Integrating Space Weather Observations & Forecasts into Aviation Operations

American Meteorological Society & SolarMetrics
Policy Workshop Report

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Integrating Space Weather Observations & Forecasts into Aviation Operations

Report of a Policy Workshop

Developed by

American Meteorological Society Policy Program

&

SolarMetrics

In coordination with

Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration/Space Environment Center (NOAA/SEC), National Science Foundation (NSF), & Next Generation Air Transportation System Joint Planning and Development Office (NextGen/JPDO)

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The American Meteorological Society (AMS) is a scientific and professional society of more than 12,000 members from the U.S. and over 100 foreign countries. SolarMetrics is a UK consultancy that provides services to airlines and corporations to enable them to deal effectively with the impacts of space weather on air travel.

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Cover image is a composite of an aircraft landing and an artist’s impression of the Sun-Earth system.

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Policy Workshop Report

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Preface

This report of a policy workshop on "Integrating Space Weather Observations & Forecasts into Aviation Operations" presents recommendations that, if implemented, could increase the safety, reliability, and efficiency of civil aviation operations through more effective use of space weather forecasts and information.

The AMS Policy Program and SolarMetrics developed this workshop as part of a broader 3 year policy study, funded by the NSF, to examine policy issues in implementing effective application of space weather services to the management of the aviation system. Participants represented the aviation community (dispatchers, operations managers, meteorologists, and international organizations); federal government (FAA, NOAA, NSF, NASA, DOD, JPDO); and the space weather community (researchers and vendors).

AMS and SolarMetrics sincerely thank all of the interview and 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 Christy Henderson and Oscar Olmedo, who documented the workshop discussions. We also thank the workshop sponsors: ITT, Lockheed Martin, Raytheon, OFCM/National Space Weather Program, and Ball Aerospace and Technologies.

Finally, we would like to especially acknowledge several individuals who were extremely valuable in helping us with the policy study and in formulating the workshop: Joe Kunches and Bill Murtagh (NOAA SEC) and Rick Heuwinkel, Steve Albersheim, and Karen Shelton-Mur (FAA).

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Executive Summary

As cross-polar traffic increases, the aviation industry is becoming more aware of the impacts space weather can have on operations. (*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.) The industry is primarily concerned about risks during high-latitude (>50°N) and polar operations (>78°N) since impacts of space weather can be greatest in these regions. Effects include disruption in High Frequency (HF) communications, satellite navigation system errors, and radiation hazards to humans and avionics. These concerns not only apply to current operations, but become even more important at all latitudes when considered within the framework for the Next Generation Air Transportation System (NextGen is an interagency initiative to transform the U.S. air transportation system by 2025). Additionally, with the potential space tourism and intercontinental space flight markets, these risks are equally important to the commercial space transportation industry.

Economic Issues

In the last several years, airspace over Russia and China has opened up to commercial traffic, allowing for polar routes between North America and Asia. These flight paths provide a shortcut to Asia, reducing travel time and operating costs (e.g., fuel, delays, reroutes). For example, a United Airlines operations manager stated that if the polar routes are not available, the additional operating costs and penalties for an unscheduled stop or reroute can escalate significantly, totaling hundreds of thousands of dollars per flight. The economics of cross-polar air traffic will become even more important as travel is expected to increase sharply in anticipation of the 2008 Summer Olympic Games in Beijing and will continue to grow.

Operational Issues

Space weather phenomena (geomagnetic storms, solar radiation storms, solar flare radio blackouts, solar radio bursts, and cosmic radiation) can impact aviation operations. Effects include degradation or loss of HF radio transmission and satellite navigation signals; navigation system disruptions; and avionics errors. Dispatchers need space weather forecasts for flight planning at high latitudes, especially for the polar routes. However, operators want additional products that assist in decision making.

Safety Issues

Impacts on aviation operations can directly impact safety, which is the primary concern of air carriers. In addition, solar radiation and cosmic rays can also impact human health. However, current medical research and epidemiological studies are inconclusive regarding the actual impacts to aircrew over the length of a flying career. This issue is a concern for the aviation and sub-orbital space industries, and more accurate data and more extensive studies are needed to assist medical research in identifying the long-term health effects.

Policy Workshop

To date, there are still a lot of gaps between the development of space weather information and the needs of the aviation industry. In response to this need, the American Meteorological Society (AMS) Policy Program and SolarMetrics conducted a policy study funded by the National Science Foundation (NSF) to research key policy issues governing effective application of space weather information to the aviation industry. In addition, AMS and SolarMetrics organized a workshop in coordination with the Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC), NSF, and NextGen/Joint Planning and Development Office (JPDO), on November 29–30, 2006 in Washington DC that led to recommendations on how to improve the safety and operations of the aviation system through better integration of space weather information. The policy study and workshop revealed that there are four main policy issues that need to be addressed to ensure the best use of current space weather information: communication, standardization of information and regulations, education and training, and cost benefit and risk analysis.

Recommendations

Participants agreed on a set of findings and recommendations, which are discussed in detail within this report. Here is a summary of the recommendations:

Communication of Space Weather Information

Communication is key in integrating observations and forecasts into operations; the information needs to be understandable and disseminated in a timely manner to the aviation industry. Within the U.S., aviation terrestrial weather services are provided to non-military aircraft primarily by NOAA, FAA, and the private sector. While the same channels for dissemination of space weather information are available in principle, communication varies. Dispatchers receive space weather information from in-house meteorologists, private sector companies, and NOAA SEC alerts and forecasts, or go directly to the NOAA SEC website. The current FAA system that distributes meteorological information in text cannot distribute graphical products required for the ease of interpreting space weather information. Currently, many aviation operators find space weather information to be too technical and prefer products that aid in decision making.

> **Recommendation: The aviation industry needs to clearly define its requirements for space weather information and how it is incorporated into the operational decision making process. The adhoc Cross Polar Trans East Working Group should lead the process for defining these requirements, ensuring that all key stakeholders are present at requirements discussions.**
>
> **Recommendation: The Cross Polar Trans East Working Group should broaden its membership by inviting NOAA SEC and the International Space Environment Services (ISES) to join in order to bring in more space weather expertise.**

Recommendation: ISES should ensure that its Regional Warning Centers will deliver space weather information in an internationally agreed upon standardized format as defined by the aviation user requirements.

Recommendation: The National Space Weather Program should introduce new elements to increase interaction between the aviation community and the space weather research and service provider community.

Recommendation: The National Space Weather Program should incorporate aviation user requirements into its space weather research planning. Internationally, ISES should ensure that aviation user requirements are incorporated into other national space weather research programs.

Recommendation: The JPDO should ensure involvement of all the necessary subteams and ensure greater involvement of NOAA SEC in the planning process. The JPDO should also coordinate space weather requirements with the Single European Sky ATM Research Programme (SESAR) and other similar global initiatives.

Standardization of Information and Regulations

Air travel is global and international cooperation is therefore essential. However, there is a lack of policy and process, both nationally and internationally, for use of space weather information in the aviation industry. Many operators are not willing to take official action based on space weather information unless they are provided more guidance on how to interpret the information. They want a level playing field. The FAA has not issued any specific requirements regarding space weather except that an operator must have effective communications capability with dispatch and air traffic control for all portions of the flight. Additionally, different U.S. and international groups are not in agreement on standards for space weather information.

Recommendation: The International Civil Aviation Organization (ICAO), World Meteorological Organization (WMO), International Standards Organization (ISO), and ISES should harmonize their separate standards for aviation space weather information, products, and services based upon a set of requirements.

Recommendation: The FAA should provide aviation operations with a minimum set of requirements for making decisions based on space weather information.

Recommendation: The FAA should mandate that space weather information be received by aviation operators and included as part of their planning and briefing process.

Recommendation: The FAA should define a minimum set of requirements for incorporating space weather into operational training for aircrew (pilots and cabin crew), dispatchers, ATC, meteorologists, and engineers.

Recommendation: The FAA should revisit the Users Needs Analysis for space weather, under its current configuration of developing requirements for services.

Recommendation: The FAA should evaluate user requirements from the Cross Polar Trans East Working Group and the NextGen Joint Planning and Development Office for integrating into requirements definition and investment analysis.

Education and Training

Overall, the aviation industry does not understand space weather effects or its impacts on operations. This inhibits awareness of the potential risks involved, and makes it difficult to get key industry stakeholders interested in education and training, which is needed at all levels.

Recommendation: Professional societies, such as the AMS, should work with the FAA, NOAA SEC, and ISES to develop aviation space weather training curricula for aviation operators and meteorologists.

Recommendation: Professional societies, such as the AMS, should work with the University Corporation for Atmospheric Research and ISES to develop aviation space weather education curricula for university students.

Recommendation: The Office of Personnel Management (OPM) Qualification Standards for General Schedule Meteorology Series (GS-1340) should include space weather or space environment courses in the list of optional courses for meteorologists.

Recommendation: ISES, through its Regional Warning Centers, should identify what aviation space weather education material exists globally.

Recommendation: ISES, through its Regional Warning Centers, should become the global public portal for aviation space weather education.

Recommendation: The FAA should propose to ICAO that the U.S. guidance for aviation space weather training and education curricula be adopted by ICAO as guidance material.

Cost Benefit and Risk Analysis

Polar routes reduce both travel time and operating costs. The challenge is how to quantify the issues associated with HF communication loss, quantify the risks associated with the lack of information and the associated operational decisions, and develop policies that will not cost the industry more money.

In 2000, NAVCANADA conducted a feasibility study which identified 33 potential city pairs that could benefit from polar routes. Some examples of time savings in minutes and dollars per flight include (in Canadian dollars):

> Atlanta – Seoul 124 minutes / $44,000
> Boston – Hong Kong 138 minutes / $33,000
> Los Angeles – Bangkok 142 minutes / $33,000
> New York – Singapore 209 minutes / $44,000

Very little information is available on how much space weather is responsible for delays or reroutes on polar routes. The aviation industry needs a better understanding from scientific, engineering, and medical communities regarding risks.

> **Recommendation: The FAA should lead the aviation community in defining and collecting operational data that can be used to assess the different impact areas, cost of improved services, and return on investment. Specifically, analysis of impacts should be segmented into HF communications, navigation, radiation, and new modes (suborbital).**
>
> **Recommendation: NOAA, DOD, and other U.S. government agencies should link aviation space weather cost benefit analysis to requirements for ongoing consistent data collection from ground and space (e.g., ACE, NPOESS, GOES).**
>
> **Recommendation: The FAA should coordinate research studies focusing on the various aviation impact areas (health, avionics, navigation, and communications).**

1. Introduction

The policy aspects of applying space weather information to the international aviation industry are of growing concern to both operators and regulators. In recent years, a lot of progress has been made in understanding impacts of space weather on aviation. The aviation industry is primarily concerned about risks during high-latitude (>50ºN) and polar operations (>78ºN) since impacts of space weather can be greatest in these regions. Effects include disruptions in High-Frequency (HF) communications, satellite navigation system errors, and radiation hazards to humans and avionics. These concerns not only apply to current operations, but become even more important at all latitudes when considered within the framework for the Next Generation Air Transportation System (NextGen) concept of operations. Additionally, with the potential space tourism and intercontinental space flight markets, these risks and policy concerns are now equally important to the developing commercial space transportation industry. However, consideration of policy issues has not been discussed in any detail.

For example:

- What space weather information does the aviation industry need to maintain safe flight operations?
- How do pilots, dispatchers, and air traffic control (ATC) decide when to use a forecast/alert to modify the operations of a flight?
- How much risk are air crew, passengers, and the federal government willing to assume?
- How do we go about educating air crew and passengers about space weather risks during flight?
- How will space weather information be integrated into meteorological information for use by airlines, business jets, Federal Aviation Administration (FAA), ATC, and the commercial space transportation industry?
- Do we need federal laws/regulations in place to ensure the safety of passengers and crew as it pertains to space weather?
- What are the costs/benefits of providing a global space weather service to the aviation industry?

Answering questions such as those above is critical to the aviation community. In particular, space weather is a concern for operators that fly commercial flights routinely over the polar cap. While it is already known that an increase in altitude and latitude means an increase in radiation, solar radiation storms (also known as Solar Proton Events [SPEs]) can further increase the radiation exposure to passengers and crew in jets especially in the polar and high-latitude regions. In addition, the SPE radiation component (i.e., dose rate) changes more rapidly with increasing altitude and latitude compared with the background Galactic Cosmic Ray (GCR) component. Therefore, if given sufficient warning, being able to change altitude and/or routing during solar radiation storms may be worthwhile. The SPE hazard can also increase the risk of errors or failures in micro-electronic components installed in aircraft systems (e.g., flight and engine management computers). New technologies will increasingly use smaller and smaller micro-electronics, thereby further increasing the risks. Geomagnetic storms, solar radiation storms, and solar flare radio blackouts can all affect HF communications. Extreme solar flares can cause complete HF radio blackout on the entire sunlit side of the Earth lasting for a number of hours. Pilots and ATC centers are concerned about these events since any loss of HF communication can be detrimental to flight safety and result in reduced aircraft flow rates through many remote and busy airspace regions (i.e., the Russian side of the Pole only has HF capability, transoceanic and Northern Canada flights still have heavy reliance upon HF). The introduction of improved communication methods such as Controller-Pilot Data Link Communications (CPDLC) may eventually replace HF as the primary means of communication, but not until the ground and airborne equipment becomes more widespread. These space weather events can also affect navigation systems like the older Loran-C (low frequency navigation signals used by maritime and general aviation systems), which may experience outages on the sunlit side of the Earth for many hours, causing loss of position. More importantly, the reliability of accurate position information from current and future developments of the GNSS is equally at risk from the extremely dynamic variations in the space environment.

