with surveying, agriculture, maritime navigation, oil and mineral exploration, the precision timing needed in banking industries, and is soon to be implemented in the future for aviation navigation. Dual-frequency receivers can remove ionospheric contributions to errors, making it less susceptible to space weather. Hybrid-frequency customers use single-frequency receivers while incorporating additional information from Satellite-Based Augmentation Systems (SBAS) to enhance the precision of the positioning data. Agriculture and airlines, among others, rely on this hybrid approach.

The ability of customers to tolerate space weather-related impacts largely depends on the end use supported by the GNSS information. Precise position customers are typically able and prepared to remain stationary for minutes to hours in order to get the most precise results they require. These users often use systems, such as dual-frequency GNSS, which provide greater resilience. Navigation or kinematic customers work with moving objects and require much more immediate operational decisions than precise positioning customers.

For example, the Federal Aviation Administration (FAA) and airlines cannot always wait 20 minutes to update aircraft landing decisions. Other customers, such as general surveyors, may schedule work with an expectation of their equipment working quickly and accurately. As a result, work schedules can be adversely affected when space-weather events impact equipment operation and performance. Timing customers use GNSS as a clock and require a GNSS signal to set a clock for the next 24 hours. SWPC works less with timing customers because few people use GNSS for nanosecond or picosecond timing that these GNSS errors introduce.

Ultimately, educating general GNSS users about space weather, or building an initial understanding of the vulnerability of their activities to space weather, is a perceived challenge because of the general disconnect among activities, space weather, and SWPC's data and tools. Specifically, no platform or process exists to document information on impacts or disruptions across the GNSS industry. Instead, many GNSS users communicate what ultimately may be space weather-related impacts directly with equipment manufacturers and providers when their systems/equipment are affected. For example, our interviewees noted anecdotally hearing how many manufacturers receive automated, on-the-fly customer error reports or receive inquiries from customers related to equipment performance/errors that may be space weather-related with the customer being unaware of the potential connection between performance and space weather.

In contrast, some navigation-focused industries and SWPC customers have space weather experts on staff who serve as an intermediary between SWPC and their on-the-ground end users to help interpret the space weather scales and other SWPC products, and to help avoid end users postponing work at arbitrary thresholds. By providing training and education materials, SWPC could help customers better understand vulnerabilities, identify relevant action thresholds, and determine appropriate mitigation options. On the other hand, a number of SWPC customers specialize in ionospheric modeling and develop innovative third-party technology and solutions for GNSS end users to address the areas identified above where SWPC could support customer needs. These entities have the ability to deliver cost-efficient products quickly, so the GNSS sector and SWPC could benefit from taking inventory of their needs and ongoing research among this group.

4.2 Technological Vulnerabilities

GNSS receiver use has increased dramatically in the last two decades. GNSS technology and services exist with a number of devices used in everyday life, from consumer-grade, single-frequency GNSS navigation devices to science-grade, dual- and triple-frequency surveying GNSS receivers. Single-frequency GNSS receivers are the most ubiquitous and the most vulnerable to space weather. The single-frequency GNSS receivers often operate on the signal band called L1, where navigation accuracy is limited by potential ionospheric path delays. The Klobuchar model is used in most GNSS receivers as a correction method to mitigate this delay under normal conditions.[30] However, the Klobuchar model is unable to provide adequate removal of the delay during intense solar and geomagnetic disturbances, resulting in an increased potential for PNT errors. During geomagnetic storms, plasma density irregularities in the ionosphere increase, causing scintillation. Scintillation is characterized by rapid fluctuations in the amplitude and phase in trans-ionospheric radio signals. Scintillation can cause cycle slips and degrade the positioning accuracy in GNSS receivers. Additionally, solar radio bursts can impact GNSS signals. Solar radio bursts occurring in the L-band (1–2 GHz frequency range of the radio spectrum) can disrupt GNSS receivers' tracking abilities in the sunlit hemisphere of the Earth, which can lead to loss of the signal lock and positioning information.[31]

In contrast, dual-frequency GNSS receivers do not require modeling of the ionosphere because two signals are available that have undergone the same ionospheric effects and can provide a direct measurement of the

[30] J.A. Klobuchar, "Ionospheric Time-Delay Algorithms for Single-Frequency GPS Users," *IEEE Transactions on Aerospace and Electronic Systems* 3 (May 1987), 325-331, doi: 10.1109/TAES.1987.310829.

[31] V. Sreeja, "Impact and mitigation of space weather effects on GNSS receiver performance," *Geoscience Letters* 3, no 24 (2016), doi: 10.1186/s40562-016-0057-0.

Total Electron Content (TEC) and a corresponding correction for the ionospheric path delay. In addition to space weather-induced errors, GNSS users are also concerned with vulnerabilities to spoofing (i.e., the GNSS receiver calculates a false position) and jamming (i.e., GNSS satellite signal interference and a loss of signal). Triple-frequency receivers make spoofing and jamming more difficult, but stakeholders suggest that many GNSS satellites will not likely have this frequency available for another decade.

Overall, GNSS vulnerabilities are generally decreasing with improved hardware and the use of multiple frequencies and satellite constellations. However, as many operations become increasingly reliant on GNSS, vulnerability to space weather impacts increases, especially if GNSS customers continue to lack an understanding of how space weather can affect their service. In contrast, many high-latitude and rural areas already commonly observe GNSS interruptions due to space weather. For example, customers that use GNSS for surveying in Alaska interact with the National Geodetic Survey (NGS) and are aware of space weather due to the large economic impacts in terms of lost efficiency and excess costs attributable to equipment performance issues from space weather. Users in these areas may remain relatively vulnerable to space weather impacts owing to their specific location, often in higher latitudes, and relative physical isolation and lack of direct connections (e.g., roads) to other populations. SWPC is working to improve regional geomagnetic products to better serve these high-latitude, rural communities with reduced outages. GNSS users also mentioned that L-band communication outages to geostationary satellites are less frequent, but still impact positioning corrections.

The use of GNSS is expected to expand in the coming years. The NGS, within NOAA, is expected to transition to a new GNSS-based U.S. coordinate system in 2022, replacing the previous benchmark-based system.[32] Precision navigation is also expanding the use of GNSS, with increasing reliance on and development of autonomous vehicles (e.g., automated snowplows). Further, the FAA’s Next Generation Air Transportation System (NextGen) is modernizing air travel with a transition to GNSS as the primary means of navigation. Specifically, the Automatic Dependent Surveillance-Broadcast (ADS-B) will provide pilots and air traffic control with traffic data from GNSS-based positioning.

4.3 Use of SWPC Products and Services

The use of SWPC products and services by GNSS stakeholders varies widely. Some GNSS stakeholders directly use SWPC products and services, while other industry customers primarily get alerts through their GNSS equipment provider, which may ultimately be relying on SWPC data and services or additional derivative products. In general, many customers subscribe to SWPC alerts and appreciate their level of detail and the options to select different information for those alerts. However, some potential customers do not have on-the-ground operators who receive SWPC warnings (e.g., surveyors, offshore ships) because they believe it would be too difficult for them to process and interpret the information; and could increase the potential for generating “false alarms,” which have potentially significant adverse impacts in terms of associated direct costs from delays and cancelled activities.

Relatively few SWPC GNSS products are available generally, so recent work by commercial entities has focused on processing publicly available GNSS data to create products to help users better understand when, where, and how space weather could be impacting their systems. A number of researchers and SWPC customers have additionally developed their own engineering or hardware solutions to address industry and customer needs. For example, heavy scintillation throughout 2014 and 2015 led one precise navigation user to develop their own 24-hour scintillation prediction tool. Likewise, precise positioning GNSS users typically have in-house expertise for monitoring space weather and associated GNSS errors, although, like most GNSS services, these staff may rely on SWPC data as the starting point for their work. For example, industries

[32] Information on new Datums replacing NAVD 88 and NAD 83: https://www.ngs.noaa.gov/datums/newdatums/index.shtml.

specializing in ionospheric modeling and forecasting use solar wind data and estimates of the planetary magnetic index[33] (Kp) from SWPC to inform their own space forecast centers.

GNSS engineers monitor service, network performance, and the ionosphere to assess space weather impacts; and to fix or develop positioning solutions. They also design and develop products to address issues such as scintillation or radio interference from other sources that can result in a loss of communication to geostationary satellites, errors from the satellite orbit and satellite clock, and physical Earth movements. Engineers take action to address these errors, but noted that changes in algorithms can take months or a year before reaching a customer's software.

