# SOARS

**(Space weather Operations Airline Risk Service)**

# Final Report


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***SOARS (the Space weather Operations Airline Risk Service) was a Service Development Activity (SDA) of ESA's Space Weather Applications Pilot Projects and was co-funded by ESA and groups working on the Project. It is led by the Mullard Space Science Laboratory of University College London (UCL-MSSL) and involves Virgin Atlantic Airways (VAA), ESYS Ltd., QinetiQ Ltd., the National Physical Laboratory (NPL) and the UK Meteorological Office. SOARS was developed from an idea of Bryn Jones (VAA/UCL-MSSL).***

# Executive Summary

**SOARS**, the **Space weather Operations Airline Risk Service**, is one of the Service Development Activities (SDA) of ESA's Space Weather Applications Pilot Projects. The SOARS project has been examining the effects space weather has on the aviation industry, determining the impacts on flight and ground operations, evaluating the risks involved and developing prototype space weather services.

The aviation industry is affected by space weather through a number of different effects and on a range of timescales. Some space weather effects can have a serious impact on the industry while others are just an inconvenience; it is also easier to forecast some effects than others. In addition, airlines are not affected equally – there are significant dependencies on where an airline is based and the route system it operates. As a consequence the environment is more complex than for many other sectors and the geographic dependence of some effects means that one solution does not fit all airlines.

The SOARS project has tried to explore these issues to determine what form of space weather forecasting service is possible and needed by the aviation industry.

During the course of the project, the emphasis placed on different aspect of the problem has evolved. This is in part due to a better understanding of the nature of the effects and how relate to aircraft operations, but it is also a consequence of the realization of what is possible/feasible when creating a space weather service. In addition, in Europe the degree of concern about cosmic radiation has reduced amongst many of those responsible for assessing the exposure of aircrews as the understanding of the risks involved has increased, and the effectiveness of the monitoring procedures has been demonstrated.

Our initial ideas were driven by an assessment of user requirements. In trying to define the scope of a space weather service we looked at exactly how badly the effects affect the ability of an airline to operate safely; we also looked in detail at what space weather products already existed and how useful they were for forecasting.

As a consequence of the changes in our understanding, we have had to go back and re-evaluate the effects, re-examine their impact on operations the risks associated with them, and determine which effects can be managed by mitigating the effects indirectly, and which we must learn to live with. From this we have drawn conclusion on what capabilities a core service needs to address.

The effects of space weather on the aviation industry differ from those caused by terrestrial weather and the associated risks are therefore different. Even so, the responses to space weather effects are essentially similar to those of terrestrial weather phenomena – delays, diversions and possibly cancellations. It is therefore beneficial if space weather information is expressed and disseminated in ways that are familiar to the airlines.

While safety and security are paramount, civil aviation is a very competitive business. Any impacts to operations are potentially expensive and it is essential that a service is able to minimize them. Airlines are used to making changes to their flight plans in response to congestion, severe terrestrial weather, etc. However the extent and duration of some space weather effects and difficulties in forecasting them can makes changes more difficult to implement.

The science of meteorology is well established and a comprehensive monitoring and forecasting system is in place. Terrestrial weather phenomena can be observed as they develop over hours, even days. Conditions that might lead to severe weather conditions can often be anticipated based on a wealth of observation made over many decades; in many cases the effects of the season and changes to global circulation patterns are responsible for long-term variations.

For space weather, forecasting capabilities are very different. Space weather effects can affect a much larger area that terrestrial weather, can occur with very little warning and can sometimes last much longer than terrestrial weather phenomena. The monitoring systems for space weather can at best be described as patchy and the organization at an international level to support forecasting is absent. The science does not afford the ability to predict some effects; for others, we know that something will occur, but not necessarily the details.

The occurrence and intensity of space weather effects varies with time and location. There is a dependence on current and recent solar activity, phase of the solar cycle, etc. Also, existing conditions in the Earth's magnetosphere and ionosphere and the relation of a location to the geomagnetic pole, local noon, etc. can all influence the severity of an effect or whether it is even experienced.

Many of the consequences of the exposure to radiation are better handle as offline issues. How to address immediate and delayed space weather effects is more difficult, particularly in how they affect operations and operational planning.

Under normal conditions, the bulk of the exposure of aircrew to cosmic radiation is due to galactic cosmic rays; cosmic rays from solar activity though intense are a relatively rare occurrence. We have found that Europe has shown that an effective programme of dose assessment is a good way to manage radiation exposure; similarly, good designs and the careful selection of components are a good way to mitigate the effects of radiation on electronics.

Immediate effects result from electromagnetic emissions from solar flares. Their onset can be very sudden and we are only able to forecast probabilities that they will occur; this make it almost impossible to include in forecasts that can be used in planning and the sudden onset presents logistical problems in terms of response during a flight.

Delayed effects are those caused by plasma that is ejected from the Sun and interacts with the Earth's magnetosphere and ionosphere. Because of the time taken for the material to complete its journey, there is at least a possibility the effects can be forecast; the main difficulties are the uncertainty of how quickly the material is moving and details of the plasma properties - e.g. density and magnetic field. Some delayed effects can persist for days and affect large areas, the higher and middle magnetic latitudes being mainly affected.

Where possible the SOARS project has drawn on existing capabilities. There are already several quite good sources of space weather information available but there are related to the area coverage and currency of the data. There is also limited information of where and exactly when effects will occur and their intensity.

Some issues could be improved by making changes to the way that data are gathered. However, we have found that there are fundamental problems associated with providing forecasts on the timescales needed by aviation; it is also particularly difficult to precisely identify when and where effects will occur in advance. This is a consequence of the basic difference between terrestrial weather and space weather – that the latter being caused by a stimulus external to the Earth's environment that is affected by conditions in transit to the Earth.

There may be a limited ability to respond to space weather effects en-route especially since a large number of aircraft could be affected over an extended area. However, warnings given sufficiently in advance could significantly reduce the costs associated with diversions.

Given that there are limitations in what a space weather service might be able to achieve, we have examined where the greatest cost savings could be found through developing new capabilities. This, with all the other information we have gathered, has helped us identify which services are essential and should be the core of any future aviation space weather service.

 

# 1. Introduction

Space weather affects the aviation industry in a number of ways on a range of timescales through a number of different phenomena. Whereas the users in many industrial sectors are only affected by a single space weather effect, since aviation is a global business with a large number of aircraft in the air at any time, and because of the speed that aircraft can move from one part of the world to another, the effects are numerous and complex. The SOARS project has therefore had to consider a wide range of effects, how they might affect aircraft depending on location and phase of the flight, and how the incidence if the effects varies with time.

While it is beyond the scope of the project to establish a fully operational space weather service, SOARS has created prototype Web-based services that illustrate what aspects of a service might look like. It has created several Web pages that bring together a range of space weather information and present them in a meaningful way in order to establish the limits of what is possible. This process has allowed us to understand the nature of the products available and how well they can be used to forecast effects; it has also allowed us to identify many gaps in the scientific and technical capabilities that would be needed to support a full service.

Because of the limitation, we have found it necessary to re-examine exactly what forecasting capabilities are really needed for an aviation space weather service and whether these can be rialized. A significant amount of effort has been expended to allow us to understand and assess the effects, determine how they affect operations and the risks involved and try to determine what could/should be done about them.

In Section 2 we outline the space weather effects that are relevant to aviation – these are discussed in more detail in Section 6.

Section 3 describes the work undertaken by the project to determine the user requirements for a space weather service. These were derived from the results of surveys and by examining information from number of other sources.

The requirements are placed in the context of the requirements of the civil aviation industry in Section 4. We examine the operational environment, how space weather affects it and how space weather forecast information can be used. We also examine space weather effects that can be dealt with offline.

In Section 5 we describe the services developed by SOARS – these are principally in the form of a series of Web pages. We also identify and discuss limitations in the science and data that we encountered in establishing the services and how these limit what is possible in term of space weather forecasting

In the light of the difficulties we experienced in creating some of the service capabilities, in Section 6 we review space weather effects in detail: which regions of the Earth are affected, how frequently the effects occur, how well they can be forecast and where and how some of the effects could be mitigated.

 

The financial impacts of space weather effects on the aviation industry are given in Section 7. We also discuss the benefits that can be gained if forecast information can be use used effectively to limits the severity of the impacts.

In Section 8 we outline the parts of a space weather service that our study has determined are essential, given the limitations that exist  (Section 5), that only some effects can be mitigated by other means (Section 6) and in the light of where the greatest cost benefits lie (Section 7). We also discuss ideas of how forecasting capabilities could be improved through new types of instrumentation.

In Section 9 we summarize the overall conclusions of the project.

Although the SOARS project was principally the work of University College London, several other groups contributed to different parts of the project. Their inputs have been folded into the body of the report, but the contributions are described in Section 10.

While some aspects of the project are presented with a UK/European perspective, we have tried to keep a global overview and the many of the comments in this document are expressed from this viewpoint. The aviation industry is dynamic with the requirements continuing to evolve – this report therefore represents a view at a particular point in time.

 

## 2. Space Weather Effects Relevant to Aviation

Space Weather is the affect of the Sun on the Earth and near-Earth environment. There are many space weather effects but, for the purposes of this report, we will concentrate on those that affect the aviation industry.

The main space weather effects relate to RF communications and cosmic radiation:

- Radio frequency (RF) communication systems may be either controlled by the ionosphere, as in the case of High Frequency (HF) communications, or simply influenced by it, as in the trans-ionospheric radio communications and navigation systems. The effects on RF communications are:
    - Disruption of HF and satellite communications (voice and data)
    - Disruption of satellite navigation services
- Radiation effects are related to short-term enhancements (and reductions) caused by solar activity superimposed on a slowly varying galactic cosmic ray background.

The space weather (SWx) effects are related to different solar phenomena each of which produces a different mix of enhanced emission. Some solar events cause little or no impact on the near-Earth environment either because their enhanced electromagnetic and/or particle emissions are too feeble, or because their particle streams may simply miss the Earth. For those events that do affect the near-Earth environment, effects can be both **immediate** and **delayed**, depending on the exact type of enhanced emission.

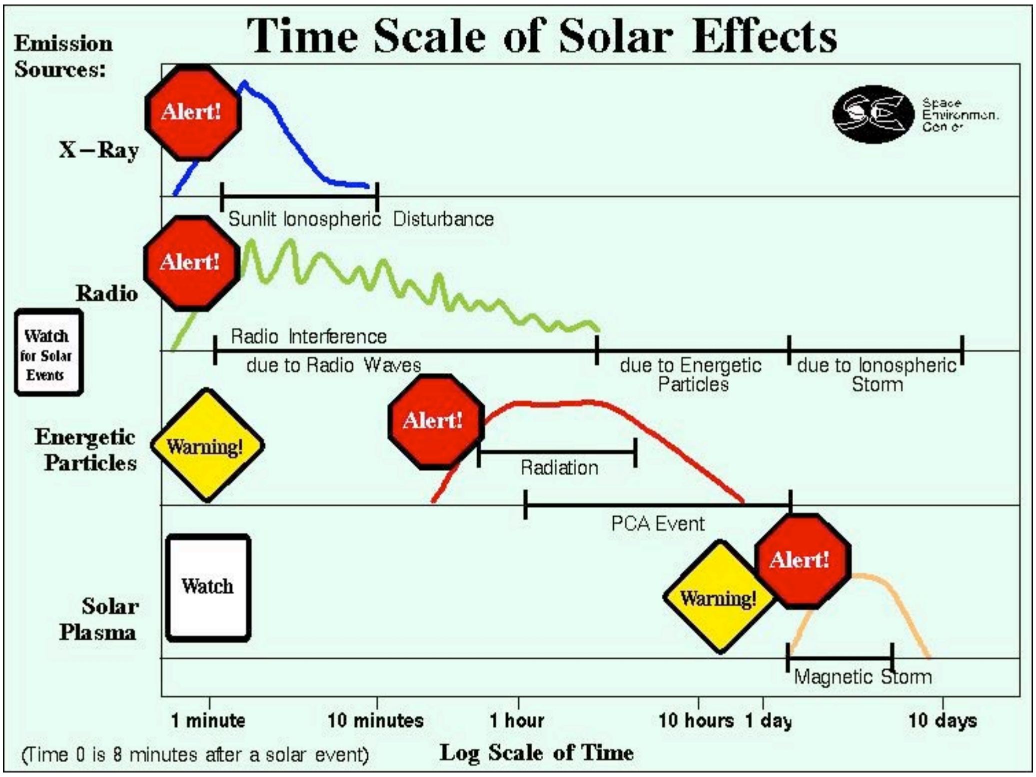


Figure 1. Timing of space weather effects and their causal events (NOAA-SWPC)

The relative timing of space weather effects is summarized in Figure 1. The differences caused by the different types of emission and different delays in response can be important in terms of how easily effects can be forecast.

 

Immediate effects are caused by enhanced **electromagnetic radiation** – i.e. γ-ray, X-ray, ultraviolet, optical and radio waves. Since all type of radiation travel at the speed of light, the time taken for them to reach the Earth is the same – about 8 minutes. So, by the time a flare is first observed it is already causing immediate effects on the near-Earth environment. As the radiation does not penetrate or bend around the Earth, the impacts are almost entirely limited to the Earth's sunlit hemisphere. Because the enhanced emissions cease when the flare ends, the effects tend to subside as well; as a result, effects caused by enhanced electromagnetic radiation tend to last only a few tens of minutes to an hour or two.

Delayed effects are caused by particles. **High-energy particles** (primarily protons, but also cosmic rays) can reach the Earth within 15 minutes to a few hours after the occurrence of a strong flare. Not all flares produce such particles and since the particles follow trajectories defined by the spiralling interplanetary magnetic field, they may miss the Earth. The major impact of the particles is felt over the polar caps, where the protons have ready access to low altitudes through funnel-like cusps in the Earth's magnetosphere. Proton events are possibly the most hazardous of space weather events; their impact can continue for a few hours to several days after the flare.

Streams of plasma, in the form of **medium and low-energy particles** (both protons and electrons), may arrive at the Earth about two to three days after a flare, but can also occur at any time due to non-flare solar activity such as coronal holes, and coronal mass ejections. The particles may cause geomagnetic and ionospheric storms that can last from hours to several days; the impacts these cause are most intense in the night-side sector of the Earth. Again these particles follow a spiral path from the Sun determined by the interplanetary magnetic field; as a consequence, only events on the western side of the solar disk can affect the Earth's environment (see Figure 2).

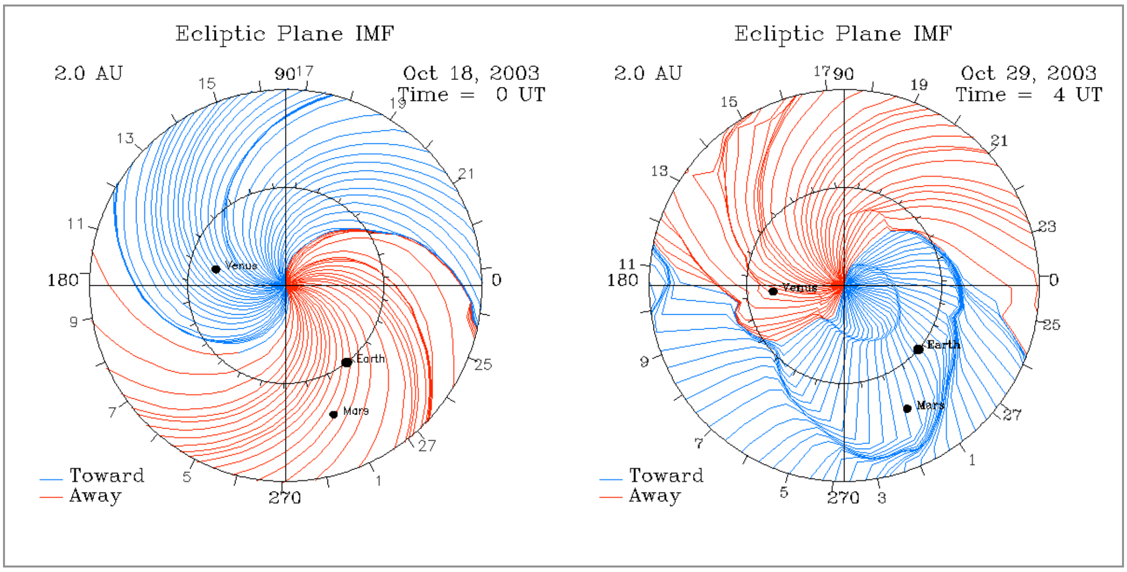


Figure 2. As the Sun rotates, the interplanetary magnetic field (IMF) lags behind and is wound into a spiral; as a consequence, active regions producing geo-effective emissions must be located ahead of the sub-Earth's point (towards the solar west limb). The figure shows the IMF under quiet conditions (left) and distorted by the passage of a number of CMEs (right). (Images U. Alaska Fairbanks)

 

| Effect | Cause |
|---|---|
| **Immediate Effects:** | |
| Disruption of HF Communication | **Short Wave Fade** (SWF) event caused by enhanced ionization of the D-region by soft X-ray from flares |
| RF Interference | Bursts of radio noise over wide spectrum |
| Enhanced Radiation | Particle emission associated with some types of energetic solar flares (Impulsive SEP Event) |
| **Delayed Effects:** | |
| Enhanced Radiation | Energetic particles emitted from shock fronts of CME driving through plasma in the heliosphere (Gradual SEP Event) |
| Disruption of HF Communication | **Polar Cap Absorption** (PCA) caused by enhanced ionization of D-region by protons from flares, etc.<br>**Ionospheric Storm** caused by disruption of the F-region |
| Disruption of trans-ionospheric signals | Small scale variations in the ionosphere cause **scintillation**<br>Regions of enhanced density and high density gradients cause **refraction** (bending) and delays of the signal |

Table 1. Summary of Immediate and Delayed space weather effects

## 2.1. Immediate Effects

The impacts of electromagnetic effects occur simultaneously with the solar flare that caused them and are almost entirely limited to the Earth's sunlit hemisphere. The effects are mainly on RF communications; near-relativistic particles from some very energetic flares can also produce enhanced radiation levels.

The influence of solar flare radiation on the ionosphere produces a family of Sudden Ionospheric Disturbances (SIDs) – the most common and troublesome of these is the **Short Wave Fade** (SWF) event. In a SWF event, the enhanced X-ray radiation from solar flares causes increase absorption of the D-region of the ionosphere and reduces the frequency window available for HF communications. In severe events the window can be completely closed and result in a radio blackout.

Solar flares can increase the amount of energy emitted at radio frequencies by the Sun by a factor of tens of thousands over bands in the VHF to SHF range (30 MHz to 30 GHz). If the Sun is in the field of view of the receiver and the bursts are at the right frequency and intense enough, they can produce direct Radio Frequency Interference (RFI) within these bands. Sometimes a large sunspot group will produce slightly elevated radio noise levels, primarily on frequencies below 400 mHz – this is called a solar radio noise storm. The enhanced noise levels may persist for days, occasionally interfering with communications or radar systems using an affected frequency.

A few flares also produce energetic particles but these are quite rare; the fastest particles can arrive tens of minutes of the X-rays. The effect is mainly on electronics – energies that are hazardous to humans are produced in the shock fronts of fast CMEs.

| Effect | When | Where |
|---|---|---|
| **Short Wave Fadeout (SWF):**<br>Electromagnetic radiation from the Sun during large solar flares causes increased ionisation in the D region that results in greater absorption of HF radio waves.<br>*(If flare large enough, whole HF spectrum can be rendered unusable).*<br>*(Also called daylight fade-outs and sudden ionospheric disturbances, SIDs)* | Starts with flare onset. Duration depends on the duration of the flare - few minutes to hours (fast onset, slow recovery)<br>More likely at solar maximum | Anywhere in daylight sector, Strongest at the sub-Sun point |
| **Polar Cap Absorption event (PCA):**<br>High-energy protons that escape from the Sun when large flares occur move along the Earth's magnetic field lines to the polar regions. Increased ionisation in the D region results in greater absorption of HF radio waves. | Starts 10 min. after flare onset and can last for several days. Most likely to occur around solar maximum, but not as common as SWF. | Polar regions – may also occur during night-time<br>(auroral zone?) |
| **Ionospheric Storms:**<br>Coronal mass ejections (CMEs) and coronal holes sometimes disturb the Earth's magnetic field. Disturbance in the geomagnetic field can often cause a disturbance in the ionosphere.<br>*(Higher frequencies most affected – they can sometimes penetrate the ionosphere. Lower the frequency being used…)* | Arrival of CME plasma cloud or as magnetic field line in the solar wind from solar coronal holes sweeps across the Earth.<br>Lasts for a number of days | High latitudes more affected than low latitudes |

Table 2. Summary of Principal Effects on HF Propagation

## 2.2. Delayed Effects

The impacts due to particles tend to occur hours to several days after the solar activity that caused them and can persist for several days. The impact is greatest in the night-time sector of the Earth (as the particles that cause them usually come from the tail of the magnetosphere), although they are not strictly limited to that time/geographic sector.

The sources of the charged particles include: solar flares, Coronal Mass Ejections (CMEs), disappearing filaments, eruptive prominences and Solar Sector Boundaries (SSBs) or High Speed Streams (HSSs) in the solar wind. Except for the most energetic particle events, charged particles tend to be guided by the spiralling interplanetary magnetic field (IMF).

### 2.2.1. Solar Energetic Particle (SEP) Events

Protons can be produced by certain types of energetic flares but can also be produced by coronal mass ejections (CMEs). These are clouds of material ejected from the Sun and if the CME front is travelling sufficiently faster that the ambient solar wind flow, it will drive a shock wave that accelerates particles to energies that can penetrate the Earth's magnetically shielded environment and can occasionally reach the Earth's surface.

### 2.2.2. Disruption of HF Communications

At high geomagnetic latitudes (above 55°) HF absorption events similar to SWF events result from the enhanced ionization of D-layer caused particle bombardment; these events can last for hours to several days, and usually occur simultaneously with other radio transmission problems. In a **Polar Cap Absorption** (PCA) event the enhanced ionization is caused by protons from a solar flare or CME entering through the funnel-like cusps in the

 

Earth's magnetic field above the polar caps; in an **Auroral Zone Absorption** (AZA) event the enhanced ionization is caused by particles from the magnetosphere's tail accelerated toward the Earth during a geomagnetic storm and are guided by magnetic field lines into the auroral zone latitudes.

When a shock front caused by a coronal mass ejection strikes the Earth's magnetic field it causes a magnetospheric storm, especially in the IMF has a southwards Bz component. With this polarity, magnetic reconnection of the field on the dayside magnetopause occurs, rapidly injecting magnetic energy and particles into the magnetosphere. The effect of this on the ionosphere – the ionosphere's F2 layers can become unstable, fragment or even disappear – is known as an **ionospheric storm** and severely affects HF communications.

### 2.2.3. Disruption of trans-ionospheric RF Communications

Satellite communication and navigation systems use RF communications that must pass through the ionosphere. The signals are affected by changes to the ionosphere that can be attributed to space weather phenomena.

**Scintillation** of radio wave signals is the rapid, random variation in signal amplitude, phase and/or polarization caused by small-scale irregularities in the electron density along a signal's path. The result of scintillation is signal fading and data dropouts on satellite command uplinks, data downlinks or on communications signals. Scintillation tends to be a highly localized effect and will only have an impact if the signal path penetrates an ionospheric region where these small-scale electron density irregularities are occurring.

Enhancements of the total electron content (TEC) in the signal path can also introduce a positioning error due to increased path length (caused by **refraction** or bending of the path) and slowing of the signal; a delay of up to 300 nanoseconds can be introduced (a position error of about 100 metres). TEC varies by season, time of day, and geo-magnetic location, but bulk values can be modelled to an extent.

| Source | Comment |
|---|---|
| Impulsive SEP Event | Short burst of energetic particles (protons) emitted by certain types of flare |
| Gradual SEP Event | Energetic particles emitted from shock fronts of CME driving through plasma in the heliosphere; energies can be higher than those emitted from a flare |
| Galactic Cosmic Ray background | Isotropic background flux energetic particles created by process outside of the solar system; modulated by the solar cycle |

Table 3. Summary of sources of Cosmic Radiation

## *2.3. Cosmic Radiation*

Cosmic radiation is discussed separately because its sources include a combination of energetic particles produced by immediate and delayed effects, together with cosmic rays originating from outside of the solar system (Table 3).

Even when there is no solar activity, increased levels of radiation are experienced at aircraft altitudes and high geomagnetic latitudes due to the ever-present Galactic Cosmic Rays

(GCR). The intensity lower energy CGRs is modulated by the solar cycle, being greater at solar minimum than at solar maximum. Levels can be increased for intervals when the sun becomes active: certain flares can produce short-lived (minutes to hours) pulses of near-relativistic protons; much longer events (hours to days) are caused by particles accelerated at the shock fronts of coronal mass ejections.

## 2.4. Regulations and Legislation

There are very few rules and regulations relevant to aircraft operations that explicitly deal with space weather issues. However, the effects of space weather on communications and the possibility of enhanced radiation mean that the ability to comply with many regulations can be affected.

In the US, aviation is regulated through a set of FAA Federal Aviation Regulations (FAR). The equivalent in Europe are the Joint Aviation Requirements (JAR) these are a set of requirements agreed by certain European civil aviation authorities.

### 2.4.1. Operations

In the US Federal regulations require that all aircraft operating in US airspace have good communications with air traffic control. The requirement relates to concerns over both safety and security; similar regulations exist in other parts of the world. The disruption of HF communications can therefore cause serious problems when aircraft are en-route; in domestic airspace communications are normally by VHF and are mostly unaffected.

There are many FAA regulations related to operations and communications; under FAR Part 121 "Operating requirements: Domestic, flag, and supplemental operations". Fisher and Jones (2007) list several as being relevant (FAR 121.99, FAR 121.103, FAR 121.533, FAR 121.603, FAR 121.607). Similar regulations exist for European carriers under JARS Subpart D "Operational Procedures".

The FAA Air Carrier Operating Specifications "B055 North Polar Operations" is also relevant to US carriers; there is a proposed Advisory Circular (AC 135-42 Extended Operations (ETOPS) and Operations in the North Polar Area) related to this.

### 2.4.2. Radiation

In 1996 the ICRP recommended that exposure of aircrews to cosmic radiation should be considered as an occupational risk (ICRP 60).

In Europe the recommendations have been incorporated in the Euratom Directive (CEC/96/29) which requires all airlines based in the European Union should monitor the exposure of their crews and take appropriate action; the Directive is implemented at the national level and the details differ between member states. Operationally, the Directive has been incorporated in the (European) Joint Aviation Requirements (JAR-OPS 1.390 Cosmic Radiation). Some other countries have adopted similar requirements, with the notable exception of the United States.

The FAA does not have requirements on radiation set out in the same way – it has however, produced two Advisory Circulars and a report:

- AC 120-61 Crewmember Training on In-Flight Radiation Exposure
- AC 120-61A Guidance on radiation dosage, including limits and calculation methods
- Report DOT/FAA/AM-92/2 Radiation Exposure of Air Carrier Crewmembers II

# 3. User Requirements for a Space Weather Service

The user requirements of the SOARS project were determined from surveys and by examining documents from a number of sources. The inputs included:

- A survey conducted for the SOARS project by ESYS and another undertaken as part of the assessment of the US National Space Weather Plan (NSWP). The findings of the surveys are summarized below – details of the questions posed and the participants are given in Appendix A.

- Relevant documents that were examined included:
  - Report of the FAA User Needs Assessment Team on Space Weather
  - Search of the UK CAA database conducted by the SOARS project
  - Review of compliance with recommendations on radiation of ICRP 60 undertaken by the SOARS project
  - Suggestions and Issues of the NOAA Space Weather Week in 2001.

- The responses of the aviation industry to two major events were also studied:
  - The effects of the solar activity of October and November 2003, including a "Service Assessment" of how the SEC performed during this interval
  - Evaluation of the response of air traffic management to the terrorist attacks of September 11 2001

## *3.1. Requirements Derived from User Surveys*

### 3.1.1. Survey Conducted by SOARS

Early in the project ESYS conducted a survey for SOARS. The survey consisted of 20-30 questions targeted at different parts of the aviation industry – Engineering, Operations and Occupational Health. The questions were on general, current & future issues and on service requirements.

It was difficult to encourage people to participate in the survey: out of 37 people that were contacted, 21 indicated there they were unable to participate or did not respond to our request; a total of 17 questionnaires were completed by 15 organizations. Although the numbers are poorer that we had hoped, it should be noted that the SOARS survey had more responses from the aviation industry than the NWSP survey. Most of the surveys were conducted by a person-to-person interview over the telephone by Maria Sega (ESYS); three organizations sent their responses by Fax. The questions posed in the survey are given in Appendix A together with a list of the organizations that responded.

The responses were very mixed and demonstrated a poor understanding/awareness of issues related to space weather. The different effects that could be experienced on short- and long-haul flights were not universally understood, nor were the effect of location and altitude; the differences between the cosmic radiation exposures on Concorde and sub-Sonic operations were not understood either (but then the radiation experts also had this wrong for a time!).

#### Service Delivery

Many people though that a space weather service was needed although some were sceptical; answers on the need for regulatory involvement were too varied to be useful. It is perhaps not a surprise that those who wanted a space weather service thought it should to free – that is funded by the State rather than the operators. Everyone wanted information to be delivered through the meteorological organizations – we believe this is due to good understanding of existing meteorological services and terminology within the aviation industry

### Conclusions

The participation was too small to draw any conclusions based on statistics, particularly since the responses were extremely varied. In hindsight the questionnaires were too long and complex. While there seemed to a reasonable understanding of the impacts of cosmic radiation, beyond this awareness of space weather effects was poor.

As a consequence or these conclusions we decided to review other sources in order to derive a set of user requirements for SOARS – see the following sections. This was to provide a larger base on which to assess the costs and benefits of a space weather service.

## 3.1.2. Survey Conducted within US NSWP Assessment

In the US, space weather is coordinated under the National Space Weather Program (NSWP). As part of an ongoing process, the capabilities of this program are assessed and there are several useful items on the NWSP Assessment Web site[1] including the responses to a survey conducted in 2005. The questions posed by the survey are listed in Appendix A; the responses relevant to aviation are summarized below:

The responses show varying degrees of understanding of space weather phenomena, but it appears to reasonably good amongst those involved in scheduling. There is clearly a need for explanations of products, effects, etc. in basic (easy to understand) language – several responses reinforced this need. Any Web pages need to have lots of links to explanatory information.

For those with good understanding, they are generally using the appropriate products; for those with poorer understanding, they sometimes misunderstand the nature of the products. As indicated by some of the comments, users are not always aware of the origins of the products – e.g. which are derived from observations by the ACE spacecraft.

The need for accurate forecasts is emphasized by the responses. One user comments that since they have no way of measuring the accuracy, they have to trust that what is provided is correct. There is a generally poor understanding of the time-scales involved: how far ahead events can be forecast; how long forecasts are valid for. For example, how long ahead it is possible to give a warning of HF Blackouts in the polar-regions compared to how long it takes to get there. There was a desire for up-to-the-minute warnings by e-mail, and by devices like Blackberrys

The responses from aircrew indicated considerable concerned about radiation, including what the radiation environment consists of. Understanding of the problem is clearly very incomplete and there is a need for guidance material expressed in terms that the crews can understand. Requested information includes safe levels of exposure and a clear explanation of the position of pregnant aircrew. *[Note: Although the FAA advisory material covers some of this, the lack of the type of (legislative) approach adopted by the European Union is causing a lot of concern amongst US aircrew.]*

[1] See URL: http://www.ofcm.noaa.gov/space_weather_assessment/ and follow the link to "User Questionnaire Responses (15 Dec 2005)".

 

## 3.2. Requirements Derived from Other Sources

### 3.2.1. NOAA SEC Statement to House of Representatives

In October 2003 the Science Committee of the US House of Representatives conducted a hearing entitled "What is Space Weather and who should forecast it?" In his testimony[2], Dr. Ernest Hildner (NOAA) made the following comments on the issues related to aviation that the Space Environment Center (SEC[3]) is trying to address:

"SEC is also active in developing products and services for the next generation air transport system. Working with both the commercial airlines and the FAA, SEC is formulating new products to serve airline operations of the future. That future is certain to include higher flying and trans-polar air routes as each allows for a faster more profitable trip. Particular issues that are impacted by space weather are navigation, radio communication, and radiation to the passengers and crew. Recent work with the FAA's User Needs Analysis Team (UNAT) has led to the implementation of SEC alerts and warnings into the operational planning for commercial airlines on trans-polar routes. Specifically, communications from air to ground, and the management of the radiation environment are points of concerns for the FAA. SEC has worked to supply the appropriate real-time information to be used by aircraft dispatchers."

### 3.2.2. FAA User Needs Report (for Space Weather)

As mention in Hildner's testimony, the US Federal Aviation Administration (FAA) established a User Needs Analysis Team (UNAT) to assess their needs with respect to space weather. The report "FAA User Needs Report" (21 Sep 2004) was presented at the National Space Weather Program Assessment and can be found[4] on its Web site. *It should be noted that some of the issues noted are relevant to US carriers but are not necessarily relevant to European carriers because of differences in the routes flown – see later sections.*

Table 4 is an abstraction from a table in the report and shows the shortfalls of current system and needed capabilities. The report can be reduced to the following requirements in relation to relevant space weather effects:

**HF Communications:**

- Real-time observations of HF radio blackouts both in the polar region and at mid and low latitudes – *graphical product to support the observations defining intensity, frequencies affected, and geographical boundaries.*
- Forecast of polar HF radio blackouts 12 hours in advance; forecast of HF radio blackouts due to geomagnetic activity and mid- and low-latitudes up to 6 hours in advance – *graphical depiction of forecast HF radio blackouts.*

**Satellite Navigation:**

- Real-time observation of mid- and low-latitude GPS disruption – *graphical product defining intensity and geographical boundaries.*

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[2] http://www.house.gov/science/hearings/ets03/oct30/hildner.pdf (Released: Thursday, October 30, 2003; Source: House Science Committee)
[3] The SEC is now known as the Space Weather Prediction Center (SWPC) but we will use SEC where we are describing the contents of documents that use the term.
[4] Under: http://www.ofcm.noaa.gov/space_weather_assessment/meetings/19-20 Dec NCR Visits/

- Forecast of geomagnetic activity that may affect single-frequency GPS accuracy up to 6 hours in advance – *graphical depiction of forecast GPS disruption*.

**Radiation:**
- Prompt delivery of radiation alerts – *e.g. from the* ***Solar Radiation Alert*** *system.*
- Longer lead-time and more accurate prediction of solar radiation storm.
- Incorporate estimated dosage from energetic particle events into cosmic radiation exposure estimates for post flight assessment.

In addition, the following notes have been distilled:
- In order to improve operational planning prior to flight, dispatchers and pilots need access to accurate forecasts for the route, especially for Polar routes.
- Decision-makers need to know the starting and ending times and the type of disturbance (radio interference or biological). Each set of users needs this weather information up to 12 hours in advance and throughout the solar event.
- The FAA's LAAS and WAAS systems are designed to minimize positional errors but are still experiencing problems due to ionospheric scintillations. Better understanding of the ionosphere – filtering out ionospheric scintillations or density bubbles that delay the GPS timing signal – should lead to improved methods of correction
- The NOAA Space Weather Scales were developed by SEC to improve understanding of space weather events among technical operators and the general public alike. However, the Scales are inadequate in their current state to support aircraft operations on polar routes – they lack essential data elements and accuracy needed for sound decision support.

### 3.2.3. Search of the CAA Database

A search was conducted of a database maintained by the UK Civil Aviation Authority that holds reports on issues that could affect aviation safety.

The search was for general problems at any time that could be attributed to space weather: It was necessary to search for specific terms and the an initial search was conducted over a five years interval for:

- Any reports of problems with:
    - HF or satellite communication (at any latitude), including difficulties with air traffic control (ATC) that could be caused by communications problems.
    - Satellite based navigation systems – possibly short-term problems
    - Avionics failures due to Single Event Effects (SEE), e.g. SEUs
- Any mention of the terms:
    - Solar activity, aurora, high latitude, polar, radiation

Although several hundred results were returned, only a few yielded anything that could be space weather related and these were all under the searches HF communications and space weather terms (solar activity, etc.). The search was then extended for these terms for an 11 year interval – the records that could be space weather related are in Table 5.

