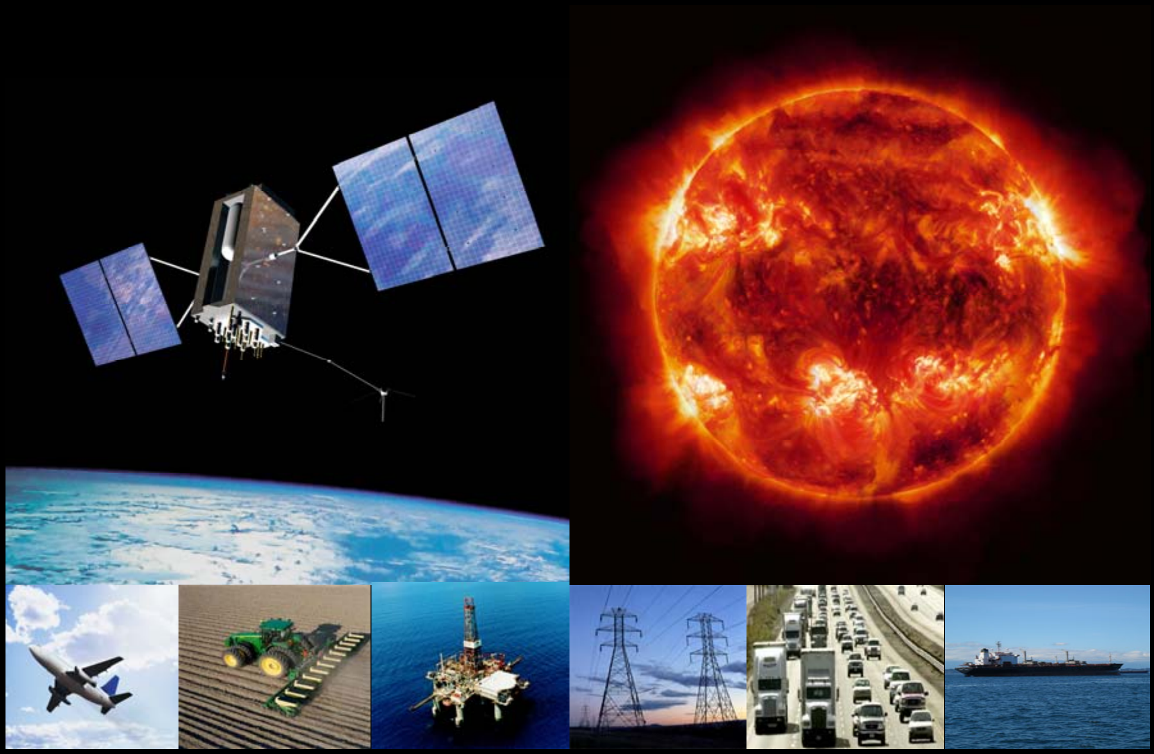
Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience



American Meteorological Society
Policy Workshop Report
March 2011

Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience

Report of a Policy Workshop

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Policy Workshop Report

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Preface

This report of a policy workshop on "Satellite Navigation & Space Weather: Understanding the Vulnerability and Building Resilience" presents recommendations that, if implemented, could help build the resiliency of our critical infrastructure that depends upon the Global Positioning System (GPS). Many of the recommendations are also consistent with those from the National Science and Technology Council (2005)'s Subcommittee on Disaster Reduction space-weather-specific implementation plan and the National Space Weather Program (2010)'s current strategic plan.

The American Meteorological Society (AMS) developed this workshop as part of a broader policy study, funded by the National Science Foundation (NSF), to examine policy issues in implementing an effective application of space weather services to GPS operations. The workshop brought together a select group of policy makers, space weather scientists, and GPS experts and users.

AMS sincerely thanks all of the workshop participants for their openness and contributions to the discussions and report. We are grateful to the speakers and moderators for stimulating the discussions. We appreciate the efforts of Jennifer Meehan and Christy Henderson, who documented the workshop discussions. We also thank the workshop industry supporters: ITT Corporation, Northrop Grumman Corporation, SAIC, and Lockheed Martin Corporation, and the government supporters: NASA, NOAA, and NSF.

We would like to especially acknowledge several individuals who were extremely valuable in helping us formulate the workshop: Joe Kunches (NOAA/SWPC), Bill Murtagh (NOAA/SWPC), Paul Kintner (Cornell University), Patricia Doherty (Boston College), and Jennifer Meehan (Utah State University).

Finally, this report is dedicated to the memory of Dr. Paul Kintner, a pioneer in studies of Earth's space environment and of space weather. In his signature way, Paul helped plan the workshop but was too ill to participate and passed away soon after on November 16, 2010. Paul was an internationally recognized authority on the interaction of radio signals—both natural and manmade—with space environments, particularly the ionosophere and magnetosphere. His research included the effect of the space environment on GPS signals. Paul was an outstanding scientist, colleague, and mentor to many people, and his work will continue to have a lasting effect in the space weather and GPS engineering fields.

Dr. Genene Fisher

AMS Policy Program

Executive Summary

Since the last solar maximum in 2000, societal dependence on the Global Navigation Satellite System (GNSS) has increased substantially. Critical applications, such as railway control, highway traffic management, precision agriculture, emergency response, commercial aviation, and marine navigation, require and depend on GNSS services. Everyday activities, such as banking, mobile phone operations, and even the control of power grids, are facilitated by the accurate timing provided by GPS, which is just one component of GNSS. As our national critical infrastructure and economy are increasingly dependent on positioning, navigation, and timing (PNT) services, our society is vulnerable to disruptions that can be caused by space weather or variable conditions on the Sun and in the space environment that can influence space-borne and ground-based technological systems.

Just as society takes for granted that electricity, heat, and clean water will be available, it also takes for granted that GPS will be available, reliable, and accurate. GPS is so entrenched in the daily activities of individuals, businesses, and government that any loss of satellite navigation services would be broadly disruptive. For example, effects can range from errors in a farm tractor's onboard navigation system to positioning errors for oil drilling in the Gulf of Mexico to errors in an aircraft's location.

Today, the vulnerabilities of GPS are well categorized, and it is understood that space weather is the largest contributor to single-frequency GPS errors and a significant factor for differential GPS. Primary space weather effects on GPS include range errors and loss of signal reception. The GPS industry faces several scientific and engineering challenges to keep pace with increasingly complex user needs: developing receivers that are resistant to scintillation and improving the prediction of the state of the ionosphere. With GPS modernization, the use of additional signals is expected to reduce errors caused by the ionosphere. However, there are several steps that can be taken now to reduce the vulnerability of GPS and its applications to space weather.

Economic Issues

Civilian demand for GPS products surged in 2000, when the DOD ended its practice of intentionally degrading the satellite's signals for security purposes. Overnight, navigation devices became 10 times more accurate and quickly became standard equipment in numerous industries, from precision agriculture to oil drilling. One market research firm estimates that the worldwide GPS market will total $75 billion (U.S. dollars) by 2013. Therefore, any interruption can be detrimental to the economy and the safety of the nation's infrastructure. For example, from NOAA (2004),

- For a 15-hour period on October 29, 2003 and an 11-hour period on October 30, 2003, the FAA's GPS-based Wide Area Augmentation System (WAAS) was severely affected. The ionosphere was so disturbed that the vertical error limit was exceeded, rendering WAAS unusable.
- In late October 2003, an international oil field services company issued an internal "technical alert" via their worldwide network to alert their surveying and drilling staff on potential effects from solar storms. They reported six cases of survey instrument interference from sites around the world.

- In October 2003, the drillship *GSF C.R. Luigs* encountered significant differential GPS (DGPS) interruptions because of solar activity. These interruptions made the DGPS solutions unreliable. The drillship ended up using its acoustic array at the seabed as the primary solution for positioning when the DGPS solutions were affected by space weather.
- On December 6, 2006, the largest solar radio burst ever recorded affected GPS receivers over the entire sunlit side of the Earth. There was a widespread loss of GPS in the mountain states region, specifically around the four corners region of New Mexico and Colorado. Several aircraft reported losing lock on GPS.

Operational Issues

GPS receivers calculate their locations by analyzing signals from a constellation of satellites, but those signals can be delayed or distorted while passing through the ionosphere. Space weather phenomena, such as solar flares and geomagnetic storms, can result in errors in position and navigation and degraded or loss of signals. Such solar activity can affect the accuracy of single-frequency GPS receivers, while dual-frequency GPS receivers can better adjust to a disturbed ionosphere, but still experience some difficulty.

GPS is used by millions of people around the world. Many GPS users will experience little or no effect during geomagnetic storms, but those requiring precise GPS measurements have a great need for NOAA/SWPC alerts and warnings of problematic space weather conditions. Most vulnerable applications include: the FAA's WAAS and future Next Generation Air Transportation System (NextGen); surveying companies using GPS measurements for land surveying, topographic work, and property boundary analysis; deep-sea drilling operations; land drilling and mining; and various DOD operations.

The importance of GPS error mitigation and robust system development should not be undervalued in our ever-growing space-reliant economy. We need to strengthen the integrity and robustness of GPS, combined with more accurate space weather prediction and real-time correction services, to ensure the safety and viability of our economy.

Policy Workshop

To date, there remain gaps in our understanding of the risks of space weather to GPS and its applications and of how to build resilience. In response to this need, the AMS Policy Program conducted a policy study funded by the NSF to research key issues involving the need for and use of space weather information. In addition, AMS organized a workshop for October 13–14, 2010 in Washington, D.C. on "Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience" that led to recommendations on how to best characterize satellite navigation's vulnerability to space weather and how to build resilience for the future. The participants discussed options for resolving policy issues facing the GPS community, better equipping government and industry leaders to make effective decisions with respect to space weather and GPS. While space weather can affect the entire international GNSS community, the workshop focused on developing a U.S. perspective.