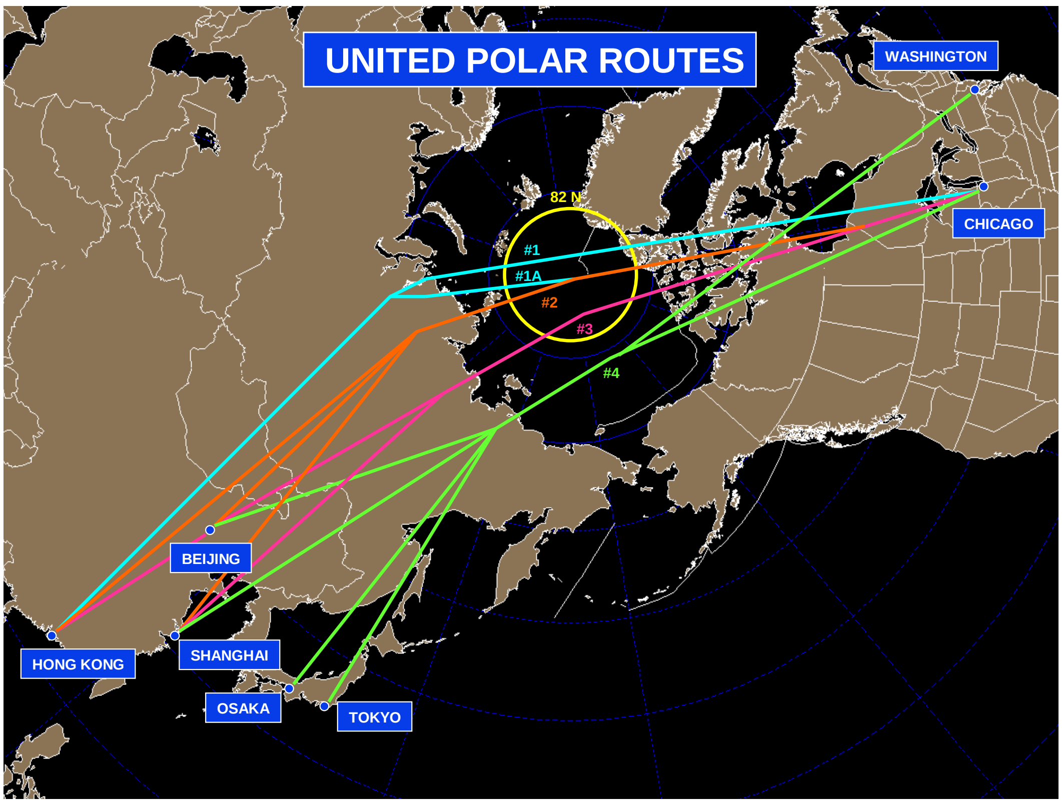

Figure 1. Polar Routes used by United Airlines (source: Mike Stills, United).

Understanding and forecasting space weather phenomena is important so that future operational, commercial, and technological development can be safely introduced. There are currently four polar routes available for operations with additional routes and altitude blocks being implemented (see Figure 1). These routes are used by U.S. and Asian airlines (Box 1) and by commercial business jets with new Ultra-Long Range (ULR) services between North America and the Far East being added. Internationally, the number of Over-the-Pole (greater than 78ºN) or polar region ULR operations have increased from a handful of demo flights in 1999 to over a dozen daily schedules. Forecasted growth in air travel will require the continued expansion of this airspace region.

Airlines Flying North Polar Routes		
United	Chicago:	Hong Kong, Beijing, Tokyo, Shanghai, Osaka
	Washington (IAD):	Tokyo
Continental	Newark:	Hong Kong, Beijing, Tokyo
Air China	New York (JFK):	Beijing
Cathay Pacific	New York (JFK):	Hong Kong
Singapore	Newark:	Singapore
Air Canada	Toronto:	Hong Kong, Beijing, Shanghai, Seoul, Tokyo
Northwest	Detroit:	Tokyo
Thai	New York (JFK):	Bangkok
American	Chicago:	Shanghai
Korean	Seoul:	from New York (JFK), Washington (IAD), Chicago (ORD), Atlanta (ATL), Toronto (YYZ)
Expected to Fly Polar: Asiana, Japan, All Nippon		

Box 1. Airlines flying north polar routes (Source: Dave Rome, NAVCANADA).

In addition to the health and operational risks, space weather can also have a direct economic impact on operations (e.g., fuel, delays, reroutes). Therefore, the aviation industry needs information that is easy to understand, consistent, and ideally in real-time as space weather impacts can vary from minutes to hours to days. If and when a space weather event is predicted or nowcasted, aviation operators want to know what is expected to happen, the magnitude of the event, when and where it will happen, how long it will last, and the potential impact on aircraft, passengers, and crew.

The space weather storms in the fall of 2003, early 2005, and again in the fall of 2006, demonstrated that there is a growing need for discussion of the regulatory framework and how the use of forecasts should affect policies. These periods resulted in the clearest evidence yet of the impacts from a varying space environment upon international commercial aviation operations. The industry's confused, lack of, or at times overly cautious response during these periods of daily impacts not only demonstrated a lack of understanding and awareness, but also highlighted the lack of globally accepted and coordinated operational information and responses. Improved accurate and timely indication of space weather conditions will directly increase safety, capacity, and aviation industry efficiency.

Envisaged advancements in aircraft design, performance and avionics systems, plus the likely development of a satellite-based airspace management system to meet the expected growth in demand for air travel, all mean that air and space operations will become more susceptible to space weather risks. There is a need to develop and provide the aviation industry with a scientific and aviation-specific, real-time global service model, and factor in future reliance on the Global Positioning System (GPS), satellite communication (SATCOM), increased polar, ULR, and high-altitude operations. The benefits would be immediate to aviation in terms of the ability to make informed decisions rather than taking very conservative precautions, as is the case now.

In the case of the burgeoning commercial sub-orbital space tourism operation, this is a highly exposed region as there is reduced atmospheric shielding from the Sun. This makes these space flights vulnerable to sudden increases in exposure levels from solar events even down to lower latitudes. Such occurrences are not everyday events, but at certain times during the solar cycle they become more frequent and/or severe in nature. A space weather monitoring element to any mission-control facility would be able to alert operations staff to their presence and provide expert advice on the various courses of action available. Therefore it would now appear prudent to extend the dissemination of a real-time global service model from current commercial aircraft altitudes to include sub-orbital space operations.

1.1 Space Weather Impacts on Aviation Operations

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 commercial air and space operations most are those that disrupt the operational systems and those that increase the radiation environment. Galactic Cosmic Rays (GCR), Coronal Mass Ejections (CME), SPEs, solar flare radio blackouts, radiation storms, geomagnetic storms, and ionospheric storms are some of the terms that will become familiar to the aviation industry (see Box 2).

Cosmic radiation is the collective term for the radiation which comes from the Sun (the solar component, i.e., SPEs) and from exploding stars from the galaxies of the Universe (the galactic component or GCRs). These high-energy cosmic rays collide with the upper atmosphere, where they produce a cascade of secondary particles that shower down through the atmosphere to the Earth’s surface. It is the highly ionizing GCRs and secondary particles that are the primary source of the cosmic radiation hazard to humans at aircraft altitudes and can cause Single Event Effects (SEE) in aircraft avionics. GCR numbers vary with the approximate 11 year solar activity cycle, such that during solar maximum (associated with increasing sunspot numbers) the GCR flux entering the solar system is reduced. During solar minimum, the opposite occurs with GCR numbers reaching their maximum intensity.

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 of minutes to hours duration. Some solar flares can release very energetic particles (primarily protons), which can arrive in the Earth’s atmosphere within 30 minutes. The Earth’s magnetic field does offer some protection, but these particles can spiral down the field lines, entering the upper atmosphere in the polar regions where they produce additional ionization in the ionosphere and increase the radiation at aircraft altitudes. A consequence of a geomagnetic storm, however, is that it weakens the amount of protection provided by the Earth’s magnetic field, thus increasing the level of ionizing radiation at aircraft altitudes.

The explosive release of CMEs from the Sun's outer atmosphere over the course of several hours can also 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, pummelling 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 degrees, mainly in the auroral regions although these effects can extend to mid-latitudes. These variations in particle fluences and magnetic fields can impact the atmospheric radiation levels as well as severely disrupt radio communications.

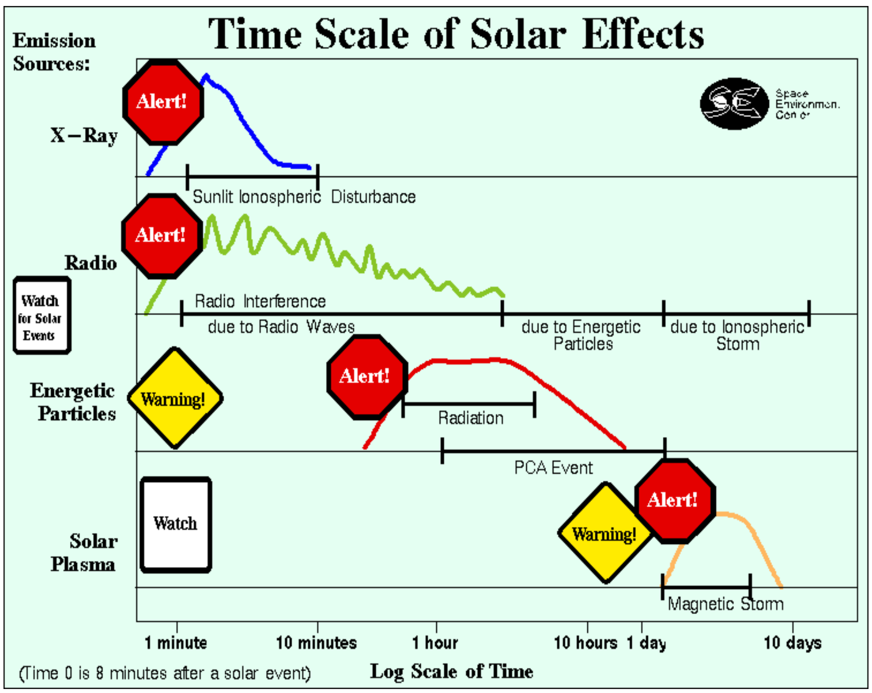

Figure 2. The time scales of solar effects (source: NOAA SEC). Eight minutes after a flare and/or a CME erupts from the Sun, the first blast of Extreme Ultraviolet (EUV) and X-ray light increases the ionospheric density, which can impact HF communication loss. 10 minutes to several hours later, energetic particles arrive. One to four days later, the CME passes and energizes the magnetosphere and ionosphere, affecting navigation systems and radio communications.

Space Weather Impacts on Aviation

Solar Flare Radio Blackouts: disturbances of the ionosphere caused by X-ray emissions from the Sun. HF radio degradation or blackouts are possible at middle and low latitudes.

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, radiation hazards to humans in flight at high altitudes or high latitudes. HF radio blackouts at high latitudes and induced positional errors to GPS are also possible.

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 ATC facilities and other national air space components are susceptible to these power outages. Geomagnetic storms also weaken the ability of the Earth's magnetic field to deflect incoming charged particles.

Box 2. Summary of space weather impacts on aviation.

Communications

Polar flights departing from North America use Very High Frequency (VHF) (30–300 MHz) communication with NAVCANADA, the Canadian ATC. Operators will communicate initially with the Edmonton control center and then transition to Arctic Radio, the agency responsible for relaying messages between flight crew and NAVCANADA. While the flight's initial communication with Arctic Radio is generally on VHF, pilots will eventually switch to HF (3–30 MHz). SATCOM is considered a backup during polar flights, but is rarely available above 82 degrees latitude.

Many communication systems utilize the ionosphere to reflect radio signals over long distances. However, if there is an ionospheric storm, HF or low VHF radio communication at all latitudes can be affected (Cannon et al, 2003). Some radio frequencies are absorbed, while others are reflected, leading to rapidly fluctuating signals and unexpected propagation paths. Solar flare ultraviolet and X-ray bursts, solar energetic particles, or geomagnetic storms can all bring on these conditions. If the effects become especially strong, it can cause a total communications blackout. SPEs produce a particular type of disturbance called Polar Cap Absorption (PCA) that can last for many days. When very energetic particles enter the atmosphere over the polar regions, the enhanced ionization produced at these low ionospheric altitudes (50–100 km) is particularly effective in absorbing HF radio signals and can render HF communications impossible throughout the polar regions. Airlines have diverted flights due to HF communication loss, which have caused en route time penalties of up to 180 minutes.