The only real conclusion that can be drawn is that space weather effects barely make their way into the database. Discussions with crew at Virgin Atlantic Airways and other UK airlines indicated that difficulties with HF communications were considered commonplace and ways to work around any problems were well established. Although only one problem

Table 4. Shortfalls and Needed Capabilities from the FAA UNAT Report

| ***Attribute*** | ***Current*** | ***Shortfall*** | ***Needed Capability*** |
|---|---|---|---|
| Observing real-time radio blackouts in polar regions | Observations of current geomagnetic and energetic particle activity allow for identification of observed radio outages | Observations are not readily available in graphical format.<br>NOAA Space Weather Scales are of limited use in defining boundaries and intensity of blackout areas. | * Real-time observation of polar HF radio blackouts<br>* Graphical product defining intensity, frequencies effected, and geographical boundaries) |
| Forecasting polar HF comms. outages | Forecasts (issued daily and every 3 hours) in text format are available | No graphical products.<br>NOAA Scales do not adequately identify forecast blackout areas. | * Forecast of polar radio blackouts 12 hours in advance<br>* Graphical depiction of forecast radio blackouts. |
| Observing real-time radio blackouts in mid- and low-latitudes | Graphical product is available for HF blackouts during X-ray flare events. | No graphical product available to depict geographic extent of mid- and low-latitude HF blackouts due to geomagnetic storms. | * Real-time observation of mid- and low-latitude HF radio blackouts due to geomagnetic storms<br>* Graphical product defining intensity, frequencies affected, and geographical boundaries. |
| Forecasting mid- and low-latitude HF comms. outages | Geomagnetic (issued daily and 3-hourly) and flare probability (issued daily) forecasts available in text format. | Near-term forecasts of flare activity are not available. | * Forecast of geomagnetic activity up to 6 hours in advance. |
| Observation of geomagnetic activity that may affect single-frequency GPS accuracy | Graphical product is available for HF blackouts during X-ray flare events. | No graphical product is available to depict geographic extent of mid- and low-latitude single-frequency GPS distruption due to geomagnetic storms. | * Real-time observation of mid- and low-latitude GPS disruption<br>* Graphical product defining intensity and geographical boundaries. |

| ***Attribute*** | ***Current*** | ***Shortfall*** | ***Needed Capability*** |
|---|---|---|---|
| Forecast of geomagnetic activity that may affect single-frequency GPS accuracy | Geomagnetic forecasts available in text format (issued daily and 3-hourly) | | * Forecast of geomagnetic activity up to 6 hours in advance.<br>* Graphical depiction of forecast GPS disruption. |
| Observing real-time radiation risk from energetic particle events | CAMI produces a Solar Radiation Alert system based on observations from GOES satellites. | Limited distribution | Provide CAMI access to WMSCR distribution network, with alerts targeted to Airlines and FAA Command Center |
| Forecasting radiation storm events | Radiation storm forecast with lead times of 20 minutes to several hours. | Accuracy and lead-time of radiation storm forecasts and warnings are not adequate for aviation operations. | Longer lead-time and more accurate prediction. |
| After flight radiation dosage estimate | CAMI provides estimated dosage from cosmic radiation after flights have occurred. | Does not include dosage from energetic particle events. | Incorporate estimated dosage from energetic particle events into cosmic radiation exposure estimates. |

Table 5. Records in CAA database identified as possibly related to Space Weather

| Occurrence No. | Occurrence Date | Summary | Sys. | Location |
|---|---|---|---|---|
| 199603578 | 11/08/1996 | Unable to contact ATC by HF; used relay by VHF | HF | 53N 015W |
| 199803412 | 10/06/1998 | Double HF failure after frequency change; rectifying action; subsequently OK | HF | 58N 030W |
| 199904699 | 01/07/1999 | Lost HF and SatCom, comms. re-established by VHF relay; aircraft returned | HF/SC | English Channel |
| 200004576 | 14/05/2000 | Double HF failure; rectifying action; subsequently OK | HF | Antigua |
| 200105087 | 18/07/2001 | Multiple failures of Electronics Interface Unit; all ground test satisfactory | SEU? | ? |
| 200102618 | 19/04/2001 | Contact lost on HF for 31 mins | HF | Airway UG862 |
| 200300092 | 03/01/2003 | Numerous aircraft unable to contact ATC; contact by VHF | HF | N20 E25, UB612 |
| 200300193 | 10/01/2003 | Unable to contact ATC for 55 min. | HF | TEBRA |
| 200307555 | 28/10/2003 | (multiple) transmission fadeout | HF? | Barton |
| 200307628 | 30/10/2003 | Unable to contact Murmansk ATC on HF for approx. 1.5 hr; multiple aircraft; sunspot activity? | HF | Murmansk |
| 200307903 | 12/11/2003 | Unable to contact Naimey ATC on HF/VHF; subsequently OK | HF | Algiers |
| 200400960 | 11/02/2004 | Unable to contact ATC prior to entry ORNAT; other aircraft had same problem | HF? | ORNAT |
| 200405641 | 12/08/2004 | Unable to make contact on HF | HF | ? |
| 200407354 | 25/09/2004 | Unable to contact ATC on any available frequency; multiple aircraft; one aircraft tried SATCOM without success | HF | KINDV |
| 200409263 | 11/12/2004 | Communications problems; multiple aircraft | VHF? | Kolkata (India) |
| 200500182 | 11/01/2005 | PLOC (prolonged loss of contact) - weak HF, also VHF (possible interference from mobile phones) | HF? | Accra (Ghana?) |
| 200500266 | 15/01/2005 | PLOC on HF; multiple aircraft; sunspot activity? | HF | Bay of Bengal |
| 200505881 | 20/07/2005 | All HF and VHF comms. lost; multiple aircraft | HF | Dakar (Senegal?) |
| 200507773 | 18/09/2005 | Unable to contact Gander of Shanwick on any HF chan. for almost 2 hours | HF | North Atlantic |

Table 5 continued

| Occurrence No. | Occurrence Date | Summary | Sys. | Location |
|---|---|---|---|---|
| 200509161 | 29/10/2005 | Unable to contact ATC; HF/VHF/SATCOM tried without success | HF | Kabul (Afganistan) |
| 200509632 | 22/11/2005 | All transmissions on VHF and HF lost; ACARS used successfully; after 45 minutes contact with Barcelona was established | HF | Airway UM608 in Algeria |
| 200600278 | 13/01/2006 | Unable to contact ATC for 50 min.; HF and VHF; eventually managed SATCOM | HF | ELGAN-KINTU |
| 200600721 | 28/01/2006 | Unable to contact ATC on HF or VHF; subsequently OK? | HF | TAVON |

possibly related to SEEs was found, this may be because most are not confirmed when the systems are examined after the flight. We know of a current problem with an avionics unit that is definitely related to SEUs, but this seems unlikely to find its way into the database.

### 3.2.4. Requirements related to Cosmic Radiation

In 1990 the International Commission on Radiological Protection (ICRP) published recommendations (ICRP 60) that the exposure of aircrew to cosmic radiation should be classed as occupational exposure. This reversed earlier recommendations made in 1976 (ICRP 26) that excluded enhanced exposure to natural radiation from any type of control.

Adoption of ICRP recommendations is done at the national level and there are differences in the way they have been implemented. These are reported in detail in Appendix B and summarized in Table 6. Below are conclusions drawn from this survey, concentrating on compliance within the European Union (EU).

In the EU radiation protection is regulated by a Directive on the protection of workers and members of the public against the hazards of ionizing radiation (CEC 96/29/EURATOM). The Directive incorporated and to some extent elaborated on recommendations of ICRP 60. It requires that radiation doses should be kept "as low as reasonably achievable", taking into account economic and social factors and classifies anyone who is liable to receive an effective dose of greater than 1 mSv per year as occupationally exposed and therefore subject to regulatory control.

Article 42 of the Euratom Directive deals specifically with the protection of aircrew. It requires that each Member State should make arrangements for aircraft operators to take account of exposure to cosmic radiation of aircrew where they are liable to be subject to an exposure of more than 1 mSv per year. The Article requires that the operators shall take the following appropriate measures:

- to assess the exposure of the crew concerned;
- to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed air crew;
- to inform the workers concerned of the health risks their work involves; and
- to apply Article 10 to female air crew.

Article 10 is concerned with the protection of the foetus and requires an employer to control the dose received following declaration of the pregnancy to less than 1 mSv in accordance with the implementation of the Directive in national legislation.

Although binding on all Member States, the Euratom Directive is not EU legislation. It is implemented at the national level and how it is implemented differs between the member countries – each country defines its own acceptable means of compliance (See Table 6).

There is generally some threshold above which some sort of action should to be taken, but whether individual records then have to be kept varies. In some countries, if the estimated dose exceeds 1 mSv individual assessment is always required; in others it is acceptable to not keep records if it can be demonstrated that 6 mSv cannot be exceeded in a calendar year. Where assessment is required, it is normally done by calculation on a flight-by-flight basis.

The main differences in the means of compliance within the EU include:

- Different procedures to manage dose records and even whether individual records need to be kept. In several cases the dose assessments must be supplied to radiation regulatory body of the country
- Different threshold at which action needs to be taken, different exposure, altitudes and even use of block/flight hours
- Differences in how the flight profile is defined
- Different computer codes deemed acceptable - CARI, EPCARD, FREE, SIEVERT, PC-AIRE
- Differences in the choice of proxy used to represent cosmic ray modulation (e.g. the heliocentric potential) and the time resolution (range from duration of flight to annual average)

Because implementation of the Directive is subject to national legislation, even within the European Union it is difficult to provide general service that would suit all requirements. There are also issues related to Data protection, especially since dose records count as medical records, and legal issues related to record keeping in the cases where the annual dose exceeds 6 mSv and records have to be kept for as long as 30 years. Except for some of the newer members of the Union, most countries/airlines already have systems in place.

Table 6. Summary of the national requirements for cosmic ray dose assessment

| | France | Germany | UK | Ireland | Spain | Netherlands | Sweden | Finland | Demark | Poland | Czech Republic |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dose records:** | | | | | | | | | | | |
| Maintained by airline | | | X | X | X | | | | | | |
| Central database | X | X | | | | X | | X | | | |
| Demonstrated >6 mSv impossible | | | x | | | | | | | X | |
| **Dose calculated using:** | | | | | | | | | ? | | ? |
| Actual flight profile | X | X | | | | | X | | | | |
| Planned flight profile | | | | | X | | | | | | |
| Representative flight profile | | | | X | | X | | | | | |
| Generic flight profile | | | X | | | | | X | | | |
| **Approved computer codes:** | | | | | | | | | | | |
| CARI-6 | | | X | X | | X | X | X | | | |
| EPCARD | | X | x | X | X | | | X | | | |
| FREE | | x | | | | | | X | | | |
| SIEVERT | X | | x | | | | | | | | |
| PC-Aire | | x | | | | | | | | | |
| | | | | | | | | | | | |

Meaning of Flight Profile definitions:

| | |
|---|---|
| Actual | Details of actual route followed (latitude, longitude, altitude) |
| Planned | Planned waypoints and altitudes |
| Representative | Profile of route followed at some time in the past |
| Generic | Great circle route with set altitude profile |

### 3.2.5. NOAA Space Weather Week Summary (2001)

Every year NOAA SWPC hosts a Space Weather Week in Boulder, Colorado. This brings together the scientific and user communities and is well attended by industry; it is the template on which the European Space Weather Week is based.

A summary of Space Weather Week of 2001 is posted on the SWPC web site[5]. The main reason for including this is that many things that were discussed at the meeting are still being requested many years later:

#### General Comments and Suggestions

Several suggestions were listed, the relevant ones are:

- Increase lead-time of warnings
- Provide alerts in plain language for some, keeping scientific language for others; use NOAA Scales; provide the level of degradation associated with each alert.
- Provide length of anomaly and approximate time when things will return to "normal".

#### Special Topic: Aviation

Individual airlines and the FAA have recently become concerned with both radiation effects and communication effects from space weather on new polar routes as well as on existing routes, especially those that go to high latitude.

- The FAA is increasingly aware of the ionospheric impacts on WAAS.
- Education from an SEC (SWPC) perspective should include the following information:
    - General discussion about space weather, solar radiation storms, and the other phenomena of concern to airlines (e.g. Radio Blackouts); (explaining the effects of space weather – where, when, and how significant)
    - Discussion about the sources of space weather information and what they provide.
    - Explanation of SEC (SPWC) products, especially the alerts but also of the data on the Web page
- Radiation:
    - Users need some indication of radiation dose with Solar Radiation Storm alerts.
    - The airlines want a different S scale for > 100 MeV and calculate radiation dose based on flux level
    - Clarification of information on radiation doses (comparison to chest X-ray), duration, thresholds, etc.

[5] URL: http:/www.swpc.noaa.gov/sww/sww01/Summary2001.html

 

## 3.3. Studies of Responses to Major Events

### 3.3.1. Solar Activity of October/November 2003

The large flare of October 1956 is often quoted as an extreme event, particularly from a radiation perspective. The main problem is that the event occurred when the aviation industry was still in its relative infancy and before detailed monitoring capabilities were available; this has lead to questions about some of the details, e.g. the actual radiation levels. A number have more recent intervals of activity have been subject to a detailed examination and the appropriate data are available for these – the activity of late October and early November 2003 is a case in point.

As a consequence of activity in the October-November time frame, there were actual effects on air traffic control and aircraft operations. Although the intensity of the activity is more extreme than normal, and some might argue with the consistency and appropriateness of some of the actions taken, we will examine what did happened and how it affected the aviation industry. *It should be noted that there were considerable differences in the way the US and European air traffic control systems responded – the affects listed below are based mainly on experiences detailed in a NOAA report assessing how their service performed.*

During the interval a total of 17 major X-ray flares (R2 – R5[6]) were observed; the flares, and the associated solar activity, were some of the strongest ever recorded. The November 04, 2003 flare saturated the GOES X-ray sensor for 12 minutes and is estimated at X28 (R5 extreme). This event is perhaps the largest flare ever measured by GOES X-ray sensors (measurements began in 1975).

The solar activity produced some of the most intense geophysical events on record. Six distinct radiation storms were discerned, including the second largest storm (S4 severe) of Solar Cycle 23; this storm ranked 4th in the all-time list dating back to 1976. There were two distinct, intense geomagnetic storms associated with this activity. The coronal mass ejections that created these storms made the Sun-Earth transit in ~19 hours, making their average speed at near 8 million km/hr. These may be the fastest transits since August 1972 and the storms were ranked as number 6 and 15 on the "Top 30 Ap Geomagnetic Storm List", which dates back to 1932.

#### *3.3.1.1. Systems Affected*

#### Communications

The October-November solar storms created a significant disruption to airline operations – although difficult to accurately assess, the dollar cost was probably in the millions of US$.

Airlines and ground controllers experienced communications problems almost daily during the activity outbreak. Initially (October 19-23), the degraded HF communications were due to elevated solar X-ray emission and the moderate to strong solar flare activity. On October 19, following the X1 (R3) flare, Air Traffic Centers reported moderate-to-severe impacts on all HF groups and HF service was degraded for over two hours. In response, a major carrier rerouted three polar flights from Polar Route 3 to Polar Route 4 (Figure 3), which is more desirable for data-link and SatCom. This required an additional 26,600 pounds of fuel and

[6] The intensity levels noted at several points in this section, e.g. R2, refer to the NOAA Space Weather Scales – see URL: http://www.swpc.noaa.gov/NOAAscales/

resulted in over 16,500 pounds of cargo being denied. More impacts to airline operations were reported on October 24 following the onset of a G3 (strong) geomagnetic storm. Solar radiation remained at background levels, but high latitude communications were severely degraded due to the geomagnetic storm.

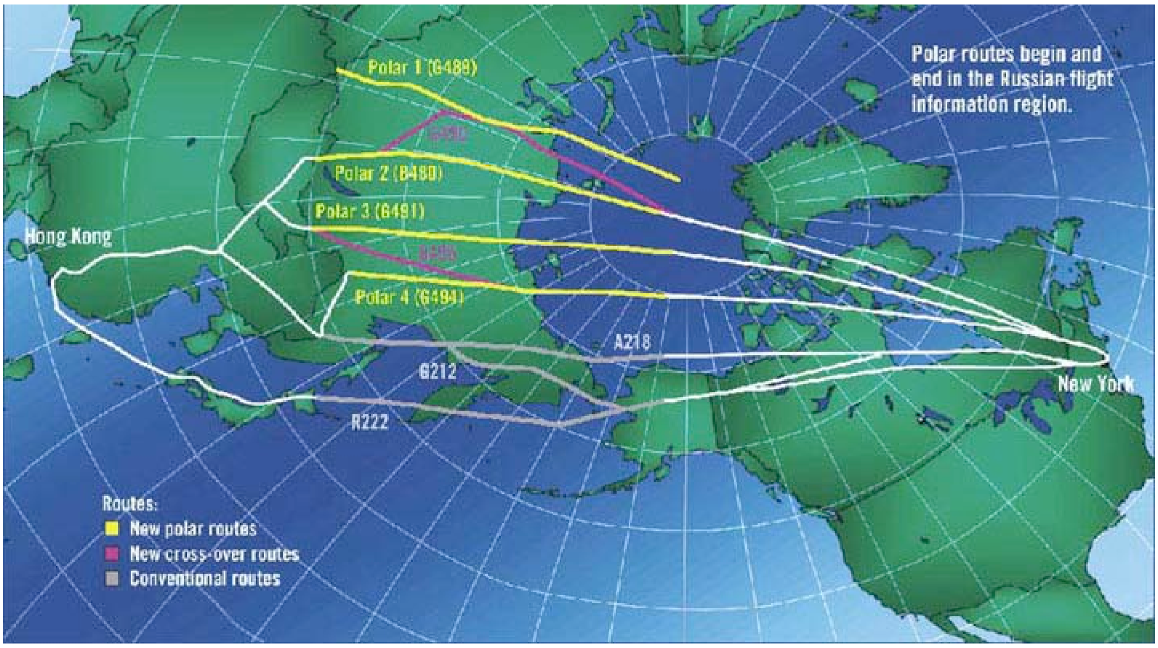


Figure 3. New routes across the North Pole between New York and the Far East.

These were the first of several such periods of severely degraded communication. As each major flare occurred, HF communications at low and mid-latitudes underwent a range of problems from minor signal degradation to complete HF blackout. Higher latitudes experienced even more difficulty following the onset of the radiation storms on October 26. Air traffic operators reported minor to severe impacts on HF communications every day between October 26 and November 05. Communications were so poor on October 30 that additional staff was necessary to handle air traffic.

On some days, flights travelling north of latitude 57° were required to stay on specific routes; these included commercial jets crossing the North Atlantic and transport planes flying over the Arctic. By prohibiting route changes, such as altitude shifts to deal with high winds, air traffic controllers were able to pinpoint a specific plane's location more easily. In the UK, the National Air Traffic Service (NATS) controllers were keeping trans-Atlantic jets on more southerly routes than usual to avoid interference with communications.

### Navigation Systems

Although position resolution was degraded to an extent, many GPS users will experience little or no impact during geomagnetic storms. While ground operators can delay activity that may be affected, the aviation industry cannot. For them, the main concern was affects on the Wide-Area Augmentations Systems (WAAS, see Section 4.1.3).

The WAAS system was seriously impacted on two occasions. For a 15-hour period on October 29 and an 11-hour interval on October 30, the ionosphere was so disturbed that the vertical error limit was exceeded – this is defined by the FAA's Lateral Navigation Vertical Navigation (LNAV/VNAV) specification to be no more that 50 meters,. This translated into commercial aircraft being unable to use the WAAS for precision approaches; if the effects had occurred at times of bad (terrestrial) weather and without other systems being available, this would have rendered the airports unusable.

### Radiation

The radiation storms were a second major concern for the airlines because of the effects of radiation on passengers and crew. With NOAA's help, airlines made critical decisions about route and/or altitude restrictions to flight operations during the period of solar activity. Flight Centers restricted flight paths due to degraded communications, but it was each individual airline's responsibility to assess the radiation threat and take appropriate action.

All US commercial aviation interests were made aware of the radiation storm levels on October 28-29, when the FAA issued their first ever advisory suggesting that flights travelling north and south of 35° latitude were subject to excessive radiation doses (Figure 4). The Advisory was based on data from the GOES particle sensors, but did not require airlines to respond. However, two US airlines conducting flights over the pole did take action to limit radiation exposure to passengers and crew. Polar flights were rerouted during this period – between October 24 and 31 one airline rerouted six polar flights to non-polar routes requiring fuel stops in Japan and/or Anchorage. US flights on the US to Europe routes flew at lower altitudes during this severe radiation storm.

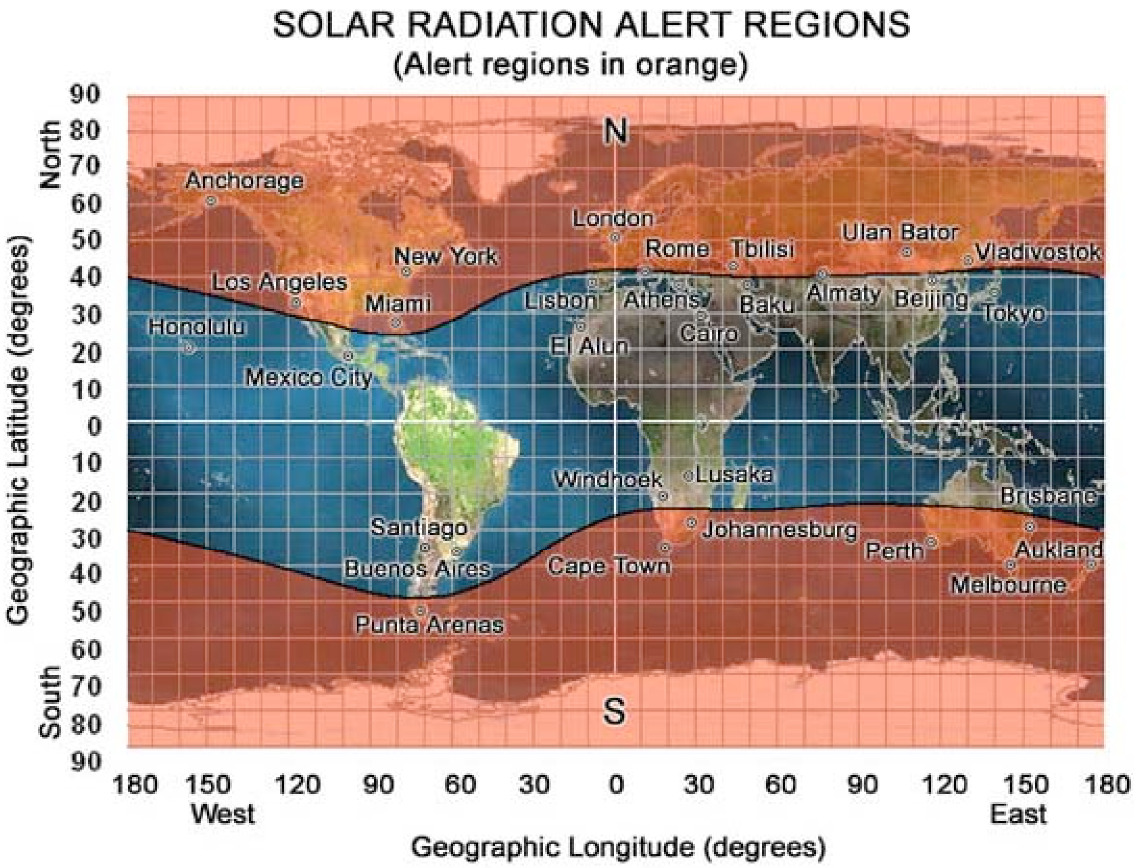


Figure 4. Radiation alert region declared by the FAA on 28-29 October 2003

NOAA forecasters started to provide dispatchers with radiation storm maximum intensity predictions during the period. Perhaps the best example of the value of this type of prediction was on November 04, when the X28 (R5 extreme) flare erupted. Airlines immediately assumed a flare this large would surely produce a significant radiation storm.

 

Forecasters advised dispatchers that because of the location of the source on the sun, an S3 storm was not likely. No route alterations were made, and the prediction materialized when a moderate size S2 radiation storm unfolded.

*Note that aviation authorities in Europe did not recommend that European airlines should fly lower over certain regions. One reason is that differences in the routes flown reduced the necessity – this is discussed later.*

#### 3.3.1.2. NOAA-SEC Service Assessment

The intense solar activity at the end of October and beginning of November 2003 resulted in many space weather effects. In order to determine how they had performed, in April 2004 NOAA did a *service assessment*[7] of the Space Environment Center (now SWPC) for this interval entitled "Intense Space Weather Storms October 19 - November 07, 2003".

The points relevant to aviation from the section "Findings and Recommendations of the Assessment Team" (p33) are summarized below:

##### Observations:

There were comments and recommendations about value and need to continue the data from SOHO LASCO imager and the *in-situ* monitoring capabilities of the ACE spacecraft.

##### Models and Guidance:

**Finding:** The current D-Region Absorption Prediction model does not provide a true overall representation of space weather effects on communications for airline operations. The D-Region plot only identifies the impact of solar flares on communications. The additional impact of radiation storms and geomagnetic storms is not depicted. This caused some confusion to the airlines when making their decisions to route flights, especially on high latitude routes.
**Recommendation:** That the model be improved.

**Finding:** The Major Event Database proved a valuable statistical tool in estimating the geophysical response to large flares.
**Recommendation:** Complete the database and interactive software.

**Finding:** Significant shortfalls exist in warning and forecast capabilities due to inadequacies in the models and tools.
**Recommendation:** The improvements (relating to aviation) that are needed are:

- Coronal Mass Ejection Propagation – CME characterization (mass, speed, direction, and magnetic structure) for predicting time of CME arrival and onset and intensity of geomagnetic storming.
- Solar Energetic Particle (SEP) – detailed predictions of onset time and duration predictions; spectra for airline (radiation) hazard prediction
- Ionosphere – predictions related to global electron density profile (EDP, causing signal path bending), global total electron content (TEC, causing signal path delays), global ionospheric currents
- Polar Scintillation – Arctic spatial and frequency distribution for communications, radar, and navigation signal corruption and outage prediction.

[7] See: http://www.weather.gov/os/assessments/pdfs/SWstorms_assessment.pdf

**Note:** *In the assessment by Oler (2004) of the prediction performance of space weather forecast centres during this interval, the SWPC did not score as well as the Solar Terrestrial Dispatch (STD) on predicting the arrival times of CMEs.*

### Warnings and Forecasts

**Finding:** Customers have established radiation storm thresholds to mitigate potential impacts: SEC models do not provide predictions of maximum flux of radiation.
**Recommendation:** That this should be provided.

**Finding:** The daily forecast (issued at 2100 UT) is not updated during the day, even if conditions change. It can therefore only be used for guidance and not as an operational tool
**Recommendation:** That this should be made dynamic.

### Coordination and Dissemination

**Finding:** Teleconferencing of SEC with airline representatives (3-5 times per day) was an important part of decisions making process for airline dispatchers, pilots and airline safety personnel. Some difficulty in understanding solar phenomena and interpreting SEC products was evident.
**Recommendations:** Understanding of space weather causes and effects could be improved by developing a web site for the airline user community, and by providing training for airline staff and management.

**Finding:** The file transfer requests from SEC web pages slowed the system down and halted processing
**Recommendation:** Establish a link with the NOAA Network Operations Center (NOC) Web Farm.

### 3.3.2. Terrorist Attacks of September 11, 2001

Although the events of September 11 are not related to space weather, the actions taken within a short time of the first attack provide an excellent example of how the air traffic control system responded to the need to modify the flight plans of a large number of aircraft.

The first attack on the World Trade Center in New York was at 08:45 (all times EDT), followed by a second at 09:03. A third attack in Washington occurred at 09:37, and a fourth plane crashed in southern Pennsylvania at 10:24.

An emergency situations centre in Ottawa was activated by NAV CANADA[8] at 09:21. While the FAA was primarily interested in closing US airspace and landing all planes flying within US boundaries, it fell to NAV CANADA to manage the air traffic approaching North America across the North Atlantic and North Pacific.

The Gander Area Control Centre is responsible for the western part of the North Atlantic and immediately began the complex task of redirecting oceanic flights. About 400 aircraft were already over the North Atlantic, en-route from Europe. Of these, about 200 had not yet passed the halfway point. Without a great deal of prior notice, these aircraft – some flying at 40,000 feet – began making 180-degree turns as they headed back to airports in Europe. The remaining 200 or so aircraft were diverted to airports in Eastern Canada. Simultaneously, over the North Pacific commercial aircraft en-route from Asia to North America were being

[8] NAV CANADA: a semi-private organization that runs Canadian air traffic control

diverted to airports in Western Canada, primarily Vancouver. In total, NAV CANADA redirected and landed 239 aircraft destined for the US and Canada – the last touched down by 18:00.

In all about 3,300 commercial and 1,200 private planes were ordered to land by the US and Canadian authorities on September 11; almost 75% of these landed within one hour of the order being made by the FAA (at 09:45). Several airports became saturated and this made it necessary to divert flights to other than the nearest landing strip. Flying resumed in waves of types of destination on the afternoon of September 12, with the last diverted flight departing on September 16.

In spite of the confusion the response to the events was remarkably rapid – perhaps because it was considered an act of war. It is not clear that the response to a space weather event would/should/could be comparable. For most space weather events, it would not be necessary to divert large number of aircraft, but for a solar energetic particle event were similar or more severe than the one of 1956, given that modern aircraft fly higher, longer and at more northerly latitudes, it might be necessary to contemplate this type of action.

It is worth considering a few issues pertinent to this study:

- In some respects, air traffic control was lucky. The (terrestrial) weather was excellent with very few storms to deal with. Also, the events were early in the day while majority of planes from Europe were in transit – many having only just started on their journey – and before the first wave of flights took off from the West Coast.
- The handing of planes that were crossing the Atlantic and Pacific was similar to what would be required for a very large SEP event, with notable exceptions:
  - There was no reduction in available airspace on the North Atlantic Tracks. In the event of an SEP, the desire would be to get all aircraft to a lower altitude as quickly as possible (and possibly to move them to more southerly tracks).
  - Communications were good. The ionospheric disturbances that would most likely be part of a space weather event would disrupt HF communications and degrade GPS navigation; a radio blackout might even occur.
- If an SEP event of 1956 level or greater occurred, the handling of planes in domestic airspace might also be considered similar to what would be required. Note that, because the geomagnetic pole is located in northern Canada, North America would be more affected that Europe.

Additional items of note:

- Some standard hand-off procedures were ditched so that the same controllers followed flights into their landing phase – this reduced the workload on the controllers.
- Over the oceans, instead of radioing flights directly, controllers must send text messages through a private firm that relays them[9] to pilots. One close call was blamed on this process when a west-bound flight across the Atlantic turned back before receiving authorization and was heading towards another at the same flight level that had not. Controllers realized this in time and ordered the flight that had turned to descend by 1000 feet.

[9] Note: This was found in one report and may relate to the ACARS system

## 3.4. Review of Requirements

In the SOARS project plan we undertook to conduct a survey of user requirements. As this progressed we began to realize that it was not giving us the results we were expecting; in part this was because we did not understand quite as much as we thought we did when we formulated the questions; we also had difficulties in persuading people to participate. We therefore broadened the review to include requirements derived or implied by a variety of other sources – this has produced a good overview of the needs of the industry.

The overall requirements are summarized and discussed below; we also identify some of the resources that were available to us. How achievable the requirements actually are raised immediate concerns – this is discussed in later sections.

### 3.4.1. Summary

The user requirements can be summarized in two groups:

General issues:

- Single stop for required space weather information
- Clear identification of the space weather effects that are important, their cause, etc.
- Explanatory documentation in terms that can be understood by the layman
- Presentation of information in a way that allows simple go/no-go decisions
- Predictions should be as far in advance as possible and be valid for as long as possible (12-18 hrs)

Specific effects:

- Prediction/information related to HF Communications problems both at low/mid latitudes and at high latitudes
- Prediction/information related affects on satellite navigation systems
- Prediction/information related affects on satellite communication system
- Prediction/information related to events that could result in dangerously high radiation levels

The first three items in the "General" group indicate that considerable attention needs to be given with regard to how the information is presented and the contents of any explanatory material provided. In particular, a clear explanation of why effects are important, etc. is needed.

Presenting information that allows go/no-go decisions is more of a challenge; also, providing predictions a long time in advance that are valid for a long time is beyond the current state of science. It was clear that it might be possible to provide services in some areas but the required time scales make it difficult, if not impossible, in others.

Details of the services created by SOARS are given in Section 5.

### 3.4.2. Discussion

A persistent thread that runs through all the sources relates to what people know and understand about Space Weather. There is a general lack of understanding (lack of knowledge) of Space Weather effects: which are important, what cases them, when/where they occur and how possible it is to forecast them. Even though a lot of information is available, it is clearly not expressed in a way that the users understand. This is the age-old problem of how to explain complex scientific issues to the layman and is certainly not unique to Space Weather. Even the requirements from the FAA's Space Weather UNAT indicates lack of understating amongst the Team: the recommendations ought to make it clear that there is a need to educate users on the time scales involved in phenomena and the difficulties in prediction them – even now this is not clear on the SWPC Web site.

The principal Space Weather effects that affect aviation are related to HF communications, satellite navigation and communications and the enhanced radiation exposure. Users in the US express concern about all of these effects, while those in other parts of the world are much less concerned and may not even experience some of them. For British aviation, space weather effects do not appear to be of a nature or severity to make their way into the CAA database (Section 3.2.3), although the effects may be worse than this suggests.

Several US airlines operate regularly over the Pole and the number of trans-polar crossing exceeded 5300 flights in 2006. This is a consequence of geography but it is also the main reason for the interest in problems with HF communication at high latitudes. Similarly, that the geomagnetic pole is located in the very northern part of North America results in a greater susceptibility to some mid and low latitude space weather effects. Satellite navigation is therefore more affected in the US than elsewhere; also the US is currently making much greater use of such system although this may change with time.

The issues surrounding cosmic radiation are complex. There is considerable variation in how countries have complied with recommendations of ICRP 60 (Section 3.2.4 and Appendix B). European aircrew appear more relaxed about radiation, mainly because the need for the airlines to comply with the Euratom Directive (CEC/96/29) ensures that the problem is well described and any actions are well defined. In contrast, the lack of legislation in the US is probably the cause of extreme concerns about radiation amongst US aircrews.

The diversity of requirements related to radiation gave us reason to rethink the needs for creating a radiation dose monitoring service within the Project. It could not satisfy all the requirements and would at best be a very simple demonstration in comparison similar capabilities available elsewhere. However, examining ways of improving forecasting related to ongoing particle events is within the scope of the Project.

### 3.4.3. Existing Products and Capabilities

The SOARS project was intended to demonstrate what a space weather service might look like. Existing sites mostly reports what is happening or has recently happened, but do not forecast effects; also, some of the plots and data streams that are available are updated at a lower cadence than is needed for real-time forecasting. We have used as much as we could from what was already available adapting products where necessary.

NOAA's Space Weather Prediction Center (SWPC) already had a variety of space weather products although these were quite generic. In response to requests during their Space Weather Weeks and from the FAA, in mid-2005 the SWPC produced a Web page to support the needs of the aviation industry; this page still exists but, although the supporting documentation is now much better, its contents have hardly changed since it was established. According to the description[10], the page provides an assortment of products that specifies and predicts changes in the space environment; it was designed to provide the most

[10] A Product Description Document for the "Space Weather for Aviation Service Providers" Web page is available at *http://www.swpc.noaa.gov/aviation/aviation_PDD.pdf*

applicable space weather information addressing aviation concerns and make it accessible in one location on the Web site – the page combines graphical and textual presentations of near real-time solar and geophysical parameters.

The page was designed around existing SWPC products and is targeted at the US aviation industry. While comprehensive, the page does not cover all aspects of Space Weather that affect the industry and is deficient in several areas. Even though difficulties with HF communications at high latitudes are a serious problem for US carriers, the D-Region Absorption page only explicitly included a prediction of the effect of SWF[11] events (at low and mid latitudes); also, there was nothing to cover any effects related to either satellite communications or navigation at any latitude. The state of NOAA Space Weather Scale flags were (and still are) ambiguities in for radiation storms (100 MeV protons are more relevant for biological effects) and radio blackout (it really only describes SWF events). A comprehensive set of alert messages was provided, some of which are very relevant, but other potentially useful SWPC products (e.g. reports on flaring activity) were not included.

A more accurate flag related to radiation that is hazardous to biological systems appears to be produced by the Solar Radiation Alert system[12] of the FAA's Civil Aerospace Medical Institute (CAMI) – this is relatively new and is only available as an email alert sent by subscription. Generic systems to estimate radiation exposure are provided by CAMI and by SEIVERT; as discussed in Appendix B, compliance with ICRP 60 requires more specific capabilities than are available through these general interfaces.

The Australian Ionospheric Protection Service (IPS) produces a set of pages that provide very comprehensive coverage of the effects on HF communications, as well as information on general conditions in the ionosphere (including total electron content, TEC). Some of this information is very relevant to aviation but the layout of the pages does not facilitate understanding.

Several institutions in Europe also produce useful products and some are used by SOARS. These include products from the Regional Warning Centres (RWC) of the International Space Environment Service (ISES) in Sweden and Belgium, the DLR Institute for Communications and Navigation (IKN) in Germany and many others. The RWC in Sweden produces forecast values of Kp and Dst three hours or more ahead of the current time – the trends in such indices and other parameters can help forecast effects caused by particles resulting from CMEs and coronal holes. The RWC in Belgium hosts the Solar Influences Data Analysis Centre (SIDC) and is also the World Data Centre for sunspot data; DLR IKN produces products related to the ionosphere.

ESA has tried to introduce some level of coherence into the European efforts through the Space Weather Pilot projects and SWENET – SOARS is one of the projects involved in this effort.

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[11] Short Wave Fade events are caused by D-Region absorption that results from intense X-rays from large solar flares – high latitude effects on HF comms, are caused by protons.
[12] See Final Report for the "Solar Radiation Alert System (SRA)" (July 2005; DOT/FAA/AM-05/14)

# 4. Requirements in a Service Context

The aviation industry is affected by space weather in many ways through a number of different effects. The impacts differ from those of terrestrial weather and the associated risks are therefore different. Even so, the responses to space weather effects are essentially similar to those of terrestrial weather phenomena – delays, diversions and possibly cancellations. It is therefore advantageous to express and disseminate space weather information in ways that are familiar to the airlines using existing standards and practices.

While safety and security are paramount, civil aviation is a very competitive business. Any impacts to operations are potentially expensive and it is essential that a space weather service is able to minimize them. Airlines are used to making changes to their flight plans in response to severe terrestrial weather, etc., but the duration and geographical extent of some space weather effects, and difficulties in forecasting their occurrence, can make it difficult to include them in operational planning.

The requirements of the industry for space weather services break down into two categories:

- Those related to operations
- Those that can be dealt with offline

The first category includes all the services that would support operational planning, both before and during a flight.

The second category is concerned with the consequences of space weather effects that need to be monitored; there are two principal areas:

- Monitoring the exposure of aircrew to cosmic radiation
- Monitoring problems that could be attributed to space weather, e.g. to avionics

In the following sections we describe the operational environment, the impacts of space weather effects, how they can be forecast and the information disseminated to the operators. Issues that are dealt with offline are also discussed.