SWPC customers noted that they rely on the G-scale as a proxy for ionospheric impacts. Additionally, to support the GNSS user community, SWPC has been providing the North American map of TEC in real-time since 2004.[34] This product uses an ionospheric data assimilation model and ingests ground-based GNSS data to produce 2-D maps of TEC to estimate delays in GNSS signals.

4.4 Product Needs and Attributes

Forecasts and Warnings

Scintillation is one of the primary challenges for GNSS users. In order for users to plan activities and mitigate against scintillation, stakeholders would like SWPC to develop warnings with spatial and temporal granularity. For example, developing warnings to provide a few hours lead time before an event causes scintillation would help users take action to avoid impacts to their operations. In addition, GNSS users noted in particular that SWPC does not have a detailed or specific product for scintillation in the equatorial zone and that this would be valuable as an expanded service or tool. Ideally, an equatorial zone scintillation warning would provide warnings in the order of an hour, with 10-minute intervals, as the ideal case. The ideal level of spatial resolution of this product would be 100 kilometer (km) by 100 km, although stakeholders recognize that this level of spatial resolution is unlikely. Because of this, users noted achieving notifications on a 500 km^2 scale would be considered very good, and 300 to 400 km^2 would be the most helpful in most areas. However, in polar regions and aurora zones, where scintillation happens over shorter distances and time intervals, customers would ideally like to have scintillation forecasts available at the 100 km^2 scale and on the order of 10-minute granularity.

Positioning customers have previously experienced disruptions with large geomagnetic storms (e.g., the G4 storm on March 17, 2015) and are uneasy with the inability and lack of understanding to anticipate potential impacts for given storms. Customers want to be able to better warn their customers, specifically regarding potential impacts from CME events. SWPC currently provides Geomagnetic Storm Watch and Warning products with forecasts of CME intensity and timing, but customers are seeking additional spatial and temporal accuracy in geomagnetic storm forecasts, to better understand the scope for potential impacts. Such a product would be valuable if it provided a warning two hours before an event on the continental scale, with a reliability of at least 90%. However, a forecast with that level of accuracy is not currently feasible.

Additionally, stakeholders would like to see a product developed that includes GNSS-specific warnings and nowcast observations that could be pushed to many commercial sector customers. Specifically, GNSS users specified that nowcasts and warnings should be listed together instead of on separate pages. Examples of warnings and nowcasts include:

- Scintillation phase and amplitude;
- TEC disturbances and gradients; and,
- Geomagnetic activity.

[33] While Kp is not raw data, it is a simple and very helpful product for GNSS technology development industries.

[34] SWPC North American TEC Product, http://www.swpc.noaa.gov/products/us-total-electron-content.

Subscribers like the quality of the services and the level of detail in the email warnings that SWPC currently provides. They particularly appreciate the ability to fine-tune warnings by intensity to avoid inundation with emails about events that are smaller than their chosen threshold of interest. Some users specified that they only get alerts for larger events (G4 and G5) or by seasons (e.g., in the summer when they are doing field work or in the winter when they are interested in increased auroras). However, interviewees commented that email notifications are generally becoming outdated because of applications that can push warnings to mobile devices. Consistent with the desire for improved spatial precision in alerts, the GNSS community expressed interest and potential benefits from being able to sign up for alerts based on geography to focus the information to their area of interest. Customers would like to be able to receive a push alert with a link to a site with space weather conditions where they are located. Alerts might also be pushed to embedded software or embedded sources such as the NGS Online Positioning User Service (OPUS)[35] tool, which is used for GNSS processing.

Because the level of space weather understanding is so variable among GNSS stakeholders, users also expressed a need for tools that help interpret the meaning of forecasts in terms of real-world impacts. For example, stakeholders expressed confusion about how they should react to the statement, "*The index is high today,*" and wonder if it means that (1) they should not operate, (2) they should not rely fully on observations from the day, or (3) they should use extra receivers. Stakeholders believed this could be addressed by providing a list of the potential impacts delivered in tandem with the forecasts (e.g., loss of communications ability). Similarly, terminology in forecasts and other products needs clarification for some users. For example, aviation and surveying customers of GNSS use the term GNSS differently (e.g., an FAA circular might alert of a space weather-induced GNSS outage, but what the alert really means is that there is an outage in broadcast communications due to space weather that is disrupting communications of GNSS corrections).

SWPC Website and Software

Stakeholders emphasized the need for space weather interpretation and provided recommendations for product modifications focused on providing a user-friendly experience. They identified the SWPC website as overwhelming to most non-scientific GNSS users. End users want to know what space weather conditions might be impacting their operations, and they currently cannot understand the science products provided. This leads to a perceived need/benefit for interpretive tools that can relate or lead SWPC customers to better understand the nature, severity, and timing of impacts they may experience. SWPC customers also recommend that users should be able to navigate easily to the correct information, which requires beginning with the lowest-common denominator for products, such as awareness of what could be affecting their equipment.

Finally, stakeholders emphasized the value in a simple mechanism that users could use to report issues and for collecting this information. The most promising mechanism is likely through software that is already being used. This will require SWPC to develop ways to receive reports through the user's software. However, this is likely infeasible given the variety of hardware.

4.5 Summary of User Data Product Requests

The four interviewees identified seven distinct data product requests for the GNSS sector.

Request 1: Develop warnings for scintillation, especially in the equatorial zone. Users would benefit from scintillation products in order to make operational decisions. An equatorial zone warning would ideally provide warnings on the order of an hour with 10-minute intervals, and have a spatial resolution of 100 km^2 as an ideal case, although anything under 500 km^2 would be good.

Request 2: Improve timing and accuracy for geomagnetic storm forecasts. GNSS experts seek additional spatial and temporal accuracy in geomagnetic storm forecasts to better understand the scope for potential

[35] https://www.ngs.noaa.gov/OPUS/.

impacts. Such a product would be valuable if it provided a warning two hours before an event on the continental scale, with a reliability of at least 90%. However, a forecast with that level of accuracy is not currently feasible.

Request 3: Develop a product that includes GNSS-specific warnings and nowcast observations. This product could be pushed to commercial sector customers and would list nowcasts and warnings together instead of on separate pages. Examples of warnings and nowcasts that would make up this product include scintillation phase and amplitude, geomagnetic storms, and TEC disturbances and gradients.

Request 4: Develop push alerts that are specific to users' geographies. Experts expressed interest in being able to sign up for alerts based on geography to focus the information based on their area of interest. Customers would like to be able to receive a push alert with a link to a site with space weather conditions where they are located.

Request 5: Provide tools to translate space weather phenomena to impacts. Experts also expressed a need for tools that help interpret the meaning of forecasts in terms of real-world impacts. They see value in SWPC providing a list of the potential impacts delivered in tandem with the forecasts.

Request 6: Improve the SWPC website for use by non-experts. The SWPC website is overwhelming to most non-scientific GNSS users. End users want to know what space weather conditions might be impacting their operations and need interpretive tools that can relate or lead SWPC customers to the nature, severity, and timing of impacts they may experience.

Request 7: Create a mechanism for users to report GNSS issues. Users could benefit from a simple mechanism to report issues and for collecting this information. The most promising mechanism is likely through software that is already being used. This will require forecasters to understand and develop products and services that work into customers' existing workflows.

5 Aviation Findings

We interviewed four space weather experts from the aviation sector to elicit distinct perspectives on the use of SWPC products and services, as well as potential enhancements and data gaps future SWPC efforts could address. Experts were generally divided between engineering and operating areas of expertise, although one subject was qualified in both (Table 9). Generally, aviation engineers are responsible for developing airplane equipment to meet certain operating parameters while operators are responsible for making flight-related decisions such as those related to staffing, timing, and routing. Because engineers and operators have distinct perspectives, we interviewed representatives of both groups to understand how they currently use SWPC data and forecasts, and to identify data gaps and enhancements that would address their respective airline sector needs.

Table 9. Space weather experts interviewed in the aviation sector by area of expertise.