Workshop objectives included the following:

- Identify the vulnerability of GPS technologies and services to space weather.
- Identify how this vulnerability affects users who depend upon GPS.
- Discuss how the current policy framework builds resilience to these adverse effects.
- Develop additional opportunities and policies for building resilience, mitigating risk, and improving application of space weather information to GPS operations.

Recommendations

Participants agreed on a set of recommendations, which are discussed in detail within this report. The most critical recommendation was the following:

Recommendation: Strengthen the integrity and robustness of the GPS system and services by

- **Completing the modernization of the GPS enterprise.**
- **Ensuring backup systems.**
- **Developing better space weather predictions.**
- **Setting standards for satellites and receivers to handle extreme space weather conditions.**
- **Examining GPS resilience through an all-hazards lens.**

Here is a summary of the other recommendations:

Vulnerability of GPS to Space Weather

Although the ionosphere is known to be a major source of unintentional interference, an in-depth threat assessment has yet to be conducted on how space weather can affect GPS, its applications, and users. A threat assessment, the first step in a risk management program, considers the full spectrum of threats and evaluates the likelihood of occurrence for each threat. Workshop participants also agreed that there is no good *quantification* of the risk to systems that depend on GPS (e.g., communications, financial, and electric power). In addition, each federal agency needs to understand space weather and PNT issues for its own purposes. Therefore, the FAA needs to understand the effects to NextGen, the DOE needs to understand the effects to timing in electric power grids, and the DHS needs to understand the impacts on its communication system, just to name a few.

Recommendation: Develop a threat assessment to consider the full spectrum of space weather threats to GPS.

Recommendation: Define and quantify vulnerabilities for different user segments and systems.

Building Resilience: Science and Engineering

Resilience is the capacity of a system to absorb a disturbance, undergo change, and retain the same essential functions. High-priority science and technology investments, coupled with sound decision making, will dramatically enhance society's resilience and thus reduce vulnerability.

Workshop participants discussed how science and engineering can build resilience of the GPS system to space weather. They considered what new technical, observational, and modeling capabilities are needed to build resiliency. Several recommendations were agreed upon.

> **Recommendation: Support basic heliophysical and geophysical research aimed at understanding the fundamental physical conditions and processes that produce space weather and its effects. This should be a top priority for a community decadal survey.**
>
> **Recommendation: Conduct further research on ionospheric storms, gradients, and irregularities to better understand and predict the state of the ionosphere.**
>
> **Recommendation: Develop a long-term plan for ground-based and space-based ionospheric measurements that will allow for improved spatial coverage of ionospheric and atmospheric space weather parameters. These data must be gathered now to meet the urgent needs society already faces.**
>
> **Recommendation: Define and categorize user requirements in terms of accuracy, service availability, and integrity requirements.**
>
> **Recommendation: Develop better products to ensure timely, accurate, and advanced space weather warnings, specifications, and forecasts.**
>
> **Recommendation: Develop receivers for multifrequency tracking, with significantly improved performance during deep scintillation fades and interference.**
>
> **Recommendation: Develop more quantitative standards for manufacturing and certifying the performance of GPS receivers.**

Building Resilience: Policy

Advances in science and technology alone cannot fully protect society from hazards. Research and major technology investments must be linked to effective policy decision making. Change must occur at both the policy level and in the societal perception of risk so that adoption and adaption keeps pace with advances in science and technology. Workshop participants discussed what measures could be taken to build resiliency and what additional policy options might be available for mitigating adverse effects of space weather, specifically in terms of investment and collaboration. Several recommendations were agreed upon.

Recommendation: Support a broad fundamental and applied research program in space weather/heliophysics to advance our present understanding of space weather and its impacts on GPS and other critical infrastructure.

Recommendation: OSTP and OMB should work with NASA and NOAA to support the transition from space weather research to operations, including the transition from research models to an operational environment, as well as the validation and improvement of existing models.

Recommendation: Develop a research-to-transition process that is iterative and carefully constructed based on deliverables in a stepwise process.

Recommendation: Create and strengthen partnerships to enhance awareness of and coordinated responses to space weather hazards to satellite navigation systems and operations.

Recommendation: Strengthen international collaboration to meet the future needs of PNT services and to reduce GNSS vulnerability to space weather.

Recommendation: Foster the exchange of ideas and information through user forums and other educational venues.

Recommendation: Develop and support a space weather–GNSS user office that collects information on space weather impacts and provides education and outreach to a broad base of users.

1. Introduction

Since the last solar maximum in 2000, societal dependence on the GNSS has increased substantially. Critical applications, such as railway control, highway traffic management, precision agriculture, emergency response, commercial aviation, and marine navigation, require and depend on GNSS services. Everyday activities, such as banking, mobile phone operations, and even the control of power grids, are facilitated by the accurate timing provided by GPS, which is just one component of GNSS. As our national critical infrastructure and economy are increasingly dependent on PNT services, our society is vulnerable to disruptions that can be caused by space weather or variable conditions on the sun and in the space environment that can influence space-borne and ground-based technological systems.

When GPS became fully operational in the mid-1990s and became widespread for civilian and personal use, it was unknown then just how much our daily lives and the economy would become reliant on PNT services. GPS transitioned from a long-range navigation and civil positioning technology to a leisure technology, and eventually to a critical infrastructure. With the United States's GPS and Russia's GLONASS, and soon with the addition of Europe's Galileo, China's Compass, and Japan's QZSS, the application by civil users of global PNT services has rapidly expanded around the world. Just as society takes for granted that electricity, heat, and clean water will be available, it also takes for granted that GPS will be available, reliable, and accurate. GPS is so entrenched into the daily activities of individuals, businesses, and government that any loss of satellite navigation services would be broadly disruptive. For example, effects can range from errors in a farm tractor's onboard navigation system to positioning errors for oil drilling in the Gulf of Mexico to errors in an aircraft's location. See Figure 1 for further examples of GPS dependencies.

Today, the vulnerabilities of GPS are well categorized and it is understood that space weather is the largest contributor to single-frequency GPS errors and a significant factor for differential GPS (DOT, 2001; Kunches, 2007). Primary space weather impacts on GPS include range errors and loss of signal reception. The 2008 U.S. Federal Radionavigation Plan states that the only practical way to mitigate errors in GPS accuracy due to space weather is to utilize models to predict the magnitude of these events and provide correctors for real-time high-accuracy positioning and navigation applications. The GPS industry faces several scientific and engineering challenges to keep pace with increasingly complex user needs: developing receivers that are resistant to scintillation and improving the prediction of the state of the ionosphere.

Worse still, assessment of GPS-related societal vulnerabilities and identification of coping strategies are attempting to hit a moving target—the emergence of GPS as a technology and its use by society are rapidly evolving in a short period compared to a single solar cycle (about 11 years). So, how can we gain a better understanding of what exactly are the GPS users' vulnerability to space weather? What can the public and private sectors do to create a better path for moving forward? By better understanding the risks and preparing the GPS community with strategies for mitigation, potential disasters can be avoided.

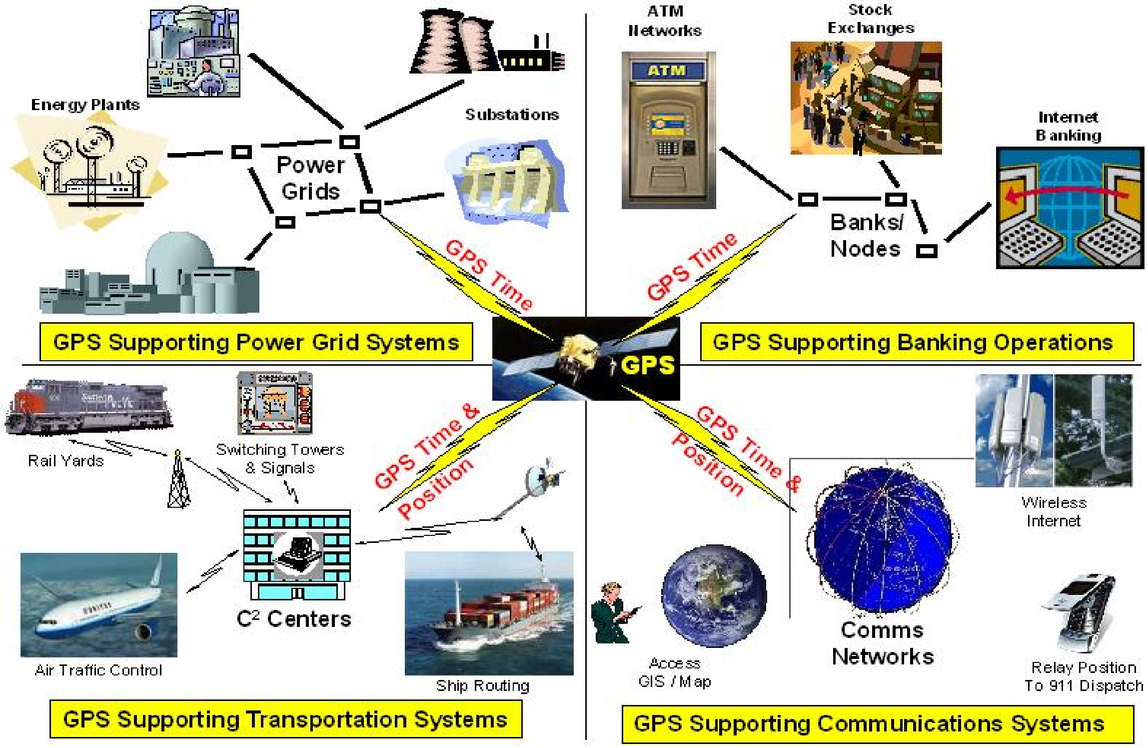

Figure 1. Examples of GPS dependencies (source K. VanDyke, DOT).

a. GPS Policy

For more than two decades, the U.S. government has maintained consistent, forward-looking policies encouraging the worldwide use of GPS and other space-based PNT services. U.S. policy has facilitated global innovation and competition, leading to new industries and applications based on GPS technology.