The exposure or aircrew to radiation actually falls into both the operational and monitoring categories: the slowly varying component due to galactic cosmic rays can be assessed using computer models; the short term increases due to solar activity may require changes to operational planning.

## *4.1. Operational Environment*

### 4.1.1. Airspace and Air Traffic Control

At any time, there are many thousands of aircraft in the sky around the world. The task of ensuring the safe operations of commercial and private aircraft falls on air traffic controllers. They must coordinate the movements of the aircraft, keep them at safe distances from each other, direct them during takeoff and landing from airports, direct them around bad weather and ensure that traffic flows smoothly with minimal delays.

The air traffic control (ATC) system[13] is designed around a number of divisions that depend on the phase of the flight – surface/airport, terminal/departure, en-route (including oceanic), terminal/arrival and surface/airport. As an aircraft travels through a given airspace division, it is monitored by the one or more air traffic controllers responsible for that division; as the plane leaves that airspace division and enters another, the air traffic controller passes it off to the controllers responsible for the new airspace division.

Before takeoff the control of an aircraft transfers from the ground control to the local controller prior to entry on the runway. As the aircraft leaves the runway and enters Terminal airspace, control is handed off to the radar controller responsible for that Terminal airspace. As the aircraft enters the En-Route domain, control transfers to the En-Route radar controller. Similarly, control transitions to the Oceanic controller if the aircraft enters Oceanic airspace. During approach and landing, a reverse set of handoffs occurs.

Air traffic control services can be divided into two major sub-groups, terminal control and en-route control. Terminal control included the control of traffic (aircraft and vehicles) on the airport proper and airborne aircraft within the immediate airport environment. En-route controllers control the traffic between terminals; they also control traffic in and out of airports where the traffic does not warrant the establishment of a terminal ATC operation.

#### *4.1.1.1. Terminal Domain*

Arriving and departing aircraft are sequenced in and out of the airport by air traffic controllers at radar facilities known as Approach or Terminal Control. To maintaining a steady flow of aircraft, particularly during peak periods, the controllers use a number of tools for sequencing and spacing aircraft more precisely; the objective is to reduce variability in services and optimize use of airspace and available runways.

Terminal Control provides ATC services for airspace located within approximately a 30–50 nautical mile radius of the airport and below 10,000 feet, although the larger facilities can also control higher altitudes. Terminal controllers establish and maintain the sequence and separation of aircraft taking off, landing, or operating within the Terminal airspace. Communications are normally by VHF radio (30–300 MHz).

#### *4.1.1.2. En-Route Domain*

En-route traffic air controllers work in facilities called Area Control Centers.

In the domestic airspace, aircraft are radar-monitored and are in good (VHF) contact with the Control Centres that provide instructions to flight crews to ensure safe separation. This is known as *Positive Control* and aircraft typically follow the fixed route structure of airways, preventing them from flying the most direct route or taking advantage of favourable winds.

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[13] In Europe, air traffic control comes under Eurocontrol that develops, coordinates and plans for implementation of pan-European air traffic management strategies and their associated action plans. In conjunction with the European Commission, Eurocontrol is working on SESAR – the Single European Sky ATM Research Programme. The objectives of the project are to eliminate the fragmented approach to ATM in Europe, transform the ATM system, synchronise the plans and actions of the different partners and federate resources. The definition phase of SESAR was completed in 2008; development and deployment should be complete by 2020.
See URL http://www.eurocontrol.int/sesar/public/subsite_homepage/homepage.html

In more remote areas, in oceanic airspace and over some landmasses, radar systems are not available and controllers provide ATC services using *Procedural Control*. These procedures use aircraft position reports, time, altitude, distance, and speed to ensure separation. This process requires aircraft to be separated by greater distances reducing the overall capacity for any given route.

Communication with controllers en-route is by VHF radio where possible, then by HF (3–30 MHz). Satellite communications (SATCOM) are becoming increasingly common away from domestic airspace but they are rarely available above 82° latitude. During cross-polar flights, communication with controllers is initially through VHF radio and then relies on HF radio.

Over oceanic airspace, aircraft follow "tracks" that are aligned each day with prevailing winds; where air traffic control capabilities are limited over less populated landmasses, the tracks are often fixed following the same route day after day. During the aircraft's passage, the ground controllers will assess requests (received only via HF) for any changes to level, speed or route, and will co-ordinate with adjacent Control Centres before authorising any such change.

### 4.1.2. ATC Capacity

The day-to-day problems faced by the air traffic control system are primarily related to the volume of traffic and weather.

Several factors dictate the amount of traffic that can be handled by an airport in a given amount of time. The time taken to process each aircraft and the number of runways limits the number of aircraft per hour that can be accommodated. Current and anticipated weather can affect this, especially if strong winds limit the number of runways available or if poor visibility (due to fog or rain) slows the movement of aircraft around the airfield.

Problems start when more arrivals are scheduled than can be physically handled, or when delays elsewhere cause groups of aircraft that would otherwise be separated in time to arrive simultaneously. Arrivals must be reduced by putting aircraft in holding patterns, reducing speed in flight or by keeping aircraft on the ground at their place of departure; sometimes aircraft are diverted to an alternate airport.

Delays en-route may be caused by changes in routing due to air traffic restrictions or bad weather. Bottlenecks can also occur due to passenger demands, the geographic location of population centres, differences in time zone and airport noise restrictions. For example, much of the North Atlantic traffic is concentrated at particular times: westbound in the late morning and afternoon, and eastbound during the night and early morning. Because of this concentration, the relatively short distance between most of the major European Airports and the start of the Atlantic routing and the limited height band for economical jet operation, the airspace is comparatively congested. There is a similar concentration of flight times between destinations in the US and SE Asia, offset by 5-8 hours.

The North Atlantic is an example of an area under *Procedural Control* – this includes oceanic areas and landmasses that do not have radar and where their remoteness often prohibits the use of VHF radio. In these areas, procedural separation often depends on flight crew voice reports of position (and time of next waypoint) using HF radio.

| Phase of Flight | Possible Terrestrial Weather Impacts |
|---|---|
| Surface/ Airport | Freezing or frozen precipitation and any thunderstorm hazards including lightening or strong winds may impact ramp and taxiway operation.<br>Wind, wind shear, low ceiling and/or visibility may impact terminal runway operations. |
| Terminal/ Departure | Wind, wind shear, microbursts , turbulence, icing and thunderstorms may impact departure operations. |
| En Route & Oceanic | Jet stream winds, mountain waves, turbulence, icing thunderstorms and volcanic ash may impact en route operations |
| Terminal/ Arrival | Wind, wind shear, microbursts , turbulence, icing and thunderstorms may impact approach and arrival operations.<br>Ceilings and visibility determine the type of approach (visual vs. instrumental) |
| Surface/ Airport | Freezing or frozen precipitation and any thunderstorm hazards including lightening or strong winds may impact ramp and taxiway operation.<br>Wind, wind shear, low ceiling and/or visibility may impact terminal runway operations. |

Table 7. Impacts of Terrestrial Weather[14] on Air Traffic Management

In Oceanic airspace, the lack of radar surveillance and direct communications between controllers and pilots require oceanic separation standards to be 20 times greater than in airspace under *Positive Control*. The large separations limit the number of aircraft that can operate in a given airspace, reducing the number of tracks that can be used. As a consequence some flights are assigned a less than optimum altitude, and there is insufficient opportunity to adjust altitudes to conserve fuel.

Progressive improvements in aircraft altimetry systems have allowed the vertical separation of tracks to be reduced. Implementation of the Reduced Vertical Separation Minima (RVSM) throughout the North Atlantic (including the West Atlantic Route System) began on 27 March 1997; the reduced separation was introduced in 41 European and North African countries on 24 January 2002. This has provided six additional cruising levels between 29,000 and 41,000 feet inclusive, resulting in substantial reductions in fuel costs and in-flight delays.

Figure 5 shows the system of organised North Atlantic Tracks (NAT) – the routes followed by aircraft across the Atlantic. These routes are standardized but change daily in position and altitude in order to compensate for varying weather factors – particularly the jet stream tailwinds and headwinds – that may be substantial at cruising altitudes and have a strong influence on trip duration and fuel economy. The illustration also shows the vertical separation between aircraft reduced to 1000 feet on tracks between 31,000 and 39,000 feet.

[14] Adapted from MetEd (UCAR) documentation on their training course "The Impacts of Weather on Air Traffic management".

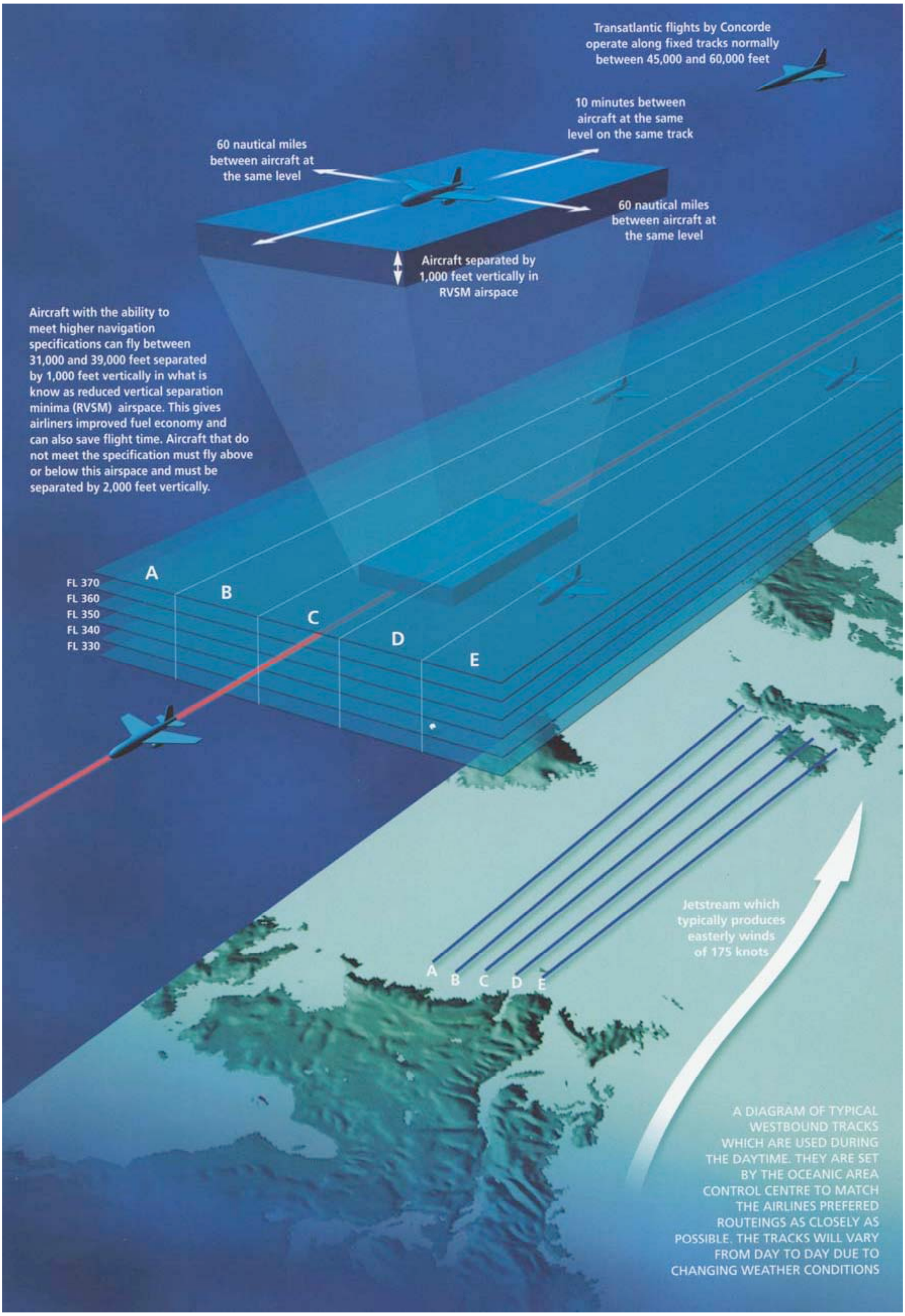


Figure 5. Illustration of the North Atlantic Tracks and RSVM structures. (Reproduced courtesy of the National Air Traffic Service ScOACC, Prestwick)

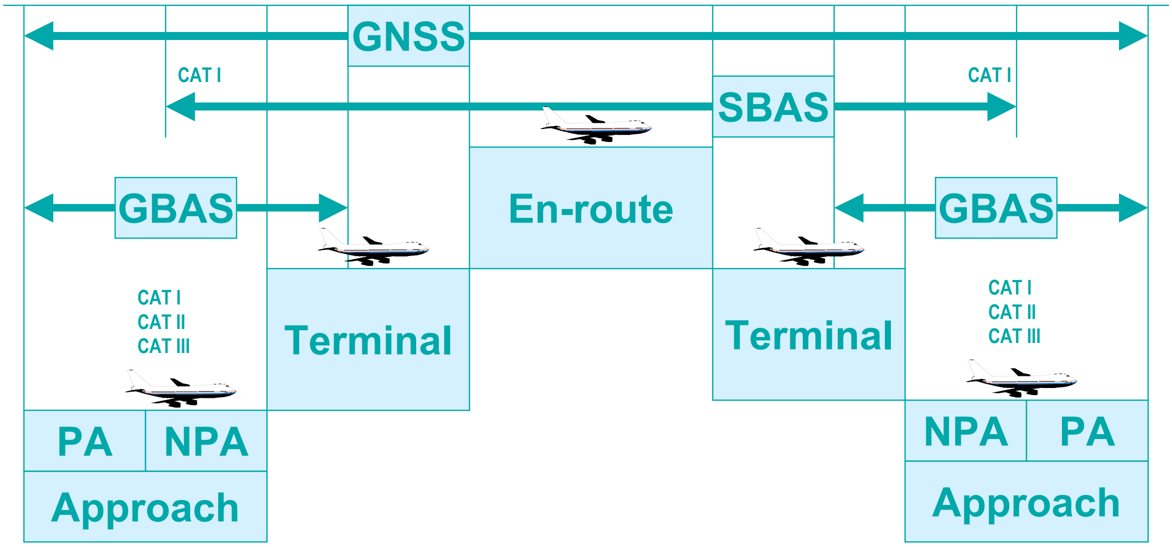


Figure 6. Navigation systems used during different phases of the flight (see text box)

### 4.1.3. Navigation Systems

Over large stretches of the oceans and some landmasses there are unavoidable gaps in air traffic control and radar coverage, as well as an absence of most types of radio navigation aids. Within these areas a high level of autonomy in navigation capability is required; aircraft must carry highly reliable systems that can determine the aircraft's course and position with great accuracy over long distances. In addition to the traditional compass, Inertial Navigation Systems (INS) and more recently satellite navigation systems (GNSS) have become an essential part of navigation.

Until satellite navigation systems became available, inertial navigation systems were the principal form of navigation away from domestic airspace. Inertial navigation is a form of dead reckoning that computes the position based on motion sensors. All inertial navigation systems suffer from integration drift, the accumulation of small velocity errors into a progressively larger one, but provide good positional information over a number of hours.

Positional information determined by over-flying radio beacons was used to update the on-board inertial system. An advance on this basic capability is Area Navigation (RNAV) – this is a method of air navigation that allows an aircraft to choose any course within a network of navigation beacons, rather than navigating directly to and from the beacons. The **navigation aids** used in this context are non-directional beacons (NDB), VHF Omni-directional Radio-ranging (VOR) and Distance Measuring Equipment (DME).

Despite the large number of conventional radio navigation aids, the signals do not cover all airports and airspace and they are costly to maintain. The migration to a system based on satellites has significantly expanded navigation and landing capabilities, improving safety and efficient use of airspace. It is reducing the infrastructure costs of ground-based systems and is also decreases the amount of avionics an aircraft requires and simplifies navigation and landing procedures.

Inertial guidance systems are now usually combined with satellite navigation systems through a digital filtering system; the inertial system provides short-term data, while the satellite system corrects accumulated errors of the inertial system. The signals of satellite navigation systems (GNSS) do not however meet the accuracy, availability, and integrity requirements critical to safety of flight – they must be augmented to meet operational standards for various phases of flight. Different combination of GNSS and its satellite- and ground-based augmentation systems (SBAS and GBAS) are used at different phases of the flight – see Figure 6 and text box for details.

Until recently, to support **precision approaches** (PA) airports needed to provide Instrument Landing Systems (ILS; one per runway end) or a Microwave Landing System (MLS; one per airfield). Satellite-based augmentation systems such as WAAS and EGNOS can provide the general and CAT I precision approach guidance for many runways at dramatically lower costs; this has let to a reduction in the use of ILS and MLS at airports in some countries (notably the US). Local ground-based augmentation systems such as LAAS can provide CAT II/III precision approach guidance at all runways at an airport. The fact that precision approaches can be achieved without the use of ILS or MLS also makes it easier to use airfields with difficult approaches and has opened up some remote areas.

Reliance on conventional ground-based navigation aids is expected to decline as satellite navigation provides equivalent or better levels of service. However, as noted above, there are still some integrity issues related to GPS, etc. that need to be resolved.

### GNSS and Augmentation Systems

The **Global Navigation Satellite System (GNSS)** provides position and velocity information. At present the GNSS consists of two independent constellations of satellites, the US Global Positioning System (**GPS**) and the Russian GLObal NAvigation Satellite System (**GLONASS**). A new European system, **Galileo**, is still under development; two test satellites (Giove A and B) have recently been launched; similar system are planned in Japan (QZSS), India (IRNSS) and China (Compass). The GPS is composed of 24 orbiting satellites in six orbital planes at an altitude of 20,200km; Galileo will be slightly higher. By picking up signals from four or more satellites, GPS receivers can determine the location within ~330 feet.

The basic signals of GPS and GLONASS must be augmented to meet operational standards for various phases of flight – they do not meet the accuracy, availability, and integrity requirements critical to safety of flight. There are three types of augmentation system:

The **Satellite Based Augmentation System (SBAS**) augments core navigation satellites by providing ranging, integrity and correction information via geostationary satellites; the service is implemented regionally. The US Wide Area Augmentation System (**WAAS**) is designed to use reference stations covering wide areas to cross check GPS signals and then relay integrity and correction information to aircraft via geostationary communication satellites; basic GPS signals are enhanced to provide more precise location information to an accuracy of ~25 feet. The European equivalent of WAAS is the European Geostationary Navigation Overlay Service **(EGNOS**); similar systems exist in Australia (GRAS), Japan (MSAS) and India (GAGAN).

**Ground Based Augmentation System** (**GBAS**) – this provide two services: the precision approach service and the GBAS positioning service. The precision approach service provides deviation guidance for the final approach segments while the GBAS position service provides horizontal position information to support 2D RNAV operations in terminal areas. The US Local Area Augmentation System (**LAAS**) provides precise correction data to airborne and surface receivers that will result in navigation accuracy of less than 40 inches to distances of 20 miles or more from the airport.

**Aircraft Based Augmentation System** (**ABAS**) – this term includes augmenting and/or integrating GNSS information with information available onboard the aircraft to enhance the performance of the core satellite system.

 

### 4.1.4. Flight Planning

Flight planning is a formal activity for which the flight plan is the required deliverable; this has to be submitted 2 hours before the planned take off time. The number of routes considered in preparing the plan will depend on the number of routes "available" – in general this will be more for a long distance flight.

In general ATC will tell an airline which routes are available (this information is made available strategically) and then the airline will plan to fly the route that suits them best (but will also consider alternatives). It would be quite possible for several airlines to file identical flight plans, but constraints would be brought to bear as soon as an aircraft seeks ATC clearance for the flight. Once an aircraft is airborne it is not required to follow the flight plan; the route followed is the result of tactical negotiation with ATC.

Information on hazards for flight planning are supplied to airlines, etc. through Significant Weather charts (SIGWX charts – see Figure 7); these reduce the complexities of terrestrial weather to a level that only contains detail that is salient to operations - locations of strong winds, squall lines, areas of severe weather, etc.

Information on hazards for tactical use is in the form of Significant Meteorological Information/Advisory (SIGMET) products. A SIGMET is a weather advisory that contains information concerning the safety of all aircraft; they are in the form of charts and/or messages; the latter are intended to be broadcast to aircraft in flight. If a significant flight/weather event is observed or forecast a SIGMET is issued by the meteorological office responsible for forecasting in that area. There are two types of SIGMETs, convective (occurrence of cumulonimbus clouds or thunderstorms) and non-convective (severe icing or severe clear air turbulence, the presence of dust, sand, or volcanic ash, etc); space weather falls into the latter category.

Forecasts of upper air wind, temperature and some meteorological hazards are provided 4 times per day for flight planning purposes. The forecasts are provided[15] for "windows" 6 hours wide and go out to about 36 hours ahead. The occurrence of hazards is often realized near real-time and SIGMENTs are issued when there is a high degree of confidence, and for a short (usually max. 4hr) period only; if conditions persist beyond the forecast period, the SIGMET is updated or reissued.

Last minute changes in conditions may modify a flight plan – for example a change of wind whilst the aircraft is taxiing from the terminal can imply a change of departure runway but this would not require a change of flight plan. Similarly an aircraft might receive a SIGMET seconds after take off and negotiate with ATC to change the routeing.

Most airlines/flight planning agencies receive these forecasts by direct broadcast over a satellite link. However more and more customers are receiving the forecasts by "dial-up FTP" which means they can get the latest forecast at a time convenient to them. Many products are also available via the Internet through Web sites; there is a growing use of password-protection and digital certificates to ensure data integrity.

[15] The data are provided on a grid with a resolution of approximately 140 km x 140 km in a format called GRIB.

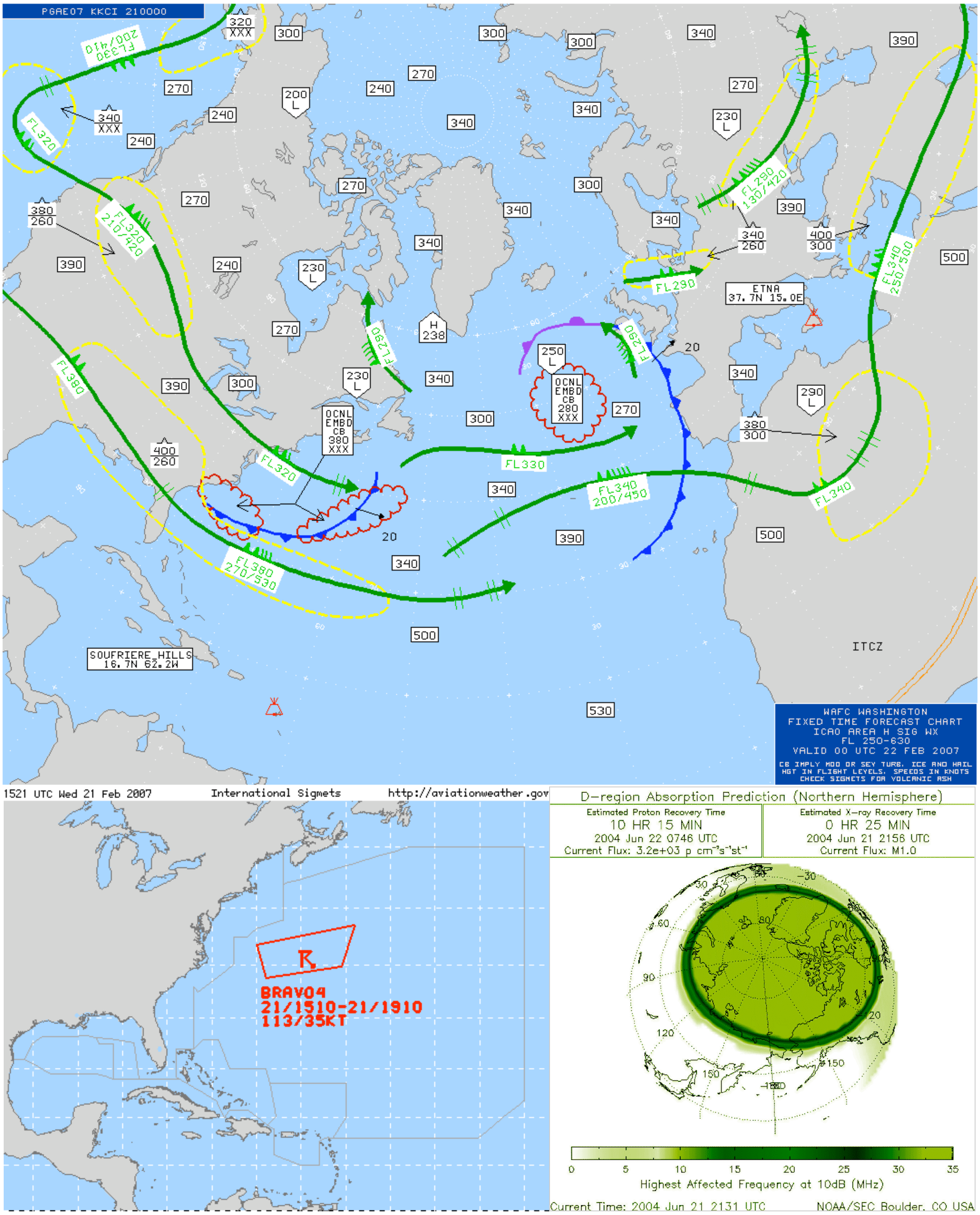


Figure 7. Example of SIGWX (top) and SIGMET (bottom left) charts used for operational planning; a region of severe weather in the western part of the North Atlantic is flagged in the SIGMET as an area that should be avoided. Alerts normally include regions that are quite small and relatively easy to avoid in comparison to areas that can be affected by space weather effects. Polar Cap Absorption (PCA) events (bottom right plot) can cover most of the polar region and last for days; the area typical affected by a Short Wave Fade (SWF) event can be seen in Figure 9 (first panel, top-left plot). *(SIGWX and SIGMET from NOAA National Weather Service; example of planned PCA prediction service from NOAA Space Weather Prediction Center)*

## 4.2. Space Weather and Operations

### 4.2.1. Impacts of Space Weather

In this section we look at impacts of space weather effects on air traffic control and airline operations. The effects are in two principal areas, although the relative importance of the effects may change as aviation moves towards a greater dependence of satellite navigation systems:

- Affects on radio frequency communications
    - Disruption of HF and satellite communications (voice and data)
    - Disruption of satellite navigation services
- Consequences of enhanced Radiation Levels

The impacts of the effects vary according to the phase of the flight; these are summarized in Table 8 and discussed below. Their significance varies across the globe; the dependence on location of the effects and the regional dependence of their affects are also discussed.

| **Phase of Flight** | **Possible Space Weather Impacts** |
|---|---|
| Surface/<br>Airport | Solar energetic particle events, effects on the ionosphere, may impact terminal operations.<br>Threat of solar energetic particle event may require delay of departure. Forecast problems with HF propagation may require rerouting (e.g. by prohibiting use of polar routes) |
| Terminal/<br>Departure | Reduced precision of GPS systems may prohibit departure from airports with complex ascent pattern when visibility is limited. |
| En Route &<br>Oceanic | Solar energetic particle events and effects on the ionosphere, may impact en route operations<br>SEPs may require reduction of flight level or rerouting.<br>Problems with HF propagation may require rerouting. |
| Terminal/<br>Arrival | Reduced accuracy of GPS systems may limit precision approaches and prohibit use of airports with complex descent patterns that do not have ILS. Problems acute during reduced visibility. |
| Surface/<br>Airport | None?? |

Table 8. Potential impacts of Space Weather on Air Traffic Management

#### *4.2.1.1. Prior to departure:*

For safety and security reasons, flying requires good communications. Conventionally this relied on VHF locally and on HF en-route; more recently satellite communications (SatComs) are increasingly common but are expensive, are not allowed for ATC purposes and cannot be used at latitudes greater than 82°.

If **communications are degraded** (or are forecast to be degraded) over the planned route, one option is to choose to reroute the flight. HF can be affected by Short Wave Fade events (see Section **Error! Reference source not found.**) at low and mid latitudes – these are caused by solar flares, can only occur on the daylight side of the Earth and are relatively short lived (minutes to hours). The effects of ionospheric storms can degrade HF communications at mid/high geomagnetic latitudes for many days. The main problem on cross-polar flights is to HF communications which can be completely disrupted and require rerouting for several days; the effect is due to Polar Cap Absorption events (see Section 2.2.2) that are caused by solar particles. Below 82° SatComs could be used instead of HF, but under certain conditions can be badly disrupted by ionospheric scintillation (see Section 2.2.3) in localized areas.

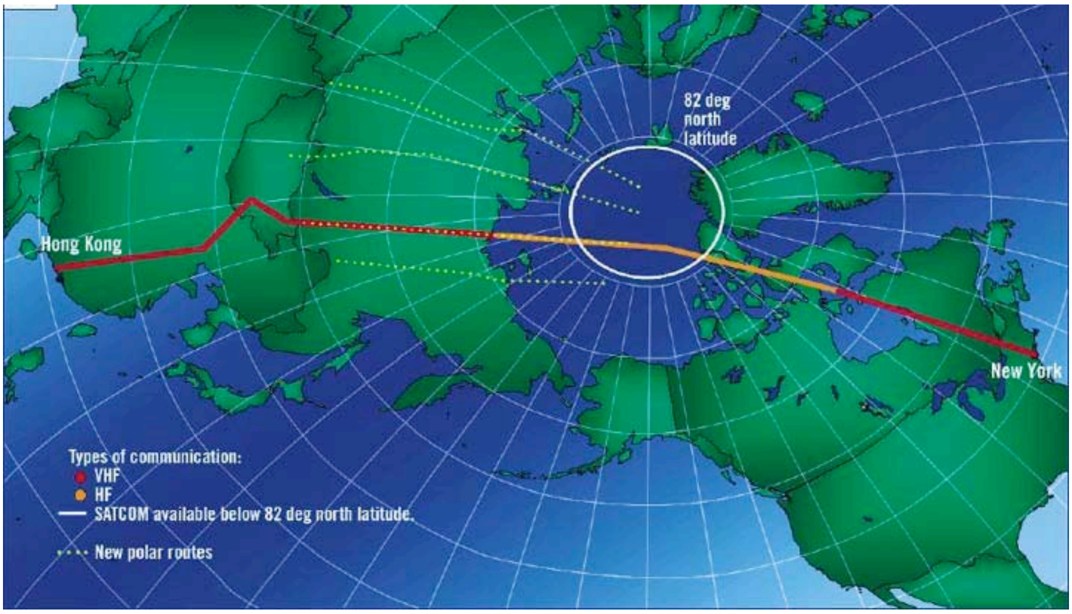


Figure 8. Typical modes of communications during cross-polar flights. VHF is used in controlled airspace and HF en-route; communications via satellite are not possible at latitudes >82°.

**Degradation of satellite navigation systems** would probably not have a serious effect on the flight plans *(at the moment)* since the prime form of navigation is by inertial reference unit. However, the dependence on satellite navigation is increasing and *in the future* if the Ground Based Augmentation System (GBAS) is required to support a precision approach were degraded, and no alternate system were available, a change to the flight plan might be required:

- If GBAS is required for departure, the flight would have to be delayed (or cancelled).
- If required for landing, the flight might need to be rerouted to a nearby airport – for destinations in populated areas this decision could be finalized en-route and need not delay the departure of a long-haul flight.

If a **radiation event is in progress** (or recurring solar activity suggests one is likely), the options are to reroute the flight (away from high latitudes and/or to lower altitude), or delay (or cancel) the flight. Solar particle events can last for several days and their occurrence cannot currently be forecast accurately, only probabilities can be given.

***The types of change described above would be consistent with modifications to flight plans currently made prior to departure because of terrestrial weather conditions, ATC problems, etc. The information to plan a reroute would be needed several hours prior to departure. The decision to delay a flight could be made quite close to the departure time, but this would require the timely transmission of prompt space weather data.***

#### *4.2.1.2. En-route:*

If **HF Communications** were **suddenly disrupted** while an aircraft is en-route, attempts can be made to contact air traffic control using (line-of-sight) VHF plane-to-plane relay, or by satellite communications (if available); the ACARS system provides a more resilient way of passing standard messages – see the text box. If neither is available, then the aircraft should just continue along the predefined flight plan until contact can be resumed.

If the **satellite navigation system** (GNSS) were **suddenly disrupted** during flight, the response would depend on the location of the aircraft:

- If away from controlled airspace the flight could continue using inertial navigation guidance systems (this is currently the principal form of navigation anyway). For short disruptions, loss of GNSS should not cause any major problems.
- In terminal airspace, there could be problems if GNSS is required for routing. At the moment, the dependence on GNSS for this is limited, but planned changes to ATC could increase the severity of the problem. While radar altimeters could help maintain vertical separation, inertial navigation might not be adequate without some form of ground systems such as VOR to correct the drift.
- If **precision approach** (PA) **using local area augmentation** (GNSS/GBAS) were required, the option would be to divert to another (local) airfield that does not have this requirement. If the degradation was observed early in the flight, the diversion could be planned ahead of time; in remote areas where an alternative airfield is not available, the flight might need to be aborted. *A change of this type would be consistent with changes in routing due to terrestrial weather, ATC problems, etc. However, reduced ability to make guided (precision) approaches into airfields with difficult approaches could be very disruptive in the less developed regions of the world. In some equatorial regions, appropriate scheduling should allow flights to avoid the time of day when ionospheric scintillation is most likely.*

If **radiation event** occurs while an aircraft is in transit, the response would depend on the intensity of the event, and the location of the aircraft in relation its geomagnetic latitude, altitude, local noon and closeness to terminal airspace. The occurrence of an event should be passed to aircraft by ATC is the same way that severe weather warnings are:

- For weak radiation events, no action need be taken.
- In the case of an intense radiation event with the aircraft in terminal airspace – i.e. under active control by ATC, not too far into its flight plan, or close to the end of it – the option would be to reduce altitude and possibly abort the flight.
- In the case of an intense radiation event with the aircraft well into its flight plan – e.g. in oceanic airspace and at altitude – *it is not clear that any response is feasible* since any changes would need to be cleared by ATC. Even if there were no problems with communications, it could take hours for ATC to safely execute a change if a large number of aircraft is involved.

**Aircraft Communication Addressing and Reporting System (ACARS)**

The ACARS data-link system came into extensive use in the late 1990's and is designed to reduce crew workload and improve data integrity. It is used to pass simple messages between an aircraft and ATC or between an aircraft and its base. ATC messages include: En Route Position Reports, Flight Plan Requests and Updates, Flight Plan Diversion, Weather Updates. ACARS uses VHF, HF or SatCom; on cross-polar routes communications are only possible by HF.

 

#### *4.2.1.3. Dependence on Location*

As reported in Section 2, some space weather effects that are relevant to aviation have a dependence of location.

Immediate effects are generally related to the location of the sub-solar point and time of day is significant:

- SWF events caused by the X-rays from solar flares affect HF communication only on the daylight side of the Earth – the effect is strongest at the sub-solar point.
- General radio frequency interference (RFI) caused by general solar activity also affects the daylight side of the Earth.
- Enhanced radiation levels caused large solar particle events are mainly experienced during daylight; the particles enter more easily in the polar region and levels are enhanced most at higher geomagnetic latitudes.
- Certain ionospheric effects, such as some types of scintillation in equatorial regions, depend on time of day. Equatorial scintillation is mainly dependant on atmospheric circulation and is strongest after dusk.

Some effects are related to proximity to the geo-magnetic pole:

- Effects on radio communications in this category are the PCA events and degraded HF communications caused by geo-magnetic storms. PCA events involve some complex chemistry in the upper atmosphere that is altered by sunlight and time of day and season are therefore also important.
- Radiation levels are generally higher at higher geo-magnetic latitudes – they plateau around 60° (geomagnetic). Therefore, accumulated dose for routes that are at high geomagnetic latitudes will be higher than those at lower ones; a small change of route can significantly reduce the dose (Section 6.2).

As a consequence, whether space weather effects have an impact depends on where an airline operates. The proximity of the geomagnetic pole and the use of cross-polar routes to South East Asia mean that US airlines experience more problems related to space weather than their European counterparts. While US carriers regularly fly at higher geomagnetic latitudes; since the end of the Cold War, there is little reason for European carriers to use high latitude routes, except for some flights to the West Coast of the US.

Of the space weather effects that are relevant to European airlines, those that affect the ionosphere and the operation of satellite navigation systems have the potential of causing the most significant problems; this includes the affects on augmentation systems designed to improve the integrity and continuity of GPS so that it can support safety critical operations.

### 4.2.2. Space Weather Forecasting Requirements

In common with terrestrial weather forecasting, the purpose of space weather forecasting is to give sufficient warning of events that may require changes to flight operations. Space weather forecasting works on different timescales depending on whether the objective is to predict future events or flag things that are happening or are about to happen:

- **Forecasts** should deal with longer-term trends in solar activity or ongoing effects. They could be incorporated into the regular weather briefing used by airlines, pilots

 

and ATC for route planning; the information needs to be available well in advance since planning for along-haul flight starts 3-4 hours before scheduled departure time.
- **Near-casts** and **now-casts** should be in response to events and should be passed to the ATC for distribution and to permit timely decisions by operational planning teams. They could also be passed to aircraft en-route for information and used to modify traffic management decisions.

#### 4.2.2.1. Forecasting Effects

A forecasting service needs to continuously assess the state of the Sun so that phenomena that may occur can be identified. Changes can occur on the Sun in the space of just a few hours; a service therefore must monitor the occurrence of flares, track the status of existing active regions and coronal holes and the emergence of new ones. The time scales over which changes can occur, coupled with the speed at which a CME can travel[16], limits the interval over which a forecast remains valid.

Radiation enhancements due to intense solar particle events (related to flares) cannot be forecast, but enhanced particle fluxes emanating from features on the solar disk (coronal holes, etc) or a CME shock front could be. Also, it might be possible to forecast the reduction in cosmic ray background caused by the effects of a CME passing through the heliosphere – a Forbush decrease. However, because the reduction is dependent on several factors[17] it is difficult to forecast the timing or severity of the effect.