Other airspace regions of civil operations also rely heavily on HF communications. The North Atlantic and Pacific Ocean regions use HF for aircraft position reporting to maintain separation while outside of ATC radar coverage. Even relatively minor space weather disturbances can seriously disrupt the HF signal causing significant impact on these oceanic region procedures. While the newest aircraft can make use of the latest automated satellite reporting system, reducing their reliance upon HF in such regions, ATC can only communicate with older aircraft via HF to ensure that safe separation is maintained. Over vast areas of the South American and African continents, and the Indian Ocean, HF is the only means of communication. Furthermore, in some parts of central Africa HF is the only way of communication between neighbouring ATC units. To compensate for the poor or non existent ATC surveillance over most of Africa, the International Air Transport Association (IATA) introduced Inflight Broadcast Procedures (IFBP) on air-to-air frequencies. Pilots transmit their flight level, direction of flight, next position and time over that position on VHF 126.9 MHz. Should a conflict arise ahead, the crews of the conflicting aircrafts will decide what avoidance action to take. A disruption of these air-to-air frequencies in conjunction with HF loss can have an immediate effect on aviation safety. Improving information and awareness of anticipated communication outages will help to maintain safety margins.

Within normal radar coverage, civil aircraft operations use VHF frequencies. Although less prone to interference, VHF signals can be lost in the noise produced by solar flares: a point not generally considered when investigating temporary losses of communication between aircraft and ATC. Action focuses primarily on aircraft equipment serviceability, with the majority resulting in a “no fault found.” Such transient losses of communication could result in aircraft separation minima being eroded as ATC avoidance transmissions are missed, or within the military sphere, a friendly aircraft is engaged as hostile due to lack of response. Ensuring robust communications will become more important for future civil and military, air and space operations within the network-centric airspace management envisaged by NextGen.

Satellite Navigation

The aviation industry is also concerned about space weather effects on the future Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LAAS): Global Positioning Satellite (GPS)–based navigation and landing systems that will provide precision guidance to aircraft in cruise and at thousands of airports and airstrips. GNSS, the collective term describing all global navigation systems (e.g., GPS [USA], GLONASS [Russia], Galileo [Europe], and Compass [China]), is expected to provide extensive satellite-based navigation to aviation users of the future. During a geomagnetic storm, the altitude of the lower boundary of the ionosphere changes rapidly and can introduce horizontal and vertical errors of several tens of meters. GNSS operates by transmitting radio waves from satellites to the ground, aircraft, or other satellites and therefore is sensitive to ionospheric changes that occur during geomagnetic storms.

Future airspace management is reliant upon the increasing use of GNSS for navigating aircraft so that the separation between aircraft can be reduced, to position the aircraft on approach, and for landing in all weather conditions. However, the accuracy of the satellite signals, which must pass through the ionosphere, is affected by ionospheric variations due to solar and geomagnetic activity. Dual-frequency satellite receivers actually measure the effect of the ionosphere on the satellite signals and can better adjust to, but not eradicate, these difficult circumstances. This is accomplished by using a network of fixed ground-based GPS receivers, separated by a few hundred km, to derive a map of the ionosphere. The map is then transmitted to the aircraft so that the GPS receiver on board can make an accurate ionospheric correction.

The WAAS was commissioned in 2003 for use in all phases of air navigation, which through the implementation of GNSS Approach with Vertical Guidance (APV), to provide users with the capability to fly approaches with vertical guidance throughout the U.S. national air space to 250 feet above a runway, even in conditions of poor visibility.

In the WAAS system, the standard GPS service is augmented with corrections for time, the GPS satellite orbits, and the ionosphere. These augmentations enable the WAAS system to meet the very stringent aviation requirements for accuracy, availability, and integrity. Quarterly performance reports have shown that the WAAS system generally meets or exceeds these requirements. However, the performance reports also verify that one of the greatest challenges for WAAS is maintaining continuous APV availability during extreme geomagnetic storm events. During the extremely disturbed days of October 29 and 30, and November 20, 2003 the APV service was unavailable over the entire contiguous U.S. (CONUS) region for periods of approximately 15 and 10 hours, respectively (OFCM, 2006).

On a smaller scale, irregularities in the density of the ionosphere 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 there in the evening hours and can cause radio waves to be misdirected. These scintillations make GPS operations difficult.

Until recently, the ionosphere has been considered as the sole source of space weather effects on GNSS signals, systems, and navigation accuracy. New research (Klobuchar et al, 1999; Cerruti et al, 2006) now suggests there is a different class of space weather effects on these signals: solar radio bursts. Solar radio bursts affect the GNSS system by attenuating the carrier-to-noise ratio, thereby degrading the received signals. These bursts can have durations from tens of seconds to a few hours.

Hazards to Humans

The principal space weather hazard to humans is exposure to cosmic radiation, which is caused primarily by GCRs. These very energetic GCRs start interacting with the atmosphere at around 130,000 ft causing secondary particles to shower down into the denser atmosphere below. This "particle shower," and the corresponding level of radiation dose, reach a maximum intensity at around 66,000ft (~20 km) and then slowly decrease with decreasing altitude down to sea level. The dose rates also increase with increasing latitude until reaching about 50 degrees, where upon it becomes almost constant (see Figure 3 and 4).

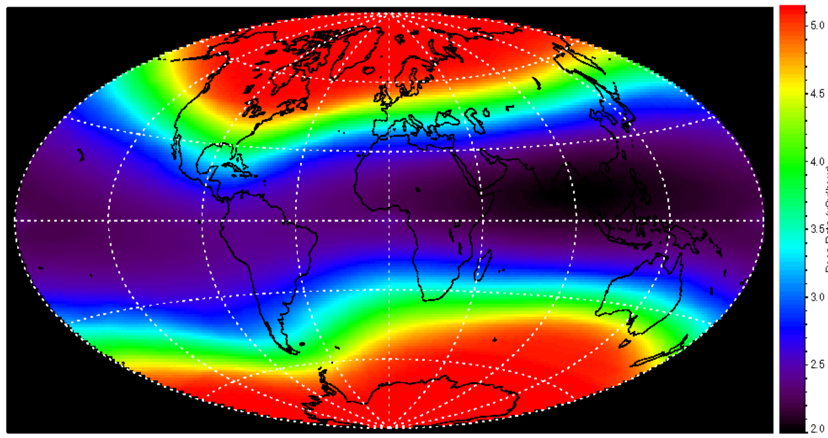

Figure 3. Projected global dose rate at 35,000 ft (Image courtesy SolarMetrics Limited).

The dose rate at an altitude of 39,000 ft (12 km) in mid-temperate latitudes (temperate zones are 23.5° to 66.5° North and South) is typically up to about 6 microSieverts (µSv) per hour, but near the equator only about 3µSv/hr. (The Sievert [1 Sv=1 Joule/kg] is a measure of potential harm from ionizing radiation.) Typically, a London to Los Angeles flight in a commercial aircraft accumulates ~65µSv (6µSv/hr); however, the solar cycle can give ± 20% variations in dose from solar minimum to maximum.

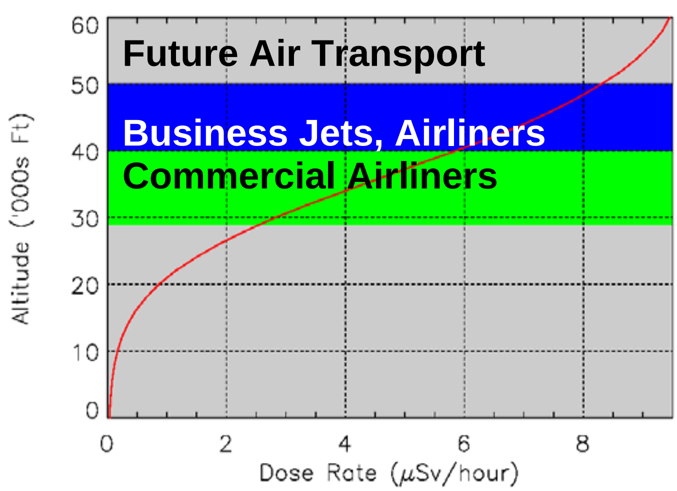

Figure 4. Change in dose rate due to cosmic radiation (GCR component) as a function of altitude and aircraft operational type (Image courtesy SolarMetrics Limited).

Besides the radiation from GCRs, of concern are those SPEs that increase the dose at aircraft altitudes. Most solar flares emit protons with energies up to 10's of MeV (electron volt [eV]: a measurement unit for energy, equal to the energy an electron [or proton] would gain when accelerated by an electric voltage of 1 volt). There have been about 10 such events per year. However, only protons with energies in excess of 300MeV can produce increases at aircraft altitudes and on average there have been approximately three events per solar cycle with sufficient intensity and energies to produce significant radiation in the atmosphere. During the SPE of 1956 it has been estimated (Dyer et al, 2006) that the radiation dose received at 40,000ft (12km) on a transatlantic flight would have been approximately 10mSv. Such events are extremely rare (once every 100 years), but recent studies of smaller more typical events in September and October 1989 indicate 2mSv for a similar flight. Any increase in the radiation doses received from solar radiation storms cannot yet be predicted and will require retrospective additions following a post-event analysis.

Monitoring occupational exposure to natural sources of ionizing radiation is currently included in the recommendations provided by the International Commission for Radiological Protection (ICRP). This includes exposure to the background cosmic radiation received while flying. Under present ICRP guidelines, the recommended dose limit for aircrew is a 5-year average dose of 20 millisieverts (mSv) per year, but with no more than 50 mSv in any single year. For a pregnant crewmember, starting when she reports her pregnancy to management, her work schedule should be such that the equivalent dose to the child does not exceed 1 mSv during the remainder of the pregnancy, with no more than 0.5m Sv (FAA recommendation only) in any month. The Council of the European Union (EU) adopted Directive 96/29 Euratom on 13 May 1996. Article 42 of the Directive imposes requirements relating to the assessment and limitation of air crew members' exposure to cosmic radiation and the provision of information on the effect of cosmic radiation. EU Member States were required to implement the Directive by 13 May 2000 through national legislation. However, in line with "best practice" radiation protection procedures, which is to keep all radiation exposures as low as reasonably achievable (ALARA principle), the EU has also adopted an "action level" of 6 mSv/yr, beyond which the EU registered operators must keep a record of an individuals' exposure. Below 6 mSv/yr exposure monitoring is only a recommendation: actual implementation varies between EU Member States. Current flight profiles and annual flight hours generally make this a workable limit when monitored through record keeping, although it still makes aircrew the most highly exposed workforce beyond even nuclear power workers. In Japan, state regulations recommend that Japanese airlines have to try to keep their aircrews below 5 mSv/yr, which is the dose limit for other occupationally exposed workers in Japan.

However, as future commercial aircraft are being designed for increased range (i.e., growth of polar-route traffic) or to utilize the available airspace at higher and higher altitudes, then significant increases in the doses are expected (8–10μSv/hr at 42,000 ft, 10–12μSv/hr at 51,000 ft). Quicker flights will reduce doses, but significant increases in cruising speeds will need to be achieved: the stillborn Sonic Cruiser flying at Mach 0.98, would have reduced flight times by 15–20%, but with envisaged operating altitudes up to 50,000 ft, the route doses would increase by 30–40%. There are two effects that contribute to increased dose at high altitudes. First, the number of secondary particles increases with altitude, reaching a maximum at approximately 20 km, as described above. Second, the secondary particle composition is quite different at higher altitudes: it becomes more and more dominated by multiply-charged ions, which have a greater potential to cause biological damage.

However, current medical research is inconclusive, so there is not enough evidence that a person can develop cancer as a result of cosmic radiation, since the total career dose is received in low doses per flight, and accumulated slowly over the length of a flying career. It is difficult through epidemiological studies to find causation of cancer due to cosmic radiation as other lifestyle risk factors exist. However, the Linear No Threshold (LNT) theory is accepted within the radiation protection community, i.e., every radiation exposure will have an effect on human health. This issue is a major concern for the aviation and sub-orbital space industries, and more accurate data and more extensive studies are needed to assist medical research of the long-term health effects.

Aircraft Avionics

The electronic components of aircraft avionic systems are susceptible to damage from the highly ionizing interactions of cosmic rays, solar particles and the secondary particles generated in the atmosphere. As these components become increasingly smaller, and therefore more susceptible, then the risk of damage also increases. This can corrupt systems leading to erroneous commands. These soft errors are referred to as Single Event Upsets (SEU). Sometimes a single particle corrupts more than one bit to give Multiple Bit Upsets (MBU). Certain devices could be triggered into a state of high current drain, leading to burn-out and hardware failure; such effects are termed single-event latch-up or single-event burn-out. All these interactions of individual particles are referred to as Single Event Effects (SEE).

Data collected from satellites incorporating sensitive Random Access Memory (RAM) indicate chips have had upset rates from one per day at quiet times to several hundred per day during solar radiation storm events. In-flight aircraft measurements of SEU sensitivity in 4Mb Static RAM (SRAM) produced a rate of 1 upset per 200 flight hours, and agreed well with the expected upset rate variations due to changing latitude. Research (Dyer et al, 2003) has already shown that 100MB of modern RAM found in laptops may suffer upsets every 2 hrs at 40,000 ft, or as much as 1 upset/minute in 1GB of memory due to the 29 September 1989 SPE event. The aviation industry has already catalogued such events on equipment: auto-pilots tripping out and flight instrument units latching into built-in tests. This problem is expected to increase as more low-power, small feature size electronics are deployed in “more electric” aircraft.