In 2000, when the government turned off selective availability (SA), the intentional degradation of the accuracy of the single-frequency GPS position by the DOD, it was known that distortion of the GPS signal as it travels through the ionosphere would now be the largest error source. Soon after, the Department of Transportation's (DOT) Volpe Center published a report titled "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System." In that report, they identified ionospheric interference as the largest source of error in GPS and that it could lead to significant degradation of the accuracy of differential GPS (DGPS) corrections. Periodically, users of single-frequency receivers would notice disruptions caused by ionospheric delays and scintillation. The assessment called for public policy to ensure that safety is maintained in the event of loss of GPS. Investing in a GPS backup was strongly advocated while realizing it may not be necessary, or cost effective, to require a backup navigation system for every application.

The current U.S. space-based PNT policy, in effect since 2004 and which replaced the U.S. GPS policy issued in 1996, calls for and requires providing uninterrupted access to U.S. space-based global, precise positioning, navigation, and timing services for U.S. and allied national security systems and capabilities through GPS.

In 2008, the government released its updated radionavigation plan. The report noted that large errors and rapid changes in GPS positional accuracy can occur during significant space weather and tropospheric weather events. The plan suggested that the only practical approach to mitigate this problem is to utilize space and lower-atmospheric weather models that assimilate all available observations to estimate and predict the magnitude of these events and to provide correctors for real-time high-accuracy positioning and navigation applications.

In June 2010, President Barack Obama signed a new national space policy addressing all U.S. government activities in space. It retains the U.S. space-based PNT policy while adding an overarching goal statement and reaffirming U.S. commitments to GPS service provision, international cooperation, and interference mitigation. One of the provisions states that the government will "invest in domestic capabilities and support international activities to detect, mitigate, and increase resiliency to harmful interference to GPS, and identify and implement, as necessary and appropriate, redundant and back-up systems or approaches for critical infrastructure, key resources, and mission-essential functions" (Obama 2010).

Currently, the U.S. lacks a national capability to protect critical infrastructure and key resources (CIKR) sectors by rapidly detecting, locating, identifying, and mitigating civil GPS interference.[1] This workshop report addresses one component of this issue—how to build resilience to space weather.

b. Policy Workshop

AMS organized a workshop for October 13–14, 2010, in Washington, D.C. on "Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience" that led to recommendations on how to best characterize satellite navigation's vulnerability to space weather and how to build resilience for the future. The participants discussed options to resolve policy issues facing the GPS community, better equipping government and industry leaders to make effective decisions with respect to space weather and GPS. While space weather can impact the entire international GNSS community, the workshop focused on developing a U.S. perspective.

[1] As noted in U.S. Policy for Space-based Positioning, Navigation, and Timing (PNT) (NSPD-39)

The workshop was supported in part by ITT, Lockheed Martin, Northrop Grumman, SAIC, NASA, NOAA, and NSF.

Participants included GPS government and industry leaders, space weather scientists and information providers, and policy makers. The number of workshop participants was intentionally kept small to enhance discussion. The program and focus questions are in Appendix C, and the participant list is in Appendix D.

Workshop objectives included the following:

- Identify the vulnerability of GPS technologies and services to space weather.
- Identify how this vulnerability affects users who depend on GPS.
- Discuss how the current policy framework builds resilience to these adverse effects.
- Develop additional opportunities and policies for building resilience, mitigating risk, and improving application of space weather information to GPS operations.

The workshop consisted of a series of background presentations followed by three discussion sessions, each designed to answer the focus questions and develop a set of findings and recommendations. These sessions were based on understanding vulnerabilities of GPS, consequences of space weather on GPS, and building resilience. The workshop concluded with a final discussion among all participants on the findings and recommendations that are included in this report. This report was circulated to all workshop participants for review before publication.

c. Space Weather Effects on GPS

GPS signals, as they leave the satellite at 20,000 km, pass through a vacuum until they get to the last few percent of their journey. They encounter the bulk of the free electrons around 350 km, and it is these electrons that affect the speed at which the signal propagates. The signals travel at the speed of light through space, but they are slowed slightly by varying degrees as they pass through the ionosphere. Normal and unusual solar activity can produce variations in the effect of the ionosphere on GNSS signals (Figure 2). Ionospheric models remove much of the variability as possible, but there are small-scale components that create errors in the position fixes. The GPS modernization program will add additional civil frequencies that will allow GPS users to better calculate the position error due to the ionosphere. For further details on space weather phenomena refer to Appendix B.

TEC-Induced Signal Delays

As GPS signals propagate through the ionosphere, the propagation speed and direction of the GPS signal are changed in proportion to the varying electron density along the line of sight between the receiver and the satellite. The accumulated effect, by the time the signal arrives at the receiver, is proportional to the integrated total electron content (TEC), the number of electrons in a column stretching from the receiver to the satellite with a cross-sectional area of one square meter. This in turn affects the GPS range observable: a delay is added to the code measurements and an advance to the phase measurements. To achieve very precise positions from GPS, this ionospheric delay/advance must be taken into account (Coster et al. 2008).

The ionosphere’s effect on satellite navigation range measurements is highly variable. During a low solar activity period, the uncorrected ionosphere would typically cause vertical (zenith) range measurement delays from 1 m at night to 5–10 m during the day. During peak periods of solar activity, the delay can vary from 1 m at night to 100 m during the early afternoon (Misra and Enge 2006). Even more important from a navigation perspective is that there can be large spatial gradients in the ionosphere’s effect on range measurements. Depending on the type of receiver used, the gradient could cause significant position errors.

It has been determined in more recent history that the variability of the ionospheric delay is highly correlated with the sunspot number. During solar maximum periods, the increased solar activity causes the sun to send out bursts of high-energy X-rays and protons that increase the density and thickness of the ionosphere. This activity also increases the electron content of the ionosphere, which directly contributes to changes in the range measurements from GNSS satellites.

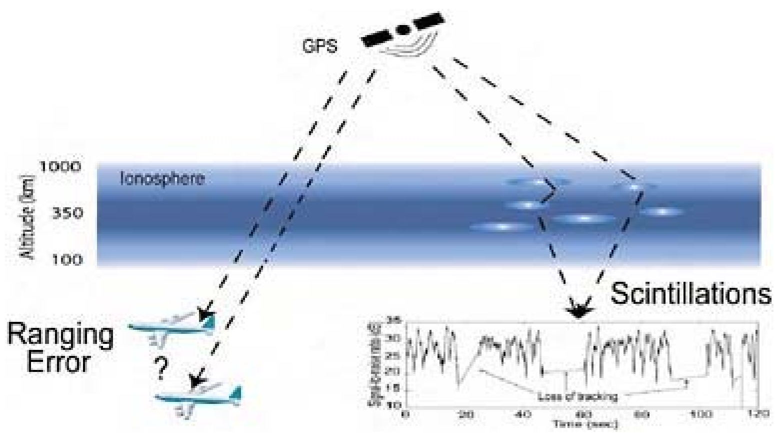

Figure 2. Ionospheric-induced GPS errors. Ionospheric range delay results from normal signal propagation through the ionosphere. Scintillation results from severe ionospheric signal scattering (Kintner 2008).

Scintillation

When a radio wave crosses through the ionosphere, it results in a distortion of phase and amplitude. These fluctuations are called scintillation, which can act in a very different way and at different times of the day. Its effect is worse at or near solar maximum years because of increased high-energy emissions from the sun. However, with scintillation, the effect is to cause rapid variations in signal power, reducing the received power and phase coherence of the GNSS signals, which can cause a loss of lock on the signal. The loss of lock results in no GNSS measurement, as opposed to the range measurement errors previously discussed (Powell and Walter 2010). The frequency of these disturbances varies greatly based on the distance from the geomagnetic equator, as shown in Figure 3.

Fortunately, the effect of scintillation is minimal throughout much of North America, Europe, northern Asia, Australia, and New Zealand; however, much of South America and the equatorial regions in Africa and Asia are affected much more severely than other parts of the world. During periods near solar maximum years, the red areas in Figure 3 will experience intense scintillation on the order of 100 days per year, while the dark blue areas less than 10 days per year (Kintner et al. 2009). Unlike the range errors that occur during daylight hours, scintillation mostly occurs during a time shortly after sunset, which is illustrated in Figure 3 for a specific time of day.

Solar Radio Bursts

Until recently, the ionosphere has been considered as the sole source of space weather effects on GNSS signals, systems, and navigation accuracy. Research now suggests there is a different class of space weather effects on these signals: solar radio bursts (Klobuchar et al. 1999; Cerruti et al. 2006; Carrano et al. 2009). On December 6, 2006, a solar flare created the most intense solar radio burst ever recorded. Solar radio bursts begin with a solar flare that injects high-energy electrons into the solar upper atmosphere. Radio waves are produced, which propagate to Earth and cover a broad frequency range. The radio waves act as noise over these frequencies, including those used by GPS and other navigational systems, which can degrade a signal. These bursts can have durations up to tens of seconds.