A space weather forecast might consist of:

- General synopsis of current solar conditions
    - Active regions and coronal holes that are visible and how they have evolved in the last few days; any signatures of change such as the emergence or submergence of magnetic flux that may affect the probability of flaring, etc.
    - Any active regions that will rotate off the disk (over the west limb) or that are expected to rotate onto the disk (around the east limb) within the forecast interval
    - Flaring and other activity in each active region over the last 24-36 hours

- Forecast of the occurrence or continuation of phenomena
    - Probability of each class of flare, particle events and CMEs over the next 6, 12 and 24 hours. This could be summarized as a series of maps showing the location of features and forecast probabilities of flaring of each active region.
    - Onset or continuation of enhanced /reduced particle fluxes originating from coronal holes, CME shock-fronts, etc.

Given the time needed to prepare long-distance flight plans and the duration of some intercontinental flights, forecasts of space weather activity need to be made at least every 6 hours and be valid for 12-18 hours; *this is achievable for some but not all phenomena.*

#### 4.2.2.2. Near-casting Effects

Near-casts describe things that are expected to happen in the near future:

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[16] CME travel times vary from 20-60 hours, depending on the velocity
[17] The reduction depends on the size of the CME, the strength of the magnetic field it contains and the proximity of the CME to the Earth.

- Significant changes in the magnetic complexity of a solar active region might need to be flagged because increased flaring might result in HF propagation problems (due to ionospheric SWF events) or produce enhanced radiation level.
- Particles from a flare, CME or coronal hole can cause disruption of HF communications because of PCA events, and effects on satellite communications and navigation due to ionospheric scintillation.

A near-cast therefore might anticipate the arrival of a CME or a change in solar wind velocity as a coronal hole boundary sweeps across the Earth's path. In the case of a CME, a near-cast might be able to report that the magnetic field of plasma cloud, measured as it passes L1, indicates that it will geo-effective (in the next 30-60 minutes) when it interacts with the Earth's magnetopause.

Near-casts require the prompt use of space weather data – they must be gathered and assessed within minutes. Information about any anticipated effects then needs to be disseminated as quickly as possible.

A near-cast warning might say: *"Anticipate loss of HF and satellite communications in xxx (location) within the next hour, possibly lasting for several hours"* or, if the Sun is undergoing an interval of intense activity: *"Active region NNN is undergoing rapid changes/ a new active region is emerging and could produce solar particle event in the next 6 hours"*.

Scintillation is localized and clouds of scintillation can drift. A specialized near-casting service could be determining whether the integrity of the GNSS/GBAS service in the locale of a particular airfield is sufficient for a precision approach. If the precision of the location is inadequate or the service is subject to interruption because of loss of lock, diversion to another airfield may be necessary.

#### 4.2.2.3. Now-casting Effects

Now-casts are issued once a flare, or geomagnetic or ionospheric storm has started. This level of forecasting needs prompt access to measurements made by space and ground based observatories.

The onset of an intense flare may lead to a radiation alert being issued. This may result in changes to flights that are scheduled for departure, but may be of limited use for flights that are en-route (see section 4.2.1.2).

That a geo-magnetic storm has started could indicate that an ionospheric storm is likely. However, once an effect that could disrupt HF propagation has started, it may be too late to pass the information to aircraft that are en-route – they may already be subject to a communications blackout.

Now-casts related to GNSS service capabilities should probably be provided at sites in the locale of a particular airfield; delays inherent in gathering scintillation data, etc. data on a global level may prohibit now-casting on a wider scale.

### 4.2.3. SWx Forecasting and Flight Planning

As summarized in Table 9, there is a finite set of solar phenomena and likely effect combinations for which warnings should be provided. Each of these types of effect can be associated with where/when categories.

SIGWX charts are in general 24 hour forecasts so the skill in forecasting hazards on these is poor. Ideally the aviation industry would like warnings of space weather hazards on the same timescales but the accuracy of such forecasts would be limited. Forecasting the timing and magnitude of effects could be particularly difficult; however, once an event has started, near-casting the magnitude it could reach might be possible. Therefore we need to consider providing space weather information using counterparts to both SIGWX and SIGMET.

| Space Weather Effect | Fore-casting | Near-casting | Now-casting |
|---|---|---|---|
| Short Wave Fade (HF) | x | X | X |
| Polar Cap Anomaly (HF) | x | X | X |
| Ionospheric Storms (HF) | X | X | X |
| Ionospheric Scintillation (L band) | | ? | X |
| Total Electron Content (TEC) | x | x | |
| Solar Cosmic Rays | x | X | X |

Table 9. Ability to provide information on different timescales

#### *4.2.3.1. Forecasting*

Taking everything into consideration, the Aviation group of the Research and Development section of the UK Met Office has proposed the concept of a space weather warning code that could be provided on a space/time grid identical to that used for wind and temperature forecasts. In this concept the code would be zero if no solar activity were expected to affect aviation operations in the space/time combination of a point in the forecast. A non-zero code would indicate that at least one type of effect was expected. If a combination of effects were expected, then the code would reflect that.

Thus for example a code of 1 could indicate that a SWF effect was expected (at that particular space/time combination), 2 that a PCA was expected, 4 an Ionospheric storm, and so on. A code of 5 could indicate that both SWF and ionospheric storm effects were to be expected (at that space/time combination), etc. Of course, because of differences in timescale related to the effects, some codes might almost never be used in a forecast, only in near- and now-casts

Each type of effect would have at least one web site associated with it from which further information was available, and, ideally, a procedure to be followed; an example of such a procedure might be something like *"Load extra fuel and be prepared to follow flight plan exactly for portion of flight for which HF propagation is inoperable"*. Any procedures that should be followed would have to be agreed ahead of time by all the actors in the aviation sector.

In planning a flight an airline would scan the code for the space/time combinations to be flown through. For the vast majority of time the code for all combinations would be zero. If the code were non-zero, the airline would collect additional information and modify the flight plan in the light of the agreed procedures; this might well involve detailed interaction with the relevant ATC authorities.

#### *4.2.3.2. Near-casting and Now-casting*

Near-casting and Now-casting might require independent approaches. However, the Met Office proposes that it might be possible to stretch the Forecasting approach described above into the near-casting time domain. The thinking here is that an airline might be able to supplement the information by contacting an FTP site at a later stage than flight planning. The FTP site would have an additional field that is the latest information available, and would, if possible, be valid for the next few hours. The airline could access this information in the period between submission of the flight plan and the point in the flight where communications with a ground server became impossible.

#### 4.2.3.3. Establishing Procedures

***The ideas discussed above would have to be "approved" by a number of bodies involved in aviation before they could be implemented but all the bodies concerned have indicated a willingness to help in principle.***

The world's air traffic control agencies – e.g., EuroControl in Brussels, National Air Traffic Services (NATS) in the UK and the Federal Aviation Administration (FAA) in the USA – working with the meteorological agencies, play an integral role in the dissemination of terrestrial weather data so that they, and the flight crews, have the latest information to ensure safe operations. It would therefore, be logical for all such agencies to be involved in the distribution of space weather information and definition of responses to effects.

It may be necessary to adopt different response procedures depending on the type of airspace management in each area. Creating these response procedures would primarily be carried out by the National ATC agencies Planning and Implementation Management Groups, which are integrated with International Civil Aviation Organization (ICAO).

Codes relating to space weather alerts[18] have been created by the NOAA SWPC that can be distributed on the NOAA Weather Wire Service (NWWS[19]); the codes are based on the existing SWPC alerts and it is recognized that some adjustments may be necessary. There are World Meteorological Organization (WMO) equivalents (see SWPC alerts Web page and ICAO-IAVWOPSG, 2005) to the SWPC codes that appear on messages from National Weather Service systems.

In the past messages containing solar and geophysical data, and predictions of solar activity, were distributed by the prediction centres in the form of URSIgrams. These were originally developed to facilitate the rapid exchange of information by telex; they are currently being revised under the auspices of the International Space Environment Service (ISES[20]).

Following the discussions at the 60th Session of the Executive Council of the World Meteorological Organization (see Section 8.2), the WMO is likely to play a bigger role in matters related to space weather in the future.

## 4.3. Monitoring the radiation exposure of aircraft crew members

The main service that is not related to forecasting, but is related to operations, is the monitoring of exposure to radiation. In the EU the Euratom Directive (CEC 96/29, 1996) requires European airlines to keep records the exposure of their aircrews to cosmic radiation and many already have procedures in place. The directive is implemented at the national

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[18] The NOAA SWPC alerts are defined on http://www.swpc.noaa.gov/alerts/AlertsTable.html
[19] The NOAA Weather Wire Service is a satellite broadcast system that distributes emergency weather conditions and forecasts to North America and parts of Central and South America. The space weather products are defined on http://www.swpc.noaa.gov/wwire.html
[20] International Space Environment Service (ISES) – see http://www.ises-spaceweather.org/

level and the requirements vary from country to country. In the UK, the Civil Aviation Authority and a group of experts produced detailed guidance material on cosmic radiation[21] for airlines – this is used as the basis for the discussion in this Section.

### 4.3.1. Requirements on Operators

Operators whose aircrew may receive an effective annual dose greater than 1 mSv, generally those operators whose aircraft operate above 8km (26 000ft), should carry out an assessment of the maximum annual dose to which their aircrew are liable. Assessment is by computer program prediction and details of the assessments of the exposures must be recorded. If the assessed dose is less than 6mSv per annum[22], the Directive does not require any further action to be taken. However, where an assessment indicates that aircrew are liable to exceed 6 mSv, monitoring of the dose received by individuals must be carried out

Although individual monitoring[23] is regarded as best practise, it is recognised that this can impose unjustifiable cost for some operators. In these circumstances the guidance material indicates that an acceptable course of action would be to rely on an assessment of maximum doses where this shows that aircrew will not be approaching annual doses of 6 mSv. A suitable cut off point would be where the assessment indicates a maximum annual dose of 4 mSv. Where aircrew are liable to receive doses in excess of 4 mSv per annum, it is recommended that there should be monitoring of individual aircrew member's exposure using computer program prediction. The purpose of such monitoring would be to ensure that annual doses did not exceed 6 mSv.

Where possible, operators should adjust a crewmember's roster to reduce exposure with the aim of preventing doses in excess of 6 mSv per annum. For a mix of routes, the dose accumulated during a year is not likely to exceed 6mSv unless there was a very large solar event. However, for crews dedicated to high latitudes routes the dose could come close to, or even exceed, 6mSv per annum. Records for any individuals exposed to more than 6 mSv per annum must be kept for a minimum of 30 years from the last annual exposure of more than 6 mSv (even if the individual concerned is deceased) or until the individual is 75 years of age, whichever is the longer period of time.

### 4.3.2. Assessing the Dose

There are several computer models/codes available to calculate the radiation dose on a flight-by-light basis – e.g. CARI-6, Sievert and EPCARD (Lantos et al, 2003). The codes use different proxies (e.g. the Heliocentic Potential) and empirical techniques to estimate the long-term modulation of the galactic cosmic background. They appear adequate for general use, but do not fully account for the effects of enhanced solar activity; inputs from proton and neutron monitors can be used to respectively determine increases (caused by flares) and Forbush decreases (caused by CMEs). Special provisions need to be made to calculate and include the effects but the codes differ in how well they do this. A study by Getley et al. (2005) demonstrated that the models do not include the effects extreme solar-terrestrial conditions; they highlight that short-term temporal variations cannot be properly described using monthly averages.

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[21] See URL: http://www.dft.gov.uk/pgr/aviation/hci/protectionofaircrewfromcosmi2961

[22] For pregnant aircrew, once a pregnancy is declared the operator must ensure that the dose does not exceed 1mSv during the remainder of the pregnancy.

[23] Using film badges to provide individual monitoring is considered best practice but could be costly to administrate for operators with large numbers of employees.

(mSv)

| Flight | Flight Date Code | Flight Route Code | TEPC H*(10) | TEPC E* | CARI-6 Feb-00 E | CARI 6M E | SIE-VERT E | EPCARD E | EPCARD H*(10) | EPCARD Ratio E/H | TEPC(E) /CARI 02/00 | TEPC(H)/ EPCARD (H) | TEPC(E)/ SIEVERT | TEPC(E) /CARI6M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lon-S/H | 17180100 | LS1 | 45.7 | 53.9 | 45.2 | 45.1 | 50.7 | 54.89 | 46.54 | 1.179 | 1.192 | 0.982 | 1.063 | 1.195 |
| Lon-S/H | 19200200 | LS2 | 41.1 | 48.2 | 42.4 | 41.9 | 49.9 | 51.32 | 43.79 | 1.172 | 1.136 | 0.939 | 0.965 | 1.150 |
| | | | | | | | | | | | 1.164 | 0.960 | 1.014 | 1.172 |
| Lon-JFK | 18190100 | LN1 | 35.9 | 43.2 | 36.9 | 36.0 | 35.8 | 46.62 | 38.75 | 1.203 | 1.170 | 0.926 | 1.206 | 1.200 |
| Lon-JFK | 27280300 | LN2 | 31.6 | 37.7 | 31.6 | 31.2 | 34.1 | 41.01 | 34.33 | 1.195 | 1.195 | 0.920 | 1.107 | 1.210 |
| JFK-Lon | 28280300 | NL2 | 30.6 | 36.4 | 30.3 | 30.1 | 33.0 | 39.53 | 33.25 | 1.189 | 1.201 | 0.920 | 1.102 | 1.209 |
| Lon-JFK | 17180400 | LN3 | 33.7 | 39.9 | 30.1 | 31.7 | 34.3 | 38.21 | 32.24 | 1.185 | 1.326 | 1.044 | 1.163 | 1.259 |
| JFK-Lon | 18180400 | NL3 | 28.9 | 34.4 | 28.8 | 27.1 | 31.1 | 36.11 | 30.34 | 1.190 | 1.194 | 0.953 | 1.106 | 1.269 |
| Lon-JFK | 17180700 | LN4 | 26.1 | 30.9 | 27.2 | 28.3 | 31.3 | 36.05 | 30.49 | 1.182 | 1.135 | 0.856 | 0.986 | 1.090 |
| | | | | | | | | | | | 1.203 | 0.937 | 1.112 | 1.206 |
| Lon-LA | 29010300 | LX1 | 53.2 | 63.1 | 53.6 | 49.2 | 58.6 | 67.36 | 56.82 | 1.185 | 1.177 | 0.936 | 1.076 | 1.282 |
| Lon-LA | 26270300 | LX2 | 48.4 | 57.1 | 50.1 | 46.0 | 56.8 | 65.08 | 55.12 | 1.181 | 1.141 | 0.878 | 1.006 | 1.242 |
| Lon-LA | 16170400 | LX3 | 52.9 | 62.7 | 53.4 | 48.6 | 57.3 | 67.17 | 56.66 | 1.185 | 1.174 | 0.934 | 1.094 | 1.290 |
| LA-Lon | 17170400 | XL3 | 46.8 | 55.6 | 49 | 46.1 | 52.3 | 62.21 | 52.35 | 1.188 | 1.134 | 0.893 | 1.063 | 1.206 |
| Lon-LA | 16170700 | LX4 | 40.2 | 47.5 | 46.3 | 43.1 | 51.5 | 60.83 | 51.46 | 1.182 | 1.026 | 0.781 | 0.923 | 1.103 |
| LA-Lon | 17170700 | XL4 | 37.3 | 44.1 | 41.6 | 39.8 | 45.8 | 55.15 | 46.62 | 1.183 | 1.059 | 0.799 | 0.962 | 1.107 |
| | | | | | | | | | | | 1.119 | 0.870 | 1.021 | 1.205 |
| Lon-JNB | 23240300 | LJ1 | 24.1 | 26.7 | 26 | 26.0 | 28.1 | 24.37 | 21.99 | 1.108 | 1.027 | 1.096 | 0.950 | 1.027 |
| JNB-Lon | 24250300 | JL1 | 22 | 24.4 | 23.5 | 23.6 | 27.9 | 22.48 | 20.24 | 1.111 | 1.040 | 1.087 | 0.876 | 1.035 |
| Lon-JNB | 02030400 | LJ2 | 24.9 | 27.6 | 26.5 | 26.4 | 26.9 | 24.57 | 22.14 | 1.110 | 1.043 | 1.125 | 1.027 | 1.047 |
| JNB-Lon | 03040400 | JL2 | 21.4 | 23.8 | 23.2 | 22.7 | 27.8 | 21.58 | 19.42 | 1.111 | 1.025 | 1.102 | 0.855 | 1.048 |
| Lon-JNB | 05060400 | LJ3 | 24.7 | 27.4 | 26.5 | 26.4 | 27.3 | 24.31 | 21.91 | 1.110 | 1.032 | 1.126 | 1.002 | 1.036 |
| JNB-Lon | 06070400 | JL3 | 26.2 | 29.3 | 29.5 | 30.0 | 28.6 | 27.00 | 24.14 | 1.118 | 0.993 | 1.085 | 1.025 | 0.977 |
| JNB-Lon | 23240400 | JL4 | 28.3 | 31.7 | 29.5 | 30.1 | 28.7 | 27.79 | 24.80 | 1.121 | 1.075 | 1.141 | 1.105 | 1.053 |
| Lon-JNB | 26270400 | LJ5 | 27.6 | 30.7 | 29.9 | 29.9 | 27.6 | 26.96 | 24.24 | 1.112 | 1.025 | 1.137 | 1.111 | 1.025 |
| | | | | | | | | | | | 1.033 | 1.112 | 0.994 | 1.031 |
| Lon-Tok | 04040400 | LT1 | 47.1 | 55.2 | 46.9 | 46.7 | 55.1 | 58.24 | 49.70 | 1.172 | 1.177 | 0.948 | 1.002 | 1.182 |
| Tok-Lon | 05050400 | TL1 | 62.2 | 74.2 | 61.1 | 61.0 | 62.7 | 75.99 | 63.66 | 1.194 | 1.215 | 0.977 | 1.184 | 1.217 |
| Lon-Tok | 24240400 | LT2 | 53.2 | 63.0 | 53.2 | 53.3 | 55.9 | 65.67 | 55.44 | 1.185 | 1.184 | 0.959 | 1.127 | 1.182 |
| Tok-Lon | 25250400 | TL2 | 58.9 | 70.2 | 59.6 | 59.1 | 63.0 | 74.36 | 62.41 | 1.191 | 1.177 | 0.944 | 1.114 | 1.187 |
| Lon-Tok | 20210700 | LT5 | 43.5 | 51.1 | 46.2 | 46.1 | 53.7 | 59.22 | 50.43 | 1.174 | 1.106 | 0.863 | 0.951 | 1.108 |
| Tok-Lon | 21210700 | TL5 | 46.5 | 55.2 | 48.5 | 48.2 | 52.9 | 63.22 | 53.23 | 1.188 | 1.139 | 0.874 | 1.044 | 1.146 |
| | | | | | | | | | | | 1.166 | 0.927 | 1.070 | 1.170 |

**LEGEND**
<5%
5% - 10%
10% - 20%
20% - 30%
>30%

Table 10. A comparison of the codes used to assess radiation dose, undertaken by NPL. The right hand columns show the ratio of the measured to calculated value, colour-coded (see legend) to flag how close the agreement is – e.g. green text indicates close agreement, red very poor.

| | | Original | Daily | Flight |
|---|---|---|---|---|
| Jo'burg | Mean | 0.9207 | 0.9224 | 0.9242 |
| | SD | 0.0236 | 0.0221 | 0.0218 |
| LA | Mean | 0.9142 | 0.9520 | 0.9493 |
| | SD | 0.0560 | 0.0157 | 0.0185 |
| Tokyo | Mean | 0.9590 | 0.9799 | 0.9807 |
| | SD | 0.0366 | 0.0215 | 0.0211 |
| New York | Mean | 0.9803 | 0.9924 | 0.9918 |
| | SD | 0.0581 | 0.0376 | 0.0417 |
| Hong Kong | Mean | 0.9308 | 0.9474 | 0.9636 |
| | SD | 0.0627 | 0.0437 | 0.0187 |
| Athens | Mean | 1.0642 | 1.0674 | 1.0690 |
| | SD | 0.0536 | 0.0574 | 0.0487 |
| Shanghai | Mean | 0.9725 | 0.9684 | 0.9673 |
| | SD | 0.0205 | 0.0115 | 0.0100 |

| |
|---|
| <2% |
| <4% |
| <6% |
| <8% |
| >8% |

Table 11. A comparison of the dose measured using a Tissue Equivalent Proportional Counter (TEPC) to values calculated using CARI-6 for many flights from London. The different columns show the effect of using values of the Heliocentric Potential calculated on a monthly basis (“Original”), and calculated on a daily basis and just for the duration of the flight; the daily and flight values were calculated using data from the ground-based neutron monitor at Apatity (Russia). In general, the size of the standard deviations is significantly reduced and for many flights the calculated values are in better agreement with the measured dose.

The pros and cons of the models are described in detail in a study carried out for the SOARS project by the UK National Physical Laboratory (NPL) – see Table 10. NPL also examined if the dose can be assessed more accurately if proxies such as the Heliocentric Potential were calculated on a daily basis or for the interval covered by the flight; they found that this improved the quality of the result – see Table 11. The validity of the calculated doses is a cause for concern and the NPL study shows that improvements are possible. However, Lantos (private communication) has argued that the route taken by the flight is the most important factor – the monitoring service used in France is based on this premise.

It is clear that the complexities of handling departures from general levels of solar activity make it difficult for operators to assess the radiation dose without assistance. A centralized service to support this capability would greatly facilitate the assessment of crew exposure. Such a service could determine the "standard" dose for a flight[24], making any adjustments due to solar activity when they are known. If it is considered desirable to automate the logging of crew exposure, the service could then:

- Relate each crewmember to the flights they were on.
- Keep a running log for each crewmember that can be summarised to give a dose quarterly, and for the last 12 months.
- Automatically flagging individual who are exceeding some threshold that could lead to an excess dose over the 12 months – for example, if they come within 10% of two thirds of the annual dose (i.e. ≥3.6 mSv) in the preceding 8 months.

It should be noted that this type of information is (almost certainly) classed as medical data and thereby it comes under Data Protection legislation within the EU. Any service would probably need to hold the records related to crew of each airline - employers should normally be registered to hold health and safety data related to their employees.

To avoid some of these issues, a central service could be used to determine the dose rate for a flight, either using generic dose from a generic flight profile or based on a supplied flight profile, and the records on crewmembers could be maintained locally to the airline. All the doses for each scheduled flight run by the airline can be calculated centrally as a block at the end of each operational day and be available for use. Statistical data on the doses received by the airlines workforce could be passed back to a central database, so long as it did not carry any information that would allow individuals to be identified.

Alternatively, a service might be able to maintain the records so long as the users were only identified by randomly generated ID codes. One option would be to supply files containing all the flights undertaken by a crewmember and calculate the accumulated dose all in one go.

[24] Strictly the dose depends on the actual flight profile (time, route and altitude), but computer codes using a generic flight profile can give surprisingly good results (Taylor, 2005). For intervals of low solar activity, the difference from the dose calculated for the actual profile for a single flight is small in comparison an individual's annual dose.

### 4.4. Monitoring problems that could be attributed to space SWx

Electronics are susceptible to radiation effects, but with good design and the selection of appropriate components many of the effects could be mitigated. Currently there are no requirements to use components in avionics that have low susceptibility to radiation effects, although new advisory standards[25] are now being adopted.

Since trends in electronic components are leading to greater susceptibility, systematically gathering information on any effects that occur would help when designing future avionics systems. However, some effects on electronics are transitory - a unit fails in service but when it is tested on the ground it is fully functional - and these are not usually reported unless the fault reoccurs (VAA, private communication).

During flight operations, aircraft may encounter space weather effects that result in problems with HF communications and satellite communications and navigation. The objective of a space weather service is the forecast these, but it is extremely useful to gather information on effects that have not been forecast to help refine the service. In advance of the service becoming operational, gathering details of effects that are encountered would help quantify the extent of the effects.

In the UK, the Civil Aviation Authority holds this type of information in a database. A search of the database (see Section 3.2.3) yields only a limited number of entries that can be tagged as related to space weather although there are many anecdotal reports in the industry of problems that could result from space weather.

There could be several reasons for this:

- Whether transitory effects in electronics are reported could depend on procedures within an organization. As with most problems of this type (in all walks of life), the normal response is to wait for them to go hard.
- HF communications problems are considered so commonplace (on some routes) that whether they are reported depends on individual crews and procedures within the airline.
- Possibly, reporting problems that are difficult to quantify to a database like that of the CAA is considered to be too big a deal.

The CAA database cannot be accessed externally, nor is it systematically correlated (as far as we can tell) with databases that are assumed to exist in similar organizations. Establishing a Europe-wide reporting procedure under the auspices ESA that was aimed at flushing out these issues would both help refine a space weather service and might also identify any equipment or procedural problems.

It is possible that filing a report to a database within a space weather service that is not connected with any of the regulatory authorities could yield more occurrences of effects than before. In addition, in order to ensure that any service is meeting the needs of its users, it would be desirable to establish a reporting procedure to receive any comments.

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[25] See Technical Specification DD IEC/TS 62396-1:2006 Process management for avionics – Atmospheric radiation effects: "Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment"

# 5. Services Developed by SOARS

Based on requirements derived from user surveys and a review of other relevant material (Section 3), the SOARS project has developed a number of prototype space weather services for the aviation industry.

The services implemented are intended to demonstrate what a full service might look like. Key objectives in creating the services were to establish what is currently possible within the existing global framework, identify where there are deficiencies and determine what is actually necessary and what is desirable.

Within the scope of the project there are limits as to what can be achieved and we rely on material generated elsewhere. A further objective has therefore been to identify any dependencies and how these can be reduced.

We have explored two services:

- A set of demonstration Web pages covering different space weather effects that are intended to illustrate many components of a forecasting service
- A demonstration radiation dose monitoring service

The range of space weather effects that affect the aviation industry is broad in comparison to some sectors, and the impacts are felt around the world and around the clock. Because aviation is a global industry with many airlines operating far-reaching long-haul routes, even though some space weather effects are not pronounced in European airspace of necessity we have had to consider their influence over a geographical area that extends well beyond Europe. However, inevitably some of the comments are more relevant to the industry in Europe.

## 5.1. Demonstration Web Pages

A demonstration set of Web pages that are intended to illustrate many components of the service can be found under URL:

http://www.mssl.ucl.ac.uk/soars.

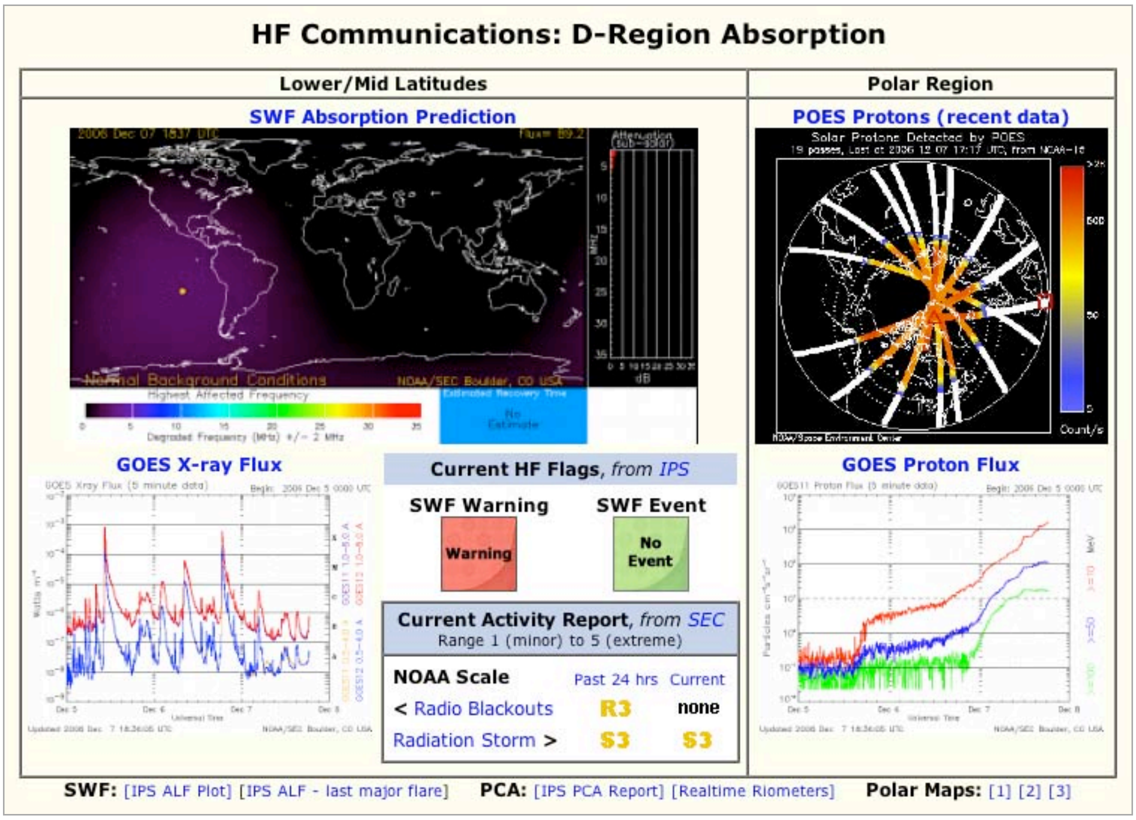
The pages show information gathered from a number of sources. Where possible we have tried to enhance understanding by combining sets of information that should help the user understand a particular phenomenon; we have also tried to re-plotted some data in formats more suited to the needs of the aviation industry. It is difficult to illustrate some effects and we are still looking at other ways of presenting information in ways that makes it easier to understand them. A list of the pages is given in Table 12.

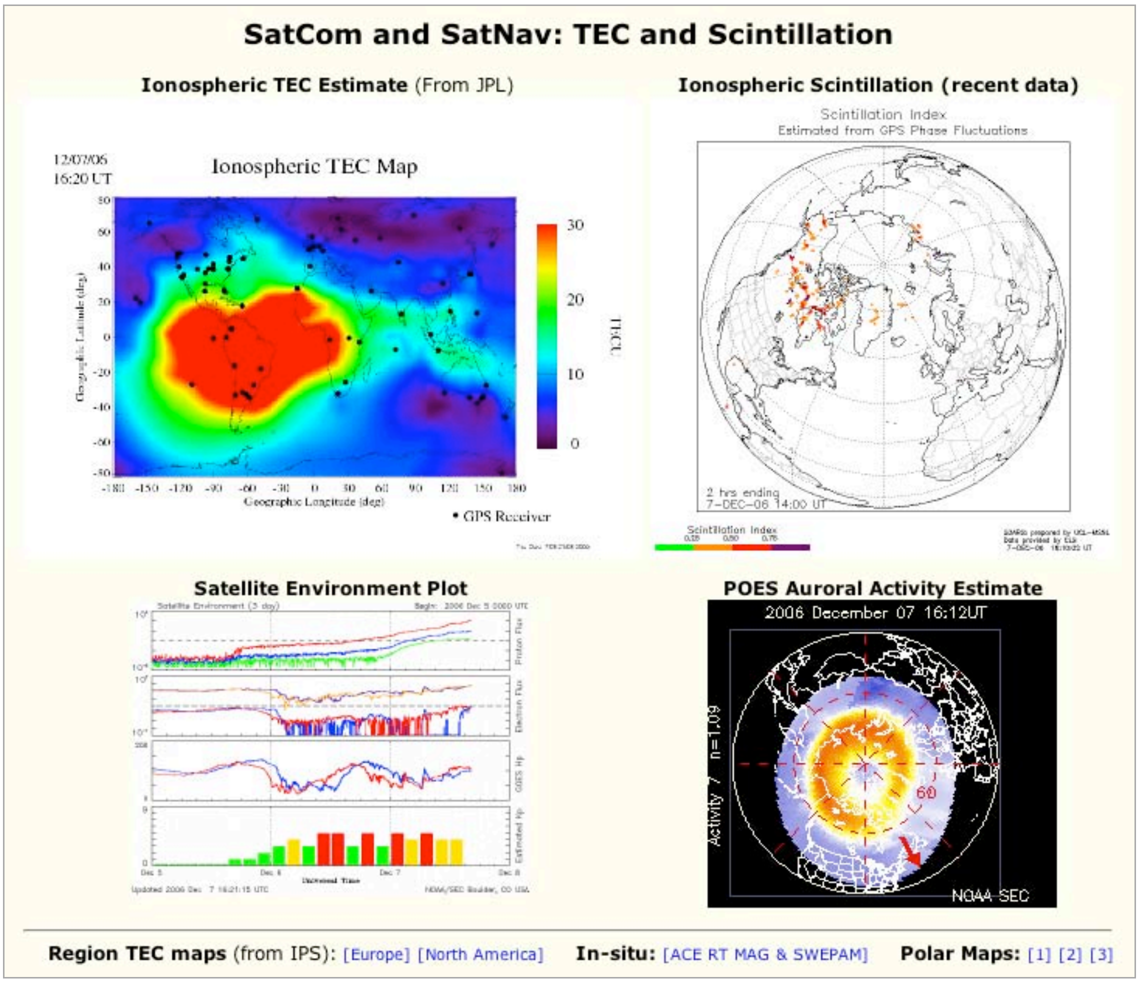
Table 12. List of Web pages created as part of SOARS Demonstration Services

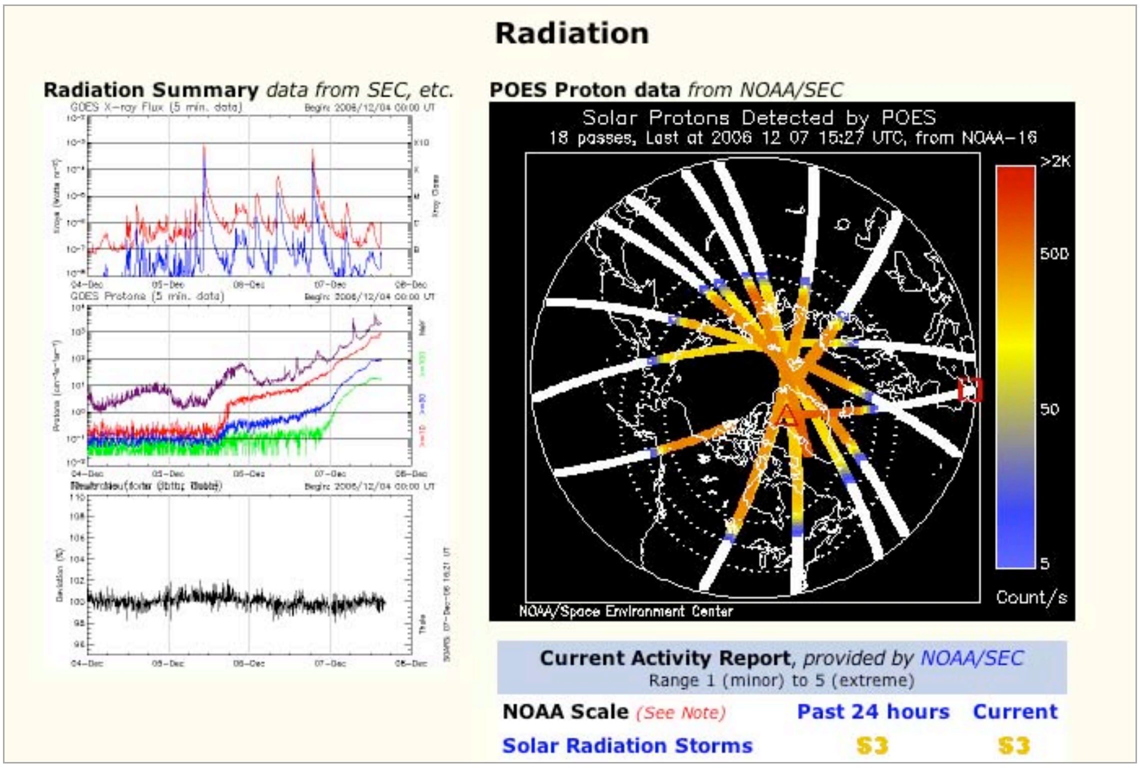
| Page Description(s) | Comments |
|---|---|
| Introduction | Outline of project and acknowledgements |
| Ionospheric D-Region Absorption | Affects on HF Communications at mid/low latitudes due to SWF and at high latitudes due to PCA |
| Ionospheric TEC and Scintillation | Effects on SatCom and SatNav globally and concentrating on the northern hemisphere |
| Cosmic Radiation | Concentrating on the northern hemisphere |
| Space Weather Conditions | Summary page generated by SOARS<br>Flaring Prediction and Reports by Active Region<br>Image data via the SolarMonitor (GSFC) pages |
| Subsidiary pages | 4 pages examining different combinations of data concentrating on the northern hemisphere |
| List of useful links | Various sources used by SOARS and other useful links of relevance |
| Help pages | Prototype help pages explaining space weather phenomena and the purpose/contents of the pages |

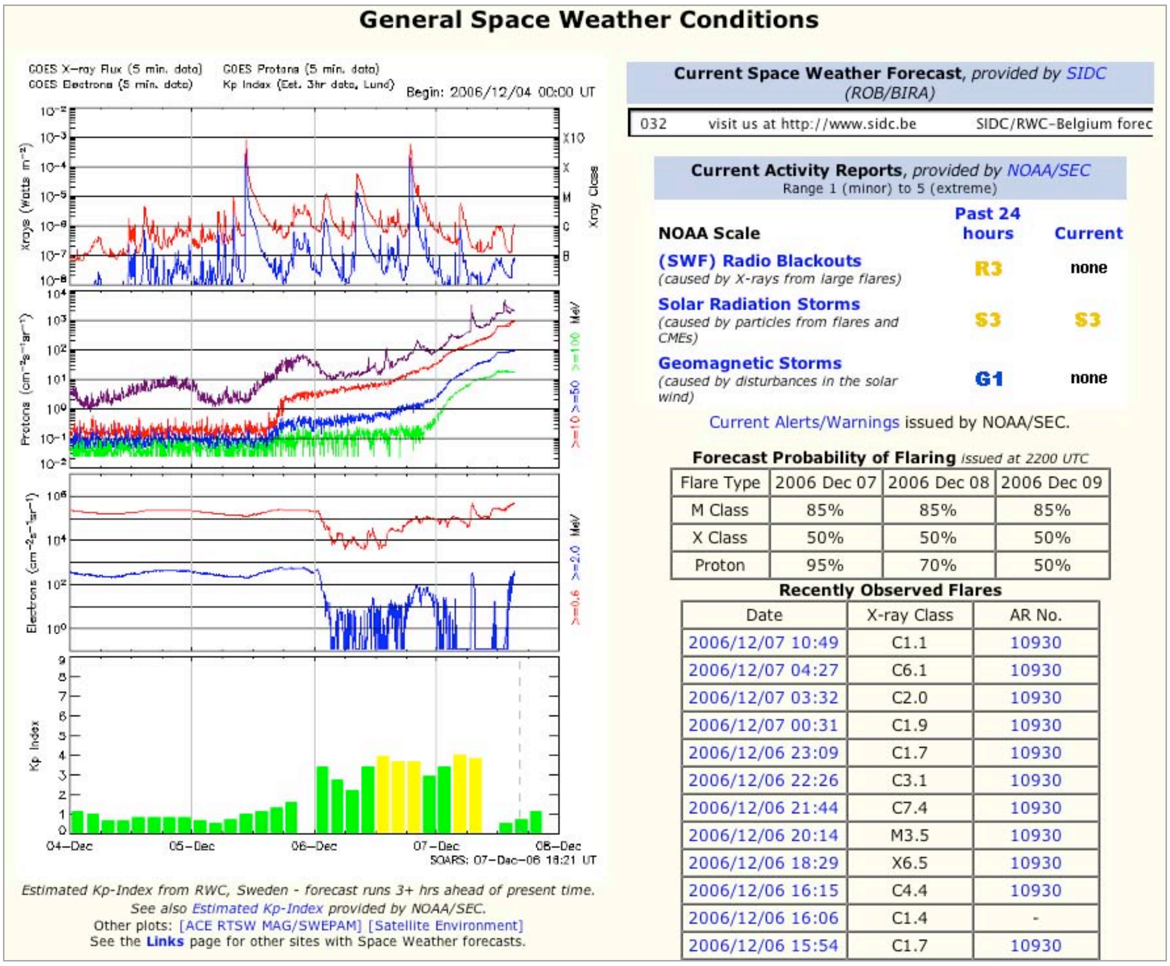
Screen captures of some of the main SOARS Web pages are shown in Figure 9. The first three Web pages are dedicated to the effect of space weather on systems that are important for aviation: HF Communication, Satellite Communications & Navigation, and Radiation; in addition, the fourth is one of two pages that allow a knowledgeable user to review general conditions on the Sun and the near-Earth environment.

