Civil Aviation Authority

Impacts of space weather on aviation

CAP 1428

Published by the Civil Aviation Authority, 2016

Civil Aviation Authority,

Aviation House,

Gatwick Airport South,

West Sussex,

RH6 0YR.

First published 2016

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The latest version of this document is available in electronic format at www.caa.co.uk/CAP1428, where you may also register for e-mail notification of amendments.

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Chapter 1

Introduction

The Earth is constantly subjected to electromagnetic and high energy particle radiation from both galactic sources and the Sun. Most of the variability is of solar origin and is collectively known as space weather. Like terrestrial weather, minor events are more common than major events. Generally the day-to-day variation in space weather has a negligible impact on technology and humans but on average several times in each solar cycle of 11 years space weather can have operational impact.

During the most extreme events, associated with rare solar superstorms (and not necessarily related to the solar cycle), there are a number of issues that the aviation industry should consider because the impact will be global and significant. Although extremely rare (1 in 100-200 years) the potential disruption caused by extreme space weather cannot be ignored and it was for this reason that these have been placed on the UK National Risk Register [Cabinet Office, 2015] requiring that mitigation be considered. Without appropriate preparedness an extreme space weather event could create large scale disruption of the aviation industry from which it would take weeks to fully recover.

Chapter 2

Scope

The purpose of this guidance is to inform all UK sectors of aviation of the phenomena and potential impacts of space weather.

Originally the CAA published Information Notice IN–2013/089 [CAA, 2013], which informed the UK aviation industry of the potential impacts of space weather. IN 2013/89 reminded UK sectors of aviation that they should consider how they may be affected by Space Weather and that they should ensure that they have appropriate procedures in place in the event of an incident. It recommended that staff should be made aware of potential effects and mitigating actions. Aircraft operators were reminded of their legal responsibility under the Air Navigation Order to protect air crew from exposure to cosmic radiation.

This document replaces IN 2013/089 following the publication of a number of reports and studies including those published by the Royal Academy of Engineering [Cannon et al., 2013a, b] which have highlighted the continuing need to be vigilant with regard to the effects of space weather.

Chapter 3

What is space weather?

According to the US National Space Weather Program, the term Space Weather refers to “the conditions of the sun and in the solar wind magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health” Short term variations in space weather originate on the Sun.

The Sun’s visible output is fairly constant but the total energy output changes over time due to variations in non-visible electromagnetic radiation, variations in the flow of magnetised plasma and eruptions of high energy particles. Space weather exhibits a climatology which varies over timescales ranging from days (i.e. diurnal variations resulting from the rotation of the Earth) to the 11-year solar cycle and longer. Superimposed on this climatology are weather-like variations; on some days space weather is more severe than on others. Minor solar storms are relatively common events; in contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two.

Although there is some influence from outside the solar system, most space weather starts at the Sun which exhibits considerable variability during storm periods at radio, extreme ultra-violet (EUV) and X-ray wavelengths – these electromagnetic radiation effects are associated with flares. During storm periods, the Sun is also more likely to generate high-energy solar energetic particles (SEPs) which travel from the Sun to the Earth at relativistic speeds taking perhaps 10-15 minutes to arrive. These have the potential to affect avionics and increase the crew and passenger radiation doses. Finally, the solar wind plasma speed and density, forming part of the solar corona, may increase substantially. Coronal mass ejections (CMEs), explosive injections of magnetised plasma into the solar wind, are one important manifestation of the latter and have important impacts because the associated energy is significant. CME’s can trigger geomagnetic storms in our magnetosphere (the region surrounding our planet where the geomagnetic field dominates) with important consequences for the electricity grid and indirect consequences for air navigation and communications systems.

Very rarely (currently estimated to be between 1 in 100 or 200 years) a solar superstorm can occur; these have the potential for significant disruption of the air transport system. It is not possible to deterministically predict when the next event will occur, even only days ahead of the event.

The largest recorded solar superstorm is known as the Carrington Event which occurred in 1859. It was associated with a large solar flare and the associated CME took only 17.6 hours to travel from the Sun to the Earth. It caused aurora in many parts of the world where they are not normally seen –even in Hawaii. One consequence of this solar superstorm was that telegraph systems across the world misbehaved with operators able to receive messages despite having disconnected their power supplies.

During minor space weather events most of the impact is felt at high and equatorial latitudes, but during major events the impacts spread to mid-latitudes. During extreme events the effects are felt globally.

Chapter 4

Probability of occurrence

Introduction

The following is a subjective assessment of the likely effects of space weather ranging from routine variations which occur every few days, through significant events which occur around ten times in each solar cycle, to the solar superstorm which occurs only once per century (or two). The quoted probabilities have been adapted from the scientific literature and mapped onto this subjective categorisation.

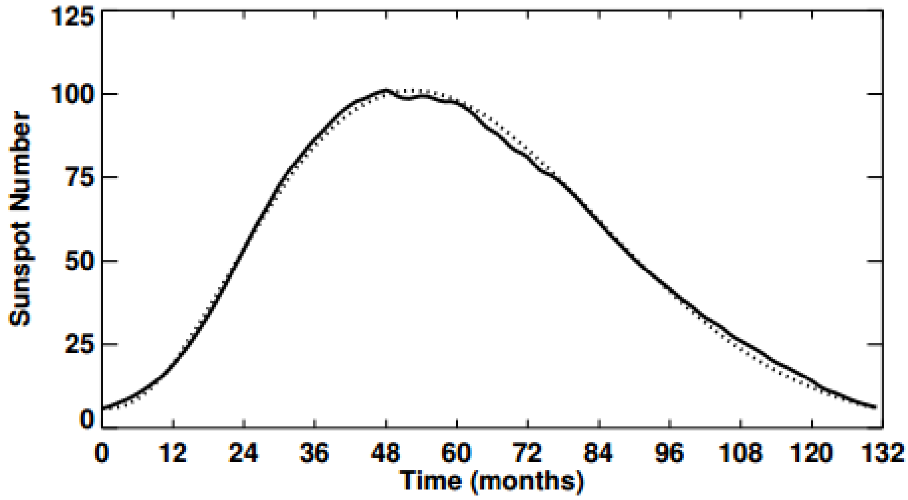

Figure 1: Average solar cycle [Hathaway 2010]