Next Generation Air Transportation System

The Next Generation Air Transportation System, or NextGen, (formally called NGATS) will address critical safety and economic needs for civil aviation in future years, out to 2025, while fully integrating national defense and homeland security improvements. Aircraft will be able to use information technology in a more robust way, with enhanced capabilities in the cockpit, better navigation and landing capabilities, and far more comprehensive and accurate knowledge of weather and traffic conditions in real time. The Joint Planning and Development Office (JPDO), which manages NextGen, includes the Departments of Transportation, Defense, Homeland Security and Commerce and the FAA, NASA and White House Office of Science and Technology Policy. The JPDO Weather Integrated Product Team has developed an operational concept for a significantly improved and integrated NextGen weather component. The JPDO recognizes that space weather must be integrated into this system and are working with government, academia, and industry to make sure it is integrated into aviation operations.

NextGen will also have to consider the interactions between the ionosphere and terrestrial weather. The ionosphere can exhibit irregular variations related to the dynamics of the underlying atmosphere. While this aspect of space weather may appear to have a non-solar origin, its effects are most pronounced when the upper-atmosphere winds or lower-ionosphere composition is enhanced by the energy inputs from the active Sun. In addition, optical phenomena called “red sprites” and “blue jets” have been observed (Heavner et al, 2000) at altitudes extending from the tops of strong thunderstorms (at around 15-km altitude) to the lower ionosphere (about 95-km altitude). Possibly related to these optical signatures, intense electromagnetic pulses (10,000 times stronger than lightning-related pulses) have been detected over thunderstorm regions by satellites. These observations suggest that there may be a stronger connection between global thunderstorm activity and the ionosphere and upper atmosphere than previously suspected. Interest in their effects will depend on the future use of this region of Earth-space.

1.2 Policy Study

AMS and SolarMetrics were awarded a three-year NSF grant in 2005 to study policy issues in integrating space weather observations and forecasts into aviation operations. The goal of this project is to conduct policy research leading to recommendations that will increase the safety, reliability, and efficiency of the nation's civil aviation operations through more effective use of space weather forecasts and information. While space weather and aviation are both international issues, this study focuses on a U.S. perspective, taking into consideration international frameworks for aviation safety and operations.

This work will characterize the present and near-term potential in applying space weather information to improve the safety and efficiency of the aviation system. It will discuss public and industrial development of strategies and plans to effectively respond to space weather information. The study will also examine policy issues in implementing effective application of space weather services to the management of the nation's aviation system and the associated tradeoffs (e.g., use of forecasts, changes in regulatory framework, and level of acceptable risk).

Major activities for year one included background research of the policy issues, discussion with relevant aviation and space weather leaders, developing the interview process, developing the interview questions, interviews with key representatives, and outreach. Year-two activities included organizing a workshop, writing this report and other publications, developing an implementation plan, and assisting stakeholders in implementing the recommendations. Year-three activities will focus on outreach and education of the policy issues and continued collaboration with stakeholders in implementing the recommendations that developed from the interviews and workshop.

Interviews were conducted either in person or over the phone with about fifty key people in the government (FAA, NOAA, JPDO, NASA, DOD); U.S. airline dispatchers, pilots, meteorologists (United, Continental, American, Delta, Northwest, carrier and business jets); Foreign airlines (Qantas, Cathay Pacific, Air Canada, Virgin Atlantic, etc.); airline unions and international regulatory organizations (ICAO, IATA); commercial space weather and meteorological vendors; and space weather researchers.

Respondents were chosen by two methods. First, key people, positions or offices were identified. Second, respondents were asked to identify others who should be included in the interviews. People were chosen who could talk knowledgably about space weather impacts on HF communication, GPS navigation, avionics and/or human health. There was also another cross section of people who could talk about aviation operations (planning, systems, safety, etc.); government services and responsibility (dissemination, regulations, education, etc.); and scientific progress (modeling capabilities, applications to operations, etc.).

Respondents were asked a set of questions (see Appendix B) which revealed the major policy issues in integrating space weather information into aviation operations. The interviews revealed that as understanding of space weather impacts on aviation increases, the need for a policy framework increases. Emerging policy issues fell into four categories: communication, standardization of information and regulations, education and training, and cost-benefit analysis.

1.3 Policy Workshop

AMS and SolarMetrics, in coordination with the FAA, NOAA/SEC, NSF, and NextGen/JPDO, organized a workshop on November 29–30, 2006 in Washington DC that led to recommendations on how to improve the safety and operations of the nation's aviation system through better integration of space weather information. The workshop was co-sponsored by the AMS Policy Program Study Series Underwriters: ITT, Lockheed Martin, and Raytheon and the workshop sponsors: the Office of the Federal Coordinator for Meteorology/National Space Weather Program* and Ball Aerospace and Technologies. Participants represented the aviation community (dispatchers, operations managers, meteorologists, and international organizations); federal government (FAA, NOAA, NSF, NASA, DOD, JPDO); and the space weather community (researchers and vendors). The number of workshop participants was intentionally kept small in order to enhance discussion. The program and participant list can be found in Appendices C and E.

Objectives of workshop:

- Bring together representatives of the aviation industry, space weather information providers, and government officials to discuss the development of space weather information and operational needs
- Identify how space weather information can be better applied to aviation operations to reduce impacts and maintain flight safety
- Discuss opportunities and policies to mitigate risk and allow for the application of space weather information to aviation operations
- Develop findings, policy options, and recommendations that foster a global seamless transfer of space weather information to aviation operations.

The workshop consisted of a series of background presentations followed by four working sessions, each designed to answer the focus questions and develop a set of findings and recommendations. These four sessions were based on the main policy issues that emerged from the interviews (communication, standardization, education and training, and cost-benefit analysis). The focus questions can be found in Appendix D. 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.

* The following agencies participate in the National Space Weather Program: DOC/NOAA, DOD, NSF, NASA, DOI/USGS, DOE, and DOT/FAA.

2. Policy Issue: Communication of Space Weather Information

Communication of space weather information is one of the main policy issues in integrating space weather observations and forecasts into aviation operations. Communication includes the *understandability* and *dissemination* of the information. Within the U.S., aviation terrestrial weather services are provided to nonmilitary aircraft primarily by the NOAA National Weather Service (NWS), the FAA, and the private sector. While the same channels for dissemination of space weather information are available in principle, communication of the information varies.

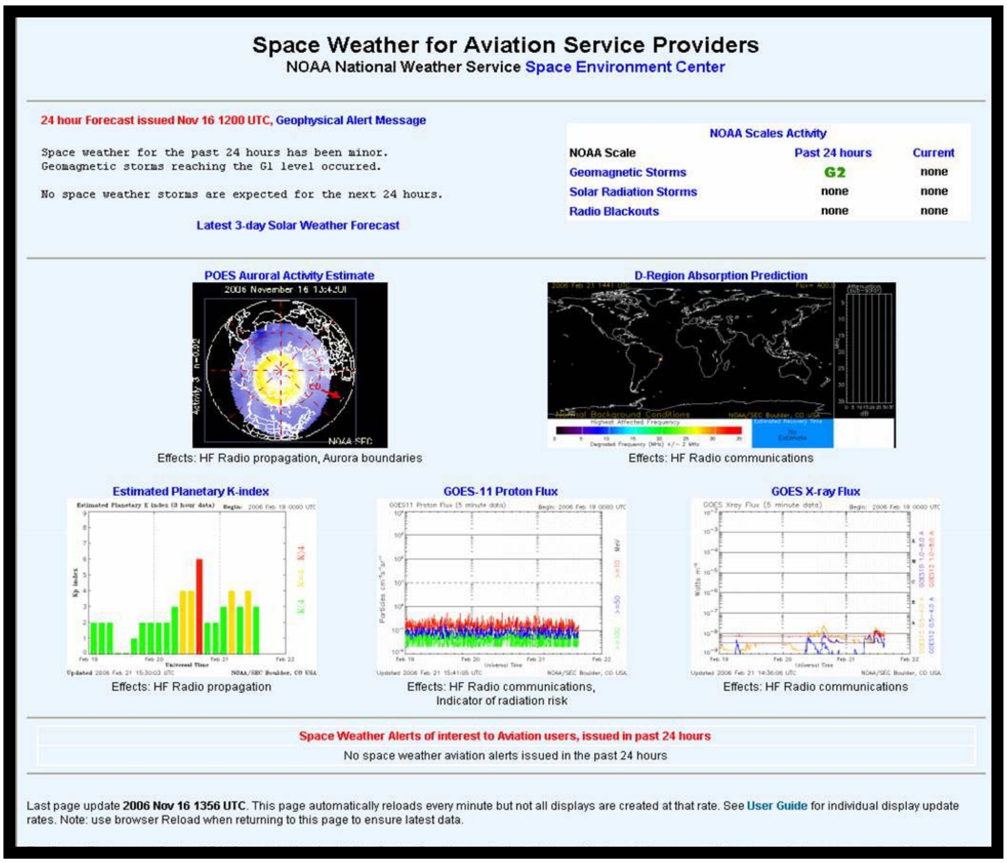

Figure 5. SEC Aviation Service Providers web page, http://www.sec.noaa.gov/aviation/index.html

The NOAA Space Environment Center (SEC), which is part of the NWS, offers a *Space Weather for Aviation Service Providers* Web page designed for the aviation community (Figure 5). This single page, while not tailored to meet the needs of aviation operation centers, offers general information such as alerts on space weather activity and different products that can be interpreted for whether HF communication could be impaired. The SEC website utilizes a set of space weather scales (levels 1–5; analogous to the hurricane scale) for geomagnetic storms, solar radiation storms, and radio blackouts. Space weather watches, warnings, and alerts are also available through NOAA's Weather Wire Service, a satellite broadcast system that distributes emergency weather conditions and forecasts to North America and part of Central and South America. Typically, dispatchers may review the NOAA SEC's website and will modify polar flight plans if there is a threat of HF communication loss. FAA rulings require that maintaining two-way communications must be considered at the planning stage. If problems are detected before departure, the Russian Far East Route is selected. If a problem occurs before reaching the polar area, the flight is rerouted, which likely results in an unplanned fuel stop that adds hours to the trip. If the problem occurs after the aircraft has entered the area, the flight continues. Some polar route operators will use more expensive SATCOM as a backup communications medium; however, only the Iridium/Intelsat systems are available above 82°N and their installation onboard commercial aircraft is not widespread due to the costs.

A solar radiation alert system developed by the FAA's Civil Aerospace Medical Institute (CAMI), with data provided by the NOAA SEC, alerts users that a solar particle event is in progress that may lead to a substantial increase in the ionizing radiation dose rates at aircraft altitudes. These solar radiation alerts are transmitted worldwide to subscribers of NOAA's Weather Wire Service. To date, this system has had limited use by operators as it is considered too coarse to assist with altitude-lowering decisions. In addition, it has been identified that the current SEC space weather scales for Solar Radiation Storms use GOES satellite particle energies (10MeV), which are appropriate for identifying communication outages at high latitudes, but are considered too weak to seriously affect dose rates at aircraft altitudes. GOES satellite particle energies greater than 300MeV are now being proposed as the basis for more accurate assessments of dose rates, although the true picture is more complex than a single satellite data source. Assessing an individuals' exposure may be achieved by using dose estimates for routes calculated using computer programs. There are several such programs available worldwide (e.g., CARI-6 [CAMI, USA], NAIRAS [NASA, USA], EPCARD [GSF, Germany], SIEVERT [Direction Generale de l'Aviation Civile, France], JISCARD-EX [Japan], QARM [QinetiQ, UK]). All programs require regular updating, especially for the effect of solar modulation and for changes in geomagnetic field conditions. However, to date there are no models available that can offer an accurate real-time solar radiation storm exposure assessment that could be utilized for decision making within operational timeframes. Greater use of inflight detectors is considered necessary, first, to collect data during solar radiation storms that will help to improve the computer models, and second, to provide real-time inflight warnings of elevated radiation levels directly to the pilots.

While space weather services are provided by the NWS, in particular by SEC, there are several communication challenges that need to be addressed before the information can be fully integrated into aviation operations.

The first challenge is making space weather information more understandable to the aviation community. Throughout the interviews, aviation representatives noted the following about how well space weather information is currently understood:

- In general, space weather information and forecasts as provided by the government are too technical for non-scientists to understand. Products should be understandable to the lay person.

- Dispatchers do not want to interpret space weather information. They want information they can use to make a decision. They need less scientific notation. Most are not sure what they are looking at on the NOAA SEC site.
- Most operators have meteorologists helping to interpret space weather information, but even they need more training to understand the information.
- There is a preference to include operational decision matrices or solutions such that there is a collective response (i.e., best decision for the industry, not the individual company).