Space weather expert	Area of expertise		
	Engineering	Operations	EM
Interviewee 1	●	●	
Interviewee 2	●		
Interviewee 3		●	
Interviewee 4		●	

5.1 Outreach Summary

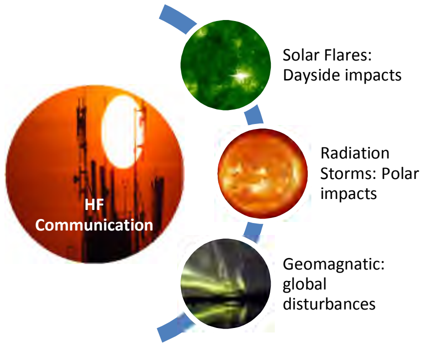
Overall, the experts expressed that space weather awareness and SWPC product understanding is low among general aviation sector stakeholders. One of the biggest perceived challenges in this sector is a misunderstanding of the magnitude of space weather events, which is especially pertinent for radiation and interpreting exposure numbers for health risk. For those in the aviation industry who are aware of space weather, the available information is regarded as being in its infancy stage and lacking in terms of the available detail, accuracy, and severity of potential impacts needed to meaningfully inform decision-making. Specifically, in the event of the loss of a system, operators need to know (1) how they can work around the loss, and (2) when the space weather event will be over. While the space weather information currently available is sufficient for situational awareness, it is not available with the granularity needed to inform these questions. In general, four categories described in prior research and requirement documents[36] remain relevant in the aviation community in terms of needs: communications, standardization, education, and risk.

While experts referred to available reports for specific user requirements, the outreach for this study focused specifically on SWPC products and services. For example, stakeholders discussed the International Civil Aviation Organization (ICAO) consideration of developing impact-based advisories to ensure the provision of actionable information (e.g., ICAO, 2018).[37] However, many different phenomena affect different technologies, all of which have been identified by NOAA scales. This is complicated by timescales of phenomena and the variability of impact based on location. For example, HF communications can be impacted on the dayside by solar flares, in the polar regions by radiation storms, while geomagnetic storms can cause global disturbances (Figure 7). This section therefore focuses on information needs of the aviation sector and how SWPC can improve scales and other resources to help improve the connection between phenomena and impacts in this sector.

[36] American Meteorological Society (AMS) Policy Program and Solar Metrics, *Integrating Space Weather Observations and Forecasts into Aviation Operations – Report of a Policy Workshop* (March 2007), https://www.ametsoc.org/ams/assets/File/space_Wx_aviation_2007.pdf.

[37] ICAO, *Manual on Space Weather Information in Support of Air Navigation, First Edition* (2018).

Figure 7. Example of different phenomena affecting HF communication and the challenge with migration from SWPC scales to impact-based scales.



While outreach did not focus on the synthesis of other relevant workgroup initiatives or ICAO efforts, stakeholders were asked to provide pertinent findings or relevant needs identified in these works. The Solar Metrics Report[38] was noted for organizing aviation recommendations in terms of communications, standardization, education, and risk; these four categories remain key needs across the sector. Other initiatives referenced include the Concept of Operations (ConOps)[39] and the Cross Polar Working Group (CPWG).[40] Overall, there is recognition that the airline industry has previously provided SWPC with technologically unobtainable requests, and that the most recent efforts are geared toward developing requests that can be met and improved upon as technology advances.

5.2 Technological Vulnerabilities

The three greatest vulnerabilities to space weather identified across the aviation sector include space weather impacts on communication and navigation and threats from radiation (Table 10). Space weather impacts aircraft communications systems when increases in radiation cause ionization in the ionosphere, leading to attenuation of HF radio waves, rather than reflection. Airborne planes use HF radio waves to send and receive critical information during oceanic or remote area operations. Similarly, ionospheric disturbances can disrupt GNSS signals, limiting navigation accuracy for flights relying on this navigation system. Radiation has the potential to threaten both airplane electronic equipment and the health of crew and passengers in flight during radiation storms. Particulate radiation can penetrate avionic equipment and cause errors in electronic components. Particulate radiation can also penetrate human cells, which can potentially lead to adverse health outcomes for crew and passengers on board aircraft receiving high doses of radiation exposure. However, the scope and extent of potential impacts of space weather radiation on human health are not yet well-understood.

Aviation vulnerabilities to space weather largely involve threats to components of air travel rather than operational processes, but there have been instances of solar radio bursts impacting some secondary radar systems [e.g., Scandinavia, Russia, Canada, and Denmark Air Traffic Control (ATC) centers].[41] To deal with

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[38] American Meteorological Society (AMS) Policy Program and Solar Metrics, *Integrating Space Weather Observations and Forecasts into Aviation Operations – Report of a Policy Workshop* (March 2007), https://www.ametsoc.org/ams/assets/File/space_Wx_aviation_2007.pdf.

[39] ICAO, *Concept of Operations for the Provision of Space Weather Information in Support of International Air Navigation* (December 2012), Appendix.

[40] CPWG, Space Weather Sub-Group, *Integrating Space Weather Observations & Forecasts into Aviation Operations*, "Aviation Space Weather User Service Needs," November 2010.

[41] C. Marque et al., "Solar radio emission as a disturbance of aeronautical radionavigation," *Journal of Space Weather and Space Climate* (August 2018).

these threats to components, the main priority for operators is determining what to do in the event of a communication or navigation failure. Pilots communicate to ATC to receive instructions and navigation, and ATC requires good system surveillance information to prevent airplane collisions and to provide initial routing information and subsequent in-flight adjustments. Operators currently receive information about space weather and use it to inform where and when to enact secondary and tertiary mitigation procedures to maintain safety in the aviation system.

At the same time, the aviation sector is undergoing changes in its basic communication and navigation technologies (Table 10). Specifically, HF communication is being replaced with satellite communications (SatCom) automatic dependent surveillance-broadcast (ADS-B) for surveillance and communications (e.g., Aieron).[42] In general, very-high frequency (VHF; 30–300 MHz) communication is used on continental, short-haul airlines; while long-haul, oceanic routes are now mostly using SatCom. VHF is also used in terminal areas, as well as in radar for plane separation. The extent to which the transition to SatCom will mitigate against space weather impacts is still unclear; communication constellations have hardened satellites, but still possess satellite-specific space weather vulnerabilities. Additionally, SatCom can be disrupted by ionospheric scintillation during space weather events and diurnal processes. The threshold for an event to impact ADS-B is also unknown. Understanding the vulnerabilities of ADS-B and the provision of engineering solutions will provide for more accurate surveillance.

Aviation navigation is also transitioning from a single-frequency to a dual-frequency global positioning system (GPS). With the introduction of a second frequency to GPS satellites, the impacts of ionospheric delay will be directly observable and the system's vulnerabilities to large errors resulting from TEC gradients in the ionosphere will be eliminated. However, even when dual-frequency receivers are available and adopted, single-frequency receivers will be used as back-up options in the event of issues, so some vulnerability to space weather will remain.

[42] https://aireon.com.

Table 10. Aviation technological effects and trends.

Physical Effects	Impact	Future Trends
Communication disruptions	Space weather events can cause changes in ionospheric density, impacting the path of HF radio signals, which can block radio signals, especially in polar regions. SatCom can also experience disruptions due to ionospheric scintillation.	Overall vulnerability may decrease, but not be eliminated over time with the transition from HF to SatCom.
Navigation (GPS) errors	Space weather events can disturb the ionosphere and increase the impacts of charged plasma on GPS signals, which the models in GPS systems are unable to correct for. Positioning systems used for airplane navigation can experience accuracy errors.	Adoption of additional GNSS frequencies will help eliminate ionosphere-induced position errors.
Human exposure to radiation	Radiation from space weather events can expose passengers on commercial airplanes to harmful radiation, especially on polar routes.	Exposures will increase as aircrafts fly farther and longer. Stakeholders' opinions differ on the magnitude of this threat.
Avionic upsets	Particulate radiation can penetrate avionic equipment and deposit energy, which can cause bit flips or circuit latch-ups and burn-outs in electronic components.	Engineering design standards account for this issue.

5.3 Use of SWPC Products and Services

Aviation sector stakeholders currently utilize SWPC products for operations and engineering, with operators primarily using alerts and forecasts. Alerts are used for situational awareness, but the level of detail with respect to location, timing, and severity of potential impacts is currently too low to support decision-making and mitigation. Beginning with forecast products, aviation customers begin assessing if space weather will impact a particular day and flight, and this helps inform decisions and options regarding potential flight re-routing. This planning typically begins at least two days in advance and includes an assessment of HF communication vulnerabilities, an increase in radiation, and, ultimately, decisions on whether or not to fly a polar route. For in-flight scenarios, pilots need to know if they can navigate using equipment and how to work around any loss in capability. If an HF forecast is inaccurate or does not arrive, operators have procedures for routes originally scheduled with a polar component, including rescheduling or re-routing. Space weather information is also particularly important for aviation use of the satellite navigation precision approach and landing systems. The major limiting factor is accuracy and integrity, especially in regard to vertical information and ionospheric anomalies exacerbated by space weather.