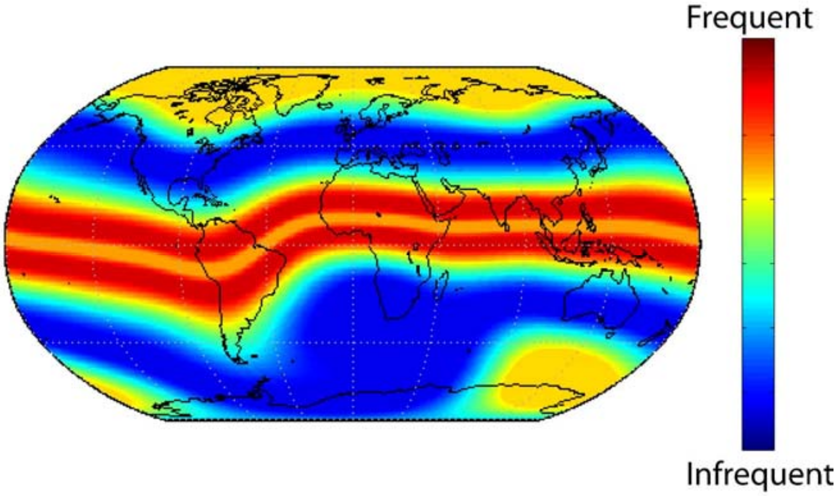

Figure 3. Scintillation map showing the frequency of disturbances at solar maximum. Scintillation is most intense and most frequent in two bands surrounding the magnetic equator, up to 100 days per year. It is less frequent at poleward latitudes, and it is least frequent at midlatitudes, a few to 10 days per year (Kintner et al. 2009).

Space Weather Impacts on Satellite Navigation

Geomagnetic Storms: Disturbances in the geomagnetic field caused by gusts in the solar wind that blows by Earth. Typical effects from geomagnetic storms include degradation of HF radio transmissions, satellite navigation degradation, and disruption of low-frequency radio navigation systems. Geomagnetic storms can also disrupt electrical power grids, and GPS operations are susceptible to these power outages. Geomagnetic storms also weaken the ability of the Earth's magnetic field to deflect incoming charged particles.

Solar Flare Radio Blackouts: Disturbances of the ionosphere caused by X-ray emissions from the sun. Low-frequency navigation signals may experience outages on the sunlit side of the Earth for hours, causing loss in positioning. Extreme events can cause increased errors in positioning for hours on the sunlit side of Earth which may spread into the night side.

Solar Radiation Storms: Elevated levels of radiation that occur when the numbers of energetic particles increase. Typical effects from solar radiation storms include degradation of satellite tracking and power systems. Induced positional errors to GPS are also possible.

Box 1. Summary of space weather impacts on satellite navigation (source: NOAA Space Weather Scales, Appendix E).

2. Vulnerability of GPS to Space Weather

When selective availability was turned off in May 2000, space weather became visible for the first time to GPS operations. It was then obvious that GPS was vulnerable to space weather and ionospheric fluctuations.

The two primary effects of space weather on GPS are:

1. Propagation delay of signals caused by the presence of the ionosphere. Result is increased errors in position and navigation.

2. Loss of signal due to scintillation effects caused by small-scale irregularities in the ionosphere. Result is increased errors due to the decreased number of useable satellites and the possible inability to navigate.

Within the last few years, scientists have discovered that solar radio bursts (a burst of radio energy from the sun) can act like noise and interfere with frequencies used by GPS and other navigation systems.

While space weather is the single largest contributor to single-frequency GPS errors, use of a dual-frequency application can minimize the errors. Augmented GPS users (e.g., WAAS) are less vulnerable to minor and moderate ionospheric disturbances; however, they can still be affected by scintillation, solar radio bursts, and major ionospheric disturbances. Also, ionospheric effects tend to be stronger at lower frequencies, where the L2C (new civilian) and L5 (safety of life) signals are located.

A Chronology of Space Weather Effects on GPS

- 1995 GPS becomes operational
- 2000 Selective availability turned off (errors decrease from 100 m to 15 m)
- 2001 Scintillation shown to cause loss of lock on GPS signal
- 2001 First TEC images show ionospheric storms at midlatitudes (over the U.S.)
- 2001 DOT Volpe report acknowledges space weather threat to GPS
- 2003 FAA WAAS activated in July (errors decrease from 15 m to 5 m)
    - In October ionospheric storm causes FAA not to use WAAS
- 2005 Fugro Chance Inc. talks publically about ionospheric storms as threat to business
- 2005 U.S. launches first modernized GPS
- 2006 Solar radio burst threatens GPS globally

Box 2. A chronology of space weather effects on GPS (source: NOAA/SWPC).

Examples of Impacts

- December 6, 2006: The largest solar radio burst ever recorded affected GPS receivers over the entire sunlit side of the Earth. This event prevented global differential GPS from generating corrections for users and marked the first time a solar radio burst event was detected on WAAS.
- November 8, 2004: A fast-moving auroral arc caused ionospheric irregularities, affecting GPS signals. Even though this event lasted only 10 seconds, because of the intensity, it caused a receiver to lose lock. The event was observed by receiver sites in Norway and Finland.
- October 29–31, 2003 (Halloween storms): A CME required precise GPS users to delay operations. For a 15-hour period on October 29 and an 11-hour period on October 30, the WAAS system was deemed unreliable.
- July 13–17, 2000 (Bastille Day storm): A coronal mass ejection caused an extremely intense geomagnetic storm that lasted for more than nine hours. There were reports of seeing the aurora lights as far south as El Paso, Texas. The solar particles from this event damaged satellites and spacecrafts and even degraded the accuracy of GPS for several hours.

Box 3. Examples of space weather impacts to GPS and WAAS (source: NOAA/SWPC).

Workshop participants discussed how space weather affects GPS and the state of the science. They considered what is needed to better understand the vulnerability of GPS technologies and services to space weather and how it will be achieved. Two major recommendations were agreed upon.

a. Perform a Threat Assessment

Workshop participants agreed that while the ionosphere is known to be a major source of unintentional interference, an in-depth threat assessment has yet to be conducted on how space weather can impact GPS, its applications, and users. A threat assessment, the first step in a risk management program, considers the full spectrum of threats and evaluates the likelihood of occurrence for each threat. This should include the full range of space-weather-related threats to GPS, the duration, and the extent of the effects.

The solar cycle must also be considered, since the sun’s level of activity varies with a period of about 11 years. As the sun enters a period of increased activity, with the expected sunspot maximum in 2013, the approaching solar maximum is likely to produce magnetic storms, ionospheric storms, and disruptions to radio signals, including GPS and other GNSSs. In some rare cases, solar radio bursts may directly interfere with GNSS signals; in other cases, ionospheric and magnetic storms will disrupt radio signals from satellites. The average solar extreme (EUV) luminosity increases substantially at solar maximum, making the ionosphere denser and thicker. Hence, GPS signals are more strongly affected by the ionosphere during solar maximum. The effects also depend on the latitude and longitude, some of which are more observed than others.

> **Recommendation: Develop a threat assessment to consider the full spectrum of space weather threats to GPS.**

b. Define User Vulnerability

Vulnerability is generally defined as any condition of susceptibility to external shocks that could threaten people's lives and livelihoods, natural resources, properties and infrastructure, economic productivity, and a region's prosperity.

Reducing vulnerability to natural hazards, such as space weather, requires special attention at two levels:

1. Analysis and characterization of hazards, which entails assessing the vulnerable areas and infrastructure, and adoption of risk reduction measures.

2. A framework for implementing risk reduction measures using policy instruments, contingency plans, and management tools.

Workshop participants agreed that the vulnerability of GPS to space weather in general is known (e.g., with respect to signals, delays, and scintillation); however, there is no good *quantification* of the risk to systems that depend on GPS (e.g., communications, financial, and electric power). Specifically, the vulnerability should be defined for different user segments and include which systems are most affected and why. Space weather can impact some technologies and users more than others, so the vulnerability thresholds for satellites, signals, systems, users, and applications should be identified. Analysis of the broad base of user vulnerabilities will contribute to a complete risk analysis and mitigation plan.

Participants discussed that when examining GPS vulnerabilities, they must be considered within each region, since different effects can occur. Also, vulnerability is different for different users, so it may be useful to categorize according to high-precision, moderate-precision, and tolerant-precision users. There was discussion on how *vulnerability* should be defined. Is it based on safety of life, efficiency, economic, or user expectation? Some effects need to be examined system by system and application by application.

In addition, each federal agency needs to understand space weather and PNT issues for its own purposes. Therefore, the FAA needs to understand the effects to NextGen, the DOE needs to understand the effects to timing in electric power grids, and the DHS needs to understand the impacts on its communication system, just to name a few.