Figure 9. The next two pages show screen captures of some of the SOARS Web pages. They show a time interval on 7 December, 2006 when there was intense solar activity resulting in wide-spread space weather effects.


HF Communications: D-Region Absorption
Lower/Mid Latitudes
Polar Region
SWF Absorption Prediction
POES Protons (recent data)
GOES X-ray Flux
Current HF Flags, from IPS
SWF Warning
Warning
SWF Event
No Event
GOES Proton Flux
Current Activity Report, from SEC
Range 1 (minor) to 5 (extreme)
NOAA Scale
Past 24 hrs
Current
< Radio Blackouts
R3
none
Radiation Storm >
S3
S3
SWF: [IPS ALF Plot] [IPS ALF - last major flare]
PCA: [IPS PCA Report] [Realtime Riometers]
Polar Maps: [1] [2] [3]


SatCom and SatNav: TEC and Scintillation
Ionospheric TEC Estimate (From JPL)
Ionospheric Scintillation (recent data)
Ionospheric TEC Map
12/07/06
16:20 UT
Scintillation Index
Estimated from GPS Phase Fluctuations
Satellite Environment Plot
POES Auroral Activity Estimate
2006 December 07 16:12UT
NOAA SEC
Region TEC maps (from IPS): [Europe] [North America]
In-situ: [ACE RT MAG & SWEPAM]
Polar Maps: [1] [2] [3]




Forecast Probability of Flaring *issued at 2200 UTC*

| Flare Type | 2006 Dec 07 | 2006 Dec 08 | 2006 Dec 09 |
|---|---|---|---|
| M Class | 85% | 85% | 85% |
| X Class | 50% | 50% | 50% |
| Proton | 95% | 70% | 50% |

Recently Observed Flares

| Date | X-ray Class | AR No. |
|---|---|---|
| 2006/12/07 10:49 | C1.1 | 10930 |
| 2006/12/07 04:27 | C6.1 | 10930 |
| 2006/12/07 03:32 | C2.0 | 10930 |
| 2006/12/07 00:31 | C1.9 | 10930 |
| 2006/12/06 23:09 | C1.7 | 10930 |
| 2006/12/06 22:26 | C3.1 | 10930 |
| 2006/12/06 21:44 | C7.4 | 10930 |
| 2006/12/06 20:14 | M3.5 | 10930 |
| 2006/12/06 18:29 | X6.5 | 10930 |
| 2006/12/06 16:15 | C4.4 | 10930 |
| 2006/12/06 16:06 | C1.4 | - |
| 2006/12/06 15:54 | C1.7 | 10930 |

### 5.1.1. What the Pages try to Show and Shortfalls

Developing the SOARS Web pages has highlighted many of the problems associated with establishing a space weather service. From a forecasting standpoint, ideally the pages should show what is expected to happen at some time in the future. *Limitations in the science and in monitoring capabilities currently do not permit this and the pages mainly show what is occurring or has recently occurred.*

The following tables (13-15) summarize what the pages show and where there are shortfalls in what can be achieved. The limitations are discussed in more detail in the following sections.

**Table 13. Cosmic Radiation**

| | SOARS is trying to show | Products Used |
|---|---|---|
| **Radiation** | Occurrence and evolution of flares and proton events | X-ray and proton fluxes measured by the GOES spacecraft |
| | Extreme events/phenomena affecting cosmic radiation level<br>*(Ground-level Events)*<br>*(Geo-effective solar particle events; Forbush decreases)* | Neutron data taken by ground-based monitors |
| | Probability that flares and proton events might occur | Activity forecasts provided by NOAA SWPC |
| | Conditions on the solar surface and in the corona<br>*(that could cause flares and SEPs)* | Solar images from various sources sourced through SOHO Ops. Center (GSFC), SolarMonitor, ground-based data, etc |
| | Occurrence and location of proton precipitation in the polar region (northern hemisphere) | POES data |

**Shortfalls:**

- Activity forecasts are only produced by the NOAA SWPC once per day (at ~2200 UT) – the solar magnetic field can evolve on much shorter time scales than this changing the probability of flaring.
- Delays in proton data from POES – consequence of data being gathered in-situ and the orbits of the spacecraft.
- Some monitors on spacecraft (e.g. GOES and ACE) saturate at high fluxes and the true intensity of flares is not known.
- The NOAA SWPC Solar Radiation Storm flag needs to be used with care since it does not apply to biological hazards. The Solar Radiation Alert system (Copeland et al, 2005) is designed to provide this type of warning.

## Table 14. HF Communications

| | SOARS is trying to show | Products Used |
|---|---|---|
| **SWF** | Occurrence and magnitude of solar flares | GOES X-ray light-curve |
| | Prediction of area affected by SWF event | Map of prediction produced by NOAA; link to map produced by IPS showing similar information |
| | Probability that a flare might occur | Activity forecasts provided by NOAA SWPC |
| **PCA** | Occurrence and magnitude SEP events. | GOES proton light-curve |
| | Locations where precipitation of protons has occurred in the polar region (Northern hemisphere) | POES data |
| **Ionospheric Storms** | Location of active regions, filaments, coronal holes, etc *(Regions that could disturb solar wind; lift-off of filaments)* | Images from SOHO-EIT and GOES-SXI, and from ground-based observatories |
| | Occurrence of Earthward directed CMEs | Coronagraph mages from SOHO-LASCO<br>CME Alerts by SIDC |
| | Arrival of CME and crossing of coronal hole boundary | Solar wind parameters measured by ACE *(shows phenomena passing L1 that could cause effect within an hour)* |
| | Location of regions of high TEC | TEC maps from JPL, etc. *(hopefully showing regions affected by storms)* |

**Shortfalls:**

- No prediction of area affected by PCA is currently available – NOAA SWPC has show examples of a service. (Note: Riometer data might show that PCA event is in progress)
- Delays in proton data from POES – consequence of data being gathered in-situ and the orbits of the spacecraft.
- Activity forecasts are only produced by the NOAA SWPC once per day (at ~2200 UT) – the solar magnetic field can evolve on much shorter time scales than this.
- NOAA warning flag for “Radio Blackouts” only shows the occurrence of SWF events.
- Dependence on other sites for some products – e.g. Kp and Dst
- Delays in retrieving data needed to produce TEC maps
- GOES SXI is not working; this is an instrument designed for operations rather than research and should be a better option than SOHO EIT. When both are not available unable to determine site of flare and hence whether events will be geo-effective.

## Table 15. Satellite Communications and Navigation

| | SOARS is trying to show | Products Used |
|---|---|---|
| **Scintillation** | Locations where scintillation has occurred (N. hemisphere) | Maps produced by SOARS from GPS data supplied by CLS |
| | Locations where the precipitation of electrons (and protons) has occurred in the polar region (N. hemisphere) | Maps of along-track measurements by POES spacecraft produced by NOAA |
| | Locations where auroral activity could be occurring (N. hemisphere) *(scintillation occurs in the auroral annulus)* | Maps showing predicted auroral activity produced by NOAA from POES data |
| **TEC** | Total Electron Content in the ionosphere | Map showing global TEC distribution derived from GPS data by JPL; regional maps are available from IPS |
| **General** | Current conditions in the solar wind | Time plots of solar wind parameters measured by ACE;<br>also derived products by IPS summarizing conditions |
| | Probability of geomagnetic disturbances | Extrapolated indices (Kp and Dst) derived from ACE data by RWC Sweden in Lund |

**Shortfalls:**

- The coverage of ground receiving stations that monitor ionospheric conditions is not uniform – there are concentrations in heavily populated areas such as Europe and parts of North America, but only sparse coverage over the oceans, Africa and northern Asia. The consequence is that some occurrences of ionospheric effects (i.e. scintillation and TEC gradients) could be missed. *Note: This is also an issue for the GPS monitoring networks used by CLS and JPL, and for the ionosonde network used by IPS.*
- There are significant delays in gaining access to the GPS data used to show where scintillation is occurring; there also appear to be some systematic problems with how the data are gathered. The delay means that SOARS is only able to produce maps that show where scintillation was occurring 2-3 hours before the current UT. *Note: TEC maps from RAL and IPS can lag those of JPL by an hour or more.*
- Many map products that could be of assistance are of too small an area, or show areas of interest in projections that are hard to interpret.
- For some products – e.g. Kp and Dst – we have a dependence on sites that are producing things on a best efforts basis and which can be subject to outrages.

### 5.1.2. Limitations in the Data

SOARS utilized data from a number of sources, including some that are in the form of space weather products. In trying to generate some of the Web pages, we have encountered difficulties related to data supply and data coverage. In general issues related to data supply can be improved, but those related to data coverage are more difficult to solve.

#### *5.1.2.1. Issued related to data coverage*

These comments relate mainly to the completeness and continuity of data and the cadence of observations.

Maps of the occurrence of scintillation and of total electron content (TEC) are derived from observations gathered from monitoring stations located around the world. Gaps in coverage over the oceans and some continents, coupled with problems with the currency of the observations, mean that the maps are the result of interpolation in both the spatial and temporal domains. This can reflect on the accuracy as well as the currency of the product and the maps are therefore of questionable use for forecasting or now-casting ionospheric effects (scintillation, etc). This problem is illustrated in Figure 10 and Figure 11.

Maps of the regions around the geomagnetic poles showing where protons from solar particle events are precipitating have a different problem. Observations by the POES spacecraft are used to construct the maps, but because the spacecraft only cross the pole every hour or so, the maps are derived from a database built up over several years using data from the most recent crossing as a pointer. The maps therefore represent a model of what might be happening rather that what is actually happening.

Poor spatial or temporal coverage also make it difficult to identify small, rapidly varying or moving features. For instance, X-ray monitors on the GOES spacecraft allow us to detect the occurrence of a flare, but unless appropriate images are also available the location of the flare cannot be determined. Flares located towards the Sun's west limb can be geo-effective but if the location in unknown then whether this might be the case is uncertain. On occasions when all sources of images at appropriate wavelengths are unavailable[26] we are blind as to where activity is occurring.

Another example is regions of storm-enhanced density (SED) in the ionosphere. Although drifting clouds of anomalous electron density can sometimes been seen in movies made after the fact when all the data have been gathered, there are limits of how well these can be monitored in real time away from areas with a high density of monitoring stations. If their occurrence cannot be monitored, the effects of these phenomena cannot be accurately predicted.

Some of the problems related to gathering the data from monitoring stations could be addressed by improving the way the data are returned – JPL appears to have done this with its network of GPS monitoring stations. However, while additional stations could be established to fill some gaps, large areas with sparse coverage would remain. Given the problems it is not clear that in-situ observations of this type are the best way to monitor conditions in the ionosphere.

[26] It is necessary to bake-out the SOHO-EIT instrument at regular intervals to remove contaminants. Unfortunately, the SXI instruments on two GOES spacecraft have failed and during EIT bake-out the alternatives are limited.

Improving the currency of maps derived from satellites passing over the poles would require additional resources. It takes time to build up a picture of what is happening over the pole using the current spacecraft and while a product of this type would be useful to indicate the area affected by an ongoing event, it would probably always be of limited use in forecasting the possible occurrence of an event. Satellites in elliptical orbits designed to "hover" over the pole are probably the solution to this problem.

*There are concerns about the dependence on data used by the space weather community that originate from aging research spacecraft, i.e. SOHO and ACE. The coronagraphs on SOHO and solar wind data from ACE are essential inputs when forecasting effects. However, both spacecraft are past their designed lifetimes and replacement spacecraft are not planned.*

#### 5.1.2.2. Issues related to Data Supply

These comments relate mainly to the availability of data, and the promptness and reliability of access.

Some extremely useful data and products are available from groups that are not funded to provide the quality of service needed to sustain a full space weather service. Many of the sites involved have been established without the system resilience/redundancy that is necessary to ensure that the products are always available. There are many examples, but a site that is used by SOARS is the Regional Weather Centre Sweden in Lund[27].

The Dst and Kp indices generated by Lund from ACE data are used to help forecast ionospheric effects. In part this is because of Lund's association with SWENET but mainly it is because Lund is possibly the only readily accessible source that projects these indices several hours into the future. Projected values are essential if they are to be used in planning flight operations otherwise it is almost impossible to forecast how long effects may continue.

There are also inherent delays when data are sourced through intermediaries. If they have problems or are slow at retrieving data from its source or in identifying events that could trigger further action, this causes delays that tend to cascade. This in turn leads to delays in the ability to issue forecasts.

A data set on the SOARS Web pages that falls into this category is the scintillation data sourced through CLS and re-plotted by the project. The data are gathered from dozens of GPS monitoring sites around the globe; within the first hour as little as 50% of the data may be available from CLS with the rest trickling in later; this compounds the problem of producing a map that is really representative of what is happening. Similar difficulties occur with the TEC maps produced by JPL although they seem to have reduced the time to produce global TEC maps to a greater extent than other sites (e.g. IPS and RAL). It is feasible to gather the required data over smaller areas – for instance within Europe or parts of the US – and this may be adequate for regional forecasting.

[27] On a number of occasions the indices generated by Lund have been unavailable for several days for a variety of reasons. We have also experienced problems with datasets mirrored from CLS (Toulouse, France), the SDAC (NASA-GSFC, US), the SOHO archives (NASA-GSFC, US and ESAC, Spain). Even the NOAA and NGDC sites have occasionally had problems.

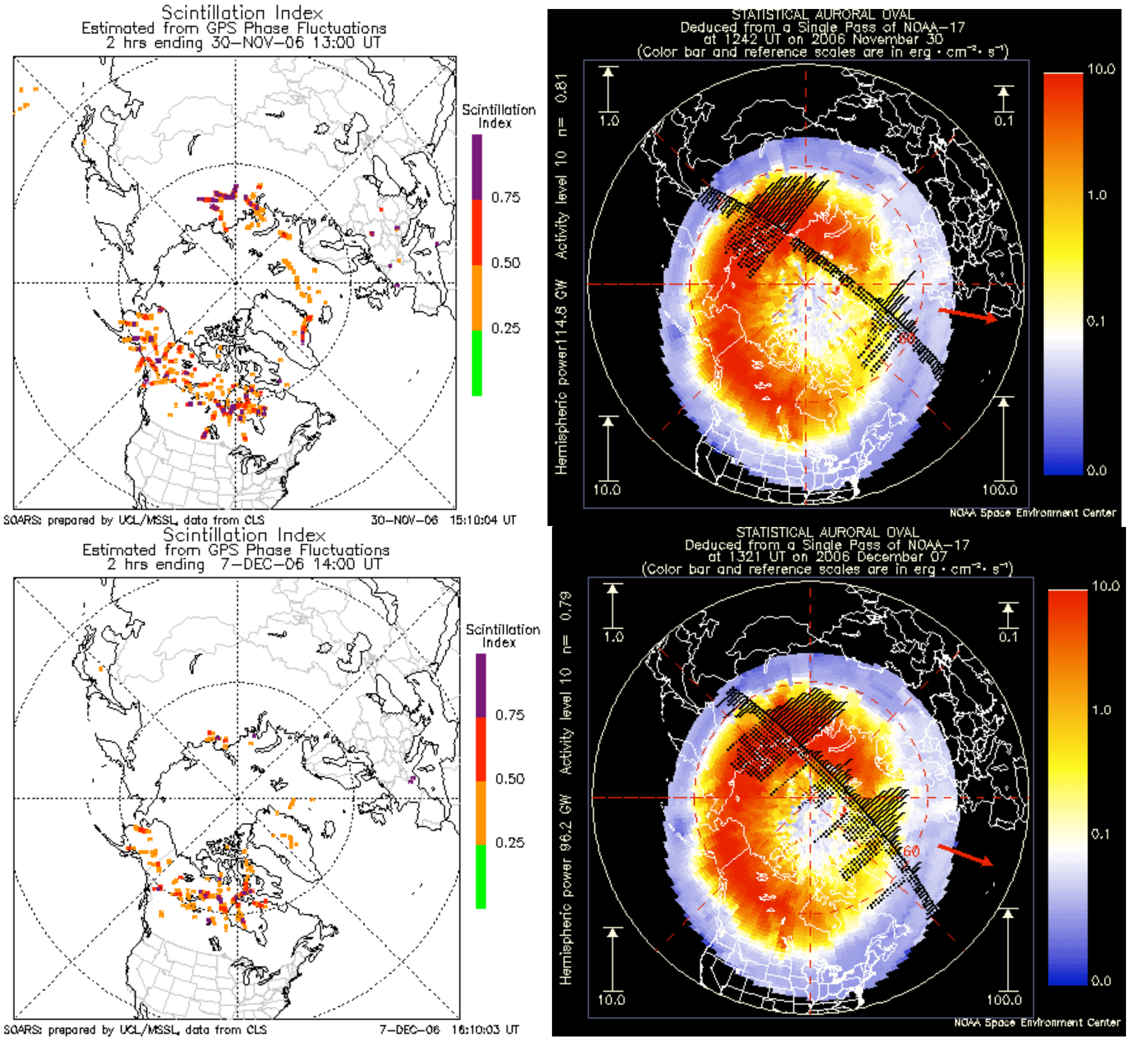



Figure 10. The panels show where scintillation is occurring (left column; derived from GPS data) and where auroral activity is forecast (right column, estimated from POES data); a good correlation is normally seen – except over northern Siberia. Gaps in where scintillation is expected are seen on both dates shown above – 30 November 2006 and 7 December 2006. The reason for this can be seen when comparing the scintillation data with the location of the monitoring stations – see next figure.

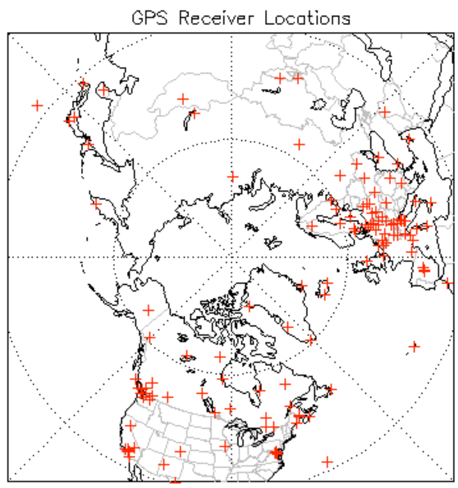



Figure 11. Location of the stations used by CLS to gather GPS data that is used to determine the location of scintillation. The stations are not distributed evenly with significant gaps over the oceans and central and northern Asia; this reduces the ability to provide forecasts for the region traversed by cross-polar routes from the US.

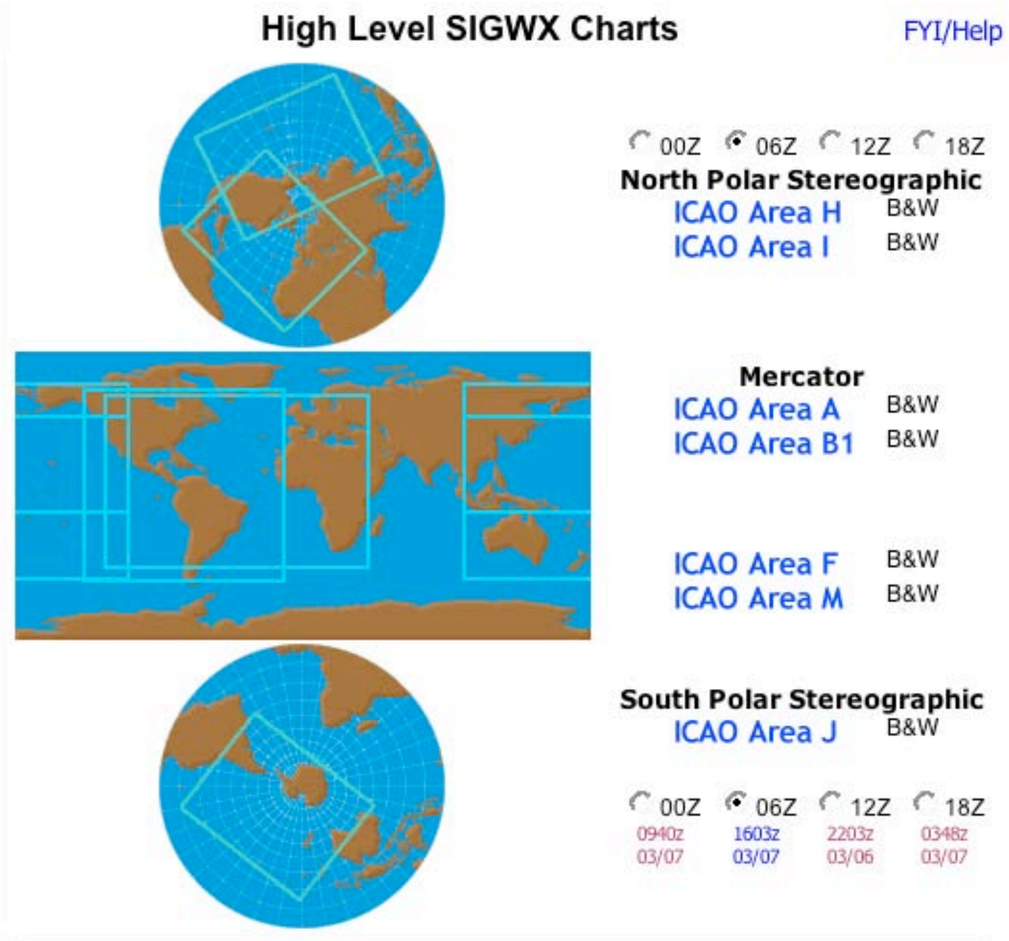



Figure 12. SIGWX regions define by the ICAO (NOAA, National Weather Service)

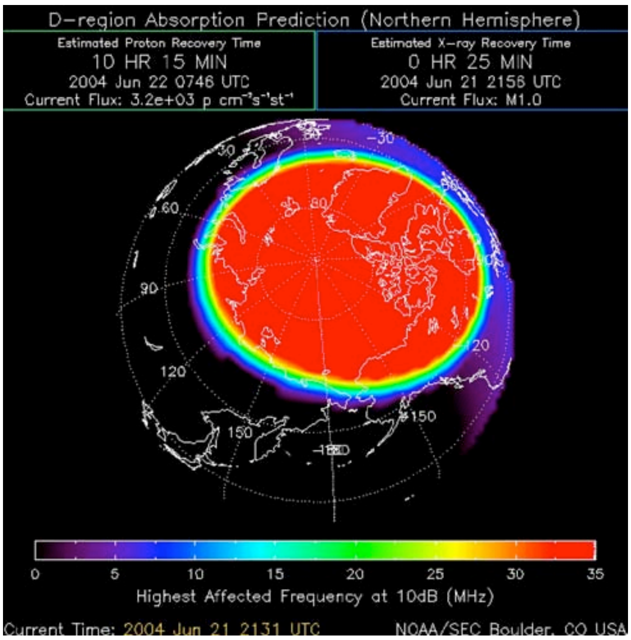



Figure 13. Example of PCA prediction proposed by NOAA SWPC

The frequency of interpretation of observations can be a problem too. It makes sense for some types of interpretation to be done centrally – e.g. the forecasting of solar activity based on observations – while the other interpretation needs to be done regionally – e.g. reduction of observations related to the ionosphere. However, any interpretation needs to be done with a frequency that matches the rate at which a situation can evolve. Thus that the SWPC only produces forecasts of solar activity once per day is insufficient for a forecasting capability that is required 24/7, particularly since significant changes can occur over the space of a few hours. Automated feature recognition systems might alleviate this problem by detecting relevant changes and alerting the forecaster.

Some of the problems related to access to data products could be solved if they were generated at sites funded to provide the required level of service. Improving the access to the raw data may require some restructuring within the community although this is already happening as the quality of network access and equipment improves.

The dependence on other sites could also be reduced if the data were accessed more directly and if any necessary products were generated in-house. There is a case for establishing multiple instances of some primary datasets in order to improve their accessibility; it might also be beneficial to co-locate the datasets and forecasting capabilities. Where derived parameters are important, dependencies on other sites could be reduced if the data were gathered directly and codes to reduce them were run at the point where the pages are being generated. This is perhaps a more cost effective approach and should also reduce delays and thereby improve the quality of forecasts.

#### *5.1.2.3. Some products need to be improved*

The target audience for products is sometimes quite general and often reflects the interests of the funding agencies responsible for the sites. This can limit their suitability for aviation and highlights the lack of a global approach to space weather.

Although some sites do produce products for other regions - for example the Australian Space Weather Agency (IPS) – for many sites map products are centred on continents, or if global have other problems associated with them – see previous section. Ideally, for aviation, maps should cover the same areas as the significant weather (SIGWX) charts defined by the International Civil Aviation Organization (ICAO) – see Figure 12.

If the information is available then replotting maps to the ICAO regions is not a major problem. However, in some cases the necessary observations are not being made and additional measurement sites, etc. would be needed so that the space weather information included on the charts can meet the required standards of reliability.

Several products of NOAA's Space Weather Prediction Center are intended for a general audience and are not ideally suited to aviation. For example, some of the flags produced by NOAA SWPC (see Table 16) should be used with care:

- The Radio Blackout flag only relates to short wave fade (SWF) events that are caused by solar flares at mid and low latitudes. The effects on HF communications of polar cap absorption (PCA) events and ionospheric storms are not represented in the flag.

- The Solar Radiation Storm scale[28] relates to lower energy particles (≥10 MeV) that are important PCA events and for electronics in space, but not for the biological effects on humans in aircraft. For these, the fluxes of particles with energies >100MeV is more relevant – the Solar Radiation Alert (SRA) system (Copeland et al., 2005) more accurately address these risks.

| NOAA Scales Activity | | |
|---|---|---|
| NOAA Scale | Past 24 hours | Current |
| Geomagnetic Storms | G3 | none |
| Solar Radiation Storms | S2 | S1 |
| Radio Blackouts | R4 | R5 |

Table 16. Space Weather Flags produced by NOAA SWPC

There are also some obvious products that are missing – an example is a prediction the occurrence of Polar Cap Absorption events. Given that it is mostly US carriers on cross-polar routes that suffer the consequences of PCA events, this is perhaps surprising. NOAA SWPC has been working on such a PCA product but this has only ever been presented in meetings (see Figure 13) – we hope that it will be available shortly.

### 5.1.3. Limitations in the Science

Limitations in the ability to predict some of the events responsible for space weather effects influences the nature and reliability of information can be included in forecasts and hence their usefulness for operational planning.

Conditions on the Sun can change on timescales that are at odds with those involved in planning and executing flights. While it is possible to provide an estimate of the probability that flares of different types could occur, their exact timing and magnitude cannot be predicted. Active regions can undergo significant changes in less than 6 hours and this could affect the probability of flaring and hence the occurrence of many related space weather effects. As a consequence, long-haul flights could be well underway before it was known that there could be problems.

Effects on the ionosphere are caused by structure in the solar wind or the passage of a coronal mass ejection – these can be forecast to an extent. Because both depend of relatively slow moving features (few hundred to a few thousand kilometres per second), their arrival can be anticipated tens of hours in advance. However, because the velocity of the features is not known accurately, there is an uncertainty in the exact timing of effects. Also, because the orientation of the magnetic field within the CME is unknown, whether it will be geo-effective not certain until it is observed as it passes spacecraft situated at L1[29], less than an hour before it impacts on the Earth's magnetosphere.

For several effects, although it is difficult to predict their onset, once they have started it is possible to provide a reasonable forecast of how long the effect might persist. Forecasting

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[28] A Proton event is defined as when the flux of 10 MeV protons exceeds 10 particles $cm^{-2}\ s^{-1}\ sr^{-1}$.
[29] Lagrange point 1 – a point of gravitation balance between the Sun and the Earth located about 1.5 million km towards the Sun from the Earth.

 

related to ongoing events is therefore more likely to yield results that are useful when planning operations. This means that while it is almost impossible to forecast the start of an intense particle event that could produce enhanced radiation levels, it is possible to provide estimates of how long the levels will persist.

There is a lot of ongoing research aimed at improving our understanding of some of the underlying processes responsible for space weather effects and this is beginning to yield results. However, even if our scientific understanding of the physical processes is improved, there are some basic mismatches between the needs for operational planning in aviation and what could be possible from space weather forecasting. This is discussed in detail in the section on mitigation (see Section 6).

## 5.2. Demonstration Dose Service

Exposure to cosmic radiation is the space weather effect that is often of greatest concern to the aircrews. Following the recommendations of the ICRP, the European Union passed legislation (Euratom Directive CEC/96/29) that requires its airlines to monitor the exposure of their crews to radiation and take steps to ensure that the dose does not exceed 6 mSv annually. Implementation of the Euratom Directive is at the national level and there are differences in the approaches adopted (see Section 3.2.4 and Appendix B).

As an illustration, SOARS established a demonstration radiation dose monitoring service that could be used to assess the exposure of individuals. The service allowed the user to establish an account, define a time interval and select a flight; it used CARI-6 (run in a special Windows-in-Linux environment) to calculate the exposure using either a standard or user specified altitude flight profile and added the results to a database.

In developing the service, we realized that there were several issues:

- SOARS was not in the position to supply the required quality-of-service to operate this service commercially. Nor was it in a position to provide a service that satisfies the requirements of the different countries or go through the process of getting approval by the national radiation protection boards.
- There are issues related to Data Protection, particularly since the dose information can be classed as medical records. If the project keeps such records we have to satisfy security requirements of the Data Protection rules within UCL, the principle institution of the SOARS consortium. While password protection alleviates some concerns about Data Protection, this problem just compounds the issues listed above.

In light of these issues, and because the European airlines have such diverse requirements for monitoring and most already have services in place, we decided that developing dose service into a full service was beyond the scope of the SOARS project. It was therefore decided that resources should be concentrated the on the aspects of the impacts of space weather that are not already covered by the airlines themselves.

An example of a dose service that satisfies the requirements of the Euratom Directive in France is Sievert[30] that was developed in collaboration between French industry and their space weather community. A number of commercial services are also available.

[30] The Sievert site is very well documented and can be found at URL http://www.sievert-system.org/WebMasters/en/

 

### *5.3. Summary*

The services developed by SOARS have allowed us to examine what is needed in order to provide a space weather service for the aviation industry. In creating the services we have established a number of issues that challenge the ability to establish a full service. Given the difficulties and constraints, it is not clear that it is currently possible to create a service that could provide forecasts with levels of confidence acceptable for operational use.

We therefore need to re-examine which space weather effects are really important for the industry – whether any can be ignored, which can be mitigated in some way and which must be dealt with. Since some effects are regional while others are global, we also need to examine how this affects where forecasts, etc. are generated and how the information is used. These issues are discussed in the next Section.

 

# 6. Forecasting and Mitigating Space Weather Effects

In Section 2 we outlined the space weather effects that are relevant to aviation whilst in Sections 3 and 4 we examined at the requirements for a space weather service for the industry and its relationship to aircraft operations. In section 0 we described the prototype services that SOARS had established and how the services exposed the limits of what can be achieved in terms of forecasting.

The limitations mean that it is not possible to provide information about many space weather effects on timescales that are required for operational planning. In this section we examine more closely which space weather effects are truly important to aviation and what risks are associated with them. We also try to determine whether any effects are of little consequence and can be ignored and whether other effects can be mitigated in any way.

Since most space weather effects are driven by events on the Sun, we will first re-examine the solar phenomena related to these effects to determine their frequency of occurrence and current capabilities of forecasting them.

## *6.1. Relevant Solar Phenomena*

### 6.1.1. Flares

**Flares** normally occur in **active regions** and the complexity of the region's magnetic field is closely linked to the rate of flaring.

It is currently not possible to predict when a flare will occur, but it is possible to can give probabilities for flares of different intensities occurring in an active region within the next 24 hours. As an active region approaches the Sun's west limb, the ejecta from flares are more likely to be geo-effective since the particles follow the spiral of the interplanetary magnetic field and are more likely to arrive at the Earth. Flares that produce energetic particles are less common and this more difficult to predict.

In the context of giving prior warning that there could be flares that might affects operations, a space weather forecasting service should include:

- Identification of active regions that could flare and/or produce an energetic particle event
- Prediction of the probability that flares or energetic particle events will occur within the next 6/12/24 hours

### 6.1.2. Coronal Mass Ejections

A **coronal mass ejection** (CME) is a plasma cloud containing a piece of the magnetic structure that has become "detached" from the solar surface. The plasma cloud travels along the spiral of the interplanetary magnetic field and can take several days to reach the Earth depending on its velocity – fast CMEs can arrive in a little as 20 hours although times of 48 to 72 hours are more typical. The strength and orientation of the magnetic field within the cloud determines whether the CME affects the Earth's magnetosphere when it arrives at the Earth. A strong southward field ($B_z$) connects with the Earth's predominantly northward field and causes the greatest magnetic disturbance.

CMEs are usually associated with filament or prominence eruptions and are sometimes related to flares. Often, but not necessarily, the region that produces a CME will be close to an active region or an area where magnetic flux is emerging or submerging. It is only possible make an estimation of the direction and speed of travel of the cloud following CME onset – it is particularly difficult to measure these quantities when the CME is directed towards the Earth. The orientation of the magnetic field can only be determined when the CME passes spacecraft at Lagrange Point 1 (L1, approximately 1 millions miles towards the Sun from the Earth).

Some of the most energetic protons are generated at the shock fronts of fast moving CMEs (Reames, 1999) although the circumstances that determine the velocity of a CME are not clear.

Thus, the forecasting service should include:
- Identification of regions on the solar disk that could produce a CME.
- Prediction of the probability that a CME will occur in the next 6/12/24 hours.
- Prediction of when an Earth-directed CME that is in transit will arrive.

### 6.1.3. Coronal Holes, etc.

**Coronal holes** and **Solar Sector Boundaries** (SSBs) can produce high-speed steam in the solar wind and if magnetically coupled to the Earth (by the interplanetary magnetic field) can affect the magnetosphere and cause geomagnetic storms, etc.

These features are often long lived and they can be observed for several solar rotations (each ~28 days). Since the features are relatively stable in form, their motion across the disk is thereby fairly predictable and the timing of when a boundary will sweep past the Earth can be therefore be forecast. The effects caused by any changes move at the speed of the solar wind will not be felt at the Earth for tens of hours.

Thus, the service forecasting coronal holes and similar features should include:
- Prediction of solar wind properties likely to be associated with a feature
- Prediction of whether a feature will affect the Earth – this will include estimating where the plane of the neutral sheet of the magnetic field is with respect to the Earth.

### 6.1.4. Dependence on the Solar Cycle

To understand how much of an impact space weather effects have, a key question is how often they occur. This depends on the frequency of occurrence of the solar phenomena that cause them.

Approximately every eleven years the level of solar activity peaks. This is known as the **solar cycle** and it is commonly described by indices such as the sunspot number. Sunspots are where concentrated bundles of magnetic flux are breaking through the solar surface and the change in their number is a manifestation of the variation of the level of magnetic activity of the Sun. Since many space weather effects result from the restructuring of the Sun's magnetic field, they are more common at solar maximum; others do not show a strong cycle dependency.