Engineers use SWPC products and alerts for retrospective studies but mostly use historical data. Historical information can be used to assess the historical precedent for different phenomena with established or likely adverse impacts in order to project how frequent and severe space weather events could be in order to understand potential future disruptions. Various engineers have been gathering this information from a number of organizations on an ad-hoc basis. Engineers also use historical characterization of the environment to design monitoring systems that measure satellite signals and errors in order to build real-time models of the ionosphere. In the event of a storm, monitors observe the ionosphere directly rather than relying on predictions of an incoming storm.

5.4 Product Needs and Attributes

Forecast Granularity and Precision

Aviation experts expressed a need for impact-based forecasts including on where issues or outages may be significant. ICAO is working to address granularity needs by dividing the globe into six latitude-based zones (high, medium, and equatorial, in both hemispheres), as well as provisions for daylight side impacts. This coarse information falls short of what users ultimately want, which is finer resolution information on the hazards to support both planning and tactical decision-making. As in meteorological services, users desire consistent, borderless service provision (e.g. avoiding discontinuities in hazard characterization at service area or Flight Information Region boundaries). The appropriate spatial scale will vary by the space weather phenomenon and operators will want to have visuals for specific flights as well as global views. Operators also recommended that information on outages and frequencies impacted would be helpful if displayed in a dynamic table. Such tables would have to be informed by space weather information that is translated to drive the tables.

Experts also expressed a need for warnings with longer lead times. ATC operates and plans routes and aircraft flow through regions, which can occur at least two days in advance. ATC uses communications to maintain plane separation, so the ability to know that HF might be disturbed or lost would be beneficial. Ideally, the warning time could improve to two days before an event and it would be useful if the potential for space weather events to cause different communication technologies to partially or totally be compromised could be described. However, accuracy at that timescale is not currently feasible. Closer to scheduled flights, warnings are more important for implementing workaround scenarios. Decisions on whether or not to operate a flight on a polar route are based on space weather information, and customers described the final decisions as currently hit or miss depending on the forecast's accuracy. SWPC provides information about forecast accuracy on its website, but improvements could include product verification statistics alongside products rather than in a separate place. This accuracy could be a range or general notes since the science does not yet exist to provide a specific accuracy number. While customers understand that accuracy is challenging to identify and will vary by users, they also recommend adding confidence levels to forecasts in order to define when space weather information will be useful. Users recommend including a statement and pictorial view on the web-based service.

Because navigation can be impacted by ground- or space-based augmentation system disturbances or outages, operators identified the need for real-time scintillation monitoring to provide short-fuse warnings and alerts. Ionospheric information should be available within 5 to 10 minutes of a phenomenon happening, available at the state-scale in the United States and country-scale elsewhere. Information has to be timely, accurate, and understandable. Along with alerts and warnings for observed phenomena, operators would like the alerts to also include a forecast for how the ionosphere will evolve over the next hour. Providing information on scintillation strength would improve decisions by informing what operations can and cannot do. Operators also identified the need for a reasonable scintillation forecast, recognizing that trials have been attempted unsuccessfully for 24-hour forecasts.

Forecast Language and Presentation

Customers emphasized the need for SWPC forecasts and warnings to be written in "aviator speak" for a lay person, with accompanying explanations. This includes replacing terminology such as *fluence* and *particle densities* and unfamiliar units with a discussion of particles of high and low energy and the impact in context. Similarly, customers would prefer if SWPC focus on the expected impacts rather than the phenomenon that could cause the impacts. For example, a statement such as, "*A CME was identified and will arrive at time X and be of Y severity*" is less useful for users than the statement, "*HF will be lost at time X. This is caused by space weather activity on the sun that occurred two days ago*." Customers recommend that the science and terminology should be provided at lower levels on SWPC products so that those interested are still able to drill down to the original science. Simultaneously, a key gap and overarching theme identified by the experts is the need for education, specifically with pilots, to understand phenomena and warnings. The aviation sector stressed that education must be standardized to ensure that misunderstandings are not caused by differences in education.

Expert stakeholders recommended that SWPC forecasts follow several standard practices in terrestrial weather for aviation. For example, a forecast for an airfield provides the date and time of publication, and updates are provided at regular set intervals. These regular, specified time intervals become established and operators understand which information to use in their decision-making. During a solar minimum, the frequency that updates and reports are released may decrease and instead be replaced with, "*All clear, no expected space weather activity for the next week*." Additionally, users recommend SWPC adopt the style of forecasting used for terrestrial weather to better communicate the severity of the forecast or observations. For example, "*Between 08:00 through 12:00 there is a prob40 rain shower,*" where prob40 means that there is a 40% probability of a rain shower in an area over a specified period. While this may not sound like a high probability of a rain shower to a non-aviation operator, aviation operators understand that this means there is a significant risk of a rain shower.

Experts also discussed the need for graphical short-term forecasts. Usability of short-term forecasts could be improved by starting with a stoplight presentation using combinations of orange and red notices for various space weather phenomena (first click), with supporting system-level specifics (second click). For example, if there is orange or red for solar radio signals, the second-level information available could be a list of potentially affected systems with a statement such as, "*HF radio may not work*." The format of the stoplight might depend on the phenomenon. Experts specified that displaying scintillation as a stoplight over a map at the state level for the United States and at the country-scale elsewhere would be helpful. The second-level supporting information could say, "*Scintillation observed with X strength. This means systems X and Y could fail*." An example resource that experts pointed at to illustrate this idea is SkyVector[43] aeronautical charts, where a Significant Meteorological Information (SIGMET) advisory layer is available for warnings and outlooks, and provides a graphic to see affected areas.

Hurricane forecasting products were also identified as an example presentation style to consider adopting now or in the near future for space weather forecasts. In particular, the uncertainty cones associated with hurricane forecasts were referenced for their ability to display both potentially affected areas and uncertainty a few days in advance of the storm's anticipated arrival. While solar flares and CMEs cannot be forecasted, and the level of geomagnetic activity cannot be forecasted until it reaches L1, stakeholders discussed color coding on a graduated scale to communicate the severity of the storm. SWPC's current revisions to the scale will include corresponding impacts, and the graduated colors should be considered part of the revised presentation.

It was also expressed that operators could benefit from mapped information about expected communication frequency outages. Ultimately, a pilot needs certain frequencies in order to communicate, and looking at a visual of the route early on with a potential overlay of potential impacts could help inform re-routing. Customers recommend having access to the frequencies that are and are not working as a dynamic table. This table could specify the timeframe that frequencies will be operational. Space weather information could be used to set up general guidelines to inform ATC on the selection of frequencies.

Post-Event Reports and Data

Operators discussed several instances of solar radio bursts impacting secondary radar systems. While SWPC cannot predict solar radio bursts because they are inherently unpredictable events, real-time reporting of solar radio bursts could be improved. Experts would like SWPC to develop better reporting of these bursts, and provide in-depth reports about significant events and associated impacts. This product might consist of rapid brief reports that describe the environmental and space weather conditions during the time of an anomaly. One example for a potential in-depth product is the Service Assessments that the NWS conducts to evaluate its performance after significant hydrometeorological, oceanographic, or geological events. This has only been done on rare occasions for space weather, such as the Service Assessment for Intense Space Weather

[43] SkyVector Aeronautical Charts, https://skyvector.com.

Storms October 19 – November 07, 2003.[44] Assessments may be initiated when one or more of the following criteria are met[45]:

- Major economic impact on a large area or population,
- Multiple fatalities or numerous serious injuries,
- Extensive national public interest or media coverage, and/or
- Unusual level of attention to NWS performance.

Aviation engineers elaborated on the use of space weather information for historical statistical descriptions of past events and after-the-fact analysis. With the addition of the L5 signal to GPS satellites, the main problem posed to aviation navigation will be scintillation effects rather than large errors due to TEC gradients. Engineers discussed the need for statistical information on scintillation fading across regions, which will ultimately inform continuity of service. While measures of scintillation (e.g., the S4) are needed, engineers design for worst-case scenarios. Engineers need to know, at any given point on the Earth, how much of the sky will be impacted by scintillation, whether there is any correlation of impacts across multiple GNSS frequencies, and the reliability of the satellites available.