Participants also debated how much to stress the impacts of a solar flare as massive as the 1859 Carrington event, which resulted in the largest recorded geomagnetic storm, disrupting telegraphs worldwide and igniting widespread fires. Even when telegraphers disconnected the batteries powering the lines, aurora-induced electric currents in the wires still allowed messages to be transmitted. Colorful aurora, normally visible only in the polar regions, were seen as far south as Rome and Hawaii. Today, it is possible that a Carrington-like event could disrupt the entire GNSS (NRC 2008). Given that the GPS satellites travel through the Van Allen radiation belts, the satellites were built to be robust to withstand the space environment. However, there has not been an open or unclassified study on how a spacecraft, such as GPS, would survive a Carrington-like storm. The economic impact has been examined on the existing geosynchronous Earth-orbiting satellite population—if an 1859-caliber superstorm event were to occur between 2008 and 2018, the minimum revenue loss, it could be on the order of $30 billion (Odenwald and Green 2007). Therefore, a solar storm as massive as the one that occurred in 1859 should be considered; however, many participants agreed that it should not govern planning, because a doomsday scenario could be created for an incident that is expected to happen only very infrequently.

Recommendation: Define and quantify vulnerabilities for different user segments and systems.

3. Building Resilience: Science and Engineering

Resilience is the capacity of a system to absorb a disturbance, undergo change, and retain the same essential functions. High priority science and technology investments, coupled with sound decision making, will dramatically enhance society's resilience and thus reduce vulnerability.

Workshop participants discussed how science and engineering can build resilience in the GPS system. They considered what new technical, observational, and modeling capabilities are needed to build resiliency. Several recommendations were agreed upon.

a. Conduct Further Research on Understanding Space Weather and Its Effects

Over the last decade, our understanding and appreciation of the ionosphere and thermosphere have changed dramatically with the realization that they are strongly coupled to each other and the magnetosphere. Chains of GPS receivers and imaging, both from ground and space, have made this advance possible. In addition, there has been progress in modeling the ionosphere and magnetosphere. Yet, researchers still do not fully understand ionospheric storms, gradients, irregularities, and traveling ionospheric disturbances.

Workshop participants discussed several research challenges that remain, for example:

> <u>TEC gradients</u>: How sharp are the sharpest gradients, what operational systems will they affect, can they be predicted, and will there be limitations to ionospheric corrections after GPS modernization?
>
> <u>Scintillation</u>: How significant is midlatitude scintillation, and will GPS modernization help mitigate scintillation effects?
>
> <u>Solar radio bursts</u>: How frequent will we see an event as large as the December 6, 2006 event, and can receivers be built to withstand solar radio bursts?

Users would like to better understand the probabilities, rather than know an event is "rare." They would like to understand what space weather does to the GPS measurements, what are the extremes, and what is the norm for each signal.

The recommendations listed below support the NSWP's goal of discovering and understanding the physical conditions and processes that produce space weather and its effects (OFCM, 2010).

Recommendation: Support basic heliophysical and geophysical research aimed at understanding the fundamental physical conditions and processes that produce space weather and its effects. This should be a top priority for a community decadal survey.

Recommendation: Conduct further research on ionospheric storms, gradients, and irregularities to better understand and predict the state of the ionosphere.

b. Develop and Maintain Observational Capabilities

Workshop participants discussed that scintillation needs to be better quantified, in both magnitude and effects. With more dual-frequency ground receiver stations, scientists can gain better spatial information of total electron content. Ideally, there should be more high-end ground-based receivers worldwide that are capable of measuring scintillation parameters. This would provide better quantification of the magnitude and effects, as additional dual-frequency ground-based receivers would obtain better ionospheric information. This is aligned with the NSWP goal to develop and sustain the necessary observational capabilities that are both vital and urgent.

Distributed instrument networks have the distinct advantage of having the ability to provide the high spatial/temporal resolution needed to characterize the ionospheric and atmospheric signatures of magnetosphere–ionosphere coupling processes and their associated space weather effects. Research into distributed radio science instrumentation is in keeping with the directives of the *The Sun to the Earth—and Beyond: A Decadal Survey of Solar and Space Physics* (NRC 2003), which has encouraged the deployment and utilization of distributed arrays of small instruments to further space physics research. With mechanisms for incorporating different types of data for all to use, research will lead to the next scientific breakthroughs. Similar to SuperDARN, an international radar network for studying the Earth's atmosphere and ionosphere, a large coordinated effort is required to incorporate a lot of different data that the space weather community can easily access. Right now, there is no central place for sharing atmospheric and ionospheric real-time data related to GPS, partially because some of the phenomena, such as scintillation, are data sparse. The science community needs an atmospheric network, a central place to go and obtain real-time data.

Recommendation: Develop a long-term plan for ground-based and space-based ionospheric measurements that will allow for improved spatial coverage of ionospheric and atmospheric space weather parameters. These data must be gathered now to meet the urgent needs society already faces.

c. Understand User Requirements

In recognition that the users of GPS services know their requirements best, workshop participants agreed that it is essential to understand the impact by user requirement. Specifically, it is useful to categorize by 1) impact accuracy requirement, 2) service interruption, and 3) when signals are unreliable. Users are more knowledgeable and sensitive to technology limitations and lifetimes. For example, an airline will typically use a given aircraft for 30 years, but only rarely update the flight management system. Thus, any new technology developments will not likely be fully implemented by the airlines until three decades from now.

Compiling a comprehensive list of requirements requires a multifaceted approach: collaboration between the Air Force GPS Wing, CGSIC, DOT, DOC, and other interagency forums. An interagency GPS requirement process exists today (Interagency Forum for Operational Requirements), but it has been met with mixed success because of the complex nature of interagency budget realities. Some participants suggested that the best way to achieve a comprehensive list of requirements is to deal with Original Equipment Manufacturers (OEMs), not end users.

A challenge will be in identifying future user requirements for all sectors. For example, as the climate changes and polar region (greater than 80°N) shipping lanes begin to open, there will be more interest in the impact of ionospheric storms on GPS in that region. With the recent news of Google building self-driving robotic cars depending on GPS, trying to capture possible future vulnerabilities is extremely challenging.

> **Recommendation: Define and categorize user requirements in terms of accuracy, service availability, and integrity requirements.**

d. Develop Better Products

Throughout the workshop, participants acknowledged that the space weather community needs to better predict the state of the ionosphere and create products that are useful and understandable to users. The NSWP's goal to provide tailored and accurate space weather information where and when it is needed was affirmed by the participants.

Currently, NOAA/SWPC offers a wide variety of products for GPS users, including nowcasts of space weather conditions over North America. SWPC products include near real-time total electron content (US-TEC), designed to estimate the signal delay for single- and dual-frequency GPS applications, produced every 15 minutes. SWPC also provides the planetary *K*-index plot, showing if there are any magnetic field disturbances during the past 72 hours. The full inventory of SWPC services and products can be found online at www.swpc.noaa.gov.

Suggestions for other products included the following:

- Add an ionospheric index to the NOAA Space Weather Scales that measures ionospheric storms and quantifies the reliability.
- Develop a product that yields nowcasts of gradients and scintillation over the U.S.—and possibly Canada and Latin America—so that when there are space weather issues with GPS, the user has a resource to diagnose the problems.
- Provide appropriate computer interface (e.g., XML) so airline customers can integrate GPS and space weather information.
- Provide forecast and nowcast products not only for ionospheric storms but also for quiet times.
- Develop products such as stoplights for certain users (e.g., GPS could mean life or death to handheld GPS users and E911, airlines want to know if they can use GPS to land a plane).
- Provide translation information on how to interpret and apply products.

There is clearly a market for tailoring ionospheric products for end users, and some companies have already begun providing services. The GPS service providers and commercial space weather providers have a growing market base, especially when it comes to training users on how to apply products and services to their specific operations.

Much of the limitations of ionospheric products and services are based on current knowledge of space weather. As the research community makes advances in space weather and heliophysics, improved predictions should be forthcoming.

Recommendation: Develop better products to ensure timely, accurate, and advanced space weather warnings, specifications, and forecasts.

e. Develop Engineering Solutions

Participants discussed that engineering solutions might be the key to reducing ionospheric interference to GPS, including building receivers that are resistant to scintillation and new signal processing.

When discussing the need for improved receivers, some participants warned that the integrity of the receivers might be an issue. Some manufacturers created receivers and tested them in Brazil during solar maximum but during benign conditions. This testing results in false expectations. Holding manufacturers to higher standards when testing for scintillation will increase confidence. A challenge is who will enforce such standards.

In addition to receivers, powerful new signal processing technology can provide game-changing benefits and resilience. Next-generation GNSSs and multifrequency signals are new resources, providing more signals at more frequencies. Multiple GNSS signals, on the order of 100–200 in view, can greatly improve the noise and ionospheric performance. Rather than the conventional tracking of one signal at a time, tracking the totality of many signals can improve ionosphere group delay and phase advance estimation. Multiple satellites in view with more advanced vector delay lock receivers are predicted to reduce scintillation degradation as well as improve noise/interference/spoofing performance. Multifrequency receivers and generalized vector processing can utilize these signals and frequencies more powerfully.

A key point made at the workshop is that for mitigation measures, another space-based system (e.g., Galileo and iGPS) would be of little help. Different phenomenology is needed to back up GPS (e.g., MEMS, inertial systems, and local atomic clocks) depending on the risk exposure of the particular user application.

Recommendation: Develop receivers for multifrequency tracking, with significantly improved performance during deep scintillation fades and interference.

Recommendation: Develop more quantitative standards for manufacturing and certifying the performance of GPS receivers.