The number of flares and the occurrence rate of CMEs follow the sunspot cycle in phase and amplitude and are considerably higher at solar maximum than at solar minimum. However, *the intensity of the galactic comic ray background is in anti-phase to the solar cycle and peaks at solar minimum*. The difference is because the density of material and strength of the magnetic field in interplanetary space (of solar origin) is greatest at solar maximum, and these act as a shield reducing the cosmic rays flux reaching the Earth.

## 6.2. Radiation Effects

Radiation levels experienced by aircraft vary quite strongly with geomagnetic latitude and altitude. The Earth's magnetic field acts as a shield and reduces the number of particles able to enter the atmosphere; the ability of energetic particles to penetrate the magnetic fields is described by the *geomagnetic cutoff rigidity* (see Figure 14). It is much easier for particles to enter in the polar region where their paths runs parallel to the magnetic field lines than it is at the equator where they are perpendicular – as a consequence, the cosmic ray flux is greater at higher geomagnetic latitudes reaching a plateau at around 60°.

The cosmic ray particles collide with atoms of the atmosphere creating cascades or showers of secondary neutrons and protons that interact with materials they encounter – tissue and the substrate of semiconductor devices are of relevance here. The atmosphere attenuates the particle flux – radiation levels increase with altitude and reach a plateau at 50–60 thousand feet.

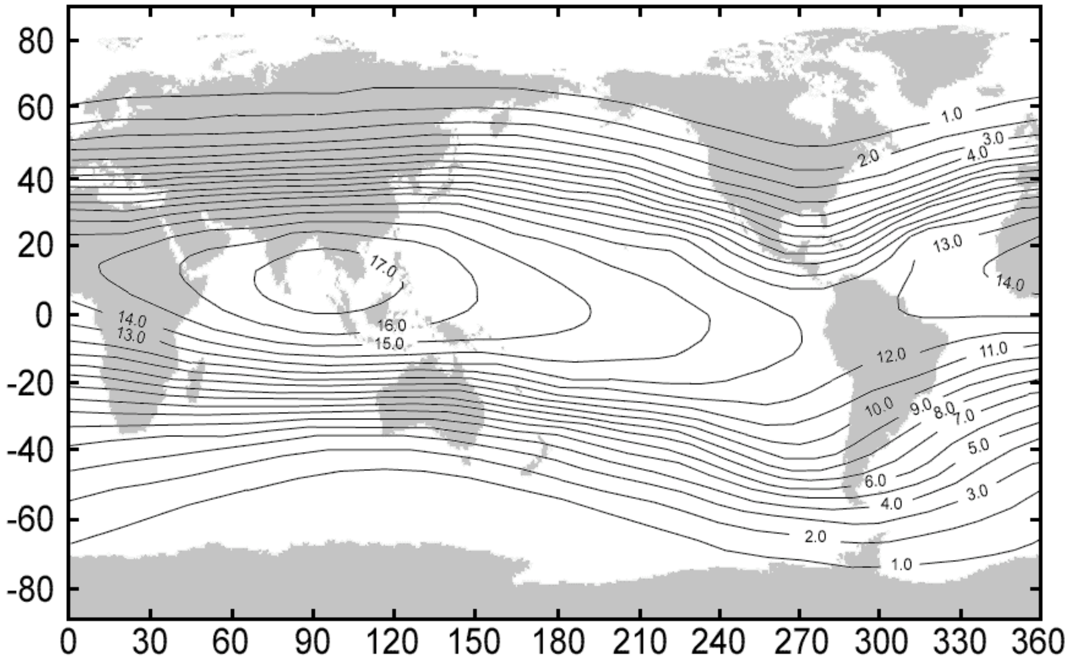


Figure 14. Global geomagnetic cutoff rigidity (in Giga-Volts) plotted against geographic location (Epoch 2000). The higher the cutoff rigidity, the lower the probability that primary particles will hit the atmosphere in order to produce secondary particles at a specific location. Cosmic ray fluxes are therefore lower at low geomagnetic latitudes. (CosmicRays.org)

As discussed earlier, the cosmic radiation has two components: a background flux of Galactic Cosmic Rays (GCR), and short-term increases in Solar Cosmic Rays (SCR).

- The background galactic cosmic ray flux originates from processes occurring far from the Earth.
- Certain types of solar activity produce particles that can an increase the cosmic ray flux for intervals of minutes to hours.

Changes in the Sun's magnetic field associated with the solar cycle modulate the galactic cosmic ray flux – it is greatest at solar minimum. Although it is not possible predicts exactly when flares will occur, or how big they will be, it is possible to give probabilities that flares of different sizes will occur in an active region; events that produce protons are less common and predicting them is thus more difficult. These are known as **Solar Energetic Particle** (SEP) events and they can be caused by proton flares and/or by the shock waves associated with fast CMEs. Severe SEP events that cause increases of radiation at ground level are known as Ground Level Events (GLEs).

The exact circumstances under which some flares produce **energetic particles** is not understood, although Zhou and Zhang (1988) and Chakavorti et al. (1990) list common characteristics of active regions that produce them; Shea and Smart (1990) found that an active region that has produced one solar energetic particle (SEP) event will often produce others. Shea and Smart (2001a) found that the number of SEP events and GLEs per cycle remained remarkably constant over 4 solar cycles; there are an average of 75 SEP events per cycle and 16% of these produce protons with energies >450 MeV that could be observed at ground level. Sudol and Harvey (2005) and Wang (2006) found that changes in the morphology of the magnetic field in an active region effects the number of flares produced by a region. Li at al. (2003) reported that bursts of radio emission are sometimes seen up to 2 days before an event.

Coronal mass ejections (CME) are clouds of material that are ejected from structures in the solar corona. The shock front created as CME drives through the heliosphere can produce protons that add to the radiation levels. Cliver (2006) reported that the bulk of protons in large SEP events are attributed to shock waves driven by fast CMEs. Gopalswamy et al. (2002) found that each SEP event was associated with CMEs that are faster and wider than the average CME.

The plasma cloud of the CME can also cause a decrease in the background GCR flux that may more than compensate for the radiation increase due to the SEP event – this is known as a Forbush Decrease.

### 6.2.1. Biological Hazards

The relatively low levels of galactic cosmic radiation (modulated by the solar cycle) account for the bulk of the radiation exposure on aircraft – this is accumulated whether the Sun is active or not. If a large particle event occurs, producing protons with energies >100 MeV, the levels can increase for intervals that last from minutes to hours and there is an increased potential risk for aircrew. In both cases the dose levels depend on the location and altitude of the aircraft.

Responding to an SEP event in real time is problematic: air traffic concerns make it almost impossible to reduce the flight levels of large numbers of aircraft quickly. Although the highest dose rates associated with a proton event are often relatively short lived and close to the start of the flare, the enhanced levels related to shocks can persist for many hours. Once an event is underway, it is possible to modify the routing for flights scheduled for takeoff or that have just taken off.

When radiation levels are enhanced, the flight profile followed (route and altitude) could make a difference to the exposure levels. Flying at lower altitude will always reduce the exposure, but this is not always possible; an alternative can be to modify the route (slightly). The doses that might be expected are related to the geomagnetic cutoff rigidity – see Figure 14. Close to the geomagnetic poles the levels are constant; around this is a region where the gradient of the cutoff rigidity is quite steep where small change of route can make a lot of difference. For example, flights from Europe to the eastern seaboard of the US, and to the

Far East, would experience lower dose levels if they chose more southerly routes. The issue is made more complex because at time of high geomagnetic activity the Earth's magnetic field can be deformed and the lines of cutoff rigidity can shift in latitude (Belov at al, 2005; Rodger et al., 2006) and enhance the dose (Clucas et al, 2005).

Of course, rerouting is much easier in some areas than in others: routes across the oceanic areas there often quite varied in order to avoid bad weather and make the best use of the jet stream; flights lanes over northern Asia are often quite rigid limiting the options; routes over Africa are also often fixed but since the exposure levels at those latitudes are quite low, this is not a problem. Because of the closeness of the magnetic pole, exposure levels on routes over the northern part of North America will generally be slightly higher than those at similar geographic latitudes in Europe. Flights from the US across the pole (Appendix B) could experience quite high exposure levels and because the routes are fixed the only options would be a lower altitude or diversion via Alaska.

The risks posed to aircrew by exposure to cosmic radiation can be managed through an effective programme of monitoring. The measures adopted by European carriers in response to the Euratom Directive[31] (CEC/96/29) have demonstrated what can be achieved – the systems the airlines have established address most of the concerns of aircrew and are proving to be an excellent way to mitigate this effect.

Exposure levels can be calculated using computer codes such as CARI and EPCARD (Lantos et al., 2003; Shea and Smart, 2001b). A core premise of these programs is that general trends in quantities affecting the cosmic ray flux can be adequately modelled. The codes work well when the Sun is relatively quiet, but how well they handle the enhanced flux caused by intense solar particle events or the effects of deformation of the Earth's magnetic field (Getley at al, 2005) depends on the quality of the information included to describe these events. This is the main cause of uncertainty in calculating the exposure to cosmic radiation and, although the work of some groups – e.g. QinetiQ – has produced more accurate models, the uncertainty with respect to the actual dose levels received on aircraft can only be reduced by permanently installing onboard monitoring equipment.

Calculations show that for a mixed route pattern most crewmembers are unlikely to exceed the 6 mSv annual limit defined by the Euratom Directive; measurements have confirmed this. Since this is the case, even the additional dose caused by modest SEP events may not pose a major problem and could be handled by the procedures already in place. The event would make an above average addition to the aircrews' monthly exposure, and it might be necessary to modify the crew roster for a while, but this can be managed unless the event is extremely large. The situation is much more complex for crews that are dedicated to routes at high geomagnetic latitude – for them, since they will already be working closer to the limit, a very large SEP event could take them over before the end of 12 months. Pregnant aircrew are subject to a different limit[32] under the Euratom Directive and need to be monitored very carefully.

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[31] Based on the recommendations of the International Commission on Radiation Protection (ICRP 90), the European Union implemented the Euratom Directive (CEC/96/29) that required airlines to monitor the exposure of their crews – this came into force in May 2000.

[32] Once the pregnancy is declared, Article 10 of the Euratom Directive requires that employers ensure that the occupational exposure of pregnant air crew to cosmic radiation is keep below 1 mSv for the remainder of the pregnancy (or as low as reasonably achievable).

A number of epidemiological studies have undertaken to try to assess the risks to aircrew associated with exposure to cosmic radiation. Boice at al. (2000) describe earlier studies and found no clear picture with regard to disease patterns although they express concern about the small sample sizes in the studies and point out that other confounding factors associated with air travel complicate the issue. Two more recent studies included tens of thousands of aircrew from several airlines over many years (Bletter et al., 2003; Zeeb et al, 2003) – these report a slightly higher incidence of melanoma, but indicate that environmental issues and lifestyle can complicate the result. Sigurdson and Ron (2004) produced a more extensive review of epidemiological studies, including nearly 20 that had been preformed since the review of Boice et al. In their report, Sigurdson and Ron concluded that there is still not a clear cause-and-effect relationship between risk of any site-specific cancer and employment as a pilot or flight attendant. They highlighted problems caused by differences between the studies due to small samples, different approaches to surrogate exposure level, difficulties in constructing exposure due to non-retention of flight histories, etc., and propose a more rigorous methodology is required for future studies.

The epidemiological studies are therefore far from conclusive and Boice at al. also argue that levels are associated with such low rates of occurrence that epidemiology would be unable to detect them. Clarke (2000) and Boice at al. discuss the risks and found that the presumed increase risk of death from a career dose of 100 mSv over 30 years is approximately 0.5%; Sigurdson and Ron give a higher figure of 1%. This should be compared to an approximate 25% lifetime risk of cancer deaths from all other causes. The conclusion is that the risks appear to be quite low when compared to other risks involved in travelling – for instance driving to the airport – but are by no means insignificant. *The risks seem to be perceived to be much greater than the evidence suggests they should be.*

There some concerns about the validity of the dose limits that have been determined from exposures to a different type of radiation[33] at high dose rates over very short intervals while the exposure to cosmic radiation if at very low levels over very long intervals. However, since the present state of knowledge of the effects of exposure at low dose levels is likely to continue for some time, a conservative approach is probably the most prudent course. The monitoring of exposure levels of aircrew required by the Euratom Directive is intended to achieve this – it ensures that aircrew do not receive excessive doses during the normal course of the work and leaves both the aircrew and airlines in a better position to handle the additional dose that could be caused by solar activity.

### 6.2.2. Effects on Electronics

Electronics are susceptible to single event effects (SEE) cause by energetic particles – these can disrupt memory devices and interrupt processors, etc. Although less of a problem at aircraft altitudes than in low-Earth orbit, the effects cannot be completely eliminated; as new components of ever increasing density are used, their vulnerability increases and it is necessary to revisit the issue regularly. However, the physics of these effects are known and by a careful choice of components and good design of circuits, the effects can be minimized.

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[33] The biological effects of low- and high-LET (linear energy transfer) radiation vary. High-LET exposure causes more biological damage than low-LET mainly because of the higher amount of ionization that occurs in the tissue. Cosmic radiation is largely composed of high-LET radiation, mostly neutrons. The exposure levels have been extrapolated from the effects of nuclear explosions – the radiation from this source is manly low-LET.

Single event upset (SEU) tolerant components include error-correcting memory and triple-mode redundant memory and other components. Although the cost of such components might be slightly higher, when compared to the cost of disruption to service cause by electronics problems, the extra cost may not be unreasonable. Many systems on a modern commercial aircraft already have redundancy built in to ensure system integrity; choosing component that are less vulnerable should be a consideration in the design of these systems and would only require a small shift in the cultural attitudes.

## *6.3. Effects on HF Communications*

Good communications are essential for safe aircraft operation. In controlled airspace, aircraft normally use VHF (30–300 MHz) communications; when outside the range of VHF, aircraft communicate via HF (3–30 MHz) with communications by satellite as a backup. HF is therefore the standard means of communications when the aircraft is on long-haul routes and it is essential for latitudes > 82° where communications using geostationary satellites are impossible.

HF communications depend on (repeated) reflection between the D and F Regions of the ionosphere – this is known as sky-wave propagation. The range of frequencies that propagate is defined by the lowest usable frequency (LUF), defined by the density of the D-Region, and the maximum usable frequency (MUF), defined by the density of the F-Region. The HF propagation window shifts and changes in width depending in ionospheric conditions: medium and long-term variations (depending on time of day, time of year and phase of the solar cycle) can be predicted to an extent; the influence of space weather effects is not so easy to forecast.

Frequency management uses well-established techniques to predict more gradual variations in the propagation window days or even weeks ahead of time – these depend on predicting driving parameters such as the sunspot number, the 10.7 cm solar radio flux, magnetic activity indices, etc. Although general trends can be derived, actual values cannot be predicted with any accuracy, and our knowledge of how they relate to the ionosphere is imprecise; long-term frequency predictions are therefore subject to a fair amount of uncertainty.

Both immediate and delayed space weather effects can affect HF communications. These affect the ionosphere in different ways – this is shown in Figure 15 and described below:

1) **Short Wave Fade (SWF)** and **Polar Cap Absorption (PCA)** events affect the properties of the D-region. Although the causes differ, in both effects the absorption of the D-regions is enhanced making it more difficult for transmissions to pass through. In extreme cases the lowest usable frequency is elevated above the maximum usable frequency and a **radio blackout** occurs.

**SWF events** are cause by X-rays from flares and potentially affect the sun-lit hemisphere, centred at the sub-solar point. In most cases the events are very short lived (tens of minutes) starting shortly after the flare; for larger flares, the effect can last longer (more than an hour) depending on the size of the loop structure involved.

SWF events are difficult to forecast with precision – if flaring is likely then there could be an event. However, although the effects can be wide spread, for most events they only cause a problem if the event occurs at a critical time and in many cases are just an irritation.

 

Communications techniques can be used to mitigate the effects for the most part – these include (VHF) aircraft-to-aircraft relays, the use of digital electronics to repeat standard messages (ACARS), satellite communications, etc. It would also be possible to hold flights on the ground for short interval until the effect has subsided.

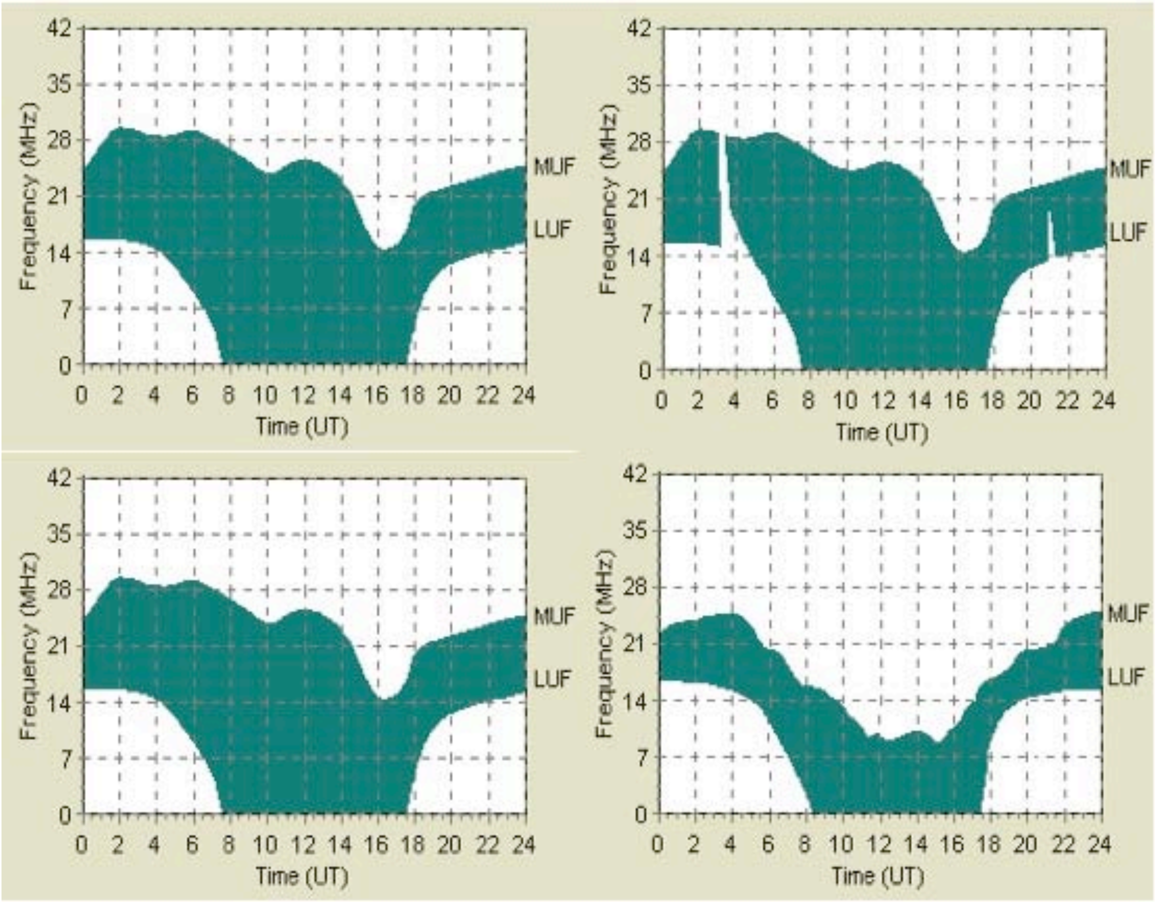


Figure 15. The affects of space weather affects on the HF Communication frequency window. The panels on the *left hand side* are under normal conditions for a site in Australia. The *top right panel* shows the effect of **SWF events**: the LUF becomes elevated and can close the window; recovery start at the higher frequencies. The *bottom right panel* shows the effects of an **ionospheric storm** when the MUF effectively drops allowing the signal to pass.

**PCA events** are cause by energetic protons (15-44 MeV; Kavenagh et al, 2004) and affect a more limited area, being restricted to regions around the geomagnetic poles within the auroral oval – see Figure 16. The events normally last much longer than SWF events and involve some complex chemistry because of the illumination angle that causes the intensity to be greater by a factor of 4-8 in the sunlit part (Perrone at al., 2004).

The protons that cause PCA events originate from certain types of energetic flares and from the shock fronts of CMEs driving through the heliosphere. Since the proton energies needed to produce PCA events are lower than for biological effects, they are more common and longer lasting than that type of event. As described earlier, although forecasting the probability of occurrence of protons events is difficult, the characteristics of solar active regions that are likely to produce them have been determined; once an active region has produced one event it could produce another, although changes in the magnetic structure can affect the flare production of a region.

 

If caused by a flare, the onset of the PCA event is delayed because of the travel time of the particles – this gives a narrow window (tens of minutes, perhaps more) when a warning can be issued. However, the onset occurs on timescales that are quite short compared to flight times and can thereby affect flights that are already en-route. Once an event has started it can persist for days and it can therefore be included in forecasts.

PCA events essentially stop HF propagation (Hunsuckler, 1992) and, because of their extent, there is the potential for severe disruption. There are fewer ways to mitigate the effects of PCA events because of remoteness of their location: satellite communications are almost impossible above 82° except for high-inclination orbit satellites (such as Iridium) that do not give continuous contact, and the number of flights using the routes is far lower limiting aircraft-to-aircraft relays.

There is another absorption effect at high latitudes, Auroral Zone Absorption (AZA). In an **AZA event** the enhanced ionization is caused by particles from the magnetosphere’s tail accelerated toward the Earth during a geomagnetic storm and guided by magnetic field lines into the auroral zone latitudes; these are the same ionizing particles (primarily electrons) that cause the aurora.

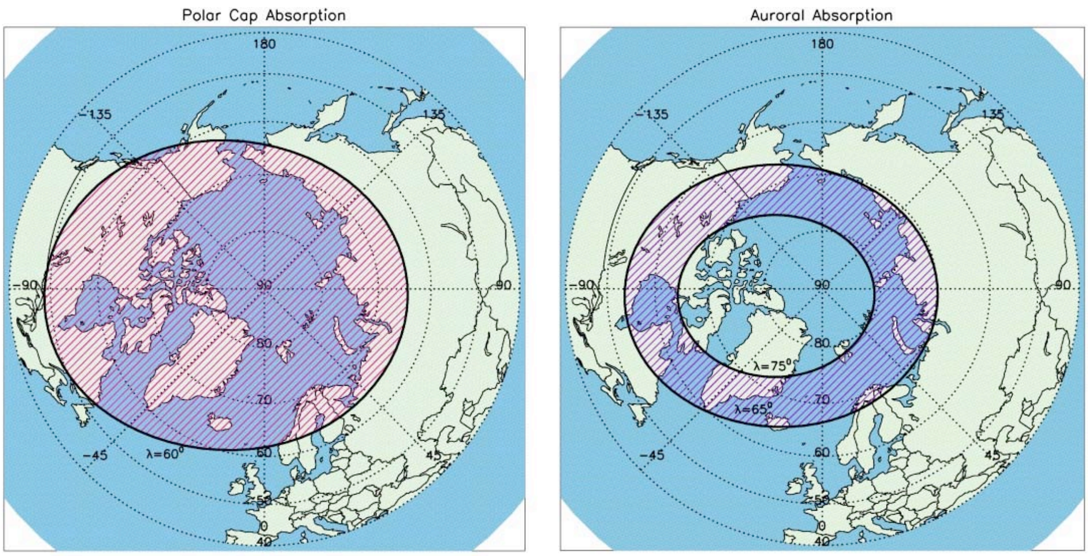


Figure 16. Representation of the regions affected by Polar Cap Absorption (**PCA**) and Auroral Zone Absorption (**AZA**) events. During the day the regions rotate around the geomagnetic pole centred on northern Canada; their size is affected by geomagnetic activity (courtesy of B. Murtagh, NOAA)

The routes most affected are those between the eastern part of North America and South-East Asia that have opened up since the end of the Cold War (see Appendix C); diversions can be lengthy and could require a stopover. Based on Great Circle routes, in the northern hemisphere flights some flights between eastern Europe and the western part of North America could also be affected, as could routes in the southern hemisphere between parts of Australia and South America, and between New Zealand and Africa; whether any of these routes are used depends on demand and whether they actually cross the zones affected could be determined by safety concerns and wind patterns.

2) **Ionospheric Storms** affect the properties of the ionosphere’s F-region; they are the result of altered circulation globally caused by precipitation of energetic electrons into Earth's ionosphere. However the pattern of enhanced and depleted ionospheric density (positive and

 

negative storm effects) varies from storm-to-storm in a complicated way that is not completely understood. Ionospheric storms can affect a wide area – time of day, location and severity of the storm can determine the extent.

Depressions in the density in the F-region of the ionosphere cause major communications problems because radio frequencies that previously had been reflecting off this layer now punch through. The maximum useable frequency can be decreased by a factor of 2 during an ionospheric storm event; storm effects are more pronounced at high latitudes and often last up to 3 days.

Ionospheric storms are usually (but not always) associated with geomagnetic storms. These are produced by disturbances in the solar wind that occur 24–72 hours after a causal solar event (e.g. a CME launch) or in response to the passing of a discontinuity in the solar wind (a sector boundary or high speed stream).

Because plasma follows a spiral path defined by the interplanetary magnetic field, only phenomena occurring west of central meridian on the Sun are able to affect the Earth and cause geomagnetic storms. The time taken for the material to travel to the Earth means that the onset of an effect can be anticipated many hours ahead of time all be it with a degree of uncertainty because velocity structure of the solar wind is not known. Whether a CME will be geo-effective is only known once the orientation of the magnetic field within the plasma cloud can be measured – less than an hour before it hits the Earth's magnetosphere.

Thus, although the effects can last longer, the delay in onset provides a better chance to issue warnings. The effects can be largely mitigated using communications techniques, although some reduction of traffic flow in oceanic airspace may be necessary (c.f. Section 4.1.2)

## 6.4. Effects on Satellite Communications

Communications and navigation using satellites depend on the integrity of signals that pass through the ionosphere; they normally work in the frequency range 3-8 GHz. Signals with frequencies above the ionospheric penetration frequency and up to ~10 GHz are modified by the large- and small-scale variations of electron density in the ionosphere. Ionospheric effects on a propagating signal include scintillation, absorption, variation in the direction of arrival, propagation delay, dispersion, frequency change, and polarization rotation (ITU-R, P.531-4, 1997).

Direct absorption is not usually a problem for the frequencies involved, but refraction and dispersion can be; scintillation can also be a problem, particularly in some regions of the world. Although communications can be affected by space weather, the main effect is on navigation systems.

## 6.5. Effects on Satellite Navigation

Satellite navigation is a specific application of satellite communications and the effects listed above are relevant but with some additional concerns because of the way such systems work. Satellite navigation systems are critically dependent on timing and anything that disturbs signal propagation affects the accuracy of system. The errors that result – perhaps tens of metres – are of little consequence in oceanic airspace but they can be an issue in crowded controlled airspace, particularly in the terminal phase of a flight.

 

Space weather effects on the ionosphere can disrupt propagation in two ways: enhanced electron density can cause signal delays; scintillation can cause receivers to loose lock.

Enhanced **Electron Density** can produce positioning errors due to increased path length (due to refraction or bending of the path) and slowing of the signal; a delay of up to 300 nano-seconds can be introduced resulting in a position error of 100 metres. Electron density along the path is measured by the total electron content (TEC). TEC varies by season, time of day and geomagnetic location. Bulk variations can be modelled to an extent but this gives no information on small variations in electron density or the Electron Density Profile (EDP) along the signal path.

**Refraction** effects can be mitigated using dual-frequency satellite navigation systems. Two frequency receivers can eliminate the ionospheric effects since the two channels suffer different amounts of signal delay for a fixed level of TEC (Goodman 2005, 2006). By measuring the time delay (or phase path) differences between the channels, it is possible to solve for TEC and, using this information, subtract the excess path due to the ionosphere. Unfortunately, two-frequency GPS systems are expensive and the equipment is not in widespread use. A variant on the idea is Differential GPS where site with a known position provides a reference; augmentation systems (see below) use a similar principle.

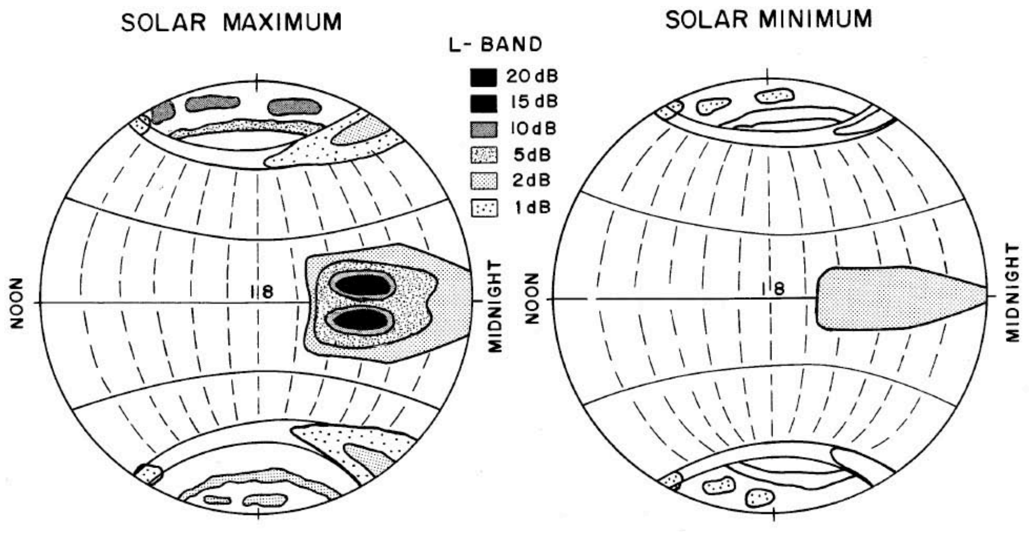


Figure 17. Location of ionospheric scintillation in geomagnetic coordinates (Basu et al., 1988)

**Scintillation** of radio wave signals is the rapid, random variation in signal amplitude, phase and/or polarization caused by turbulence in the form of small-scale structures (cm to hundreds of metres) or irregularities embedded in the large-scale (tens of kilometres) ambient ionosphere. Scintillation occurs most during solar maximum; its effects are most intense in the equatorial region, moderate at high latitudes and least at middle latitudes (Figure 17):

- Low-latitude scintillation generally occurs within ±15° of the magnetic equator, beginning approximately one hour after local sunset and persisting for 4–6 hours. The scintillation is caused by bubbles that form in the bottom of the F region and percolate upwards through the topside ionosphere, emerging just after sunset and distorting into plumes (Gwal et al, 2004; Birsa et al, 2002); it is more intense around the equinoxes, being most intense in spring. Low latitude scintillation is the greatest cause of positional errors; the most intense source of scintillation is around the edges of rod-shaped magnetic-field-aligned bubbles (F-spread) that are formed in the F-layer just after sunset. The thermosphere and the ionosphere seem to internally control the generation of irregularities in the equatorial region with forcing by solar transients as an additional modulating factor; space weather is therefore not a major driving force in this type of scintillation.

- High-latitude scintillation occurs mostly within the auroral belt and persists while particle precipitation is occurring; the effect is especially strong at night. The mechanisms that generate irregularities in the high-latitude ionosphere seem to be driven by magnetospheric processes and scintillations at these latitude is related to solar activity in the form of flares and coronal mass ejections. (Dubey et al.; Groves and Basu)

Within these windows the precise characteristics of the scintillation and associated radio frequency propagation effects vary substantially – forecasting scintillation is heavily dependant on its known association with other phenomena and on scintillation climatology. During ionospheric storms regions of enhanced and depleted ionospheric density (or TEC) form; large TEC gradients around regions of storm enhanced density (SED) can pose particular problems for navigation systems as the location of intense scintillation. For a fast moving aircraft, how patches of scintillation might affect its ability to use satellite navigation can change rapidly, however, it is likely that several satellites will always be in view.

The density structure of the ionosphere can be monitored using GPS signals and ionospheric sounders (ionosondes) – this is often shown as maps of total electron content; the occurrence of scintillation can also be determined by monitoring errors in GPS signals. However, real-time maps produced from these data are inherently poor representations of what is actually happening because of delays in retrieving the data and gaps in the coverage and they do not provide a good tool for forecasting – see Section 5.1.2.

Although it is difficult to predict the exact location and time of formation of regions of SED, it is possible to forecast that such features could occur. Once a feature has formed, its westwards drift is understood and potential outages can be anticipated; its expansion and extension northwards are harder to predict.

Regions of SED have been reported mainly at longitudes in the North American sector. Similar features have been seen over Europe, although less frequently; this is because the tilt of the Earth's magnetic dipole puts most of Europe at a lower geomagnetic latitude (Yizengaw et al, 2006; Groves and Basu, 2002; Basu et al., 2002; Snoeij et al, 2001)

### 6.5.1. Satellite Based Augmentation Systems

Augmentation systems are used to improve the integrity and continuity of satellite navigation systems – they are required for certain applications, particularly safety-critical applications. By examining the signals received from GPS spacecraft, satellite-based augmentation systems (SBAS) such as WAAS (US) and EGNOS (Europe) construct grids of ionospheric corrections that should be applied to the data – these are then made available through spacecraft in geo-synchronous orbits such as Inmarsat.

When the ionosphere is badly disturbed, augmentation system can experience problems; the receiving stations cannot adequately monitor the GPS signals and the grids cannot be calculated. This is partly because the stations have difficulty locking onto the spacecraft, but an insufficient number of monitoring stations can make it difficult to accurately describe the detail of the density structure of the ionosphere; regions of storm enhanced density can cause particular problems.

Plumes of SED that formed over the continental US during intense storms on 29 and 30 October 2003 (NOAA 2004a; NOAA 2004b) were responsible for the outages of WAAS on those days (15 hours on 29 October 29 and 11 hours on 30 October). When they formed around 19:00 UT, the SED features extended from New England (US), across the Great Lakes and into central Canada; they moved westwards over several hours. Skone at al suggest that the problems experienced when calculating the WAAS corrections in October 2003 were caused by difficulties in modelling large spatial gradients in TEC and the sparse coverage by WAAS reference stations (and therefore ionospheric observations) over the northern parts of North America. (Skone et al, 2004; Yizengaw et al, 2005 Yousuf and Skone 2005).

For aviation, augmentation systems are used primarily in the terminal phase of flights – i.e. for take-off and landing. When augmentation systems are not available, precision approaches may not be possible at some airports under adverse conditions. The option in this case would be to divert to an alternate airfield, a response similar to that taken for unexpected severe terrestrial weather.

## *6.6. Summary and Discussion*

When preparing flight plans, if space weather effects are to be included, planners need warning of effects that are in progress or that are expected, and how long any effects last, where they will be felt, and how serious any impact is likely to be. The following timescales, etc. are important:

- When information are needed if they are to be included in flight planning
- The time in advance of onset that forecasts of space weather effects can be made and warnings given, and their validity
- The time taken to detect the onset of a space weather effect and report it
- When and whether it is possible to act on warnings during a flight

As shown in Figure 1, space weather effects are felt on a number of time scales: the effects due to X-rays from flares are almost immediate while those of solar energetic particle (SEP) events are delayed by 20 minutes to several hours; effects caused by "ejected" bulk material (CMEs, solar wind) are delayed 20-72 hours.

For those effects that are immediate in nature it is currently impossible to provide an accurate forecast but they are normally over quite quickly (tens of minutes). However, the delays related to the onset of other types of effects offers a better prospect for forecasts that can be used in operational planning and once started these effects often last for many hours or days. In addition, these effects are normally only associated with activity located towards the west limb of the Sun and it is possible to anticipate when an active region will move into the geo-effective longitude zone.

Looking more closely at the causes of effects:

**Flares:**

- It is not possible to forecast the occurrence of flares exactly, but the probability that flares could occur can be provided. Probabilities are determined from the magnetic structure of the solar active region – this can evolve over hours and days.
- Flare events are usually short lived, except for a few very large events that can last for more than an hour – the effects follow flare onset almost immediate and cease shortly after the end of the flare.
- The principal effect of flares is to HF communications caused by SWF events. For the most part it is possible to mitigate the consequences of this effect.

**Ejected material:**

- The many hours of delay in onset of effects caused by material ejected from the Sun means their occurrence can be anticipated and warnings issued. However, because the exact velocity of the material is unknown, there is an uncertainty in the exact onset time: the velocities of CMEs are hard to determine because they are coming straight at the Earth; the location of the boundaries of high-speed streams in the solar wind associated with coronal holes is also hard to determine, but the effects related to some solar features can recur every solar rotation (27 days).
- Some very complex mechanisms in the Earth's magnetosphere and ionosphere make it difficult to predict exactly where effects will be felt – these include the existing conditions, (local) time of arrival, etc. General probabilities that depend on geomagnetic latitude can be generated, but localized changes in density are hard to predict; there is a significant dependence on geomagnetic activity (i.e. storms).
- The effects caused by ejected material can be widespread, but patchy in intensity; localized density effects are very difficult to predict and hard to monitor. The effects relate to HF communications and to Satellite Communications and Navigation: the effects on HF communications can be mitigated; those on satellite navigation only have real consequences during the terminal phase of a flight.

**SEP events:**

- It is not possible to forecast the occurrence of SEP events exactly but they are far less common than other types of flare. Although the reasons why some flares produce SEP events is not fully understood, statistical studies have identified "typical" characteristics of active regions that produce them making it possible to give a probability of occurrence. Once an active region has produced one SEP event, it is quite likely that it will produce another; some studies have suggested that radio bursts are observed up to two days before an SEP event. Intense SEP events are not always associated with large flares; they are usually associated with fast CMEs.
- The delay in onset of effects means may be possible to flag an event is in progress before it peaks; once it has started, an event last long enough to be included in forecasts (initial pulse?). The Earth's magnetic field has influence on extent of effects due to SEP events and they also some dependence on geomagnetic activity (i.e. storms).
- The main effects caused by SEP events are PCA events (which affect HF communications at high geomagnetic latitudes) and enhanced radiation levels. There are limited means mitigating communications problems because of the remoteness of the region; rerouting may be possible for flights crossing the edges of the region affected (see Appendix C). Knowing that SEP events are unlikely is useful for operational planning.