SWPC Website

Customers recommended that SWPC provide all relevant information in one place, as well as links to allow users to self-educate. This is especially important for radiation exposure information. Experts recommended that SWPC determine who is responsible for delivering the information on radiation exposure and, at a minimum, include a link to this information on the SWPC website.

Stakeholders also provided specific feedback on the aviation dashboard. Overall, users would like to see current and future conditions in one place for products. The dashboard should also clearly label when a prediction expires (e.g., *"Valid for X minutes or valid until X"*). Additionally, products should be extended to a global scale, as applicable, such as with the Total Electron Count product, and localized to continental or major oceans, such as for the Planetary K index (Kp). For the Ovation auroral forecast, experts recommend that SWPC use the University of Alaska Fairbanks as a model for a 28-day forecast (Figure 8).[46] The D-Region Absorption Prediction specifically was identified as a useful product and stakeholders recommended adding a similar window for SATCOM frequencies.

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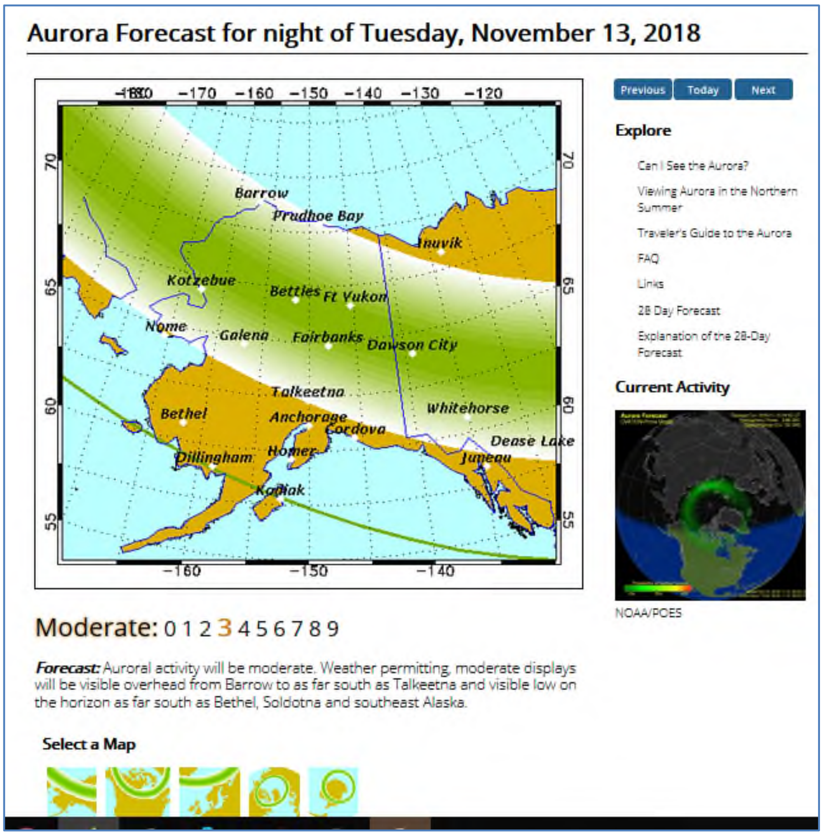
[44] National Oceanic and Atmospheric Administration (NOAA), *Service Assessment Intense Space Weather Storms October 19 – November 07, 2003* (2004), https://www.weather.gov/media/publications/assessments/SWstorms_assessment.pdf

[45] NWS Service Assessments, https://www.weather.gov/publications/assessments.

[46] University of Alaska Fairbanks, Geophysical Institute Aurora Forecast Tool, http://auroraforecast.gi.alaska.edu/.

Figure 8. Aurora 28-day forecast from the University of Alaska Fairbanks.



5.5 Summary of User Data Product Requests

The four interviewees identified 12 distinct product requests for the aviation sector.

Request 1: Develop geographically targeted forecasts and warnings. Experts would like geographical information to be included in warnings through the identification of where issues or outages may be significant.

Request 2: Provide warnings with longer lead times and confidence intervals. Ideally, the warning time for HF communications outages could improve to two days before an event and describe the potential for space weather events to cause different communication technologies to be partially or totally compromised. However, accuracy at that timescale is not currently feasible. For short-term warnings, experts recommend adding confidence levels to forecasts in order to define when space weather information will be useful.

Request 3: Develop scintillation forecasts and real-time monitoring. Ionospheric information should be available within 5 to 10 minutes of a phenomenon happening. Operators also identified the need for a reasonable scintillation forecast.

Request 4: Communicate SWPC forecasts and warnings in "aviator speak" and follow standard practices for terrestrial weather for aviation. Customers emphasized the need for SWPC forecasts and warnings to be written in "aviator speak" for a lay person, with accompanying explanations. This could also include adopting the style of forecasting used for terrestrial weather to better communicate the severity of the forecast or observations.

Request 5: Produce graphical short-term forecasts. Experts recommended improving the usability of short-term forecasts by starting with a stoplight presentation using combinations of orange and red notices for various space weather phenomena (first click), with supporting system-level specifics (second click).

Request 6: Consider adopting hurricane forecasting products' presentation style. In particular, experts recommended color coding on a graduated scale to communicate the severity of a space weather event.

Request 7: Summarize expected communications frequency outages. Experts recommend having access to communications frequencies that are and are not working as a dynamic table that specifies the timeframes that frequencies will be operational and the combinations of frequencies that can be used.

Request 8: Develop solar radio burst reporting requirements. Experts would like SWPC to develop a requirement for better reporting of solar radio bursts and provide in-depth reports about significant events and associated impacts, as there is value in providing evidence relating significant events to impacts.

Request 9: Provide statistical information on scintillation fading across regions. Engineers discussed the need for statistical information on scintillation fading across regions, which will ultimately inform the continuity of service. Engineers need to know, at any given point on the Earth, how much of the sky will be impacted by scintillation, the reliability of the satellites available, and the frequency-to-frequency correlations.

Request 10: Organize all relevant information in one place. Customers recommended that SWPC provide all relevant information in one place, as well as links to allow users to self-educate. This is especially important for radiation exposure information. Experts recommended that SWPC determine who is responsible for delivering the information on radiation exposure and, at a minimum, include as a service the link to information on the SWPC website.

Request 11: Improve the aviation dashboard. Overall, users would like to see current and future conditions in one place for products. The dashboard should also clearly label when a prediction expires (e.g., "*Valid for X minutes or valid until X*"). Additionally, products should be extended to a global scale, as applicable, such as with the Total Electron Count product; and localized to continental or major oceans, such as for the Planetary K index.

6 Emergency Management Findings

We interviewed four experts from the EM sector to elicit distinct perspectives on the use of SWPC products and services, as well as potential enhancements and data gaps that future SWPC efforts could address (see Table 11). Emergency managers are tasked with “All Hazards,” meaning that they need to understand, prepare for, and effectively manage the entire range of hazards, including natural, industrial and technological accidents, and adversarial threats and terrorism. Since space weather is a natural hazard, the primary responsibility for emergency managers is to understand the hazard, assess the vulnerabilities, and quantify the risk they are willing to accept in order to plan investments in preventing, mitigating, and responding to associated potential impacts. In particular, emergency managers are focused on understanding worst-case scenarios and possible cascading impacts from an event, such as the loss of power resulting in the inability to provide water treatment services. However, there is a general space weather knowledge gap across the field, with most emergency managers either unaware of space weather as a potential hazard or not understanding the potential impacts from space weather events. In fact, it appears that for many EM-oriented organizations, much of the space weather knowledge has been self-taught, with it being unusual for agencies to have previously had an institutional focus or awareness of space weather.

Table 11. Space weather experts interviewed in the EM sector by area of expertise.

Space weather expert	Area of expertise		
	Engineering	Operations	EM
Interviewee 1			●
Interviewee 2			●
Interviewee 3			●
Interviewee 4			●

6.1 Outreach Summary

Many EM stakeholders report having done much research on their own to better understand space weather phenomena and SWPC products. Many of those who monitor or research space weather are meteorologists or have some background in a science field (e.g., geology). Emergency managers in geographical areas that are more susceptible to space weather also tended to be more aware of it.