The second communication challenge is making sure space weather information is disseminated in a timely and effective manner. NOAA SEC provides space weather information that can be useful for understanding risk to HF communications, GPS, avionics, and human health. During the interviews, aviation representatives noted the following about dissemination of the space weather information:

- Dispatchers receive space weather information in various ways: from in-house meteorologists, private-sector companies, and NOAA SEC alerts and forecasts, or by going directly to the NOAA SEC website.
- Operators would like better space weather forecasts that are more timely for improved decision making.
- The aviation industry is not receiving space weather information from the FAA or NWS Aviation Weather Center. There is no requirement for the issuance of a SIGMET (SIGnificant METeorological information) for space weather information. Most are getting information directly from NOAA SEC website or email alerts.
- The current FAA system, WMSCR (Weather Message Switch Center Replacement), that distributes meteorological information as text to the aviation industry cannot distribute graphical products which are required for ease of interpretation for space weather. Other FAA services are not adequate for space weather, e.g., NOTAM.
- Aviation communication providers, such as ARINC, monitor space weather information and will notify ATC if there may be delays in communicating with aircraft en route.
- While FAA CAMI does offer information on solar radiation, many operators are not accessing this information.
- It would be more efficient if space weather and meteorological information were integrated or packaged together by the NWS or aviation meteorologists.
- The NextGen JPDO plans to fuse global weather observations and forecasts into a single information system, which will be dynamically updated as needed.

Although dispatchers will make decisions based on the NOAA SEC space weather scales, some have suggested that decision tools (e.g., graphics similar to traffic lights) would be more helpful in making operational decisions. However, while NOAA SEC provides new products based on user requests, it is limited in what it can provide based on NWS public–private sector partnership policy. Dispatchers also suggest that space weather forecasts need to be available and accurate, and in the case of HF, issued a minimum of 12–18 hours before a flight to be applied to pre-flight operational planning. This capability is currently not available; therefore improved observations, modeling, and scientific understanding are needed in order to improve forecasts.

Workshop Findings and Recommendations

During the communication session at the workshop, the participants were asked the following questions which led to findings and recommendations:

- How is space weather communicated and what improvements are needed?
- What technical, observational, and modeling capabilities are needed to improve decision making and how will/can they be achieved?
- Who are the best people to deliver space weather information?
- From where do you want to receive the information?
- What policy options are needed to improve communication of space weather information and ensure seamless integration into the local, regional, and global operational decision processes?

Participants brought up many of the same issues revealed in the interviews. Aviation operators want products that are less technical. They are not interested in interpreting scientific graphs, but instead want products they can use to make an operational decision. They would like "one-stop shopping" for space weather information. Suggestions spanned from a space weather SIGMET to a stoplight graph (red, yellow, green) to a 4D data cube with estimates of uncertainty. All of these have their own shortcomings and are not easy solutions.

Everyone agreed that in order to provide tools for aviation operations, the scientific community needs to understand the user requirements. There is a disconnect between space weather research and operational needs. Scientific models are too technical and their products need to be simplified for the user. Documenting the user requirements and understanding what geophysical phenomena are important will allow both the space weather and aviation communities to better communicate space weather information. Once this is accomplished, the government can identify the best people to deliver space weather information, where they should receive the information from, and how to set standards on data and tools. Once these requirements are identified, the FAA and NWS can provide additional products that are useful to aviation operators. If there are unmet requirements, that promotes areas for research.

The participants discussed who would be the best group to lead the process of defining user requirements. The Cross Polar Trans East Working Group (CPTEWG), an adhoc group of U.S., Canadian, and Russian air traffic controllers; airline dispatchers and operations managers; and IATA meet periodically to discuss issues of importance in operating the polar North Atlantic and Pacific routes. However, this group does not include representatives with space weather expertise. NOAA SEC and the International Space Environment Service (ISES) were suggested as new partners with the CPTEWG. The SEC is part of the ISES World Warning Agency, acting as a hub for space weather data exchange and forecasts. ISES consists of 11 Regional Warning Centers (Sweden, Poland, Czech Republic, Russia, China, India, Japan, Australia, United States, Canada, and Belgium). These centers supply data and forecasts to the NOAA SEC for consideration in the daily global forecast issued by SEC.

The CPTEWG is linked very strongly with NAVCANADA which has taken the lead in understanding and using space weather information as part of its operational control of the North

Polar Region. NAVCANADA, Canada's provider of civil air navigation services, is a private corporation providing ATC, flight information, and weather briefings. NAVCANADA works with Natural Resources Canada (NRCan) on improving HF observational tools and forecasting. In order for CPTWEG to deliver user requirements, it will need to expand its discussions to include space weather and bring in appropriate expertise. In addition, key stakeholders need to be part of the user requirements defining process. This includes not only commercial airlines, but cargo carriers, business aviation, unions, private-sector service providers, and federal and international organizations.

Finding: Neither the aviation industry nor the space weather community have a clear understanding of the aviation industry's requirements for space weather information (e.g., content, timing, interpretation, level of risk).

Recommendation: The aviation industry needs to clearly define its requirements for space weather information and how it is incorporated into the operational decision making process. The adhoc Cross Polar Trans East Working Group should lead the process for defining these requirements, ensuring that all key stakeholders are present at requirements discussions.

Finding: As currently constituted, the adhoc Cross Polar Trans East Working Group does not sufficiently include space weather experts.

Recommendation: The Cross Polar Trans East Working Group should broaden its membership by inviting NOAA SEC and the International Space Environment Services (ISES) to join in order to bring in more space weather expertise.

Dispatchers and meteorologists do refer to space weather products. However, NOAA SEC and NRCan offer different "space weather scales," which can cause confusion for users looking at different sources of information.

ISES brings together space weather agencies, or Regional Warning Centers, from around the globe to encourage and facilitate near real-time international monitoring and prediction of the space environment. Since both NOAA SEC and NRCan are both Regional Warning Centers, ISES could play a significant role in ensuring that these and other centers are developing agreed upon formats as defined by the user requirements.

Finding: NOAA SEC, NRCan, and other international partners offer a variety of operational tools, but these are not standardized and therefore cause confusion to aviation operators.

Recommendation: ISES should ensure that its Regional Warning Centers will deliver space weather information in an internationally agreed upon standardized format as defined by the aviation user requirements.

In the last several years, the space weather community has paid more attention to customer needs. The NOAA SEC aviation customer base now includes over 50 air carriers. They also work with vendors who are interested in providing value-added products and services for the aviation industry. However, the market for commercial aviation space weather products is growing very slowly. Space weather researchers want to conduct research or provide services that can be useful to the aviation community. However, the aviation community, not understanding space weather, does not know what they need. In order to identify user requirements and quantify the benefits of space weather services to the aviation industry, more communication is needed between the various groups. The recent NSWP assessment report offered a recommendation that, "the NSWP should institute a coordinated effort to fund a series of space weather benefit studies that would cover the primary topics of concern to operators of space weather–vulnerable systems." This effort would greatly increase communication and understanding between the space weather and aviation communities.

> **Finding: Providers of space weather information and the users of that information need to collaborate more closely.**
>
> > **Recommendation: The National Space Weather Program should introduce new elements to increase interaction between the aviation community and the space weather research and service provider community.**
>
> **Finding: The space weather research community does not adequately understand aviation industry requirements and therefore does not conduct much targeted research for the user community.**
>
> > **Recommendation: The National Space Weather Program should incorporate aviation user requirements into its space weather research planning. Internationally, ISES should ensure that aviation user requirements are incorporated into other national space weather research programs.**

The deployment of NextGen is reliant upon terrestrial and space weather products and forecasts becoming more reliable. Just as important as the quality of weather information is how decision-makers respond to the information and utilize it. Collection, management, and dissemination of space weather–related information will also be critical.

The technological developments required to implement the NextGen system (e.g., avionics, GPS use for WAAS, LAAS, communication for data transmission) will all become more susceptible to space weather impacts, thereby requiring the JPDO, and all its relevant Integrated Product Teams (IPT), to become involved in greater interaction between the user and space weather research communities including the discussions with the Single European Sky ATM Research Programme (SESAR) and other similar global bodies.

> **Finding: The JPDO, its IPTs, providers of space weather information, and the users of that information are operating largely separately and not coordinating sufficiently.**
>
> > **Recommendation: The JPDO should ensure involvement of all the necessary subteams and ensure greater involvement of NOAA SEC in the planning process. The JPDO should also coordinate space weather requirements with the Single European Sky ATM Research Programme (SESAR) and other similar global initiatives.**

3. Policy Issue: Standardization of Information and Regulations

Standardization of space weather information and regulations is another key policy issue in integrating space weather observations and forecasts into aviation operations. In general, aviation operators are not willing to take action based on space weather information that does not create a level playing field. Therefore, some would prefer that the FAA set guidance that all operators would have to follow, similar to guidance on HF communication loss.

Throughout the interviews, aviation and government representatives noted the following about standardization of information:

- Many in the aviation community prefer that terminology and formatting of space weather information be similar to terrestrial weather.
- There is a lack of space weather requirements being provided to the NWS. First, operators have to tell the FAA their requirements. Then the FAA has to task the NWS to provide new space weather products as the FAA does for terrestrial weather information.

Throughout the interviews, aviation and government representatives noted the following about standardization of regulations:

- Many operators are not willing to take official action based on space weather information unless they are provided more guidance on how to interpret the information (it does not create a level playing field).
- Some would prefer that FAA become more engaged in space weather issues to determine what regulatory actions have to be considered, similar to the Federal Aviation Regulations (FAR) on communication.
- Some in the aviation community would like to see ICAO set global standards for the issuance of space weather products and its use.
- It is clear what actions need to be taken when loss of HF is at risk, but there are no policies for GPS or radiation risks.
- There is a lack of policy and process for space weather information.

Workshop Findings and Recommendations

During the standardization session at the workshop, participants were asked the following questions which led to findings and recommendations:

- How do pilots, dispatchers, and air traffic controllers decide when to use a space weather forecast/alert to modify the operations of a flight?
- What regulations are needed to be in place to ensure that standardized space weather information is integrated into global aviation operations? What national and global processes are available to achieve this?

The discussion focused on guidance documents to interpret space weather information, standard formatted messages, and regulatory issues for communication and health. In general, there is a clear lack of policy and process for integrating space weather information into aviation operational planning.

FAA Requirements and Guidance

The current FAA requirements for space weather information that deal with communication issues include:

> FAR 121.99 Requires reliable and rapid communication over the entire route between the airplane and the appropriate dispatch office and between each airplane and the appropriate air traffic control unit.
>
> FAR 121.103 Requires flag operators to show for each proposed route that non-visual ground aids are available over the route for navigating aircraft and that non-visual aids are available to allow navigation to alternate airports for the operation involved.
>
> FAR 121.533 Provides that an aircraft dispatcher is responsible for monitoring the progress of each flight and issuing as necessary information for the safety of the flight.
>
> FAR 121.603 Requires the pilot in command to obtain any additional available information of meteorological conditions that may affect the safety of the flight.
>
> FAR 121.607 States that no person may dispatch an airplane over a route unless communications and navigation facilities required by Secs. 121.99 and 121.103 for that route are in satisfactory operating condition.

There are also other documents that pertain to space weather:

Air Carrier Operating Specifications B055	North Polar Operations
Advisory Circular 120-61	Crewmember Training on In-Flight Radiation Exposure
Advisory Circular 120-61A	Guidance on radiation dosage, including limits and calculation methods
Report DOT/FAA/AM-92/2	Radiation Exposure of Air Carrier Crewmembers II

In addition, the FAA Flight Plan for 2007–2011 calls for improving the navigation systems through support of WAAS by increased landing capacity, improved safety with reduced separation minimums, user preferred flight paths, situational awareness, and accurate reporting.

In the network-centric NextGen system, the requirement is for a common weather picture to support decision making. More accurate forecasts and tens of thousands of real-time global weather observations, including those from the ground, aircraft, and satellites will be fused into a "single picture" that is automatically updated and distributed to everyone. The concept is called NextGen Network Enabled Weather.

International Guidance

The International Civil Aviation Organization (ICAO) is a specialized agency of the United Nations (UN). ICAO sets the standards for aviation safety, security, efficiency, and regularity, as well as for aviation environmental protection, and encourages their implementation. The governing body of ICAO, the Council, has the duty of adopting international standards and recommended practices (SARPs) and incorporating these into the Annexes to the Convention on International Civil Aviation. ICAO also works closely with other UN agencies, such as the World Meteorological Organization (WMO) which promotes standards for meteorological and related observations. The International Air Transport Association (IATA), the International Federation of Air Line Pilots' Associations (IFALPA), and other international organizations participate in many ICAO meetings.

ICAO recognizes the need for information and products that support international air navigation, but Annex 3 (Meteorological Service for International Air Navigation) contains no standard or recommended practices for space weather. Annex 15 (Aeronautical Information Services) does allow for issuance of a NOTAM for solar radiation, but provides very little guidance for message content. With the growing interest in space weather, the ICAO International Airways Volcano Watch Operations Group, which currently has responsibility for space weather issues, is assessing needs for information about solar radiation storms.

At the same time, the International Organization for Standards (ISO), a network of the national standards institutes of 157 countries, is the world's largest developer of standards. ISO has already begun assessing space weather with ISO 15390, which specifies GCR fluences, and ISO 21348, which describes a standard process for determining solar irradiances.