 

In order to modify flight plans, information on the timing and location of effects is needed. Currently it is difficult to include area warnings on SIGMETs, etc. – apart from SWF events, which are normally too short-lived to be included, almost nothing is provided that forecasts where effects will occur (or reports where it is occurring).

It should be possible to map the expected approximate extent of PCA events, given the proton flux and Kp. Maps of TEC and scintillation are produced by some groups, but these give information very much after the fact. Once effects are in progress the maps can be a useful guide, but delays in recovering the data and gaps in the coverage mean that they cannot accurately describe the dynamic nature of the effects. The westwards drift of long-lived regions of high TEC and of scintillation can be anticipated, once their extent has been mapped.

Because of the difficulties in providing reliable forecasts sufficiently far in advance, as far as possible we should try to mitigate the consequences of space weather effects.

- HF communications techniques can be used to mitigate most SWF events and less intense ionospheric storms. It is harder to mitigate for PCA events but they only affect a few flights – however, for those affected, communications can be impossible.
- Satellite navigation can be affected by scintillation in the annulus of the auroral oval. However, unless the oval has extended because of intense storm conditions, this normally only effects a few flights that are en-route in the high latitudes and conventional (inertial) navigation techniques are adequate. Regions of storm-enhanced density can cause problems with WAAS and the only option may be to divert.
- Scintillation at low latitudes can occurs without space weather effects, but is more intense and more extensive when the effects are also occurring. Navigation and communications can be almost impossible when the effects are intense and mitigation is difficult.

Most of the exposure to cosmic radiation occurs in the absence of space weather effects and an adequate programme of monitoring the exposure of aircrew is essential. SEP events (where the flux above 100 Mev is significant) can cause additions to the normal exposure, but these can be managed through the monitoring programme except for the largest events. During a very large SEP event, or when repeated large events are expected, the conservative approach would be to reroute to lower geomagnetic latitudes.

# 7. Cost Benefit Analysis

For the aviation industry, many of problems associated with space weather (Section 4.2.1) are related to the disruption of en-route operations caused by poor communications; there are also issue related to diversions because of enhanced radiation due to solar energetic particle (SEP) events. In the terminal phase of a flight there are concerns about the degradation of satellite based augmentation systems capabilities requiring diversion to an alternate airport (see Section 4.1.3 and 6.5.1).

All delays and diversions can be extremely expensive: crews and aircraft can end up in the wrong place; extended flight times require extra fuel and can result in crews exceeding their allowed hours and in need of replacement; unplanned diversion may require stopover resulting in layover costs, etc. These can result in significant unplanned and unbudgeted expenditures that make flying more expensive, both for the passengers and for the industry.

Delays are already experienced for a number of reasons: poor visibility and severe weather, air traffic problems and bottlenecks within the air traffic control system (see Section 4.1.2). The delays that are caused by space weather effects can be judged as just an additional reason, but the effects can extend over much greater areas and in some cases can last for days and responding in near real time can be problematic because of the difficulty in anticipating their onset.

Any problems in air traffic management can quickly lead to congestion and cause addition delays. The knock-on effects can last for one or more days and further compound the expense and loss of revenue. Clearly the costs can be reduced if the impacts of space weather can be minimized and normal operations resumed as soon as possible.

Not all diversions can be avoided, but improved traffic management and the appropriate use of terrestrial and space weather information could do a great deal toward reducing their occurrence and cost. The main benefits that good space weather forecasting capabilities could produce are related to:

- Reducing number of unnecessary responses (delays/diversions) due to SWx effects
- Reducing the time that aircraft need to be held waiting for an effect to end
- Minimizing need for diversions (including flying lower) by understanding the severity and extent of effects
- The rapid restoration of normal operations after an event - e.g. air lane flow patterns in oceanic (procedural) airspace

The main issues for space weather forecasting relate to how far in advance warnings can be provided and whether they are reliable enough to be used to plan operations.

- Credible warning can be given for ongoing effects, but the quality of forecasts of effect onset is still limited.
- It is currently not possible to forecast immediate (flare related) effects. Probabilities of flaring can be provided but, unless a region had been very active, this is probably not sufficient for any action to be taken. Even if it was possible to forecast onset, it is difficult to in responding quickly in all but the terminal domain.
- It is possible to forecast the onset of delayed effects due to a coronal mass ejection. Uncertainties in the velocity of the CME and the orientation of the magnetic field

within the plasma cloud mean that the exact timing and severity of the effects are not known, but a credible warning of possible effects during the course of a long-haul flight could be given.

There could be significant benefits in improving warnings about ongoing events and about the onset of delayed effects. Because of the geographical dependence of some effects, the relative importance and impact of each effect varies with location.

## 7.1. Effects and Flight Domains

### 7.1.1. Terminal domain

In the terminal domain most communications are by VHF radio and are mostly unaffected by space weather. However, effects that are anticipated for later in a flight could have an impact.

If flights are held on the ground then this could affect airport capacity. Potentially, there could also be route capacity issues if many aircraft are delayed (at several airports) and all want to take off at the same time when effect ends. In both cases there is the possibility of knock-on delays.

Waiting for the effects of a short wave fade event to subside of would produce a short delay of the order as those experienced for other reasons. For most flares the delay would be far less than an hour and could be less than the time taken to get to the end of the runway.

The effect on satellite based augmentation systems (e.g. WAAS and EGNOS) could be more of a problem. If a precision approach were required the response would be to divert to a nearby airfield that did not have these requirements, with the associated costs of doing this. If a precision departure were required because of poor visibility or difficult terrain, the only choice would be to hold the flight on the ground.

### 7.1.2. En-route domain

HF communications are used in the en-route domain. Poor communications in oceanic areas reduces traffic flow because of need for increased spacing between aircraft; communications blackouts on cross-polar flights make safe operations extremely difficult. Although there are also affects on satellite navigation systems, the consequence are minimal in oceanic airspace and have limited cost impact.

In oceanic areas such as the North Atlantic, reduced flow rates can have serious knock-on effects and cost saving can be realized the sooner normal flow rates can be resumed. There are also potential savings if knowledge of cause and extent of HF communication problems reduces risk of acting inappropriately – i.e. implementing restrictions that are not necessary. Similarly, an understanding of the potential impact an event may permit the use of a wider range of latitudes to increase flow rates.

Polar routes are used to some destinations because they save flying time – this reduces fuel costs and in many cases need for an extra crew (see below). Although there may be many reasons for an airline to want to fly over the poles, it is these regions that are impacted most by solar activity – airlines on polar routes must contend with degraded communications and the potential biological impacts from radiation storms. If communications are degraded at latitudes above 82°, the consequence can be the completely closure of a route since alternate communication techniques (VHF relay or satellite) are probably unavailable. If the effect is ongoing a diversion can be planned and a difficulty arises in that this type of effect can start with almost no warning – for example, while a flight is already en-route.

The communications impacts on cross-Polar routes only affect traffic between the between eastern US and Far East since European carriers currently do not fly at such high latitudes. The principal effect for European carriers on the high latitude routes is the increased radiation dose levels.

## 7.2. Costs Implications

### 7.2.1. Diversions and Delays

Utilizing space weather information either means flying on a different route or lower and/or delaying flights on the ground. The commercial considerations for such actions en-route are the extra fuel burn because of the addition flying time and the possibility of a diversion to refuel. In some cases cargo may be offloaded so that an increased fuel load can be carried – this represent a loss of revenue for the flight.

Flying at a lower altitude can be particularly expensive because of the increased use of fuel at lower, less economical altitudes. Another consideration is possible increased costs due to operating the engines outside of their optimum parameters.

A refuelling stop incurs landing, handling and fuel charges. Flying time for airline pilots is restricted to 16 hours per day; the additional time caused by the diversion or delays on the ground during refuelling may then lead to a minimum 12-hour stopover due to crew duty hour limitations. This would then incur further charges – i.e. accommodation for passengers and crew – as well as severe disruption to the flight schedule with aircraft and crew in the wrong place.

### 7.2.2. Cosmic Radiation

Flights at higher geomagnetic latitudes may be subject to increased radiation levels particularly during times of enhanced solar activity. As already noted, a response in real-time is difficult; there is currently no universally accepted course of action for operational planning.

The FAA issued its first every advisory about radiation during the intense solar activity of October and November 2003 – see the text panel. Since that time it has developed the Solar Radiation Alert (SRA) system based on GOES particle data (Copeland et al, 2005). The SRA uses a wide range of particle energies and is more appropriate for aviation than the NOAA Solar Radiation Storm scales; Copeland (private communication) reports that since 1986 36 alerts and/or continuations would have been issued for 27 Solar Particle Events and that all the alerts would have been the associated with GLEs or S4 (NOAA space weather scale) level events.

The airlines are not required to take action over a radiation advisory from the FAA, but the suggested response is to fly at a lower altitude in areas north and south of 35° geomagnetic latitude (c.f. Figure 4); European carriers did not respond in this way in 2003 and do not currently use this type of product. Clearly there are large cost implications for those that do respond because of the additional fuel requirements. If all airlines in the zones indicated by the FAA were to respond to an alert, there would be severe disruption as and the air traffic flow management struggled to cope.

 

The European carriers undertake a continuous assessment of radiation exposure, a procedure that is not carried out by US carriers – see the discussion in other sections of this report. The relative merits of the EU and US approaches has not been studied, but there must be concerns in the US about the cost of *unnecessarily diverting flights* because of concerns over radiation when the actual effects on the crew are not known because they are not properly assessed. A study by Lantos and Fuller (2003) suggests that the rerouting of flights by United (in 2000), Continental (in April 2001) and NorthWest Airlines were needless in terms of radiation doses and incurred reported costs were $100,000 and delays of up to 5.5 hours.

The *costs of managing the exposure are relatively low* and it provides a solid base on which to respond to unusual events. The additions to annual dose limits for all but the largest radiation events can be relatively small but could be significant to aircrew that are dedicated to high-dose routes. Knowing the accumulated exposure of individual crew members allows airlines to adjust rosters to ensure annual limits are not exceeded – if done properly this could *reduce the need for additional crew* and hence provide a cost saving.

Managing the dose is also good for *industrial relations*. It is difficult to place a monetary value on this but it is clear that many US aircrew are extremely concerned about the issue – see aircrew presentations at several NOAA Space Weather Week conferences.

Note that routes from Europe to East Coast of the US more or less the parallel contours of rigidity cutoff (Figure 14) and even a small diversion to the south can significantly reduce exposure levels – at minimal cost.

**Halloween Storms, 2003 (NOAA Service Assessment)**

The October-November 2003 solar storms created a significant disruption to airline operations, and though difficult to accurately assess, the dollar cost was likely in the millions.

On October 19, following the X1 (R3) flare, Air Traffic Centres reported moderate-to-severe impacts on all HF groups and HF service was degraded for over two hours. In response, a major carrier rerouted three polar flights from Polar Route 3 to Polar Route 4 (cf Figure 3), which is more desirable for data-link and SatCom. This required an additional 26,600 pounds of fuel and resulted in over 16,500 pounds of cargo being denied.

More impacts to airline operations were reported on October 24 following the onset of a G3 (strong) geomagnetic storm. Solar radiation remained at background levels, but high latitude communications were severely degraded due to the geomagnetic storm.

All commercial aviation interests were made aware of the radiation storm levels on October 28-29, when the FAA issued their first ever advisory suggesting that flights travelling north and south of 35° latitude were subject to excessive radiation doses (cf Figure 4). Two US airlines were using cross-polar routes at the time – both took action to limit radiation exposure to passengers and crew. (Note: European airlines did not fly at lower altitudes during this radiation storm.)

Polar flights were rerouted during this period – for example, between October 24 and 31 one major airline rerouted six polar flights to non-polar routes requiring fuel stops in Japan and/or Anchorage.

### 7.2.3. The End of the Cold War

It is not always possible to fly the most direct route between two locations and Cold War placed many restrictions on the aviation industry. Anchorage was a common stopover[34] for passengers flying to East Asia from the 1960s to the late 1980s because aircraft from the US, Asia, and Western Europe could not fly over Soviet airspace, and because they did not have the range that modern aircraft have.

From around 1990, flights from Europe to SE Asia started to fly over northern Siberia instead of via Anchorage – the saving in flight times were substantial. For example, a flight from London to Tokyo via Anchorage used to take around 18 hours of flight time, plus an hour or more on the ground for refuelling; the direct route takes 12-13 hours (depending on the direction).

Direct flights from the US to SE Asia started later; the first flights were 2000 and for the next 3 years there were around 800 flights per year. Since 2004 the number of flights has started to increase year-on-year with 2053 in 2004, 3731 in 2005 and 5308 in 2006 (ICAO A36-WP/114, 2007). One of the reasons for the increase in traffic was a bilateral air service agreement signed between the US and China in June 2004 that the US Department of Transport estimated would be provide $12 billion in additional revenue for US carriers over seven years (Murtagh, 2005).

Airlines using polar routes benefit from additional passenger revenue, while producing significant savings on fuel and crew costs. Typical time and cost savings for a polar flight from New York to Singapore is 209 minutes and $44,000 (2003 prices[35]); similarly, a flight from Boston to Hong Kong saves 138 minutes and $33,000.

The typical flight duration for a polar route from a North American destination to Asia is over 15 hours. If the flight must divert for any reason, an additional stop-off is required. This results in considerable time loss, additional fuel, and the added time will require a whole new crew. The average cost of this kind of diversion is approximately $100,000.

The consequences of the changes following the end of the Cold War are interesting with respect to space weather. Not only are the flight times from Europe to SE Asia significantly reduced, the routes are much less prone to space weather effects – the new route crosses at much lower geographic latitudes, and even lower geomagnetic latitudes. As a result, the European carries are far less likely to be affected by PCA events; radiation dose levels are also lower that for the indirect flights.

Conversely, flights from the Eastern US to Asia now have much greater problems as a result of space weather effects than before. The direct routes are almost all cross at latitudes greater than 82° (geographic) and, because Magnetic Pole is located over northern Canada, they cannot avoid crossing the zones most likely to be affected by PCA events and higher radiation levels.

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[34] Today, many cargo carriers continue to use Anchorage and a few passenger aircraft still stop at Anchorage on flights between Asia and the eastern United States.

[35] Given the rapid increases in oil prices in 2007/2008 these costs are now probably much higher.

### 7.2.4. Future Developments

Currently there are very few flights from the Nordic countries to the West Coast of North America – in part this is because of their relatively low populations. Also, to date there are no flights from the new accession countries of the EU on the most eastern side of Europe, but this may change as their economies grow.

In both cases, the most direct route for flight would take them across higher latitudes than flights from Western Europe. Except for destinations like Vancouver, these tend to be at lower latitudes and a small shift southwards would avoid most of the problems due to high-latitude HF absorption effects and enhanced radiation. Similar shifts are already made because of the path of the Jet Stream, although a shift to avoid space weather effects may result in more adverse terrestrial weather conditions and higher fuel use.

If the routes over Russian and Chinese airspace were to close, the routes over and through Anchorage would again become important. Even with the increased range of modern aircraft, refuelling stops would be required for some destinations, particularly on flights from Europe. Although space weather affects relatively few flights across this area at the moment, given the combined volumes of traffic to Asia from the US and Europe, such a change could produce major air traffic management problems and the large increases in cost.

Future aircraft may fly at higher altitudes but may also be more direct and faster. A comparison of the relative doses experienced by Concorde and conventional aircraft suggests that these advances may not significantly affect these conclusions.

## *7.3. Summary*

The impacts of space weather effects on aviation can be costly particularly if unplanned diversions are required. To minimize the costs, it is extremely important that any space weather warnings that are issued are valid and every effort should made to ensure that the end times of effects are determined as soon and as accurately as possible.

The US is particularly challenged with respect to space weather. Because the geomagnetic pole is located over northern Canada high geomagnetic latitude effects are felt further south (geographically) than in other parts of the world. Also, the most direct routes to many of the US's developing markets lie directly across the regions most affected. In comparison, since the end of the Cold War, Europe has a much simpler environment to deal with.

 

# 8. The Essential Services

There are many space weather effects relevant to aviation. The impact of some effects can be severe, but others may be of little or no consequence. In some cases an effect is short-lived and only affects the dayside of the Earth; others can persist for days and cause widespread disruption. The relevance of an effect also shows a significant dependence on an observer's location in relation to the Earth's magnetic poles.

We have examined many of the existing space weather forecasting products and explored their deficiencies (Section 5). Limitations in the science and the data mean that it is not possible to do some of the things that are desirable; in some cases, it may never be possible to do this. The cost benefit analysis (Section 7) indicates that the commercial implication of effects varies depending on the route system an airline operates with those flying across the pole being most affected. Our study suggests that the impact of some effects can be mitigated (Section 6) and that adopting this approach wherever possible reduces the impact in many cases.

Within the scope of the SOARS project it has not been feasible to develop a full space weather service and we are not in the position to solve the science and data problems that exist. However, a closer look at the issues shows that not all elements of an ideal service are totally necessary and we are able to make observations and recommendations on where the greatest benefit from services can be returned.

There are difficulties in responding to space weather effects in real-time en-route it therefore makes sense to take steps to mitigate effects to lessen their impact in case you get caught out. But while it is difficult to forecast the onset of many effects on the required timescales, it is possible to incorporate a response in operational planning for the continuation and end of ongoing events.

There are clearly cost saving if the airlines only need to respond when it is really necessary and if normal operations are resumed as soon as possible when they have taken steps. We therefore suggest that it is important to concentrate on these aspects of forecasting.

## *8.1. Observations and Modelling*

Any forecasting depends on an adequate supply of the appropriate data; for some data modelling is required in order to combine many individual observations.

Activity on the Sun is responsible for most space weather effects and ensuring a flow of good quality solar observations is essential. It is possible to make observations of the Sun from the ground but these cannot be relied on because of the difficulty in making a continuous set of observations then providing access. Space-based observations from Lagrange Point 1, or from geo-stationary orbit provide the required solar observations but some types of data are now at risk because of the age of the spacecraft currently used.

Obtaining observations of the ionosphere can be problematic. Although there are worldwide networks that gather data from GPS ground stations and from ionosondes, there are gaps in the coverage over the oceans and regions with low populations and it takes time for the data to be returned. This compromises the ionospheric modelling – the models work quite well at the Equator, but are less satisfactory at the poles. This is partly because of difference in underlying causes of the effects: at the equator many ionospheric effects are driven by atmospheric phenomena and time of day while those at higher latitudes tend to be driven by external stimuli – i.e. space weather phenomena.

The onset of some ionospheric effects can sometimes be anticipated from proxies – e.g. in-situ solar wind data from ACE – but this technique only predicts that an effect will probably happen without any real indication of location. Whether remote-sensed images could be used to improve our real-time knowledge of the ionosphere is discussed later in this section. Magnetospheric observations also suffer from sparse grids of monitoring points and whether remote-sensed images could be used is discussed as well.

From a data security standpoint, there should be multiple archives of the basic data that are needed. Ideally there should also be multiple sources for the data – i.e. more than one set of observing stations and spacecraft.

It is important that the necessary steps are taken to secure these data sources in the future – particularly key data sets from spacecraft. Adapting experimental instruments for applications satellites – as was done for the GOES-SXI instrument – is the best way to do this and the route followed by NOAA. There appear to be no equivalent possibilities within the European space programme.

## 8.2. Space Weather Forecasting

The airlines need the relevant space weather information presented in a form that they can use with minimum interpretation. Here we address where and how this should be achieved.

There have been a number of calls for a one-stop website of space weather information – a site that provides everything that is needed. In a recent presentation to the Cross-Polar Air Traffic Management Working Group, Murtagh (2007) of NOAA SWPC indicated that the International Space Environment Service (ISES) site[36] would host this although so far it does not carry any forecast information.

There are significant regional variations in the occurrence of space weather effects and our study suggests that a single site could prove difficult to use. On the SOARS Web pages we have experimented with combinations of different data to determine which are easiest to interpret. We have found that trying to combine too much information onto a page can be confusing; we have also found that the products of some existing resources are too general in the way they present the data.

We believe that for some effects these data need to be presented "regionally". This could be done through a number of sites with the a shared responsibility for providing appropriate information, but a common site structure – each would only carry information pertinent to a particular region. It would also be possible to have a single site divided into regional areas but given the different interests involved, and the need to have reliable access to the site, this may not work so well.

Such a regional approach is analogous with the way terrestrial forecasting works and there is a basis on which to build – the Regional Warning Centres already established by the ISES. Providing a service on a regions basis would also facilitate cooperation with other interested

[36] See URL: http://www.ises-spaceweather.org

 

bodies; in the case of North America, NAV CANADA and other air traffic agencies and the relevant aviation weather agencies should be involved.

A centre covering North America would therefore have the responsibility of providing information about ionospheric effects in the (northern) polar region. The displays would show the occurrence of D-region absorption due PCA and AZA events, but possibly not SWF events, and the display would be formatted as map projections relevant to flight planning operational tools for that region.

At the 60th Session of the Executive Council of the World Meteorological Organization[37] in June 2008, the inclusion of space weather in the remit of the WMO was discussed; a report was presented on the “Potential Role of WMO in Relation to Space Weather” (WMO-1, 2008). It was agreed (WMO-2, 2008) that "the experience of WMO in coordinating global operational observation and communication networks, its key role in organizing warning and alert systems, and its active links with operational user communities are expected to help space weather transitioning from research to operations". Although there are still some issues to be resolved related to funding, this should lead to the international coordination of space weather activities that is badly needed.

## 8.3. Solar Forecasting

Good quality solar observations are key to providing advanced warning of events. These need to be interpreted regularly since activity on the Sun can evolve significantly on timescales comparable to the duration of some long-haul flights. The skills needed for solar forecasting are different to space weather and it is possible to centralize the capability.

To ensure resilience in a solar forecasting service, there needs to be a minimum of two centres, preferably at least three; each should have its own archive of relevant data. To share the burden, it would be reasonable for these to be spread around the time zones: the US, Europe and Australia or Japan is one possibility. It would also seem logical that the centres should be associated with support of the International Space Stations (ISS) since there is definitely a shared interest in underlying space weather phenomena and a need for continuous support; this would imply a service jointly with the agencies involved, i.e. ESA (Europe), NASA (US), RKA (Russia) and JAXA (Japan).

## 8.4. Cosmic Radiation

The effect of cosmic radiation on aviation is really a problem in several parts that are related to the effects on biological and electrical systems. It is reasonable to assume that there should not be any immediate response related to effects of radiation on electronics and that everything regarding this effect is covered by mitigation, i.e. careful choice of components, redundant systems, etc. This leaves the biological effects.

The biological effects need to be considered in two parts:

- A slowly varying component caused by the Galactic Cosmic Rays (GCR)
- The contribution of cosmic rays from sporadic solar events (SCR)

In the absence of any solar activity there is still a substantial exposure due to galactic cosmic radiation. This in fact forms the bulk of the exposure that aircrew experience for the majority of the time.

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[37] http://www.hydrometeoindustry.org/Reports2008/Report_WMO_60th_ExecutiveCouncil2008.htm

Within the European Union, the requirement on airlines to monitor the exposure of aircrew to cosmic radiation is covered by the Euratom Directive (CEC/96/29). The Directive is implemented at the national level and requirements for a service differ from country to country; this makes it difficult to provide a centralized dose service. However, this way of accomplishing the monitoring suggested by ICRP 60 is a good model for a global approach to the problem of cosmic radiation.

With an effective program of monitoring, coupled with appropriate action by the airlines with regard to crew rosters, aircrew worldwide should be confident that under normal conditions their annual radiation exposure would not exceed international dose limits. Such a system also provides a good base on which to manage the less predictable component caused by solar activity. *It is therefore strongly recommended that all countries adopt a monitoring program similar to that of the European Union.*

The contribution due to solar activity is a more difficult issue. Forecasting can only provide probabilities that flares will occur and a response in real-time to an impulsive SEP event causes problems for air traffic management. However, in most cases it is probably possible to provide warnings about a gradual SEP event before it reaches it maximum count levels – if the CME velocity, etc. can be determined, it may also be possible to warn that hazardous proton energy levels are expected.

The space weather service contribution to this would be:

- Flag any impulsive SEP events – determine whether or not they of biological concern
- Warn of possible onset of gradual SEP events – determine velocity of CME, assess density within solar wind, etc.
- Warn of any ongoing gradual SEP events
- Help finalize additions to the proxies used to represent variations in the cosmic ray flux in the computer models

In addition, it is important that the Solar Radiation Alert system is validated and made more widely available.

## 8.5. Future Instrumentation

There are limitations in monitoring capabilities that seriously reduce the ability to provide forecasts of space weather events that are relevant to aviation. These include:

- A perspective from close to the Earth-Sun line makes it difficult to measure the velocity of an Earth-directed CME and reduced the accuracy of forecasts.
- The conditions in the solar wind are unknown until they are sampled as phenomena pass the Lagrange point L1. Spacecraft located there provide advance warning of how the Earth's magnetosphere might be affected – at best this is only an hour before onset of space weather effects.
- The sparse grid of monitoring stations for the ionosphere and magnetosphere make it difficult to build an accurate picture of how any activity is evolving

There are also concerns that space weather forecasting capabilities are heavily dependant on observations made by two spacecraft – SOHO and ACE. The spacecraft are located at L1, were primarily designed as research spacecraft and are now past their planned operational lifetimes. Currently they are the only source of continuous observations of key parameters.

In the light of the need to replace the two spacecraft, and in consideration of limitations that exist and capabilities that are desired, in this section we examine the types of instruments that are needed and the locations that observations can be made from in order to determine which combination would provide the most useful data.

In 1999, ESA awarded two parallel contracts[38] to consortia led by Rutherford Appleton Laboratories (RAL; UK) and Alcatel Space (France) that performed wide-ranging analyses of the need for a European space weather programme and the possible content of such a programme. The reports considered all types of instrumentation, both ground- and space-based, including dedicated payload and ones piggybacked on other missions. The remarks in this section are more focused on aviation than either of the studies, but both provide alternate ideas to those presented here.

Spacecraft in geostationary orbit provide a good platform for continuous remote-sensed observations but it is not possible to make the required in-situ measurements of the solar wind because of the constantly changing aspect of the spacecraft to the Earth-Sun line. Spacecraft in low and medium Earth orbits cannot provide continuous observations because they are eclipsed by the Earth and can only provide in-situ observations of the inner regions of the magnetosphere. The L1 point is a good location because continuous observations of all types are possible and because in-situ measurements of the solar wind provide a warning of what will happen in the Earth's environment in the near future (less than a hour ahead).

There are other stable orbits that could be considered as useful locations for observatories; two other Lagrange points L4 and L5 could provide an interesting viewpoint since they are located away from the Earth-Sun line. The locations of all the Lagrange points are shown in Figure 18 – L4 and L5 are located 60° ahead and behind the Earth at 1 AU.

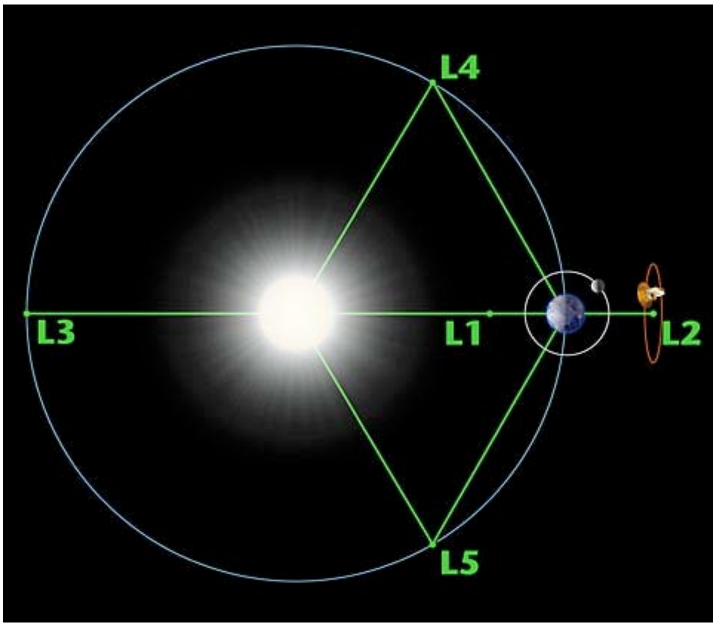


Figure 18. Locations of the Lagrange Points.

[38] See http://www.esa-spaceweather.net/spweather/esa_initiatives/ and follow the links under the section on "Space Weather Programme Feasibility Studies".

An assessment of the quality of observations at the different location is provided in Table 17 – the scale is from 0 (worst) to 5 (best). Instrumentation placed away from the Earth-Sun line could address many of the limitations listed above. The pros and cons of different instruments on possible payloads of spacecraft located at L4 and L5 are discussed below and summarized in Table 18.

| | LEO/MEO | GEO | L1 | L5 | L4 |
|---|---|---|---|---|---|
| Flares, SEP events | 3 | 5 | 5 | 2 | 5 |
| Active Region evolution | 4 | 5 | 5 | 5 | 3 |
| CME lift-off (geo-effective) | 3 | 3 | 3 | 5 | 3 |
| CME passage (geo-effective) | 2 | 2 | 2 | 5 | 5 |
| In-situ data (geo-effective) | 0 | 0 | 5 | 0 | 0 |
| AR evolution before regions on disk | 1 | 1 | 1 | 5 | 0 |
| Advance information on in-situ conditions | 0 | 0 | 0 | 5 | 0 |

Table 17. Assessment of the quality of SWx observables relevant to aviation from various locations.

| Instrument | L5 | L4 |
|---|---|---|
| Coronagraph and/or instrument similar to STEREO/COR | Good view of Earth-directed CME during lift-off and in transit | Poor view of Earth-directed CME during lift-off; reasonable view during transit |
| EUV/SXR imager (similar to GOES-SXI)<br><br>Magnetograph and white light imager | Evolution of active region<br><br>*View-point gives warning of "new" activity 4–5 days before crossing onto disk.*<br>*View is cut off as active region approaches west limb* | Evolution of active region |
| In-situ solar wind monitor *(plasma density, velocity and temperature, and magnetic field)* | Measure properties of solar wind<br><br>*View-point gives 4–5 days warning of structure of solar wind before features sweep past the Earth* | Measure properties of solar wind |
| Magnetospheric Imager | Provides overview of the activity in Earth's magnetosphere | Provides overview of the activity in Earth's magnetosphere |
| Ionospheric Imager | Provides overview of the activity in Earth's ionosphere | Provides overview of the activity in Earth's ionosphere |

Table 18. Summary of capabilities of proposed instrument for observatories at L4 and L5

There are several advantages to placing a spacecraft at L5:

- It provides advance warning of the evolution of active regions many days (4-5) before they rotate onto the disk as view from Earth; this would improve the ability to forecast probability of flaring. However, the longitudes towards the west limb (as seen from Earth) are not visible from this location.
- From L5, observations of the lift-off and transit of CMEs that are directed at the Earth are almost perpendicular to plane-of-the-sky, giving a much better perspective than is possible from near to the Earth-Sun line. Measurements of the CME's velocity and calculations of its arrival time would consequently be more accurate.
- Located at L5, the spacecraft is trailing the Earth and given the direction of rotation of the Sun this means that it is in section of solar structure that will sweep past the Earth 4-5 days later (cf. Figure 2). For structure that is rooted in relatively stable features like coronal holes, etc. this would provide a much better capability to forecast possible affects on the magnetosphere and ionosphere.
- The remote views of the magnetosphere and ionosphere[39] would provide a much more complete picture of what is happening than the sparse sampling grids currently available. A spacecraft at L5 could be part of network providing such images; examples of what has been achieved by near-Earth mission are shown in Figure 19.

A spacecraft at L4 could also provide interesting observations, but these would be less useful for forecasting:

- While the view of active region evolution is not of great value for forecasting in itself, when combined with the information from the spacecraft located at L5 the two perspectives provide coverage of approximately 5/6ths of whole solar sphere.
- Because L4 is ~60° ahead of the Earth-Sun line, it is almost overhead the lift-off point of any Earth-directed CME. As such it provides poor quality information about the lift-off but a reasonable view once the CME is a certain distance from the Sun.
- The remote views of the magnetosphere and ionosphere would provide a much more complete picture of what is happening than the sparse sampling grids currently available. The instrument provides a view on the opposite side to the L5 spacecraft.
- Any in-situ measurements are of no use for forecasting but are of scientific interest.

From L4 and L5 it is possible to obtain a good view of the side the Earth, a reasonable (overlapping) view of the sunward face and a poor view of the poles, but it is not possible to observe the night side of the Earth; placing similar imagers on a spacecraft at L2 (see Figure 18) would solve this problem. Obtaining a better view of poles is extremely difficult from spacecraft in the plane of the Ecliptic and a spacecraft in a polar orbit might be the best solution – this option is discussed in the ESA Feasibility Studies.

While detector resolution is probably not an issue, whether there would be enough flux to operate magnetospheric and ionospheric imagers from the distance of L4/ L5[40] needs to be determined. The distance of the spacecraft from the Earth at L4/L5 would also present some limitations on downlink capabilities, but since the orbits are stable and the locations are

[39] The IMAGE spacecraft provided images of the magnetosphere; it is hoped that instruments on the TWINS spacecraft will provide an even better magnetospheric imaging capability. PIXIE instrument on the Polar spacecraft provided images of the ionosphere.
[40] The distance of the L4 and L5 points from the Earth is the same as the Earth from the Sun.

 

fixed in relation to the Earth, many problems would be much simpler to solve than for missions like Solar Orbiter.

A spacecraft placed L5 would provide the most useful information for space weather forecasting although soft X-ray or EUV images from close to the Earth-Sun line (or L4) would also be needed. If it were decided that remote views of the magnetosphere and ionosphere were needed, a combination of several spacecraft would be required.

The possibility of using L5 was mentioned in ESA study led by RAL, but was not covered in detail. More recently, the idea has been floated in Japan (Akioka et al, 2005) as concept for a future mission. It should be noted that the STEREO mission provides an opportunity to test out these proposals; the two spacecraft STEREO-A and STEREO-B ("ahead" and "behind" respectively) will be at locations equivalent to L4 and L5 about 3 years into the mission.

*Even if a spacecraft is not developed for deployment at L5, it is essential that the monitoring capabilities provided by SOHO and ACE are maintained and therefore that spacecraft carrying similar instruments be deployed at L1.*

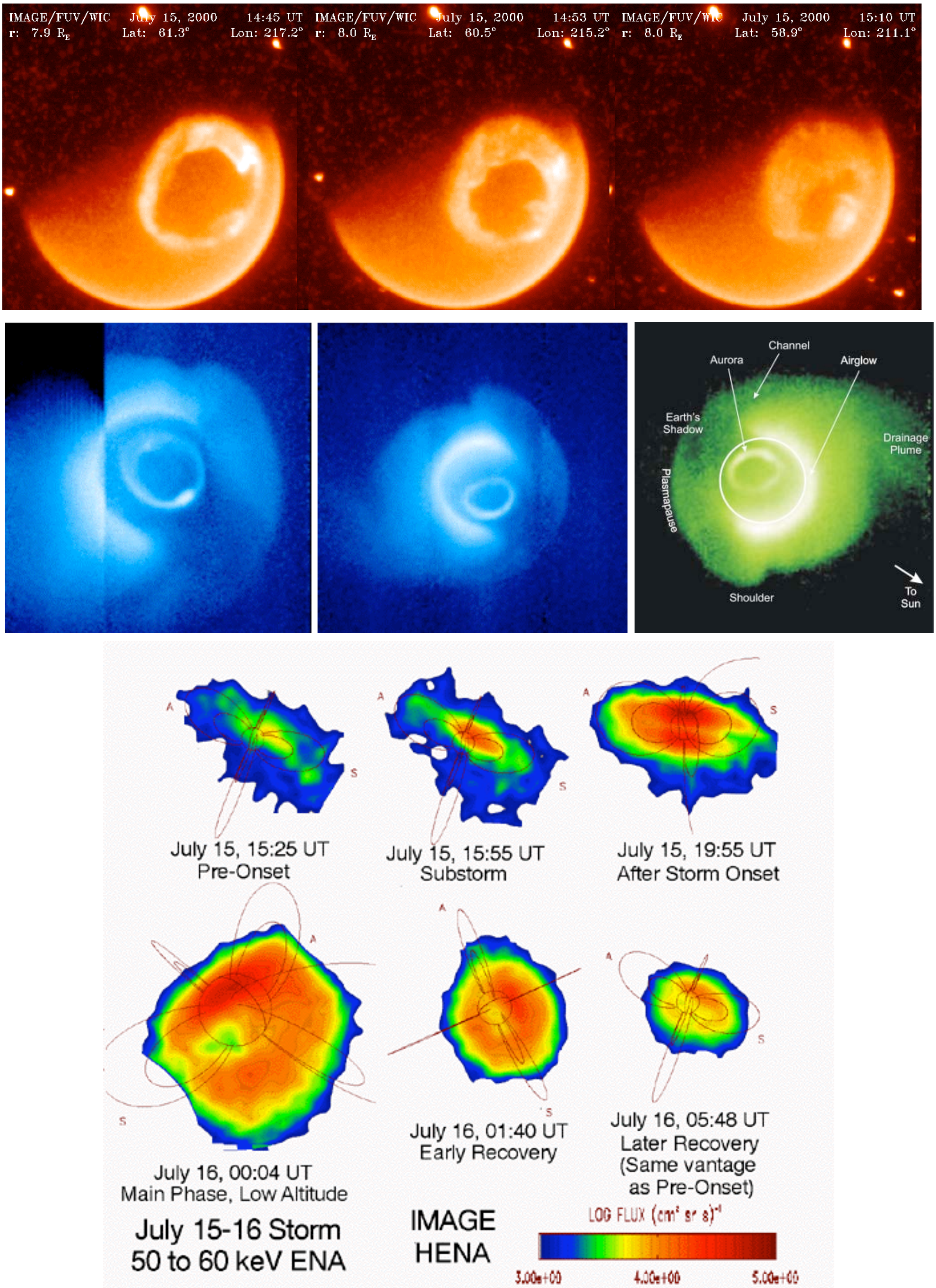


Figure 19. Data from NASA's IMAGE mission illustrating the sort of overview that is currently possible. Top row: images from the Wideband Imaging Camera of the FUV Imager showing the aurora during a storm on 15 July 2000; middle row: the Earth's plasmasphere viewed by the EUV Imager; bottom row: the inner magnetosphere shown on images from the High-Energy Neutral Atom (HENA) Imager of the storm on 15-16 July 2000.