In response to the Space Weather Operations, Research, and Mitigation (SWORM) subcommittee, federal agencies are working at the national security level on a concept of operations that describes how to respond to an impending space weather event and includes guidance for state and local agencies.[47] Federal stakeholders recognize that many emergency managers may have never heard of space weather and its potential effects, and one goal is for emergency managers to take more proactive actions such as registering for SWPC alerts and to begin developing response plans. Continuity of operations planning ensures that emergency managers can continue to operate or have built-in contingency plans, which requires an understanding of the stakeholder’s current system and its vulnerabilities.

6.2 Technological Vulnerabilities

EM stakeholders are primarily concerned with space weather impacts to satellites, communications, and power grids, but they also need to be aware of any systems that could potentially be impacted by space weather. However, there is a gap in knowledge between emergency managers and those in the sectors that emergency managers are concerned about. Some stakeholders assume that many sectors, such as the electric power sector, are likely more advanced in terms of planning and risk assessments than the EM sector. They recognize the need to better understand where these sectors are in their preparations so that the EM sector is better able to provide adequate support. Specifically, emergency managers have some understanding of what

[47] K. Russell, “US Government Seeks to Improve Space Weather Awareness,” *Via Satellite*, June 28, 2017, https://www.satellitetoday.com/government-military/2017/06/28/will-us-government-respond-space-weather-emergency/.

utilities do in the event of a geomagnetic storm, but they do not have the same level of understanding in the event of said storm of the utility itself and therefore need to establish working relationships with utilities on these and other events. While industry is largely responsible for taking action, the EM sector is concerned about collateral damages, being able to respond in a timely manner, and extreme consequences.

Emergency managers recognize that because many in their field are unaware of space weather, there is a lack of redundancy within existing operational plans, and, ultimately, a lack of understanding of technological vulnerabilities. Specific to the EM community, stakeholders need an understanding of the vulnerability of equipment essential to emergency response operations, including communications and positioning capabilities.

6.3 Use of SWPC Products and Services

The EM sector varies in its preparations and investments for space weather, which are largely driven by the perceived vulnerability and understanding of space weather by emergency managers. Many emergency managers do not subscribe to SWPC products and cited the primary reasons for this as too much information is released, it is difficult to decipher the information, it is unclear what is important, and they are unsure of what should or should not warrant an EM alert. Likewise, those who subscribe to products have a difficult time using the products and finding ways to make them applicable to their work. In the case of terrestrial weather, emergency managers can contact their local NWS office with questions, whose staff understand context for the questions and are familiar with the areas at risk. Additionally, some emergency managers take NWS products issued for the region and distill the information for local impacts. Emergency managers would like to be able to perform similar repackaging for space weather. In particular, the emergency managers consistently noted the need to be able to translate SWPC information into potential impacts, as this is the basis of their planning and response to events. The non-federal emergency managers also noted the current spatial scale and limited lead time with the current warning products would be insufficient for their work in terms or relaying actionable messages to the public or other agencies in their jurisdictions.

Stakeholders are also familiar with the SWPC EM dashboard, although most are currently unable to use it because it requires an extensive familiarity with SWPC products. For example, the general interpretation is that a red scale indicates that somewhere on the planet a high-level event is happening. However, knowing there are specific variables that determine the impact, such as geomagnetic latitude, requires extra knowledge that most emergency managers do not have. Stakeholders specifically discussed trying to use Geospace Ground Magnetic Perturbation maps,[48] which are complicated because there are no instructions for how to use them. Emergency managers are also unclear on how to describe the impacts of space weather to the public and other emergency managers.

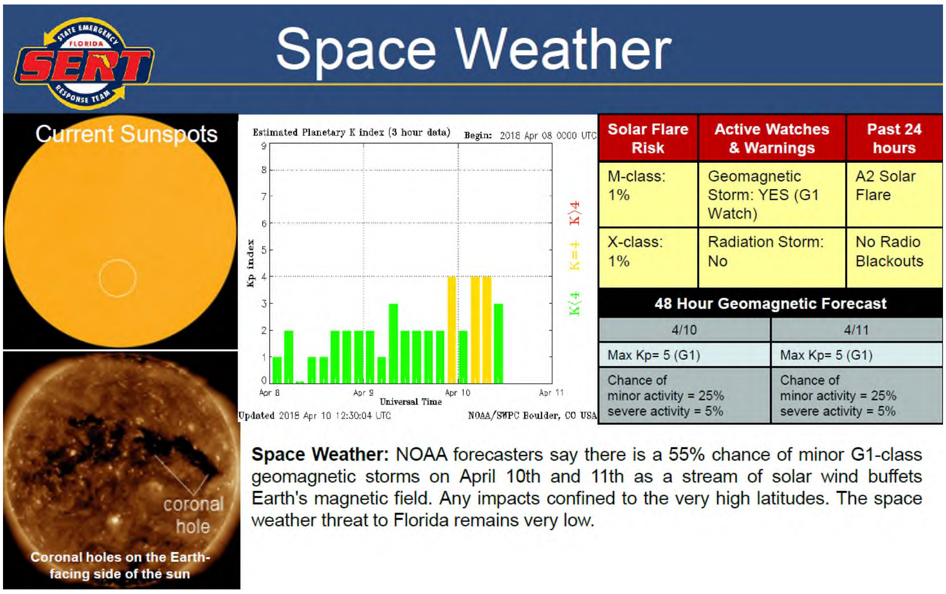
More advanced EM divisions have conducted several in-house training sessions and incorporate space weather as a specific item within their daily situational reports similar to the Federal Emergency Management Agency (FEMA) daily outlook. Their reporting is focused on explaining the impacts of space weather events and using graphics, the preferred format for emergency managers. For example, the State of Florida produces a daily situational report that is released to all counties and state agencies (for an example see Figure 9). It includes the overall picture of space weather for the day and uses information from SWPC and other resources to provide helpful graphics.[49] This daily report also includes a picture of the solar disks, images of sunspots or coronal holes, and a bar graph of the observed Kp-index. Observations are then discussed, including the strongest flare over the past 24 hours, impacts to date, and any radio blackouts or storms. The forecast information includes the chance of more events and active watches or warnings, which are verified from several sources. Finally, a brief text statement summarizes the overall picture of space weather for the day and provides a synthesis of all the graphical information (e.g., "*Today the solar disk is*

[48] SWPC Geospace Ground Magnetic Perturbation maps, https://www.swpc.noaa.gov/products/geospace-ground-magnetic-perturbation-maps.

[49] Specifically, websites referenced as having particularly helpful graphics include http://spaceweather.com/ and http://www.solarham.net/.

quiet in terms of sunspots; however, we may get minor geomagnetic storming due to the solar wind from the coronal hole”).

Figure 9. Florida EM example of daily situational space weather report that focuses on observations, forecasts, and use of graphics.



Stakeholders prefer to explicitly describe impacts to other EM offices rather than just forward alerts because the alerts tend to send EM offices into a state of chaos due to a misunderstanding of the information related to warnings provided in the alerts. For example, stakeholders will specify that the anticipated impacts are for high latitudes and will not impact their state.

Ultimately, the EM sector would like to use SWPC information for preparations and pre-staging responses. Knowing that a geomagnetic storm is coming and the anticipated impact, such as power outages, will allow locals to have generators fielded and other necessary resources mobilized, which is not possible to do after an impact has already occurred. Emergency managers have recommended responses to mimic those for other hazards such as hurricanes.

6.4 Product Needs and Attributes

Forecasts and Alerts

The EM sector needs more precise information sooner, with much more spatial precision by location, in order to make proper preparations. The current state of available information in SWPC notifications generally leaves emergency managers waiting until after an event or impact to understand the significance of the event and how to respond. With accurate information on the event’s strength and severity, a lead time of one to two days would be ideal for the EM community. A lead time of one day would allow sufficient time to alert the community on a possible space weather hazard. The St. Patrick’s Day storm in 2015, for example, was initially a G1 watch but ended up producing a G4 storm, and emergency managers struggled to get the word out and were forced to respond to numerous calls with on-the-fly insight and recommendations. Clear information on the impacts is also critical, including a reference to the hazard and the NOAA scale.