In addition, the International Space Environment Service (ISES) provides standardized rapid free exchange of space weather information and forecasts through its Regional Warning Centers (RWC). The NOAA SEC, the RWC for the U.S., issues space weather scales, but they are not standards and do not carry a legal requirement. Recently, ISO has asked ISES to develop a standard for space weather activity measurements.

These different U.S. and international groups are not unifying their standards for space weather information. For example, the global harmonization of all standards dealing with human exposure to cosmic radiation and solar particle events (e.g., validation of computer programs, annual and maximum event dose rates, monitoring, record-keeping) must be achieved in order for any exposure-reducing decisions (e.g., altitude lowering) to be applied safely and correctly in any airspace region. Universally accepted policies for exposure risk levels would provide a level commercial playing field for the industry as well bolster confidence in passengers and crew that the aviation and space tourism industries were dealing correctly with this issue. Recent progress has already been made by the International Electrotechnical Commission (IEC) for setting some basic standards for avionics manufacturers.

Finding: The different international organizations currently set standards for aviation and space weather independently.

> **Recommendation: The International Civil Aviation Organization (ICAO), World Meteorological Organization (WMO), International Standards Organization (ISO), and ISES should harmonize their separate standards for aviation space weather information, products, and services based upon a set of requirements.**

Operators want a level playing field in the commercial market. They are not willing to take action based on space weather information unless they are provided with more guidance on how to interpret the information. At the same time, operators do not want additional rules or regulations limiting their ability to make decisions that are best for their company.

The FAA has not issued any specific requirements regarding space weather except that an operator must have effective communications capability with dispatch and ATC for all portions of the flight (FAR part 121.99, Communication Facilities). In addition, if operators fly polar routes, they need to demonstrate that they can do so safely. FAA OpSpec B055 requires operators to gain specific approval to conduct north polar operations, in addition to FAA approval for flight in the area of magnetic unreliability (OpSpec B040).

Some operators may choose to alter operations based on the NOAA SEC space weather scales. For example, if a S4 (solar radiation storm level 4) alert or higher is issued, operations managers may request that a flight avoid the polar regions since loss of HF communication is very likely. There is no guidance from FAA on how operators should respond to the solar flare radio blackout, solar radiation storms, or geomagnetic storm alerts. Operators are making decisions based on knowledge they receive from NOAA SEC and past experiences.

Finding: Aviation operators prefer that the governing federal and international agencies provide a minimum set of requirements, rather than regulations, for making decisions based on space weather information.

> **Recommendation: The FAA should provide aviation operations with a minimum set of requirements for making decisions based on space weather information.**

> **Recommendation: The FAA should mandate that space weather information be received by aviation operators and included as part of their planning and briefing process.**

Currently, there are no requirements for the aviation industry to educate their aircrew, dispatchers, meteorologists, or engineers about the risks imposed by space weather on operations. Likewise, the FAA has no requirement to train ATC about space weather, whereas terrestrial weather is an integral part of the training process for any airman or ATC personnel (e.g., FAA-H-8083-25 Pilot's Handbook of Aeronautical Knowledge: "Weather Theory – H951-H956", "Weather Reports, Forecasts, and Charts – H957-H963").

The FAA Circular AC 120-61, "Crewmember Training on In-Flight Radiation Exposure" recommends operators (1) inform crewmembers about radiation exposure and known associated health risks; and (2) assist crewmembers in making informed decisions with regard to their work on commercial air carriers. However, a broader requirement is needed to ensure that space weather is part of operational training. A minimum set of requirements allows the operators to set their own training policies and formats.

> **Finding: Currently, space weather information is not integrated into operational training.**
>
> > **Recommendation: The FAA should define a minimum set of requirements for incorporating space weather into operational training for aircrew (pilots and cabin crew), dispatchers, ATC, meteorologists, and engineers.**

The FAA Aerospace Weather Policy and Standards office conducted a Users' Needs Analysis (UNA) in 2004 to determine what types of weather products users need to improve their decision-making process with respect to space weather phenomena. It discussed needed capabilities and shortfalls. The draft report concluded that:

> "Immediate action is required to provide the improved space weather forecast products identified by the UNA. If no action is taken, decision-makers will continue to make decisions based on limited or time-delayed data. Without improvements in space weather forecasts, timely decision-making is compromised, resulting in reduced airport arrival and departure rates, ultimately leading to a systemic slow-down effect throughout the National Airspace System (NAS)."

However since the UNA was conducted, the FAA has revised its configuration of developing requirements for services, so the final report was never published.

> **Finding: The FAA has not officially issued a set of user needs for space weather.**
>
> > **Recommendation: The FAA should revisit the Users Needs Analysis for space weather under its current configuration of developing requirements for services.**
> >
> > **Recommendation: The FAA should evaluate user requirements from the Cross Polar Trans East Working Group and the NextGen Joint Planning and Development Planning Office for integrating into requirements definition and investment analysis.**

4. Policy Issue: Education and Training

Overall, the aviation industry does not understand space weather effects or their impacts on aviation operations. This inhibits awareness of the potential risks involved, and makes it difficult to get key industry stakeholders interested in education and training, which is needed at all levels.

During the interviews, aviation representatives stated that:

- There is poor awareness and understanding of space weather effects on aviation operations.
- As there is little understanding of space weather, there is little perception of the risks. Therefore, it is difficult to establish the need for an education process.
- Education is needed at all levels (dispatchers, ATC, pilots, crew, and passengers, private astronauts/space tourists, management).
- People who are applying space weather information need to understand it.
- Currently there are 1–2 people at an airline, typically the dispatchers, who know something about space weather. They receive that information from NOAA SEC, attending meetings, IATA, etc. and then disseminate it to other staff.
- Operators have education and training programs already. All aspects of space weather impacts should be a part of these.

Government representatives stated that:

- In general, ATC receives little or no education about space weather. Although NAV CANADA now includes some relevant education.
- FAA should evaluate the need to require space weather training for dispatchers and pilots.
- Awareness is improving, but there still needs to be a standardized education plan.
- Center Weather Service Units (CWSUs) and NWS forecast offices receive little or no education about space weather.

The scientific community offered suggestions such as:

- UCAR's COMET (Cooperative Program for Operational Meteorology, Education and Training) program provides training on meteorology and aviation; could provide space weather and aviation training.
- The space weather community can provide better services once it gains a better understanding of aviation requirements.
- Space weather scientists and universities could have a role in the education process.

Workshop Findings and Recommendations

During this session, the participants were asked the following questions:

- How do employees at your company/organization learn about space weather?
- What educational programs are needed for decision makers (pilots, ATC, crew, operations managers, dispatchers, engineers, etc.)?

- How do you establish even the need for an education process when the risk is not visible to the end-user?
- What lessons can be learned from established space weather users (i.e., NASA, USAF, ESA) about developing space weather education programs?
- What policy options are needed to develop and promote education programs?

Participants discussed the lack of knowledge about space weather and its associated risks and the need for mandatory training versus recommended training. The participants could not agree on whether education should be regulated or not. Many aviation representatives stated that the FAA should define a minimum set of requirements to ensure that space weather is integrated into operational training. This may still not be adequate, but it is a first step.

A major challenge is that operators do not really understand space weather forecasts and information and therefore do not know how to make operational decisions based on the information. Even aviation meteorologists, while trained to interpret scientific data, are not educated about the specialized area of space weather. For them to incorporate space weather into their terrestrial weather briefings they need to understand the terminology. It is evident that education is needed at all levels (e.g., dispatchers, aircrew, ATC, meteorologists). While operators and unions have education and training programs already, most do not include space weather as a topic. When it comes to HF communications, operators need to understand what are the usable frequencies. To understand navigation, they need to understand uncertainty in GPS. With respect to radiation, operators need to understand atmospheric ionizing radiation and how to interpret tools for monitoring and mitigating radiation health hazards to aircrew and passengers.

With limited understanding of space weather, there is limited perception of the risks. Therefore, establishing the need for an education process remains a challenge. A standardized training and education plan can provide the aviation and meteorological communities with a level playing field. These materials need to be simple and standard. In generating materials, aviation organizations, companies, and unions should be surveyed to find out what they want. Whoever has the most resources and the greatest influence should lead the education and training in this area.

The AMS provides standards for meteorological education at universities, but these do not currently address space weather. Space weather could be included in introductory meteorology courses. The AMS also has a Certified Consulting Meteorologist program, which has no requirement for space weather. The FAA and NWS provide guidance on aviation weather training, but that does not include space weather either. The Office of Personnel Management (OPM) Qualification Standard describing the appropriate courses for entry-level meteorologists in the Meteorology series (GS-1340) mentions *aeronomy* but this is a rather limited sub-specialty within space weather.

There are various organizations and companies that produce, or can produce, educational materials for understanding aviation space weather. For example, the University Corporation for Atmospheric Research (UCAR) Cooperative Program for Operational Meteorology, Education, and Training (COMET) offers numerous aviation weather online modules, which have been funded by the NWS. Space weather could be integrated into these distance-learning offerings. The U.S. Air Force has also produced space weather material that could be useful to the commercial aviation industry. All available materials (Web, textbook, or university based) should be coordinated.

Finding: There are varying levels of education and training needed within both the aviation and meteorological communities. In addition, no standardized plans exist to serve these communities.

> **Recommendation: Professional societies, such as the AMS, should work with the FAA, NOAA SEC, and ISES to develop aviation space weather training curricula for aviation operators and meteorologists.**
>
> **Recommendation: Professional societies, such as the AMS, should work with the University Corporation for Atmospheric Research and ISES to develop aviation space weather education curricula for university students.**
>
> **Recommendation: The Office of Personnel Management (OPM) Qualification Standards for General Schedule Meteorology Series (GS-1340) should include space weather or space environment courses in the list of optional courses for meteorologists.**

There is no official source for aviation space weather training or education materials. In addition, it is not well known what information is available. Each company, agency, or organization may disseminate educational materials using varying delivery methods (e.g., brochures, briefings), but it is up to the reader to actually read or pay attention to the material.

ISES is currently working on a new website, http://www.spaceweather.org, that will provide space weather information and serve as a gateway to all websites on space weather. In particular, it will host information services provided by ISES and examine space weather effects on technological systems. Space weather services for the aviation community will also be provided. The target audience includes scientists, end users, and the public.

Finding: Internationally, the aviation community has limited awareness and understanding of space weather effects on operations and there is no authoritative voice for aviation space weather education and training.

> **Recommendation: ISES, through its Regional Warning Centers, should identify what aviation space weather education material exists globally.**
>
> **Recommendation: ISES, through its Regional Warning Centers, should become the global public portal for aviation space weather education.**
>
> **Recommendation: The FAA should propose to ICAO that the U.S. guidance for aviation space weather training and education curricula be adopted by ICAO as guidance material.**

5. Policy Issue: Cost-Benefit and Risk Analysis

In commercial aviation, terrestrial weather has major impacts on operating costs which are well documented. For example, snow can lead to flight delays resulting in losses of $3.2 billion annually for U.S. carriers (Adams et al, 2004). However, a similar kind of study has not been conducted for space weather. How much is space weather responsible for delays or reroutes, and how can we assess the benefits of improved space environment information? Are the benefits quantifiable?

User requirements still need to be clearly identified and an extensive risk analysis study of space weather impacts needs to be pursued. A two-step process requires: (i) a risk analysis impact study to gather data and (ii) a cost-benefit analysis of any potential services.

During the interviews, everyone agreed that a cost-benefit analysis was needed. Who should take the lead or fund it was not as clear. Comments included the following:

- Economic savings have established the polar routes as a viable and expanding operation.
- Operators may alter routes to avoid HF communications loss over the poles, which can incur costs to the company (e.g., additional fuel, diversions, stopovers).
- Operators need better understanding from scientific, engineering, and medical communities regarding risks.
- Operators do not want policies that are going to cost them more money.
- Even when HF communications is poor or lost, the need for satellite communications to replace HF radio has not yet increased.
- Ensuring that cost-benefit analyses are carried out may require industry buy-in, federal coordination, legislation, etc.
- Improving and integrating space weather information could be a cost saver to the aviation industry. The challenge is assessing the risks and determining the benefits.

The challenge for the scientific community is that in order to increase investment in space weather research the aviation community needs to demonstrate a need, which requires further risk assessment of the impacts. However, the aviation community is still trying to understand why they should care about space weather. Risk analysis includes the identification of possible risks, assessment of their likelihood and impact, and creation of methods to avoid or reduce them. Aviation operators must understand risk if they are expected to manage it.

Aviation groups can assess their expected costs against the total expected benefits of actions based on space weather products. It is difficult to measure benefits monetarily, but one option is that dollar values can be assigned to the intangibles (e.g., reputation, market position, safety).

In 2000, NAV CANADA conducted a feasibility study which identified 33 potential city pairs that could benefit from polar routes. Some examples of time savings in minutes and dollars per flight identified in the study include (in Canadian dollars):

Atlanta — Seoul 124 minutes / $44,000
Boston — Hong Kong 138 minutes / $33,000
Los Angeles — Bangkok 142 minutes / $33,000
New York — Singapore 209 minutes / $44,000
Vancouver — Beijing 108 minutes / $33,000
Vancouver — Hong Kong 125 minutes / $33,000

The bottom line is that direct polar routes save passengers travel time and cost less. Stopovers are avoided, reducing both passenger travel time and operating costs. Airline flight times are reduced, and fuel, maintenance, and operation costs are reduced as well. The challenge is how to quantify these costs and benefits associated with polar routes and issues associated with HF communication loss, quantify the risks associated with the lack of information and the associated operational decisions, and develop policies that will not cost the industry more money.