# 9. Summary and Conclusions

The SOARS project has created prototype space weather services for the aviation industry. The capabilities of the services have been limited by what is possible within scope of the project, but they address the main elements of what is required and have allowed us to examine the issues involved. We have detailed where the services are deficient and how these issues could be addressed. We have also described what a full service might entail and discussed how necessary different parts of it are.

It is clear that there are limitations in the science and data that restrict the ability to provide forecasts on the timescales needed by the aviation industry. While many issues related to data coverage and supply could be alleviated by a coordinated global effort, we find that there are fundamental difficulties in mapping the occurrence and extent of some effects. It is not clear whether the science will ever support forecasts as far in advance as the industry would like; predicting the many space weather effects is problematic, but there is more scope for providing forecasts for duration and the intensity of ongoing events.

Since the ability to provide forecasts and warnings is limited, and possibly always will be, we have examined the effects in detail and investigated how they can be mitigated. This has allowed us to understand which effects have the greatest impact on flight operations and how this affects the requirements form a space weather service. We have found that there is a strong dependence on location – which effects are important, and therefore which services are necessary, depends on where an airline is based and the routes it operates.

Whether a global approach to forecasting for aviation is needed is therefore not straightforward and the problem is compounded by the speed at which aircraft can move from one location to another. A few services could be centralized, but most effects caused by the influence of space weather on the ionosphere need to be handled regionally. Exposure to cosmic radiation can be managed by the airlines using monitoring procedures of the type employed in the Europe Union since 2001.

In general, space weather forecasting should be closely linked to the existing aviation weather services. Coordination between national programmes supports global terrestrial weather forecasting and a similar approach could used to sustain space weather forecasting; the process of defining the standards that are needed to facilitate the supply and exchange of information has already started.

A few specialist centres around the world should provide a forecasting service for solar activity; the centres could also quantify the variation in radiation levels caused by solar activity and provide the proxy information required by dose estimation codes. Since they share some common interests, there is some logic in incorporating the centres with the forecasting needs of ESA and NASA with respect to the International Space Station and other manned space flight.

Presenting space weather information in a way that can be easily understood by non-specialists is difficult and we continue to try to find better ways of doing so.

# 10. Acknowledgements

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- QinetiQ Ltd.
- UK National Physical Laboratory (NPL)
- UK Met Office
- Virgin Atlantic Airways (VAA)

ESYS Ltd conducted the survey of user requirements based on information provided by Bryn Jones and Bob Bentley; they also helped in the analysis of the survey. The results of the survey are given in Section 3.1.1 and Appendix A.1. Particular thanks go to Maria Sega, and Andy Shaw of ESYS.

Graeme Taylor of the UK National Physical Laboratory conducted a review of the computer models used to calculate the exposure to cosmic radiation; this material has been folded into Section 6.2.1. Graeme Taylor also contributes to the survey of compliance to the Euratom Directive (Sections 4.3.1 and Appendix B)

Within the Project, QinetiQ Ltd extended their work on the QinetiQ Atmospheric Radiation Model (QARM); they also provided information on the effects of cosmic radiation on electronics. QARM a comprehensive atmospheric radiation model constructed using Monte Carlo simulations of particle transport through the atmosphere; it uses atmospheric response matrices containing the response of the atmosphere to incident particles on the upper atmosphere; we believe that QARM produces a better result than many other computer models. Information related to the work on QARM is folded into Section 6.2.1 and is also available as a separate report; the input related to electronics is folded into Section 6.2.2. Particular thanks go to Simon Clucas and Clive Dyer.

Bob Lunnon, manager of the Aviation group in the Research and Development section of the UK Met Office, investigated how space weather information could be folded into existing aviation planning information; he also provided helpful comments on operational planning. The information is folded into Section 4.2.

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[41] Sadly, Pierre Lantos died on 1 March 2007.

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# 12. List of Acronyms

| | |
|---|---|
| ABAS | Aircraft Based Augmentation System |
| ACARS | Aircraft Communication Addressing and Reporting System |
| ACE | Advanced Composition Explorer (NASA spacecraft) |
| ATB | Air Traffic Bulletin (FAA) |
| ATC | Air Traffic Control |
| AZA | Auroral Zone Absorption |
| BA | British Airways |
| CAA | (UK) Civil Aviation Authority |
| CARI | (aircraft radiation prediction code; US) |
| CAMI | Civil Aerospace Medical Institute (FAA) |
| CH | Coronal Hole |
| CLS | Collecte Localisation Satellites (CNES) |
| CME | Coronal Mass Ejection |
| CNES | Centre National d'Etudes Spatiales (France) |
| DME | Distance Measuring Equipment (navigation) |
| DOSMAX | Dosimetry of Aircrew Exposure to Radiation during Solar Maximum (FP5) |
| ECAC | European Civil Aviation Conference |
| EDP | Electron Density Profile |
| EGNOS | European Geostationary Navigation Overlay Service |
| EIT | Extreme ultraviolet Imaging Telescope (SOHO instrument) |
| EPCARD | European Program package for the Calculation of Aviation Radiation Dose (aircraft radiation prediction code; Germany) |
| ESA | European Space Agency |
| ESAC | European Space Astronomy Centre (ESA) |
| ESTEC | European Space Research and Technology Centre (ESA) |
| EURODOS | European Radiation Dosimetry Group |
| EUV | Extreme Ultra-Violet (electromagnetic radiation) |
| FAA | (US) Federal Aviation Administration (aviation regulatory body) |
| FTP | File Transfer Protocol |
| FUV | Far Ultra-Violet (electromagnetic radiation) |
| GCR | Galactic Cosmic Rays |
| GBAS | Ground-Based Augmentation System (e.g. LAAS) |
| GLE | Ground Level Enhancement (or Event) |
| GLONASS | GLObal NAvigation Satellite System (navigation; Russian) |
| GNSS | Global Navigation Satellite System (incl. GPS, Galileo, GLONASS) |
| GOES | Geostationary Operational Environmental Satellite (NOAA spacecraft) |
| GPS | Global Positioning System (navigation; US) |
| GRIB | GRIdded Binary (data format in meteorology) |
| GSFC | Goddard Space Flight Center (NASA) |
| HF | High Frequency (communications; 3-30 MHz) |
| HSS | High Speed Stream |
| ICAO | International Civil Aviation Organization |
| ICRP | International Commission on Radiological Protection |
| ILS | Instrument Landing System |
| IMAGE | Imager for Magnetosphere-to-Aurora Global Exploration (NASA spacecraft) |
| IMF | Interplanetary Magnetic Field |
| INS | Inertial Navigation System |

| | |
|---|---|
| IPS | Ionospheric Prediction Service (of the Australian SWx Agency) |
| ISES | International Space Environment Service |
| JAA | Joint Aviation Authorities (associate body of ECAC representing civil aviation regulatory authorities in Europe) |
| JAR | Joint Aviation Requirement (JAA) |
| JAXA | Japanese Aerospace Exploration Agency |
| JPL | Jet Propulsion Laboratory (NASA, California Institute for Technology) |
| LAAS | Local-Area Augmentation System (navigation) |
| LASCO | Large Angle Spectroscopic Coronagraph (SOHO instrument) |
| L1 | Lagrange Point 1 (similarly, L2, L3, L4 and L5) |
| LUF | Lowest Usable Frequency |
| MLS | Microwave Landing System |
| MSSL | Mullard Space Science Laboratory (UCL) |
| MUF | Maximum Usable Frequency |
| NASA | (US) National Aeronautical and Space Administration |
| NAT | North Atlantic Tracks |
| NATS | (UK) National Air Traffic Services |
| NDB | Non-Directional Beacon (navigation) |
| NGDC | (US) National Geophysical Data Center |
| NOAA | (US) National Atmospheric and Atmospheric Administration |
| NOTAM | Notice to Airmen |
| NPA | Non-precision approach |
| NPL | (UK) National Physical Laboratory |
| NWS | (US) National Weather Service (NOAA) |
| NWWS | (US) NOAA Weather Wire Service |
| NSWP | (US) National Space Weather Plan |
| PCA | Polar Cap Absorption (SWx effect) |
| PCAIRE | Prediction Code for AIrcrew Radiation Exposure (aircraft radiation prediction code; Canada) |
| POES | Polar Orbiting Environmental Satellite (NOAA spacecraft) |
| QARM | QinetiQ Atmospheric Radiation Model |
| RAL | Rutherford Appleton Laboratory |
| RF | Radio Frequency |
| RFI | Radio Frequency Interference |
| RKA | Russian Federal Space Agency |
| RNAV | Area Navigation |
| RVSM | Reduced Vertical Separation Minima |
| RWC | (SWx) Regional Warning Centre |
| SATCOM | Satellite Communications |
| SATNAV | Satellite Navigation |
| SBAS | Satellite-Based Augmentation System (e.g. WAAS, EGNOS) |
| SCR | Solar Cosmic Rays |
| SDA | Service Development Activity (ESA SWx Pilot Project) |
| SDAC | Solar Data Analysis Center (NASA-GSFC) |
| SEC | Space Environment Center (NOAA; now the SWPC) |
| SED | Storm Enhanced Density |
| SEE | Single Event Effects |
| SEIVERT | (aircraft radiation prediction code; France) |
| SEP | Solar Energetic Particle event |
| SESAR | The Single European Sky ATM Research Programme of Eurocontrol. |

| | |
|---|---|
| SEU | Single Event Upset (type of SEE) |
| SHF | Super High Frequency (communication; 3-30 GHz) |
| SID | Sudden Ionospheric Disturbance |
| SIDC | Solar Influences Data Analysis Centre (RWC Belgium) |
| SIGMET | SIGnificant METeorological information |
| SIGWX | SIGnificant Weather (aviation charts) |
| SOARS | Space weather Operational Airline Risk Service |
| SOHO | SOlar and Heliospheric Observatory (NASA/ESA spacecraft) |
| SRA | Solar Radiation Alert system (FAA-CAMI) |
| SSB | Solar Sector Boundary |
| STD | Solar Terrestrial Dispatch |
| STEREO | Solar TErrestrial RElations Observatory (NASA spacecraft) |
| SXI | Soft X-ray Imager (GOES instrument) |
| SXR | Soft X-ray (electromagnetic radiation) |
| SWENET | Space Weather European NETwork |
| SWF | Short Wave Fade (SWx effect) |
| SWPC | Space Weather Prediction Center (NOAA; formally the SEC) |
| SWx | Space Weather |
| SXI | Solar X-ray Imager (GOES instrument) |
| TEC | Total Electron Content |
| TEPC | Tissue Equivalent Proportional Counter – type of radiation detector |
| TWINS | Two Wide-angle Imaging Neutral-atom Spectrometers missions (future NASA spacecraft) |
| UCAR | University Corporation for Atmospheric Research |
| UCL | University College London |
| UHF | Ultra-high Frequency |
| UNAT | (FAA) User Needs Assessment Team |
| URSI | Union Radio-Scientifique Internationale – International Union of Radio Science |
| UV | Ultra-Violet (electromagnetic radiation) |
| VAA | Virgin Atlantic Airways |
| VHF | Very High Frequency (communications; 30-300 MHz) |
| VOR | VHF Omni-directional radio Ranger (navigation) |
| WAAS | Wide-Area Augmentation System (navigation) |
| WMO | World Meteorological Organization |
| WMSCR | Weather Message Switching Center Replacement (FAA) |
| Wx | Terrestrial Weather |
| XRS | X-ray Sensor (GOES instrument) |

# Appendix A. User Requirement Surveys

## *A.1. Survey conducted by SOARS*

### A.1.1. Questions used in SOARS Survey

The questions in sections A and D were the same for all target groups, although the sub-questions to question 3 depended on the group.

**A. General:**
1. How familiar are you with the term Space Weather (SpW)?
2. Do you use any form of Space Weather information or prediction service now?
3. Can you please indicate the size of the impact of the following Space Weather problems?
4. What are the commercial impacts of these Space Weather problems?

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**The questions in sections B and C depended on the target group**

Engineering:

**B. Current Issues:**
5. How common are Single Event Effects (SEEs) in electronics caused by Cosmic Rays & Solar Flares? (If aware, please specify frequency).
6. How did you find out about the effects of Single Event Effects (SEEs)?
7. Do you take account of such effects in current aircraft design?
8. How important are these effects in the overall design?
9. Which aircraft components and/or systems are critically affected by Space Weather?
10. Do you accumulate flight data on avionic faults, which could be analysed for such effects?
11. If you accumulate flight data on avionic faults, how do you go on about analysing them for such effects?

**C. Future Issues:**
12. If previous data could be analysed to find correlation with Space Weather events, would this be useful to you? If so how?
13. Which of the following future technological developments will make an aircraft more susceptible to Space weather impacts and in what time frame?
14. Are there any future design trends in aircraft design, relating to Space Weather, and what are they?

Operations:

**B. Current Issues:**
5. Do you monitor cosmic radiation doses for aircrew as part of your rostering/scheduling operation? If so, how?
6. Do you use dose predictions to assist with crew planning requirements and how often?
7. Has Space Weather been responsible for problems caused on:
8. Routing is often changed to benefit from, or avoid terrestrial weather. Might you also change routing to reduce the effects of Space Weather?

**C. Future Issues:**
9. Can you see potential increases in the risks from Space Weather with envisaged changes in future operations and work patterns? If so, can you give examples?
10. Do you foresee using improved Command, Control, Communication and Information (C3I) systems for day-to-day airline Flight and Engineering operations?
12. If so, how do you rate the risks from Space Weather events on that new infrastructure?

13. If Space Weather warnings or predictions were available would you integrate them into your future operational procedures? If so, how?
14. If your future operations were found to be at risk from Space Weather events what action would you take?

Occupational Health:

**B. Current Issues:**
5. Are you aware of the regulation regarding exposure to cosmic radiation aircrew in the EU?
6. In comparison to long-haul routes, how serious a problem do you consider cosmic radiation exposure is for short-haul routes?
7. For long-haul route patterns, are you aware of the relative doses of cosmic radiation on different routes?
8. Do you currently monitor exposure to cosmic radiation for the following? If so, how?
9. Under any circumstances are crew working patterns changed because of exposure to, or potential exposure to cosmic radiation?
10. Are you confident that current monitoring methods are sufficient?
11. Do you have a method for adding doses due to solar particle events and what does this method involve?
12. What are your sources for dose information?
13. Should all aircraft be provided with an instrument to record dose rates?
14. How do you communicate Cosmic Radiation information to your aircrew and passengers?
15. Would you be interested if a radiation monitoring service for all aircraft were available?

**C. Future Issues:**
16. Can you see potential increases in the risks from Space Weather with envisaged changes in future operations and work patterns? If so, can you give examples ?
17. If so, how do you rate the risks from Space Weather events on those new operations?
19. If your future employees were found to be at greater risk from Space Weather events what action would you take?

---

**D. Service Requirements:**
15. What information should a Space Weather service provide?
16. Which of the following services would be of interest?
17. Which of the following two would you prefer?

D.2. Use of Information:
18. If Space Weather provided notification of a severe solar flare, do you believe that re-routing or altitude reductions are viable?
19. Would you be happy to provide post-event data to help the industry as a whole, mitigate Space Weather impacts?
20. Would you consider providing the Space Weather information and services to your passengers?

D.3. Service Delivery:
21. For each one of the following, please indicate what kind of involvement you believe they should have in the development of a Space Weather service?
22. Who should deliver the information to the industry?
23. What communication methods and services do you currently use for operational data?
24. In what format would you like to see Space Weather information provided?
25. What time scale do you need for each of your impacted?
26. How accurate do Space Weather warnings or predictions have to be before you will consider taking actions?

D.4. Service cost and packaging:
27. Would you prefer to have Space Weather information integrated with other services?
28. Which of the following two would you prefer?
29. How would you prefer to see Space Weather services paid for?
30. How supportive are you for the development of Space Weather training courses specifically for the airline industry?

### A.1.2. Contact details

In the survey by ESYS, we made contacted with 37 people from an initial list of 43. A total of 17 surveys returned by 15 organizations; these are grouped by type of survey in the tables below:

**Operations**

| | | |
|---|---|---|
| **1** | JCB Aviation | Hayo Harmens |
| **2** | BA | Steve Hull |
| **3** | IATA (Montreal) | Bernard Gonsalves |
| **4** | FAA | Paul Armbruster |
| **5** | Northwest Airlines | Jeffrey Zimmerman |
| **6** | Northwest Airlines | Gary Berg |
| **7** | FlyBMI | Steve Saint |
| **8** | Continental | Greg Dale |
| **9** | United Airlines | Gene Cameron |
| **10** | NATS | William Muir |

**Occupational Health**

| | | |
|---|---|---|
| **11** | Aer Lingus | Deide O'Kenredy |
| **12** | JCB Aviation | Hayo Harmens |
| **13** | Emirates | Ian Hosegood |
| **14** | BMI | Graham Cresswell |

**Engineering**

| | | |
|---|---|---|
| **15** | IATA (Montreal) | Kors van den Boorgaard |
| **16** | Goodrich Birmingham | Bob Edwards |
| **17** | Airbus | Patrick Heins |

The response statistics can be grouped by type of organization:

| | |
|---|---|
| Commercial Airlines | 9 |
| Business Jet | 2 |
| Manufacturers | 2 |
| Regulatory | 4 |

and type of questionnaire:

| | |
|---|---|
| Operations | 10 |
| Occupational Health | 4 |
| Engineering | 3 |

 

## *A.2. US NSWP Assessment Survey*

### A.2.1. Questions used in the NSWP Survey

The questions listed below were used in the NSWP survey. There were 13 responses that selected "Aviation" to Q1 from both airline personnel responsible for flight operations and from aircrew:

Q1) What is your primary professional activity or interest as they relate to space weather? Select one of the following options: "Aurora Viewing", "Aviation", "DoD Operations", "Electric Power Industry", "GPS, Navigation, Surveying, Drilling", "HF, UHF Communications", "Ham Operator", "Land-line Communications", "Oil or Gas Pipeline", "Spacecraft and Space Operations", "Media", "Other".

Q2) What source do you prefer to use in acquiring space weather information? Options are: "NOAA/SEC", "Other Government Agency", "Private Vendor", "Educational Facilities ", "Foreign Source", "Other" .

Q3) How would you rate your understanding of space weather and its potential impact on your area of interest?

Q4) What can the space weather community do to improve your understanding of space weather?

Q5) Which space weather products or data are used by you or your organization?

Q6) How would you rate the accuracy of the forecast products provided by space weather service providers?

Q7) What other products and services could the space weather service providers offer in order to serve you better?

Q8) In your opinion, what is the greatest shortfall in today's operational space weather service industry?

Q9) What would be the impact(s) on your operations if upstream solar wind and charged particle data such as that currently provided by the Advanced Composition Explorer (ACE) Satellite would not be available at some time in the future?

Q10) Please include any special instructions you may have for the disposition of your submitted comments (i.e. are your comments confidential, etc.)

Q11) Name:

Q12) Email Address:

### A.2.2. Contact Details

There were a total of 180 responses to the NWSP survey; as the questions above show, this covered all aspects of space weather. Grouped by area of interest, the following categories are relevant to SOARS:

- Aviation – 11 responses
- HF, UHF communications – 13 responses
- GPS – 10 responses

Responses related to aviation were completed by the following organizations:

- United Airline (meteorology)
- American Airlines (Captain)
- Continental Airlines
- American Airlines (System Operations Control)
- FedEx (Flight Dispatch Operations)
- Jet Aviation Business Jets (Captain)
- Canadian Department of Transport
- QinetiQ
- 3 individuals from unspecified organizations

# Appendix B. Survey of Compliance to ICRP 60

The 1976 recommendations of the International Commission on Radiological Protection (ICRP 26) exclude all natural radiation from any control - cosmic radiation was therefore not classed as occupational exposure. However, the 1990 recommendations of the ICRP (ICRP 60) reversed this position and recommended the inclusion of exposure of aircrew to cosmic radiation.

ICRP 60 recommended that the occupational exposure limit for workers should not exceed an effective dose of 20 mSv per year averaged over 5 years, with not more than 50 mSv in any single year. Although it is unlikely that aircrew would reach the annual dose level of 20 mSv in present conditions, it is generally recommended that an intervention level of 6 mSv be adopted. The intervention level is the level at which a specific protective or remedial action is taken; the value of 6 mSv is set as 3/10 of the nuclear energy worker 20 mSv limit and is in keeping with the ALARA[42] principle, where some intervention must be taken well below the nuclear energy worker limit. When employees approach 6 mSv per annum, the operator should put measures in place to adjust their working schedule so that their subsequent flights, for the remainder of the calendar year, would result in minor additional exposure.

Adoption of ICRP recommendations is done at the national level and there are differences in the way they have been implemented. There is generally some threshold above which some sort of action should to be taken, but whether individual records then have to be kept varies. In some countries if the estimated dose exceeds 1 mSv individual assessment is always required, in others it is acceptable to not keep records if it can be demonstrated that 6 mSv cannot be exceeded in a calendar year. Where assessment is required, it is normally done by calculation on a flight-by -flight basis.

The differences in the means of compliance include:

- Different procedures to manage dose records and even whether individual records need to be kept. In several cases the dose assessments must be supplied to radiation regulatory body of he country
- Different threshold at which action needs to be taken, different exposure, altitudes and even use of block/flight hours
- Differences in how the flight profile is defined
- Different computer codes deemed acceptable - CARI, EPCARD, FREE, SIEVERT, PC-AIRE
- Differences in the choice of proxy used to represent cosmic ray modulation (e.g. heliocentric potential) and the time resolution (range from duration of flight to annual average)

## B.1. Compliance Measures by Country

In 2006 we have surveyed the information available on how the recommendations have been implemented and our findings are summarized below. It has been possible to find most about countries within the European Union, but comments about several non-EU countries are also included.

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[42] ALARA: As Low As Reasonably Achievable

 

### B.1.1. European Union

In the European Union (EU), radiation protection is regulated by a Directive on the protection of workers and members of the public against the hazards of ionizing radiation (CEC Directive 96/29/EURATOM). The Euratom Directive incorporated and to some extent elaborated on recommendations of ICRP 60; it requires that radiation doses should be kept "as low as reasonably achievable", taking into account economic and social factors and classifies anyone who is liable to receive an effective dose of greater than 1 mSv per year as occupationally exposed and therefore subject to regulatory control.

It should be noted that although binding on all Member States, the Directive is not EU legislation. How the Directive is implemented differs between the EU member countries; each country defines its own acceptable means of compliance and implementation is subject to national legislation. For example, the radiation regulatory bodies within the Nordic countries agreed to interpret the ICRP recommendations in the same way, but the way they have actually been adopted has been determined by the legislation passed in each country.

All annual dose calculations within the EU are based on block hours, except for Finland.

#### France

- Sievert used to calculate the exposure - developed by French General Directorate of Civil Aviation with partners: the Institute for Radiation Protection and Nuclear Safety (IRSN), the Paris Observatory and the French Institute for Polar Research – Paul-Emile Victor (IPEV).
- Use actual flight plan - these have to be submitted to the Sievert system that also maintains the dose records.
- Assessment initially based on CARI, now EPCARD.

#### Germany

- Competent supervisory authority is the Federal Office of Civil Aviation (LBA).
- German Commission on Radiological Protection (SSK) has recommended use of computer codes to comply with regulations. Codes approved by LBA based on expert opinion of National Metrology Institute (PTB) - EPCARD, FREE and PC-Aire approved, CARI currently is not. Campaign of radiation measurements onboard aircraft used to verify of dose calculation.

- Airlines (just Lufthansa?) can apply for an exemption if expected dose <1 mSv/calendar year; medical examination for employee if >6 mSv in a year.
- Calculation made using EPCARD based on actual flight data. (BY WHOM?)
- Records are stored in a flight dose database (CALVADOS) operated by the German Aerospace Centre (DLR, Cologne).

#### Spain

- Regulated by the Directorate General for Civil, with advice and information from the (Spanish) Nuclear Safety Council. (just IBERIA?)
- Doses are calculated by airlines using EPCARD 3.2 based on predicted flight plans held in the IBERIA planning system. ("more realistic that great circle approach")
- Records stored in a database that is supervised by the IBERIA Medical Service – the Regulator requires an annual report.

 

- Instrumental validation of the EPCARD calculations is conducted annually on the more characteristic (trans-Atlantic) routes. IBERIA has fitted MDU-Liulin LET spectrometers to some of their aircraft are part of this programme.

### United Kingdom

- Civil Aviation Authority (CAA) responsible to monitoring compliance. Advisory material on cosmic rays provided by Department for Transport (DfT), Civil Aviation Authority (CAA) and National Radiation Protection Board (NRPB) with input from a panel of experts from government, the airlines, unions and space science; this group defined means of compliance with the legislation, etc.
- Assessment done by individual airlines, each of which has developed its own monitoring system - there is no centralized database.
- BA and Virgin have similar system based on CARI-6 using general flight profiles. Doses calculated using monthly HP value - dose records kept for each crewmember. (BA grounds any pregnant crewmember, once pregnancy declared).
- BMI uses CARI to determine the dose for each of its routes every few (?) months and uses the dose rate from the worst route scaled to a working year of 800 block hours to demonstrate that no crew member can possibly exceed 4 mSv (?) in a year. On this basis they are not required to keep individual records.

### Ireland

- Guidance material produced by Radiological Protection Institute of Ireland (RPII)
- Calculations can be by either EPCARD or CARI-6 (both approved by RPII)
- Crew flying below 8000m considered unlikely to exceed 1 mSv.
- In range 1-6 mSv: operator may opt for simplified calculation based on annual average route dose and group roster data - annual average dose calculated using annual HP value; groups must be defined as based of similar work rosters. If assessed value >5 mSv must reassess using method below.
- Above mSv: dose assessments based on monthly averaged route doses and individual roster data; typical flight profiles used rather than actual flight data.
- Grouping and flight profiles must be reviewed at appropriate intervals and available for inspection by RPII.

### Netherlands

- Monitoring is a task of the Nuclear Research and consultancy Group (NRG; a dosimetric service).
- Dose calculations based on generated (typical?) flight plan rather than the profile of the actual flight plan - much less effort that using actual plan, sufficiently low uncertainty and minimal administrative workload.
- System independent of code by CARI-6M "currently used".
- Validity of approach was tested using different code, examining the impact of variations of flight profiles; conclusion was that uncertainty due to codes and route, with a safety margin, was only 21% and within the international standards (ICRP 60, IAEA RS-G-1.3)
- Data stored in National Dose Register and Information System (NDRIS).

### Sweden

- Seem to be working to ICRP 26 - enhanced levels of natural radiation are not considered a hazard in the workplace.
- Regulatory authority is Swedish Radiation Protection Authority (SSI); enforced by the Swedish Civil Aviation Authority.

- Once per year, airlines have to report statistics on effective dose of crewmembers - Swedish National Dose Register used for all radiation records.
- Doses based on calculations using CARI-6 and actual flight profiles.
- Excluded if <0.1 mSv/month; no doses above 5 mSv/year reported.

### Finland

- Regulatory body is Finnish Radiation and Nuclear Safety Authority (STUK)
- If likely to exceed 1 mSv must determine exposure - report must be submitted to STUK. Report must specify the most common routes and altitudes used by airline; it must also estimated annual doses and annual maximum flying hours.
- Estimation can be by either: i) using an approved computer code (CARI, EPCARD or FREE) and generic(??) flight profiles, or ii) calculating the dose using dose values supplied in a table and the flying hours at given altitude and latitude (solar activity?)
- Dose records must be supplied to STUK by end of Jan. of following year.
- Note: Finland uses Flight Time - interval the aircraft airborne - NOT block hours

### Denmark

- Globalog - used by airlines?? Says developed in association with Danish National Laboratory and has been tested by the Danish Space Research Institute...
- Uses actual flight plan, "minute-by-minute" cosmic radiation values over duration of the flight; maintains logs for each crew member
- NOT clear what code used to calculate the dose! Also, does NOT describe how accounts for solar flares (GBO neutron data not enough!)

### Poland

- There is no dose monitoring in Poland. Twice a year a maximum number of flight hours is set, basing on CARI calculations. (private communication)

### Czech Republic

- Radiation protection is done by the Nuclear Physics Institute.

## B.1.2. Non-EU Countries

### United States

The Federal Aviation Administration has published documents discussing aircrew radiation exposure and issued recommendations to airlines on educating aircrew about the risks — it has not issued dose limits.

FAA Advisory Circular 120-52, “Radiation Exposure of Air Carrier Crewmembers”, dated 5 March 1990, provides information on cosmic radiation, guidelines for exposure, estimates of the amount of radiation on various routes and example calculations for estimating health risk. Advisory Circular 120-61, dated 19 May 1994, recommends that airlines educate crewmembers on the types and amounts of radiation received during air travel, etc.

The FAA's Civil Aerospace Medical Institute has developed the computer program called CARI to estimate cosmic radiation doses - the latest version (CARI-6) is now widely used around the world.

US airlines have not voluntarily adopted training or dose monitoring programs similar to those in the nuclear power industry.

## Canada

Commercial and Business Aviation Advisory Circular (CBAAC) 183 provides recommendations for air operators in Canada. It recommends that operators develop a program for managing the cosmic radiation exposure of their employees who work onboard aircraft, based on the likelihood of exceeding an exposure of 1 mSv annually. CBAAC 183 uses the doses set by the Canadian Nuclear Safety Commission (CNSC) in the Nuclear Safety and Control Act, 31 May 2000 - these follow the recommendations on ICRP 60.

Air operators are required to send the dose record of their employees to the Canadian "National Dose Registry". It is recommended that the doses be determined using existing route dose data (using PC-Aire?); as an alternative, the theoretically based CARI or EPCARD codes can be used.

## New Zealand

Based on the latest document on the web site of the National Radiation Laboratory of New Zealand (IS-19; dated 1998), under the Radiation Protection Act 1965, the Radiation Protection Regulations 1982 effectively adopt the 1976 recommendations of the International Commission on Radiological
Protection (ICRP 26); under ICRP 26, all natural radiation is excluded from any control and cosmic radiation is not classed as occupational exposure for aircrew. IS-19 recommends the adoption of the 1990 recommendations of the ICRP (ICRP 60) - this would mean that exposure of aircrew to cosmic radiation would be considered occupational exposure and thereby subject to the limits specified - but there is no indication that this has happened.

The figures given in IS-19 are based on a working year of 1000 hours. It is assumed that this is intended to produce a worst case result - it is longer than the working year assumed by other countries and the exposures quoted are correspondingly higher. IS-19 suggests that some aircrew receive exposures in excess of 6.5 mSv per annum, based on calculation using doses reported by O'Brien et al. (1992) and Regulla and Davis (1993). Even though the numbers are high in comparison to those used in Europe, they are within the recommended limits given in ICRP 60; a threshold on 2 mSv is recommended for pregnant aircrew.

## Hong Kong

In Hong Kong, the Civil Aviation Department set up a working group on cosmic radiation in the Hong Kong aviation industry including representatives from government, airlines and the unions. In September 2002, the group adopted the Euratom Directive (CEC/96/29) although Cathay Pacific adopted the key elements in April 2002.

Doses are assessed using CARI; typical flight profiles are used. EPCARD and SIEVERT were considered acceptable but CARI was adopted as the most commonly used computer code.

 

## *B.2. Summary*

Below we summarize how countries within the European Union have complied. We restrict the comparison to these countries since all are required to comply with EU Directive 96/29/Euratom which defines how the recommendations of ICRP 60 should be adopted within Europe.

| | France | Germany | UK | Ireland | Spain | Netherlands | Sweden | Finland | Demark | Poland | Czech Republic |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dose records:** | | | | | | | | | | | |
| Maintained by airline | | | X | X | X | | | | | | |
| Central database | X | X | | | | X | | X | | | |
| Demonstrated >6 mSv impossible | | | x | | | | | | | X | |
| **Dose calculated using:** | | | | | | | | | ? | | ? |
| Actual flight profile | X | X | | | | | X | | | | |
| Planned flight profile | | | | | X | | | | | | |
| Representative flight profile | | | | X | | X | | | | | |
| Generic flight profile | | | X | | | | | X | | | |
| **Approved computer codes:** | | | | | | | | | | | |
| CARI-6 | | | X | X | | X | X | X | | | |
| EPCARD | | X | x | X | X | | | X | | | |
| FREE | | x | | | | | | X | | | |
| SIEVERT | X | | x | | | | | | | | |
| PC-Aire | | x | | | | | | | | | |
| | | | | | | | | | | | |

Meaning of Flight Profile definitions:

| | |
|---|---|
| Actual | Details of actual route followed (latitude, longitude, altitude) |
| Planned | Planned waypoints and altitudes |
| Representative | Profile of route followed at some time in the past |
| Generic | Great circle route with set altitude profile |

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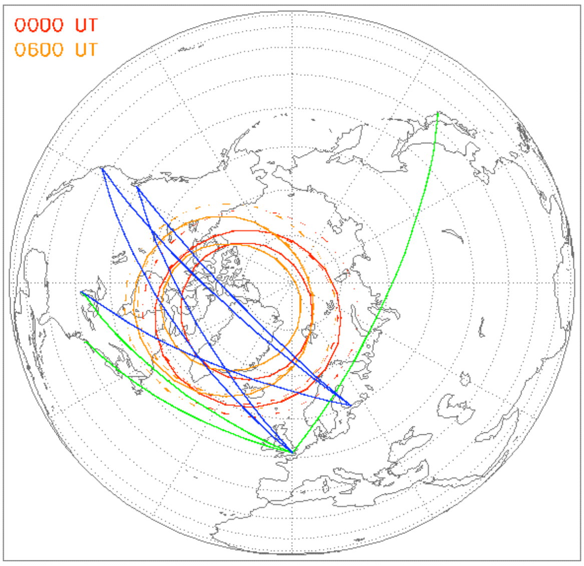
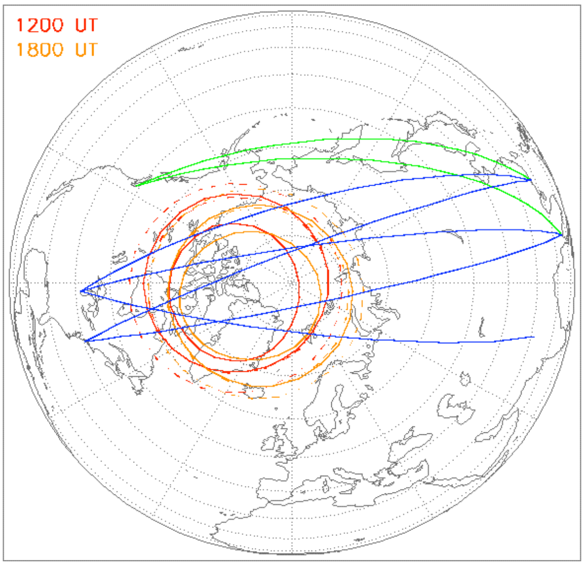
**Note:** We have found a presentation about an EC project (FP6?) given at the Space Weather Symposium in Vienna in 2006 that is assessing "The Implementation of the European Directive on the Protection of Aircraft Crew - Exposure due to Cosmic Radiation". The presentation suggests that this project will conclude in 2008, but we have not been able to find out anything else about the project.

*http://www.radiation-seibersdorf.at/getbinobj.asp?id=1712*

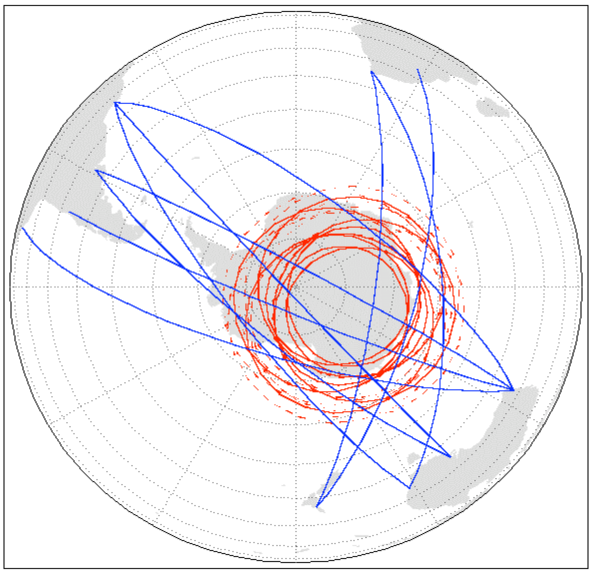
# Appendix C. Polar Routes and the Auroral Oval




Great Circle routes across high latitude regions in the northern hemisphere are shown in relation to the auroral oval. The oval shifts around a region centred on the geomagnetic pole – its location is plotted at 6 hr intervals for relatively quite conditions. Inside the auroral oval protons from intense solar flares can cause polar cap absorption; within the annulus of the oval small-scale anomalies in electrons density can cause scintillation.

Although in principle many of the routes from Europe could be cross the area affected, in practise airlines do not always follow the Great Circle routes for a variety of reasons. Also, flight from western Europe can avoid the region with relatively small diversions (similar to those already made for other reasons) and very few airlines from eastern Europe currently fly to the US West Coast. However, flights from the eastern US to Asia cannot easily avoid the region and if HF communications are affected the only option may be to reroute.



In the southern hemisphere, the routes that could be affected between Australia and South America are not currently in use, presumably because of lack of demand.

*(Auroral oval plot routine developed by Center for Space Physics, Boston University, based on Kauristie 1995)*