The EM sector ultimately is focused on the need to understand what impacts can be expected and what actions they should be taking in preparation for space weather events. During an event, emergency managers need to be able to transmit information in a timely manner as the storm unfolds. They recognize that extreme space weather is a low-probability event, but they still need information on hand to inform their vulnerabilities and monitor events, and an understanding to ensure they take the right actions. This will require establishment of EM responsibilities since many EM offices do not operate 24/7.

Existing SWPC observations and warnings also need to be geographically relevant and clear. Terms such as "geomagnetic latitudes" are very different from the standard suite of warnings that emergency managers typically handle. A statement such as, "*There is a high probability that the Northeast could experience impact X*," would enable emergency managers to provide appropriate alerts and to assess if specific areas may need more attention. This would also allow the EM sector to alert staff that they may need to come into work to respond to a hazard. The key attribute identified across the EM sector is localized information. Emergency managers work in a set geographic area, and they need familiarity with the area they manage.

Stakeholders also had suggestions for SWPC alert products. Some stakeholders do not subscribe to alerts because they find the information difficult to understand and lacking critical details for their purposes. The EM sector emphasized the need for information to be shared in ways that allow non-technical people to clearly understand the issues and vulnerability. Communication products should describe potential vulnerabilities across sectors, with products starting with specific sectors and impacts rather than products starting with a focus on the space weather phenomenon and associated scientific details. This format would be an improvement over having impact information buried and potentially lost in product descriptions.

Some stakeholders believe alerts should remain text-based products because smaller communities or states may not be able to understand high-technology data. However, the wording needs to be revised and translated so that it can be understood by emergency managers. Rather than alerts reading, "*S1 minor, no significant active regions favorable for radiation storms*," stakeholders recommend the following: "*There is a possibility that the Southwest region may be impacted by solar storms and the following sectors may be impacted: GNSS, communications, etc.*" Providing the warning by region will inform which people need to be prepared, and defining impacts provides a clear link to recommended actions.

Stakeholders also believe that watches and warnings could be relayed to the public in a more readily understandable format. Stakeholders recommend adding a scrolling banner during a watch or warning that could catch people's attention and provide links to get additional information. Emergency managers also suggest that SWPC provide explicit context to support the interpretation of products. For example, a Bz of 5 (in the stoplight-scale banner) is considered a normal day-to-day value, but a Bz of 50 or higher suggests abnormal activity. However, many people are not currently familiar with this information and cannot assess normal versus abnormal and potential resulting impacts. In general, the emergency managers noted that scientific details in the message were distracting for their purposes and the critical information they needed related to elements of the impacts defined by the questions, When and where will it happen?; How long will it last?; and, How bad will it get?

Emergency managers would like forecasts and nowcasts with impacts clearly delineated on a map, instead of only the banner of scales and stoplight colors. They suggested that a simple box outlining the warning area would be more helpful than interpreting scales. The standard unit of warning in terrestrial weather is a county, which might be too small for space weather; a state level would be acceptable, as well as specific states within a region. A list of all the technologies that could be vulnerable to the event would also be helpful. While there is much interest in understanding the different effects based on the type and characteristics of an event that determine its magnitude, there remains a huge gap in the state of knowledge, and emergency managers ultimately need to know what systems they should be concerned about. For example, when an event is defined as a G1 watch, a user has to perform searches on the SWPC website to determine that G1 impacts would occur > 60 degrees. Stakeholders would prefer that all of this information is put on a map with a defined impact area, which would let users know exactly where on the globe these impacts are expected.

Communication

Stakeholders described prior conversations about potentially training a regional NWS meteorologist at SWPC, who would then return to the local office to serve as the space weather point of contact for emergency managers, and others, in the region's service area. This would be helpful since emergency managers have existing and trusting relationships in place and interact regularly for other needs. The adoption of a national and local center structure could follow the terrestrial weather chain-of-operations framework. Prior to a storm's onset, emergency managers look to the national level; however, during a storm event emergency managers turn to the local Weather Forecast Office (WFO) to report hail or downed tree observations. Emergency managers discussed the need for a local office to gather impact reports and for real-time geospatial information about on-the-ground impacts. A local office could also provide emergency managers with real-time geospatial information about on-the-ground impacts to understand what happened, the damages and injuries, and if a response is needed.

Similarly, emergency managers would like more contact with SWPC and clear pathways of communication at the national and local scales to answer localized questions. The localized information needs range from understanding what a solar storm hazard means for a city or county to local characteristics, such as complex geology. To address this requires mapping at a more granular level to better understand what is and is not most likely at risk. Emergency managers have information on infrastructure such as power plants, power lines, substations, and transformers, but they do not have a sense of how it all interacts and how it translates to vulnerability. Specifically, emergency managers would like hazard maps for different types of space weather phenomena that can impact technologies essential for EM. Then, emergency managers could identify key parts of the critical infrastructure that are most vulnerable, identify potential consequences, and work on corresponding mitigation and response plans. The information available in most SWPC communication products is seen as complicated, vague, and at a resolution inconsistent with detail most emergency managers need for planning purposes. The U.S. Geological Survey (USGS) is working on developing a geoelectric hazard map[50]; however, there is still a challenge in understanding how to transform this general assessment into regional or localized planning.

Some emergency managers also described a gap in understanding space weather standards and preparations for utilities such as the power sector, and noted they have had little contact and considerable difficulty extracting details regarding space weather planning and response efforts from larger utilities. For example, while local emergency managers typically know the point of contact for other utilities, especially at smaller cooperatives where it is easy to quickly find the right contact, they do not have a similar point of contact for space weather events at larger utilities. Emergency managers are interested in developing space weather contacts with critical infrastructure representatives in order to understand vulnerability concerns and how emergency managers can provide support. This area is where SWPC could facilitate contacts and provide education support to emergency managers, as well as work with EM at the federal scale to develop guidance for state and local emergency managers. Further, stakeholders believe it would be helpful to have a workshop with representatives from the critical infrastructure industry to understand what the industry has learned from their vulnerability assessments and to discuss how this information can be used for emergency managers to develop their plans, instead of reconstructing separate plans. Emergency managers cited examples for this direct contact, noting how past federal assessments have been performed for sectors such as the rail industry, but the local level rarely receives or is able to access these assessments. In regard to preparedness, a significant need for the EM community and any agency that has a need to protect is a better understanding of asset vulnerability to space weather. An entity or purchaser for emergency communications needs to at least understand what equipment has higher vulnerabilities to different types of space weather events. Emergency managers suggest this will require SWPC and industry to work better with one another and for industry to better explain their work. Ultimately, there is a need to understand how systems fare during a space weather event.

Education and Training

Stakeholders believe that SWPC currently has great sites and information for scientists but fewer accessible resources and information for non-scientists. Because of the knowledge gap in space weather, stakeholders recommend an education initiative to better communicate the hazard and potential impacts. In addition, the

[50] J. Love et al., "Geoelectric hazard maps for the continental United States," *Geophysical Research Letters* 43 (2016): 9415–9424, doi:10.1002/2016GL070469.

education needs to be geographically relevant. It would be helpful to have webinars that help emergency managers understand SWPC products and how to interpret and use the items listed on the EM dashboards. While some of the EM regions are increasingly contacting SWPC to improve their awareness and understanding of space weather, SWPC could engage with EM communities in the public and private sectors to describe their work and the latest relevant information. They also recommend that SWPC invite and target the EM community to participate in conferences to build this knowledge base.

In addition to needs from SWPC, emergency managers have the desire to adopt economic impact studies performed for various hazards to inform their investments in space weather hazard preparations. However, emergency managers need more technical information to know where to invest (e.g., sensors, plan development). The EM sector recommends a broader education initiative before introducing the topic so that a larger sector is aware of space weather and gains knowledge. This will require a clear campaign to educate people so that they understand they are not prepared for an event and how they can respond. This audience might include the private sector, such as large retailers who have their own emergency managers.

SWPC Website and Tools

EM stakeholders identified tools that they would like to see developed based on NOAA-NWS tools they already use. Existing sophisticated systems like the NWSChat instant messaging program are highly regarded by emergency managers for communicating impacts and flooding information. The EM community would like a tool similar to this, especially during busy solar periods, which could be used to ask questions and report information. Emergency managers also discussed the need to train local NWS staff, which would equip them and allow for space weather to be easily integrated into NWSChat. Because the scope and available resources of EM programs varies across the United States, taking advantage of an existing platform or system will allow it to be more widely adopted. Additionally, NWSChat is a mature system, and NWS has the exclusive responsibility to issue warnings. This is important because emergency managers declare action in response to trusted NWS terrestrial warnings and have systems in place to send alerts to television, radio, and other mechanisms. However, for space weather, emergency managers are not aware of who to contact or how to warn people. One recommendation is to develop a pilot program with a few jurisdictions, in which NOAA and others could provide instruments and training to assess the value of localized monitoring and response preparations.