Workshop Findings and Recommendations

During the cost-benefit and risk analysis session at the workshop, the participants were asked the following questions which led to findings and recommendations:

- What kind of cost-benefit analyses could be implemented?
- How do we go about collecting information? Will operators/ATC/engineers accept the process, and capture and submit data?
- Who should drive cost-benefit analyses?
- What policy options are needed to ensure that cost-benefit analyses are conducted?

At the workshop, the manager of International Operations of United Airlines presented some of the challenges they are faced with when planning for a polar flight. United began operating polar routes in 2000 and has increased the number of operations each year (in June 2006, United operated its 5000th polar flight). United also showed some of the costs associated with operations when these routes are not available. For example, in September 2005, the Chicago to Hong Kong flight made a stop in Anchorage that resulted in a schedule penalty of 180 minutes. The additional operating costs and penalties can escalate significantly, totaling hundreds of thousands of dollars.

The National Air Traffic Manager of NAVCANADA's National Operations Center provided more of a global perspective. The challenge of providing space weather information is not necessarily a U.S. issue, but one of international service standards. The operators that are most interested in this information operate in the Asia-Pacific and North American regions. There are vast areas between Canada and Russia where SATCOM is not available and operators are dependent on HF communication, which is very susceptible to space weather events. This has been a concern in the past and will be increasingly problematic moving forward. Figure 6 shows how much cross-polar traffic levels rose from 2000 to 2005. Polar operations are increasing rapidly as there is more and more demand to use these polar routes by international air carriers, especially as the 2008 Summer Olympic Games in Beijing approaches.

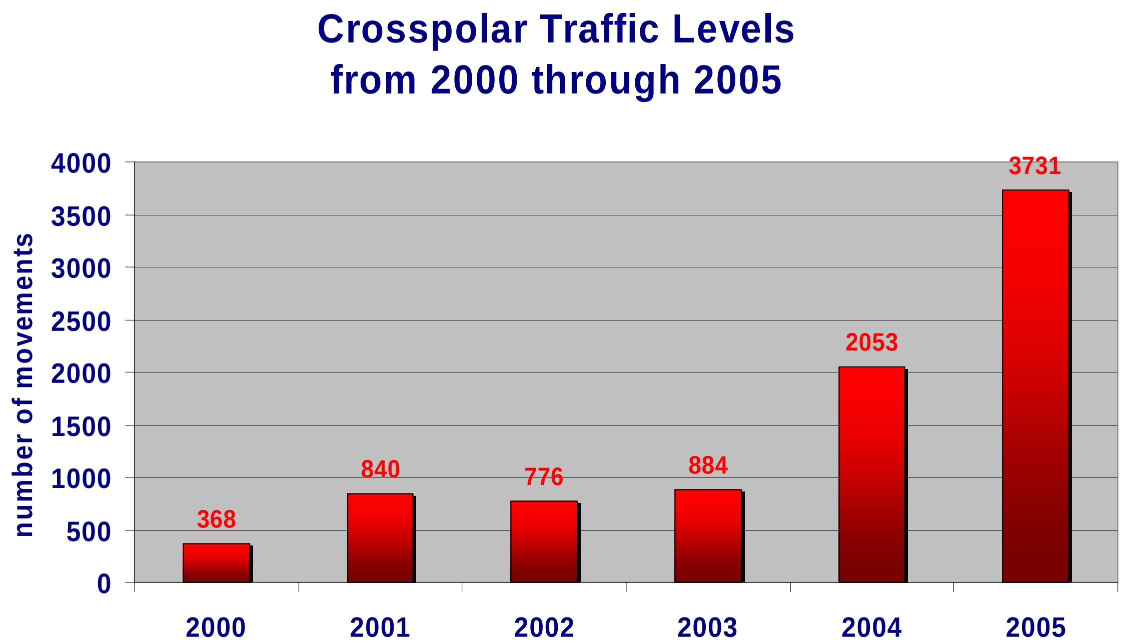

Figure 6. Cross-polar traffic levels for the years 2000–2005 (Source: Dave Rome, NAVCANADA).

The manager of FAA aviation weather policy gave an overview of shortfalls in space weather services. He noted that identifying these shortfalls is an important first step, but not sufficient to drive investment decisions. How much will improved services cost? What will be the return on the investment? Along these lines, the following questions were posed to the participants:

- What is the minimum threshold for product accuracy/reliability in order for decision makers to rely on it?
- What is the optimum level of these parameters?
- How does one determine these levels, testimonials, simulations, prototyping?
- What is the cost of meeting each level?
- What benefits will accrue at each level?

In order for the federal government to decide how much to invest, these questions need to be addressed. The FAA will consider these questions in an investment analysis study, as a follow-up to its draft user needs analysis report.

To reinforce this message, an ICAO representative stated that before ICAO could implement any standards and recommended practices (SARP), further space weather guidance material and its impact on all aspects of air operations is needed. Cost-benefit and risk analyses would provide this.

Space weather events and phenomena create a dynamic environment that can affect different aspects of aviation operations at the same time or at different times. Therefore, any risk analysis should examine the impacts in three categories: radiation (avionics and human), communications (HF, VHF, SATCOM), and navigation (GNSS, WAAS, LAAS, etc).

The National Academy of Sciences, through an ad hoc committee of the Space Studies Board (SSB), is convening a workshop to assess the U.S. current and future ability to manage space weather events and their societal and economic impact. The workshop will provide an initial forum for gathering information on specific space weather effects, as well as the status and unmet challenges of forecasting. This cost-benefit study should be extremely useful to the aviation industry.

> **Finding: The aviation industry and federal agencies know very little about risk assessment and cost-benefit of all space weather impacts upon aviation.**
>
> > **Recommendation: The FAA should lead the aviation community in defining and collecting operational data that can be used to assess the different impact areas, cost of improved services, and return on investment. Specifically, analysis of impacts should be segmented into HF communications, navigation, radiation, and new modes (suborbital).**

> **Finding: Space weather practitioners have limited involvement in the user requirement process, operational needs, risk studies, and service definition decisions. This contributes to the lack of attention on the scientific needs and funding of future observational platforms.**
>
> > **Recommendation: NOAA, DOD, and other U.S. government agencies should link aviation space weather cost-benefit analysis to requirements for ongoing consistent data collection from ground and space (e.g., ACE, NPOESS, GOES).**

Some airline unions have expressed major concerns about radiation risks to human health. They have been pushing for legislation that classifies aircrew as radiation workers. They feel the industry's commercial managers are not doing enough about educating or protecting crew or the public from potential radiation exposure. However, the aviation, medical, and space physics communities do not agree on this issue since medical evidence is inconclusive and more research is needed. The Center for Disease Control/National Institute for Occupational Safety and Health (NIOSH), FAA/CAMI, NASA, and private companies continue to do research on radiation hazards in flight, in particular on the increased risks from space weather events.

Although there are no U.S. regulations on aviation personnel radiation exposure or education, the FAA has recommended that operators educate crews about radiation hazards. In Europe, EU State regulation is currently limited to crew exposure to cosmic radiation. At present, the regulations allow precautionary measures, which are purely subjective, and decisions are based on unclear and uncoordinated personal assessments within individual operations. This guidance tends to be very conservative given that the precise science in data gathering, analysis, forecasting, and prediction for its specific effects on aviation operational subsets has still got a long way to go. Also, as the commercial space transportation industry continues to grow, it will require a better understanding of space weather radiation risks.

The recent NSWP assessment report offers two recommendations that can be useful to the aviation community. Recommendation 3.1.1 states the NSWP should institute a series of space weather benefit studies. Recommendation 3.2.1 is more tailored to the aviation community and states that, "the NSWP should encourage and facilitate collection and analysis of real-time background radiation levels at space and aircraft altitudes. As a body, the NSWP should devote interagency resources to incorporate estimated dosage from energetic particle events into cosmic radiation exposure estimates and to make the specifications and results easily accessible, usable, and interpretable by the public via the Internet."

> **Finding: The aviation industry needs to learn more from the scientific/forecasting, engineering, and medical communities regarding risks.**
>
> > **Recommendation: The FAA should coordinate research studies focusing on the various aviation impact areas (health, avionics, navigation, and communications).**

References

Adams, R., L. Houston, R. Weiher, 2004: “The Value of Snow and Snow Information Services,” Report prepared for NOAA’s National Operational Hydrological Remote Sensing Center, August, 2004.

Cannon, P. S., M.J. Angling, J.A.T. Fieaton, N.C. Rogers, A.K. Shukla, 2004: “The Effects of Space Weather on Radio Systems,” *Proceedings of the NATO Advanced Research Workshop on Effects of Space Weather on Technology Infrastructure*, Rhodes, Greece 25-29 March 2003, Kluwer Vol II/176, pp. 185-201, 2004.

Cerruti, Alessandro P.; Kintner, Paul M.; Gary, Dale E.; Lanzerotti, Louis J.; de Paula, Eurico R.; Vo, Hien B., 2006: Observed solar radio burst effects on GPS/Wide Area Augmentation System carrier-to-noise ratio, *Space Weather*, Vol. 4, No. 10, S10006, 10.1029/2006SW000254.

Council Directive 96/29/EURATOM of 13 May 1996: “Laying down basic safety standards for protection of the health of workers and the general public against the dangers arising from ionising radiation.” Official Journal of the European Communities, 39, L159. 29 June 1996.

Dyer, C.S., F. Lei, P.Truscott, 2006: “Solar Particle Events in the QinetiQ Atmospheric Radiation Model,” Paper presented at RADECS 2006 and accepted for publication in IEEE Transactions on Nuclear Science

Dyer, C.S., F. Lei, S. N. Clucas, D.F. Smart, M. A. Shea, 2003: “Solar Particle Enhancements of Single Event Effect Rates at Aircraft Altitudes,” *IEEE Transactions on Nuclear Science*, Vol. 50, No. 6, pp. 2038-2045, December 2003.

FAA, 2004: Aerospace Weather Policy and Standards Staff (ARS-20), “Users’ needs analysis, space weather draft report,” 15 April 2004.

Heavner, M.J., D.D. Sentman, D.R. Moudry, E.M. Wescott, C.L. Siefring, J.S. Morrill, E.J. Bucsela, 2000: “Sprites, Blue Jets, and Elves: Optical Evidence of Energy Transport Across the Stratopause”, AGU Monograph 123 *Atmospheric Science Across the Stratopause*, p 69-82.

Jones, B., 2004: “Space Weather Effects on Aircraft Operations,” Proceedings of the NATO Advanced Research Workshop on Effects of Space Weather on Technology Infrastructure, Rhodes, Greece 25-29 March 2003, Kluwer Vol II/176, pp. 215-234, 2004.

Jones, B., 2004: “Space Weather - Operational & Business Impacts,” Airline Space Weather Workshop Report, NOAA SEC, Boulder, CO 23-24 February 2004, http://www.solarmetrics.com

Klobuchar, J.A., J.M. Kunches, and A.J. VanDierendonck, 1999: “Eye on the Ionosphere: Potential Solar Radio Burst Effects on GPs Signal to Noise, *GPS Solutions*, Vol. 3, No. 2, fall 1999, P. 69.

NOAA, 2004: Service Assessment: Intense Space Weather Storms, October 19-November 07, 2003, April 2004. Washington, D.C.: U.S. Department of Commerce.

Normand, E., 1996: “Single event upset at ground level,” IEEE *Trans. on Nucl. Sci*, 43, 6, pp 2742-2750.

OFCM, 2000: The National Space Weather Program. The Implementation Plan: 2nd Edition, July 2000. Committee for Space Weather, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

OFCM, 2006: Report of the Assessment Committee for the National Space Weather Program, June 2006, Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, D.C.

Olsen, J., P. E. Becher, P. B. Fynbo, P. Raaby, J. Schultz, 1993: “Neutron-induced single event upsets in static RAMs observed at 10 km flight altitude,” *IEEE Trans. on Nucl. Sci.*, 40, 2, pp 74-77.

Taber, A. and E. Normand, 1993: “Single event upset in avionics,” *IEEE Trans. on Nucl. Sci*., 40, 2, pp 120-125.