4. Building Resilience: Policy

Advances in science and technology alone cannot fully protect society from hazards. Research and major technology investments must be linked to effective policy decision making. Change must occur at both the policy level and in the societal perception of risk, so that adoption and adaption keep pace with advances in science and technology. Workshop participants discussed what measures could be taken to build resiliency and what additional policy options might be available for mitigating adverse effects of space weather, specifically in terms of investment and collaboration. Several recommendations were agreed upon.

a. Investment in Research

Fully understanding space weather impacts on GPS requires adequately and wisely invested resources. A strong space weather research program will produce essential scientific data and understanding of the source processes of space weather hazards. This research will enable effective forecasting and mitigation. The workshop participants discussed the need for the government to support a broad fundamental and applied research program to advance our present understanding of space weather and its impacts on GPS and other critical infrastructure. This investment includes observations, research, and modeling.

Several options for investments were proposed, including the following:

- Fully fund an atmospheric and ionospheric network. Observations from both space and ground are key to monitoring space weather variables and developing models. Specifically, more dual-frequency space weather monitors will allow for greater spatial coverage and understanding of ionospheric conditions.
- Develop a strategy to ensure long-term continuity of essential space-weather-observing systems and critical observation data. Included are the spacecraft that now acquire data at stations well beyond the orbit of the Earth to permit longer warning times (e.g., ACE). Future research and model development to improve forecast capabilities are critically dependent on these observations and the infusion of these data into research and operations centers.
- During the upcoming solar maximum, develop a product that yields nowcasts of gradients and scintillation over the U.S.—and possibly Canada and Latin America—so that when there are space weather issues with GPS, the user has a resource to diagnose the problems. It was suggested that this could be achieved through an NSF grant.

Recommendation: Support a broad fundamental and applied research program in space weather/heliophysics to advance our present understanding of space weather and its impacts on GPS and other critical infrastructure.

b. Attention to Research–to–Operations Transition

Throughout the workshop, the issue of transitioning from research to operations was discussed as a critical issue. Transitioning new knowledge from the research domain to the operations environment is a long, arduous process, with many barriers. It requires assistance and advice from the researchers; it also requires a sizable, well-funded, and knowledgeable cadre of people in the operational units who can construct fast, efficient, and trustworthy research codes.

For years, the atmospheric, Earth, and space science communities have called for a comprehensive strategy to transition NASA research satellites to operational NOAA weather and climate satellites. To date, this has not happened effectively for a variety of reasons, including budget constraints and agency mission differences. Government agencies are not positioned to handle this implementation. The government should provide leadership through OSTP and OMB, which can work with these agencies to support these important transition issues.

To be successful in a transition process, a culture must be built within the research and operations communities. Activities should be scaled to maximize the likelihood for success. This includes an iterative process, based on deliverables, in a stepwise process, rather than just an unattainable decade-long process. The NSWP has identified the transition from research to operations as a key element to providing accurate space weather information when and where it is needed.

> **Recommendation: OSTP and OMB should work with NASA and NOAA to support the transition from space weather research to operations, including the transition from research models to an operational environment, as well as the validation and improvement of existing models.**
>
> **Recommendation: Develop a research-to-transition process that is iterative and carefully constructed based on interim deliverables in a stepwise process.**

c. Create and Strengthen Partnerships

Government cannot address GPS resiliency issues adequately by itself. It takes the combined efforts of government, private enterprise, and the academic community—and, of course, the international community—to make inroads. Workshop participants agreed that the government must listen to the private sector since they determine and influence the GPS market. GPS service providers, receiver manufacturers, utility providers, financial sector, commercial space weather service providers, and other economic sectors—each one has a special role to play. The federal government should take the lead in establishing and strengthening frameworks to enable and foster needed collaboration. Some of this is already happening through the U.S. Coast Guard's Navigation Center, the Civil Global Positioning System Service Interface Committee (CGSIC), and the National Executive Committee for Space-Based

PNT. Organizations, such as ION and ICAO, should also continue advancing knowledge of the role of space weather in GPS operations. The NSWP also has a role to play in strengthening the communication between the space weather enterprise and GPS sector. In general, collaborations must go above individual to individual and become institutionalized so they will be more strategic and robust.

> **Recommendation: Create and strengthen partnerships to enhance awareness of and coordinated responses to space weather hazards to satellite navigation systems and operations.**

d. International Collaboration

The U.S. must continue to work cooperatively with other nations to reduce GPS vulnerability to hazards, including space weather. Workshop participants agreed that as several other countries are building their own navigation systems—Galileo, Compass, GLONASS, QZSS—it is crucial to determine how to best synchronize the different GNSSs. Given that each country will have the challenge of balancing sovereignty with international cooperation, it will be a learning process over the next two decades.

Workshop participants noted that international collaboration presents an opportunity to maximize the use of all GNSS signals, thereby reducing scintillation effects. The addition of more signals and new constellations will help reduce or eliminate errors. This requires the development and certification of receivers that can incorporate hundreds of GNSS signals.

The U.S. Department of State has a special role to play with compatibility and interoperability issues to raise the level of positioning, navigation, and timing services for users worldwide.

> **Recommendation: Strengthen international collaboration to meet the future needs of PNT services and to reduce GNSS vulnerability to space weather.**

e. Develop Education and Outreach to Users

Participants discussed that given the GPS user base is so diverse, a top-down command control approach to building resilience may not be the best option. The space weather community should educate the users about space weather and its effects but not tell them what they need. The key is to ask the users what they want. Through education and outreach, users can determine their requirements and then the operations community can determine which services to provide.

Overall, there was consensus that this education and outreach should be targeted to the OEMs and third-party GPS service providers, not individual users.

Everyone discussed options for reaching out to users. One recommendation is a users' forum, where there is an opportunity to discuss space weather impacts and needs. There should also be targeted outreach to government stakeholders, such as Congress and federal agencies that depend on GPS.

Presently, there are channels for disseminating information about space weather and they should continue to be promoted: NOAA/SWPC Web page, NOAA Weather Wire Service, NOTAMs, and smart phone applications. Yet, there is a challenge for users of GPS services to determine how they know if the information applies to them and if they need to take any action. Raising national awareness of the impacts of space weather is a goal of the NSWP. Training will be required on how to interpret products.

> **Recommendation: Foster the exchange of ideas and information through user forums and other educational venues.**

> **Recommendation: Develop and support a space weather–GNSS user office that collects information on space weather impacts and provides education and outreach to a broad base of users.**

f. Strengthen Integrity and Robustness of the System

The idea of strengthening the integrity and robustness of GPS was a theme running through much of the workshop. The challenge is how to ensure that GPS will perform its intended functions without being degraded or impaired by changes or disruptions in its internal or external environment.

Several options were discussed for this overarching recommendation, including the following:

Completing the Modernization of the GPS Enterprise

The GPS modernization program is an ongoing effort by the U.S. government to implement improvements to the GPS service. The program includes new signals for military and civil use as well as increased accuracy and integrity for all users while also maintaining backward compatibility for the current installed base of GPS user equipment. Three new GPS signals designed for civilian use—L2C, L5, and L1C—are being added as well as a new military signal. In addition, the GPS ground control segment is being modernized to operate these new signals.

These new civil signals will enable the development of lower-cost, multi-frequency civil GPS receivers that allow for correction of ionospheric time-delay errors. Additionally, the new L5 will lie in the "aeronautical radionavigation service" frequency band, which is afforded particular protections and will be used for transportation safety-of-life use, specifically aviation. The L1C signal is being implemented per an agreement between the U.S. and the European Union to provide a signal that is both compatible and interoperable with Europe's Galileo as well as other international GNSSs. The L1C will also be broadcast at a higher power level and have a new advanced design for enhanced performance. Further, all of these new civil signals provide redundancy in the event of either intentional or unintentional interference to the current GPS civil signal.

These new GPS signals are being phased in incrementally as new GPS satellites are launched to replace older satellites. Some of these new signals are currently available from a number of GPS satellites in orbit. The benefits of these signals will increase as more modernized satellites are launched, however the full benefit of these signals require a full constellation of 24 or more satellites on orbit with the above signals and the ability to operate them to their full capability. Therefore, it is critical that the GPS modernization effort continues to achieve an on-orbit GPS constellation complete with all these new signals. Only then will the full benefits of these additional signals be available to GPS users throughout the globe.

Ensuring backup systems

The 2001 DOT Volpe report recognized that GPS is vulnerable, and specifically to ionospheric conditions. Therefore, rather than figuring out how to make GPS "unbreakable," the focus should be on "survivability" through an event. Further, the current PNT architecture recognizes the need for alternatives to GPS. Participants agreed that the government and private sectors need to identify appropriate redundancies to mitigate potential safety, security, and economic impacts due to the loss of GPS service. Simulation exercises should be conducted to test and practice the use of the redundant systems.

One way to mitigate overreliance on GPS is to educate the GPS user community that this technology is vulnerable to unintentional and intentional disruptions that can be reduced, but never eliminated. Even the military, despite its reliance on GPS, recognizes the need for alternative/backup systems or operational procedures. The military has taken great strides to increase the probability that GPS will be available; however, if the military were denied GPS, it would still be prepared to accomplish its mission. First responders need to view GPS the same way. It is there to help, but the success of each mission should not be directly dependent on it without having appropriate backup procedures or systems. The government and private sector should conduct an inventory of their functions that rely on GPS to determine if a backup system is required.

Developing better space weather predictions

Accurate space weather prediction could save society hundreds of million dollars a year. As the modern world becomes more dependent on technologies, like GPS, that are vulnerable to space weather, the need for improved forecasting only increases. Forecasters continually monitor the space environment using both space- and ground-based assets and issue alerts and warnings of a likely impact at Earth. These assets also provide the space weather community with a long-term baseline on which to base, test, and ultimately improve global prediction models.