Stakeholders referenced a number of sites as examples of how to better present information visually, but prefer SWPC's streamlined and less-busy website. For example, http://spaceweather.com has several images and clear descriptions upfront to describe current space weather conditions. Stakeholders recommend adding a headline above NOAA scales banner that provides a high-level overview of the event's current status. This might be a simple statement such as, "*Space weather is quiet today*" or "*Minor storming today due to solar wind,*" with a few images and possibly bulleted main points with links to additional information. Another user friendly resource is http://solarham.net, which pulls products from SWPC and repackages them in a different format to provide a clear story. This is important for emergency managers who do not like searching through multiple links and pages for the information they need. Stoplight charts are helpful for emergency managers and provide intuitive interpretations of the information, specifically identifying what information users should pay attention to.

6.5 Summary of User Data Product Requirements

The four interviewees identified 10 distinct product requests for the EM sector.

Request 1: Provide forecasts with one to two days lead time. The EM sector needs more precise information sooner, with accurate information on the event's strength and severity. A lead time of one day would allow sufficient time to alert the community on a possible space weather hazard.

Request 2: Tailor warnings to specific geographies. Existing SWPC observations and warnings also need to be geographically relevant and clear. An S statement such as, "*There is a high probability that the*

Northeast could experience impact X,” would enable emergency managers to provide appropriate alerts and to assess if specific areas may need more attention.

Request 3: Develop impact-based products. Experts recommended providing communication products that describe potential vulnerabilities across sectors, with products starting with the specific sectors and impacts rather than products starting with a focus on the space weather phenomenon and associated scientific details.

Request 4: Produce graphical forecasts. Emergency managers would like forecasts and nowcasts with impacts clearly delineated on a map, instead of only the banner of scales and stoplight colors. They suggested that a simple box outlining the warning area would be more helpful than interpreting scales. These products would be most useful if they were at the state level.

Request 5: Train regional points of contact or develop local space weather offices. Stakeholders recommended training a regional NWS meteorologist at SWPC, who would then return to the local office to serve as the space weather point of contact for emergency managers in the region’s service area. Emergency managers discussed the need for a local office to gather impact reports and for real-time geospatial information about on-the-ground impacts.

Request 6: Develop hazard maps for different space weather phenomenon. Emergency managers would like hazard maps for different types of space weather phenomenon that can impact technologies that are essential for EM. Then, emergency managers could identify key parts of critical infrastructure that are most vulnerable, identify potential consequences, and work on corresponding mitigation and response plans.

Request 7: Facilitate communication between emergency managers and industries impacted by space weather. Emergency managers are interested in developing space weather contacts with critical infrastructure representatives in order to understand vulnerability concerns and how emergency managers can provide support. Stakeholders believe it would be helpful to have a workshop with representatives from the critical infrastructure industry to understand what the industry has learned from their vulnerability assessments.

Request 8: Create an education initiative to communicate space weather impacts. Stakeholders recommend an education initiative to better communicate the hazard and potential impacts. It would be helpful to have webinars that help emergency managers understand SWPC products and how to interpret and use the items listed on the EM dashboards.

Request 9: Provide information on economic impacts of space weather. Emergency managers want to adopt economic impact studies performed for various hazards to inform their investments in space weather hazard preparations but need more technical information to know where to invest. The EM sector recommends a broader education initiative before introducing the topic so that a larger sector is aware of space weather and gains knowledge.

Request 10: Develop tools for space weather communication like NWSChat. Existing sophisticated systems like the NWSChat instant messaging program are highly regarded by emergency managers for communicating impacts and flooding information. The EM community would like a tool similar to this, especially during busy solar periods, which could be used to ask questions and report information.

7 Key Findings and Conclusions

This study uses information provided in a series of interviews with industry experts to develop an assessment of customer usage and needs of historical, forecast, and nowcast space weather products and services. The industry experts were able to inform us about the uses of and needs for space weather products and services. Participants from engineering and operations provided perspectives from the electric power, satellite, GNSS, and aviation sectors. Emergency managers were interviewed as well. Our interviews also included discussion of technological components affected by space weather in the respective sectors, and potential future trends with respect to these vulnerabilities based on their understanding of technological improvements and engineering advances and trends.

A critical overall theme emerged through the interviews: many stakeholders in industries that are potentially vulnerable to experiencing adverse impacts from space weather events are generally unaware of these potential risks and of the products and services provided by SWPC that might help them mitigate potential impacts. At the same time, our interviews also revealed that even among the subset of experts who are aware of space weather, many are not able to interpret the products and apply the technical information to support or improve their decision-making. This lack of understanding in turn is reflected in a number of the requests for SWPC that are infeasible given current technology or the basic characteristics of the event (e.g., deterministic flare forecasts). However, many interviewees are well-versed in space weather and were able to provide valuable suggestions for SWPC.

This study was designed to provide a tractable framework that will allow for ongoing customer feedback. The feedback will support ongoing assessment of vulnerabilities, technology, and requests for space weather information and services. While the information collected focused on specific product parameters such as lead time, cadence, and uncertainty and the format of delivery to end users, several key themes and findings emerged. These requests for additional information are summarized below.

Increased Forecast Precision and Lead-Time

Interviewees across sectors expressed a desire for more precise forecasts. These forecasts would predict space weather events earlier. Earlier warnings with a greater degree of confidence in their accuracy would allow stakeholders to use forecasts to mitigate the impacts of space weather. If the accuracy of a forecast is not able to be improved, many stakeholders expressed a desire for some measure of confidence to be provided with a forecast to communicate the forecast's certainty, such as through confidence intervals. However, improvements to the precision and warning time of forecasts are currently constrained by the limits of current science.

Localized Forecasts

Interviewees also consistently requested that forecasts be provided for more localized areas. Current forecasts used by interviewees provide warnings on a global scale, in general, and most stakeholders do not operate at that level. Forecasts that provide stakeholders with warnings on a sub-global scale would have more utility because stakeholders would have more confidence that the predicted space weather event would impact their operations and be more likely to take action based on the forecast. However, similar to improvements to the precision and warning time of forecasts, opportunities for improvements to the spatial scale of forecasts are limited by current science.

Historical Data Products

Interviewees across sectors expressed a desire for improved access to historical space weather data. These data are important for assessing past conditions to better understand relationships between observed/forecast conditions and historical impacts. These data in turn help with the development of mitigation strategies both by helping determine what actions would have been needed to avoid impacts, the potential level of impacts that might be avoided with certain measures, and how frequently events of varying severity might occur. Interviewees who currently use SWPC's historical data for engineering and operations noted challenges in being able to readily access the data with the current website, easily select and retrieve data from particular periods of interest, or search the data for using queries to return data on events with specific characteristics.

Plain-Language Products

Because of the relatively limited awareness and understanding of space weather in many sectors, interviewees emphasized the need for non-technical descriptions of space weather information. Interviewees believe current SWPC products are tailored for a scientific audience, which limits the ability for non-scientists to understand and fully incorporate pertinent information into their operations. If forecasts and other products included plain-language descriptions along with more technical information, the interviewees believe they would be useful for both scientific and non-scientific audiences.

Impact-Based Products

Interviewees across all sectors recommended SWPC provide products that tie space weather phenomena to sector-relevant impacts. For example, if users receive an alert warning them of potential GNSS errors rather than technical details of ionospheric scintillation, they will be more likely to review and revise operational decisions as necessary. Impact-based products were also viewed as a measure that could help bridge the gap between those who are very aware of space weather and those who are not. With this request, interviewees also noted that the SWPC could look to a number of other weather and forecast products produced by NOAA that interviewees believed might provide useful templates. A specific example offered was the tropical storm forecast maps that include information with respect to timing, location, potential severity of impacts, and uncertainty. A related element of this request concerned a desire for explicit recognition of times without events being tracked or forecast. Having an "all clear" status among the information the SWPC could provide was seen as beneficial for the relative certainty it would provide, which could be used to help schedule critical operations and maintenance activities.

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