Appendix A: Acronyms

ACE	Advanced Composition Explorer
AMS	American Meteorological Society
APV	Approach with Vertical Guidance
ATC	Air Traffic Control
CAMI	Civil Aerospace Medical Institute
COMET	Cooperative Program for Operational Meteorology, Education, and Training
CME	Coronal Mass Ejection
CPDLC	Controller-Pilot Data Link Communications
CPTEWG	Cross Polar Trans East Working Group
DOD	Department of Defense
DOT	Department of Transportation
ESA	European Space Agency
EU	European Union
EUV	Extreme Ultra Violet
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
GCR	Galactic Cosmic Ray
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HF	High Frequency
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICRP	International Commission for Radiobiological Protection
IEC	International Electrotechnical Commission
IFALPA	International Federation of Air Line Pilots' Association
IPT	Integrated Product Team
ISES	International Space Environment Service
ISO	International Organization for Standards
JPDO	Joint Planning and Development Office
LAAS	Local Area Augmentation System (LAAS)
MBU	Multiple Bit Upsets
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System (formally known as NGATS)
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Air Men
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRCan	Natural Resources Canada
NSF	National Science Foundation
NSWP	National Space Weather Program
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorology
OPM	Office of Personnel Management
OPSPEC	Operational Specification

PCA	Polar Cap Absorption
RAM	Random Access Memory
RWC	Regional Warning Centers
SARP	Standards and Recommended Practices
SEC	Space Environment Center
SEE	Single Event Effects
SESAR	Single European Sky ATM Research
SEU	Single Event Upsets
SIGMET	Significant Meteorological Information
SPE	Solar Proton Events
SRAM	Static Random Access Memory
Sv	Sieverts
UCAR	University Corporation for Atmospheric Research
ULR	Ultra Long Range
UN	United Nations
UNA	User Needs Analysis
USAF	United States Air Force
VHF	Very High Frequency
WAAS	Wide Area Augmentation System
WMO	World Meteorological Organization

Appendix B: Policy Study Questionnaire

Policy Research Study on
Integrating Space Weather Observations and Forecasts into Aviation Operations

Conducted by the American Meteorological Society and SolarMetrics Ltd
Funded by the National Science Foundation

Interview Questions:

1) What best describes your role in aviation services?

2) What dimensions most interest you (HF communications, radiation-humans, radiation-avionics, satellite navigation, communication of info, training & education, and international and national procedures)?

3) What are the key policy issues in promoting effective application of space weather information to the aviation industry?

4) What opportunities are emerging in your area (e.g., HF comm., reducing radiation risks to humans and/or avionics, sat navigation, communication of info) and what impediments are in place?

5) What technical, observational, and modeling capabilities are needed to improve decision making and how will they be achieved?

6) How should space weather information be integrated into meteorological information for use by airlines, FAA, etc?

7) How well is space weather information communicated and what improvements are needed?

8) Where/how do employees in your company or organization learn about space weather?

9) How do we go about establishing an educational program for decision makers (pilots, ATC, crew, operations managers, dispatchers, engineers, etc)?

10) How do pilots, dispatchers, and ATC decide when to use a forecast/alert to modify the operations of a flight? Who should control the decision/response process (airlines, FAA, ICAO)?

11) How much risk are airlines, crew and the federal government willing to assume?

12) What public policies, if any, are needed to foster application of space weather services to the aviation system? What policies are needed to ensure the safety of aircraft and crew?

13) If appropriate: What are the public-private sector coordination issues?

14) If appropriate (given the discussion to this point): Have you given any thought to the cost implications of the policies/policy issues we have been discussing and how they may be financed?

15) Who else should we be talking to?

Appendix C: Workshop Program

Integrating Space Weather Observations and Forecasts into Aviation Operations

Workshop

developed by the

American Meteorological Society Policy Program

&

SolarMetrics

in coordination with
Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration/Space Environment Center (NOAA/SEC), National Science Foundation (NSF), & Next Generation Air Transportation System Joint Planning and Development Office (JPDO)

co-sponsored by
The AMS Policy Program Study Series Underwriters: ITT, Raytheon & Lockheed Martin & Workshop Sponsors: The Office of the Federal Coordinator for Meteorology/National Space Weather Program* and Ball Aerospace and Technologies

The I Street Conference Center (ASAE)
1575 I Street, NW
Washington, DC

Wednesday – November 29, 2006

0830 Opening Remarks/Welcome: Dr. Genene Fisher, Senior Policy Fellow, AMS; Captain Bryn Jones, CEO, SolarMetrics

0840 JPDO plans for the Next Generation Air Transportation System– Mark Andrews, Weather Integrated Product Team Lead, Joint Planning and Development Office

0900 FAA—Rick Heuwinkel, Division Manager, Aviation Weather Policy, FAA

0920 NOAA Space Environment Center—Dr. Thomas Bogdan, Director, NOAA Space Environment Center

0940 Space Weather Impacts on Airline Operations—Mike Stills, Manager, International Operations, Flight Operations Division, United Airlines

1000 NAV Canada Polar Operations—David Rome, National Air Traffic Flow Manager, NAV Canada

1020 Break

1040 National Space Weather Program Assessment Report—Dr. Delores Knipp, Professor of Physics, U.S. Air Force Academy & National Space Weather Program Assessment Committee

1100 Workshop Overview-- Genene Fisher, AMS; Bryn Jones, SolarMetrics

* The following agencies participate in the NSWP: DOC/NOAA, DOD, NSF, NASA, DOI/USGS, DOE, and DOT/FAA.

1130 Lunch

1300 NOAA National Weather Service—Brig. Gen. D.L. Johnson (USAF ret), Director, National Weather Service

1330 Discussion of Policy Issue 1: Communication of Space Weather Information

Discussion leader: Joe Kunches, NOAA Space Environment Center

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

How is space weather information communicated and what improvements are needed?

What technical, observational, and modeling capabilities are needed to improve decision making and how will/can they be achieved?

1515 Break

1545 Discussion of Policy Issue 2: Standardization of Regulations and Information

Discussion leader: Steve Albersheim, FAA Air Traffic Organization

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

How do pilots, dispatchers, and ATC decide when to use a forecast/alert to modify the operations of a flight?

What regulations are needed to be in place to ensure standardized space weather information is integrated into global aviation operations?

1730 First day wrap-up

1800 Reception and Dinner

Tuscana West Restaurant, 1350 I Street, NW, Washington, DC

***Speaker* – George Whitesides, Executive Director, National Space Society**
The Future of Commercial Space Transportation

Thursday – November 30, 2006

0815 Preliminary Remarks Genene Fisher, AMS; Bryn Jones, SolarMetrics

0830 Discussion of Policy Issue 3: Education and Training

Discussion leader: Delores Knipp, U.S. Air Force Academy

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

How do employees at your company/organization learn about space weather?

What educational programs are needed for decision makers (pilots, ATC, crew, operations managers, dispatchers, engineers, etc)?

1000 Break

1030 Discussion of Policy Issue 4: Cost Benefit Analysis

Discussion leader: Bill Murtagh, NOAA Space Environment Center

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

What cost-benefit analysis could be implemented?

How do we go about collecting information? Will airlines/ATC/engineers accept the process, capture data and submit?

1200 Lunch

1300 Discussion of the overarching findings and recommendations of the workshop

1430 Actions and Next Steps

1500 Adjourn

Appendix D: Workshop Focus Questions

Policy Issue 1: Communication of Space Weather Information

- How is space weather information communicated and what improvements are needed?
- What technical, observational, and modeling capabilities are needed to improve decision making and how will/can they be achieved?
- Who are the best people to deliver space weather information?
- From where do you want to receive the information?
- What policy options are needed to improve communication of space weather information and ensure seamless integration into the local, regional and global operational decision processes?

Policy Issue 2: Standardization of Regulations and Information

- How do pilots, dispatchers, and air traffic controllers ATC decide when to use a space weather forecast/alert to modify the operations of a flight?
- What regulations are needed to be in place to ensure standardized space weather information is integrated into global aviation operations?
- What national and global processes are available to achieve this?

Policy Issue 3: Education and Training

- How do employees at your company/organization learn about space weather?
- What educational programs are needed for decision makers (pilots, ATC, crew, operations managers, dispatchers, engineers, etc)?
- How do you establish even the need for an education process when the risk is not visible to the end-user?
- What lessons can be learned from established space weather users (i.e., NASA, USAF, ESA) about developing space weather education programs?
- What policy options are needed to develop and promote education programs?

Policy Issue 4: Cost Benefit Analysis

- What kind of cost-benefit analyses could be implemented?
- How do we go about collecting information? Will airlines/ATC/engineers accept the process, capture data and submit?
- Who should drive cost-benefit analyses (regulatory or company)?
- What policy options are needed to ensure that cost-benefit analyses are conducted?

Appendix E: Workshop Participants

Name	Affiliation	Role/office
Steve Albersheim	FAA	Aviation Weather Policy & Standards
Mark Andrews	NexGen Joint Planning & Development Office	Director, Weather IPT
Philip Ardanuy	Raytheon	Chief Scientist, Raytheon Information Solutions
Rich Behnke	NSF	Section Head, Upper Atmosphere Section
Jay Bjornstad	Northwest Airlines	Chief International Dispatcher
Tom Bogdan	NOAA Space Environment Center	Director, SEC
David Boteler	Natural Resources Canada	Leader, Space Weather Hazards Group
Deane Bunce	FAA	WAAS Space Segment Lead ATO-W, Navigation Services
David Byers	Air Force Office of Scientific Research	Program Manager, Space Sciences
Bruce Carmichael	National Center for Atmospheric Research (NCAR)	Manager of Aviation Weather Programs
Greg Dale	Continental Airlines	Manager, International Operations Planning
Clive Dyer	QinetiQ	Chief Scientist
Genene Fisher	AMS	AMS Policy Program
Alan Fraser	Raytheon	Integrated Terminal Weather System Program Manager
Mark Gunzelman	NOAA/OFCM	National Space Weather Program
Dick Hallgren	AMS	AMS Executive Director Emeritus
Mike Heer	ARINC	IT Sr Manager, Engineering Services
Christy Henderson	George Mason University	space weather PhD grad student
Michael Hesse	NASA/Goddard Space Flight Center	Director, The Community Coordinated Modeling Center
Richard Heuwinkel	FAA	Aviation Weather Policy & Standards
Bill Hooke	AMS	Director, AMS Policy Program

Doug Jenkins	FedEx	GOC Fedex Flight Dispatch
D.L. Johnson	NOAA NWS	NOAA's Assistant Administrator for Weather Services
Bryn Jones	SolarMetrics Limited	CEO
Bob Kerr	NSF	Upper Atmosphere Research Section
Delores Knipp	USAF Academy	Professor & NSWP Assessment Committee
Joseph Kunches	NOAA SEC	Chief, Forecast and Analysis Branch
Lou Lanzerotti	New Jersey Institute of Technology	Professor & NSWP Assessment Committee Chair
Henning Luebbe	International Federation of Air Line Pilots` Associations (IFALPA)	IFALPA HUPER (Human Performance) Committee
Jon Malay	Lockheed Martin Corp.	Director, Civil Space Programs
Josh Martin	Congressman Michael C. Burgess, M.D. (TX-26) office	Staff Director
Beth McNulty	NOAA/NWS Aviation Services Branch	NWS Aviation Services Branch
Ron McPherson	AMS	AMS Executive Director Emeritus
Therese Moretto Jorgensen	NSF	Upper Atmosphere Research Section
John Murray	NASA	Atmospheric Scientist, Chemistry & Dynamics Branch
Bill Murtagh	NOAA SEC	Forecast and Analysis Branch
Kristine Nelson	NWS	Center Weather Service Unit (Anchorage)
Oscar Olmedo	George Mason University	space weather PhD grad student
Jim Olson	Ball Aerospace and Technologies Corp	Director, Business Development Weather and Environment
Alec Pook	Air Canada	Manager Flight Dispatch Standards & Training
Kimberly Reasoner	Congressman Michael C. Burgess, M.D. (TX-26) office	Legislative Counsel
Bob Robinson	NSF	Upper Atmosphere Research Section
Dave Rome	NAV CANADA	Manager National Operations Centre
Raul Romero	International Civil Aviation Organization (ICAO)	Technical Officer
Jerry Sanders	HQ Air Force Weather Agency	Contractor HQ AFWA/XORS
Karen Shelton-Mur	FAA/AST	Commercial Space Transportation, Meteorologist

Bob Showalter	CSSI, Inc (FAA (SETA-II))	CSSI Program Manager (SETA II)/FAA Ops, Planning, and Systems Engineering
Danny Sims	FAA	ATC, Traffic Flow Management Weather Programs
Cheryl Souders	FAA	ATO Operations, Planning, and Systems Engineering
Chris St. Cyr	NASA-GSFC	Sr Project Scientist, Living With a Star Program
Michael Stewart	ITT	Space Systems Division
Michael Stills	United Airlines	Manager, International Operations, Flight Operations Division
Keith Strong	Lockheed Martin Corp.	Advanced Technology Center
Curtis Taylor	Northwest Airlines	Manager International Operations & ATC
Wendy Thomas	AMS	AMS Policy Program
W. Kent Tobiska	Space Environment Technologies	President and Chief Scientist
Elizabeth Toedt	NetJets International, Inc.	Pilot
George Whitesides	National Space Society	Executive Director
Jan Wilkerson	AMS	AMS Policy Program
Sam Williamson	DOC/NOAA/OFCM	Federal Coordinator for Meteorology
Mike Wooster	Ball Aerospace and Technologies Corp	Director, Environmental Programs
Jeff Zimmerman	Northwest Airlines & Int'l Air Transport Association (IATA) rep	Forecasting Techniques Meteorologist

Appendix F: NOAA SEC 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 Blackouts

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.