Current space weather predictions are focused primarily on five areas: (1) solar flares and eruptions impacting communications, radar, and GPS receivers; (2) radiation storms affecting airlines, astronauts, satellites, and communications; (3) disturbances in Earth's magnetic field impacting electric power grids, GPS, satellites, and airlines; (4) atmospheric heating from increased short-wavelength radiation which shortens the lifetime of low-Earth orbiting satellites; and (5) ionospheric storms which degrade navigation systems, GPS dependent technologies, and high frequency and satellite communications.

Many space weather events are forecasted, but with minimal lead time because of a lack of real-time data and limited model capabilities. Considering the vast volume of space involved, the environment is highly undersampled. Investments by the federal government and the global community into space weather related research and technologies are rapidly advancing the state of knowledge and show great promise for producing improved forecasting capabilities. Space weather service providers should continue to leverage research and models developed by government, academia, and the private sector. Operational forecasters need more accurate and finer resolution models with regionalized products to satisfy critical needs identified by a fast-growing and diverse customer base.

Set standards for satellites and receivers to handle extreme space weather conditions

Workshop participants discussed the need for holding satellite and receiver manufacturers to a higher standard within harsh space environment conditions. Similar to how there are building codes to ensure structures withstand category 3 hurricane winds, satellites and receivers should be held to a similar standard for space weather. Caution should be applied when using receivers that manufacturers claim are "solar max proof," since it may not be clear if conditions (e.g., latitude and space environment) could have created a false validity. Thus, ensuring the integrity of GPS is a challenge.

The International Organization for Standardization (ISO), a network of the national standards institutes of 157 counties, published the upgraded ISO ionosphere standard last year (ISO 2009). This standard provides guidance to potential users for the specification of ionospheric densities, temperatures, and total content of electrons. It was suggested that since there are a number of GPS, aviation, and ionosphere standards activities that are ongoing and mature (e.g., ISO, ICAO, ITU-R, and ECSS), the space weather community should provide input into standards and formats.

Examine GPS resiliency through an all-hazards lens

GPS faces many different risks--space weather needs to be understood in the greater context. While space weather can influence GPS, the system is also vulnerable to other hazards, both unintentional (e.g., radio frequency interference, GPS testing, spectrum congestion) and intentional (e.g., jamming, spoofing, and system damage). The Department of Homeland Security has stressed that GPS resilience should be examined through an all-hazards lens. This allows decision makers to recognize and reduce vulnerability of interdependent critical infrastructure. By addressing these interdependent systems (e.g., communications, electricity, financial, and transportation) and using integrated models, additional vulnerabilities can be identified and addressed. Viewing GPS resiliency through an all-hazards perspective allows decision makers at all levels to respond to hazards rapidly and effectively.

Recommendation: Strengthen the integrity and robustness of the GPS system and services by

- **Completing the modernization of the GPS enterprise.**
- **Ensuring backup systems.**
- **Developing better space weather predictions.**
- **Setting standards for satellites and receivers to handle extreme space weather conditions.**
- **Examining GPS resilience through an all-hazards lens.**

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Appendix A: Acronyms

ACE	Advanced Composition Explorer
AMS	American Meteorological Society
CGSIC	Civil Global Positioning System Service Interface Committee
CIKR	Critical Infrastructure and Key Resources
CME	Coronal Mass Ejection
COMPASS	Compass Navigation Satellite System (or Beidou II; commonly referred as Compass)
DGPS	Differential Global Positioning System
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
ECSS	European Cooperation for Space Standardization
EUV	Extreme Ultraviolet
FAA	Federal Aviation Administration
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HF	High Frequency
ICAO	International Civil Aviation Organization
iGPS	Intelligent Global Pooling Systems
ION	Institute of Navigation
ISO	International Organization for Standards
ITU-R	International Telecommunications Union Radiocommunication Sector
MEMS	Microelectromechanical Systems
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Air Men
NSF	National Science Foundation
NSWP	National Space Weather Program
OEM	Original Equipment Manufacturer
OFCM	Office of the Federal Coordinator for Meteorology
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PNT	Positioning, Navigation, and Timing
QZSS	Quasi-Zenith Satellite System
SA	Selective Availability
SEP	Solar Energetic Particles
SuperDARN	Super Dual Auroral Radar Network
SWPC	Space Weather Prediction Center
TEC	Total Electron Content
UV	Ultraviolet
WAAS	Wide Area Augmentation System
XML	Extensible Markup Language

Appendix B: Space Weather Phenomena

Space weather refers to the conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health (OFCM, 2000). The space weather events that concern satellite navigation operations are primarily solar flare radio blackouts, Coronal Mass Ejections (CME), Solar Energetic Particles (SEP), geomagnetic storms, and ionospheric storms.

Solar Flares

Solar flares, with lifetimes ranging from tens of seconds to hours, release X-ray, ultraviolet, and radio emissions, producing ionospheric disturbances in the sunlit hemisphere with durations lasting from minutes to hours. Some solar flares can cause sudden increases in total electron content (TEC) on the dayside, although those occurrences are short lived and generally not problematic for GPS. Occasionally, very strong flares produce *solar radio bursts* that may directly affect the ability of some GPS receivers on the dayside of the Earth.

Coronal Mass Ejections

The explosive release of CMEs from the sun's outer atmosphere over the course of several hours can rapidly shower the Earth with energetic particles (radiation storm). Since the solar wind varies over time scales as short as seconds, the boundary between interplanetary space and the Earth's magnetosphere is extremely dynamic. One to four days after a solar disturbance, a plasma cloud reaches the Earth, pummeling the magnetosphere and causing a geomagnetic storm. During these storms, very large electrical currents of up to a million amperes can flow through the ionosphere and magnetosphere, which can change the direction of the Earth's magnetic field at the surface by up to 1° or 2°, mainly in the auroral regions, although these effects can extend to midlatitudes. These variations in particle fluences and magnetic fields can affect the atmospheric radiation levels as well as severely disrupt radio communications.

Solar Energetic Particles

Occasionally, but more often during the years near solar maximum, the sun ejects large quantities of energetic protons and electrons. These energetic particle events persist for a few days at a time; they can affect both ground-based and space-based systems but in different ways. Satellite signal propagation is degraded, especially at polar latitudes, because of the ionosphere's response to the addition of these solar particles (primarily protons). GPS and all other satellites must contend with the detrimental effects energetic particles have on the onboard system.

Geomagnetic and Ionospheric Storms

Solar flares and CMEs can induce geomagnetic storms that make the ionosphere unstable. The geomagnetic field is affected by solar stimuli, whose frequency and intensity differ according to the phase of the solar cycle. Geomagnetic storms usually result in ionospheric storms and, hence, they affect navigation systems. Unlike solar X-rays, which affect only the sunlit hemisphere of Earth, geomagnetic storms are ubiquitous. However, the ionospheric response to these storms is dependent on latitude; thus, conditions nearer to the equator or nearer to the pole vary for the navigator. Paradoxically, a quiet, undisturbed geomagnetic field does not necessarily dictate an undisturbed equatorial ionosphere; this underscores the great variability in the environment.

GPS operations anywhere on Earth are affected by the changes in TEC of the ionosphere along the path to the satellite during large magnetic storms. Large increases and decreases in the bulk plasma TEC directly influence the accuracy of single-frequency GPS receivers. Dual-frequency GPS receivers actually measure the effect of the ionosphere on the GPS signals and can better adjust to these difficult circumstances.

On a smaller scale, irregularities in TEC that produce scintillations occur in varying amounts, depending on latitude. For example, the equatorial region (the latitude zone that spans 15°–20° either side of the magnetic equator) is the site of some of the greatest ionospheric irregularities, even when magnetic storms do not occur. Seemingly unpredictable episodes of density enhancements in the upper ionosphere can occur in the evening hours there and can cause radio waves to be misdirected. These scintillations make GPS operations difficult, and they can affect both dual- and single-frequency GPS receivers.

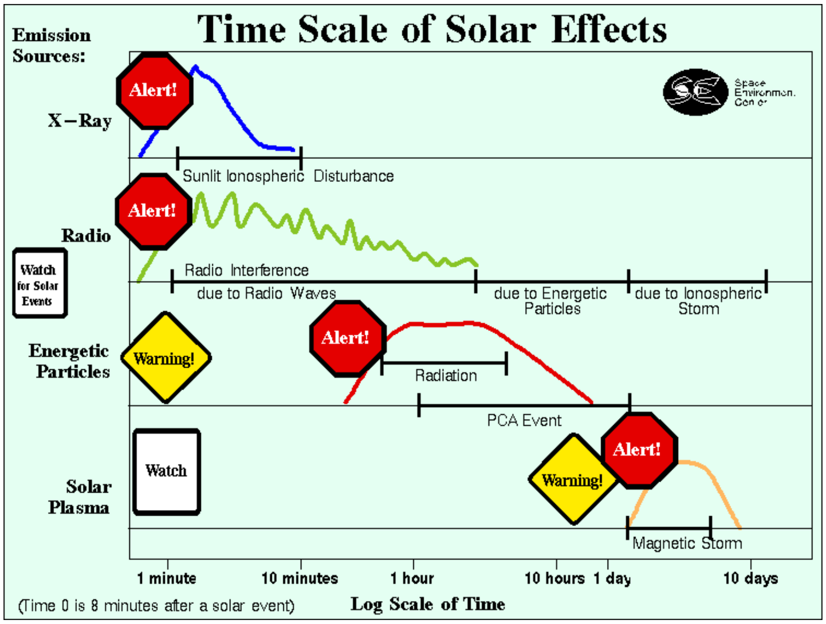

Figure B1. The time scales of solar effects (source: NOAA/SWPC). Eight minutes after a flare and/or a CME erupts from the sun, the first blast of EUV and X-ray light increases the ionospheric density, which can affect HF communication loss. Ten minutes to several hours later, energetic particles arrive. One to four days later, the CME passes and energizes the magnetosphere and ionosphere, affecting navigation systems and radio communications.

Appendix C: Workshop Program

Workshop on Satellite Navigation & Space Weather: Understanding the Vulnerability & Building Resilience

Developed by the
American Meteorological Society Policy Program

Supported in part by
ITT, Lockheed Martin, Northrop Grumman, SAIC,
National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and National Science Foundation (NSF)

October 13–14, 2010
UC Berkeley Washington Center
1608 Rhode Island Ave., NW
Washington, DC 20036

Wednesday—October 13, 2010

0730 Registration Opens, Continental Breakfast

0820 Welcome/Introductory Remarks, *Dr. Genene Fisher, Senior Policy Fellow, AMS Policy Program, and Mr. Jonathan Malay, AMS President-Elect and Director, Civil Space and Environment Programs, Lockheed Martin*

0830 Opening Keynote Address, *The Honorable Arif Alikhan, Assistant Secretary, Policy Development, Department of Homeland Security*

0850 Discussion

0905 GPS Modernization: On the Road to the Future, *Mr. Michael Shaw, Director, Navigation Systems Global Business Development, Lockheed Martin Space Systems*

0925 Discussion

0940 Space Weather Future Operational Prospects, *Dr. Thomas Bogdan, Director, NOAA/Space Weather Prediction Center*

1000 Discussion

1015 Break

1035 GPS/GNSS and the Next Generation Air Transportation System (NextGen), *Mr. Leo Eldredge, GNSS Group Manager, Federal Aviation Administration*

1055 Discussion

1110 GPS/GNSS and Critical Infrastructure, *Mr. Jim Caverly, Director, Partnership and Outreach Division, Office of Infrastructure Protection, Department of Homeland Security*

1130 Discussion

1145 Lunch

1300 Discussion of Policy Issue 1: Vulnerability of GPS to Space Weather

Discussion leader: Patricia Doherty, Senior Research Scientist, Institute for Scientific Research, Boston College

Two talks to address the questions listed below *(Patricia Doherty and Karen VanDyke, Technical Expert on GPS, Volpe Center, Department of Transportation)*

A brief overview of the issue will be presented followed by participant discussion and recommendations focused on, for example, the following questions:

How does space weather affect GPS technologies and services?

Will the proposed signals and additional satellites (Galileo, Glonass, etc.) alleviate space weather errors?

What is the state of science in understanding the space-weather-induced GPS issues now?

What is needed to better understand the vulnerability of GPS technologies and services to space weather, and how will it be achieved?

1445 Break

1515 Discussion of Policy Issue 2: Consequences of Space Weather Impacts on GPS Stakeholders and Customers

Discussion leader: *Joseph Kunches, Space Scientist, NOAA/Space Weather Prediction Center*

Overview talk to address the questions listed below (*William Murtagh, Program Coordinator, NOAA/ Space Weather Prediction Center)*

A brief overview of the issue will be presented followed by participant discussion and recommendations focused on, for example, the following questions:

What is the impact of space weather on users who depend on GPS, in terms of property loss and economic disruption?

How does the GPS industry receive space weather information, and how do users decide when to use a forecast/alert to modify operations?

What new technical, observational, and/or modeling capabilities are needed to anticipate new space weather services for GPS, and how will they be achieved?

1700 First day wrap-up

1715 Adjourn

Thursday—October 14, 2010

0730 Registration Opens, Continental Breakfast

0800 Preliminary Remarks, *Dr. Genene Fisher, AMS Policy Program, and Dr. William Hooke, Director, AMS Policy Program*

0805 Keynote Talk: Ionosphere Effects on GNSS Services: A Glimpse of Future Systems & Technology, *Dr. James Spilker, Professor, Electrical Engineering and Aeronautics and Astronautics Departments, Stanford University*

0820 Discussion

0830 Discussion of Policy Issue 3: Building Resilience to Space Weather and Its Impacts

Discussion leader: *Dr. William Hooke, Director, AMS Policy Program*

Two talks to address the questions listed below (*Dr. Scott Pace, Director, George Washington University Space Policy Institute, and Mr. Mike Kangior, Director, Emergency Management Policy, Department of Homeland Security)*

A brief overview of the issue will be presented followed by participant discussion and recommendations focused on, for example, the following questions:

What measures could be taken to build resiliency (e.g., policies, research and development, changing practices, public–private sector collaboration)?

Would GPS users, now and in the future, benefit from formal policies that focus the science and services to build resilience?

What additional policy options might be available for mitigating the adverse effects of space weather? What do these options imply in terms of investment, public–private sector collaboration, and collaboration between GPS service providers and users?

1015 Break

1030 Discussion of the Overarching Findings and Recommendations of the Workshop

1130 Actions and Next Steps

1200 Adjourn

Appendix D: Workshop Participants

Assistant Secretary Arif Alikhan
U.S. Department of Homeland Security

Dr. Chaminda Basnayake
General Motors Research & Development

Mr. Randall Bass
ITT/Geospatial Systems

Dr. Thomas Bogdan
NOAA/Space Weather Prediction Center

Mr. Michael Bonadonna
Office of the Federal Coordinator for Meteorology

Ms. Caitlin Buzzas
AMS Policy Program

Prof. Paul Cannon
QinetiQ/Royal Academy of Engineering

Mr. James Caverly
U.S. Department of Homeland Security

Dr. Dave Chenette
Lockheed Martin Advanced Technology Center

Ms. Barbara Clark
Federal Aviation Administration

Mr. Clayton Coker
Naval Research Lab

Dr. Anthea Coster
MIT Haystack Observatory

Mr. Robert Crane
National Coordination Office for Space-Based PNT

Dr. Geoff Crowley
Atmospheric & Space Technology Research Associates

Prof. Patricia Doherty
Boston College

Mr. Ted Driver
Analytical Graphics, Inc

Mr. Nigel Eite
UK Civil Aviation Authority

Mr. Leo Eldredge
Federal Aviation Administration

Dr. Genene Fisher
AMS Policy Program

Dr. Barry Geldzahler
NASA HQ

Dr. John Goodman
Radio Propagation Services, Inc

Mr. David Gootzit
CENTRA Technology

Mr. Ronald Hatch
NavCom Technology/Deere

Dr. Jim Head
U.S. Department of State

Ms. Christy Henderson
George Mason University

Dr. Michael Hesse
NASA CCMC

Colonel Robert Hessin
U.S. Air Force

Dr. Paul Higgins
AMS Policy Program

Dr. William Hooke
AMS Policy Program

Dr. Robert Hunter
UK Civil Aviation Authority

Dr. David Jackson
UK Met Office

Dr. Norbert Jakowski
German Aerospace Center

Captain Bryn Jones
Solar Metrics Ltd.

Dr. Farzad Kamalabadi
National Science Foundation

Mr. Mike Kangior
U.S. Department of Homeland Security

Dr. Omid Kia
ITT Industries

Mr. Jason Kim
Office of Space Commercialization, Department of Commerce

Mr. Dennis Koehler
SAIC

Mr. Joseph Kunches
NOAA/Space Weather Prediction Center

Mr. John Lasley
SAIC

Mr. L.A. Lewis
Federal Emergency Management Agency, U.S. Department of Homeland Security

Mr. Tom MacPhail
Federal Aviation Administration

Mr. Jonathan Malay
Lockheed Martin

Dr. Robert McCoy
Office of Naval Research

Ms. Jennifer Meehan
Utah State University

Dr. Cecilia Miner
NOAA/National Weather Service

Mr. Tim Murphy
Boeing

Mr. Bill Murtagh
NOAA/Space Weather Prediction Center

Mr. Mitch Narins
Federal Aviation Administration

Ms. Ann Ngo
International Trade Administration, U.S. Department of Commerce

Dr. Scott Pace
Space Policy Institute, George Washington University

Dr. Jag Pamulapati
Office of Science and Technology Policy

Dr. Xiaoqing Pi
NASA/Jet Propulsion Laboratory

Dr. Robert Robinson
National Science Foundation

Mr. Mike Shaw
Lockheed Martin

Dr. Susan Skone
University of Calgary

Dr. James Spilker
Stanford University

Ms. Wendy Thomas
AMS Policy Program

Dr. W. Kent Tobiska
Space Weather Center, Utah State University

Ms. Karen Van Dyke
Volpe Center, U.S. Department of Transportation

Appendix E: NOAA Space Weather Scales

NOAA Space Weather Scale for Geomagnetic Storms

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

* The K-index used to generate these messages is derived in real-time from the Boulder NOAA Magnetometer. The Boulder K-index, in most cases, approximates the Planetary Kp-index referenced in the NOAA Space Weather Scales. The Planetary Kp-index is not available in real-time.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings.

NOAA Space Weather Scale for Solar Radiation Storms

Category		Effect	Physical measure	Average Freq. (1 cycle=11 yrs)
Scale	**Descriptor**	**Duration of event will influence severity of effects**		
Solar Radiation Storms			**Flux level of >= 10 MeV particles (ions)***	**Number of events when flux level was met (number of storm days)**
S 5	**Extreme**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	**Severe**	**Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	**Strong**	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles$\cdot s^{-1}\cdot ster^{-1}\cdot cm^{-2}$. Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

NOAA Space Weather Scale for Radio Blackout

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

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