The Sun has an approximate 11 year cycle which is defined by the number of sunspots on the visible face of the Sun. It begins at solar minimum, with periods of very few, or no, visible sunspots, rising to solar maximum between 3 and 5 years after solar minimum, when there is a maximum in visible sunspots followed by a slow decline over the next 6 or 7 years back to solar minimum. Figure 1 shows the evolution in time of the 'average' solar cycle. Space weather therefore tends to occur more frequently in the 8 or so years straddling solar maximum, although significant events have occurred near solar minimum.

Solar flares (radio blackouts – X-ray flares)

Category	**Aviation impact**	**Probability** (outside of solar minimum)
Solar superstorm	▪ Complete HF radio blackout on the entire sunlit side of the Earth for a number of hours. ▪ Enhanced radio noise causing significant degradation in global navigation satellite systems (GNSS).	~ 1 in 100 years
Significant	▪ HF radio communication blackout (due to absorption) on the sunlit side of Earth for one to two hours.	At least once per year
Routine	▪ Minor absorption of HF radio communication on sunlit side through signal absorption. ▪ Otherwise no significant effect.	~ 100 days per year

Solar radiation storms

Category	**Aviation impact**	**Probability** (outside of solar minimum)
Solar superstorm	▪ Aircraft electronic systems will experience single event effects (SEE) which can cause unexpected systems behaviour. The rate of SEE depends on flight path and the storm characteristics. Multiple events may occur over a number of days. ▪ Depending on flight path and the storm characteristics, potentially significant contribution to annual advisable	~ 1 in 100 years

	radiation dose for crew and passengers. ▪ HF communications blackout in the polar cap regions. ▪ Contribution to loss of up to 10% of the satellite fleet	
Significant	▪ Aircraft electronic systems may experience single event effects (SEE) which can cause unexpected systems behaviour. The rate of SEE depends on flight path and the storm characteristics. ▪ Depending on flight path and the storm characteristics, noteworthy contribution to annual permitted advisable dose for crew and passengers. ▪ HF communications blackout in the polar cap regions. ▪ Contribution to loss of one or two of the satellite fleet.	~ 2 in 11 years
Routine	▪ No significant effect.	~ 3 or 4 days per year

Geomagnetic storms

Category	**Aviation impact**	**Probability** (outside of solar minimum)
Solar superstorm	▪ GNSS positioning and timing degraded for up to three days, due to signal fading and uncharacterised signal delays. ▪ HF communication will be impossible or at best difficult to manage for one to two	~ 1 in 100 years

	days, due to fading and unusual propagation conditions. ▪ Aircraft SATCOMS lost or poor at most latitudes due to fading; worst for polar flights. ▪ Contribution to loss of 10% of the satellite infrastructure. ▪ Potential disruption to the electricity network due to ground induced currents (GICs), with possible consequences for air traffic control infrastructure.	
Significant	▪ GNSS positioning and timing degraded for hours, due to signal fading and uncharacterised signal delays. ▪ HF communication will be impossible or at best difficult to manage for one to two days, due to fading and unusual propagation conditions. ▪ Aircraft SATCOMS poor at most latitudes due to fading, worst for polar flights. ▪ Contribution to loss of one or two of the satellite fleet.	~ 4 to 6 days per year
Routine	▪ HF communications need managing. ▪ Otherwise no significant effect.	~ 100 days per year

Chapter 5

Observing and forecasting space weather

Previous space weather events

1859 Carrington event

On the morning of 1 September 1859 amateur astronomer Richard Carrington observed the start of the largest space weather storm recorded when he became aware of two patches of bright light on the Sun's surface. Within minutes the bright light vanished but after a few hours the effects of the event were felt across the Earth. Carrington had observed a massive solar flare, and unknown to him at the time, the release of a significant CME which resulted in a geomagnetic storm (and no doubt a radiation storm) which induced currents in telegraph wires around the world. The power of the storm was not recorded, but it is likely the strongest in the last 150 years. The Carrington event serves as our reasonable worse case example and it is anticipated that such a storm today would have significant impact on aviation. There is emerging evidence that storms at least ten times larger have occurred.

1989 Quebec power outage

In March 1989 the third strongest recorded geomagnetic storm struck Earth. In less than a minute induced current in transmission lines caused overload safety systems to trip closing down sections of the Quebec power network. A cascade effect then caused the network to collapse and the region to fall into darkness. Electricity was unavailable for nine hours, and restoration was made more difficult due to the fact that backup equipment had also been affected by the storm.

2003 Halloween solar storms

During the declining phase of the solar cycle the Sun unexpectedly burst into activity. A number of CMEs and flares resulted from a very large and complex group of sunspots. These resulted in geomagnetic storms that caused outages in high frequency (HF) communication systems, fluctuations in power systems and minor to severe impacts on satellite systems. This included two Inmarsat satellites (used by the aviation industry) of which one required manual intervention to correct its orbit and the other went offline due to central processor unit (CPU) failures. These were just two of forty-seven satellites reported to have service interruptions lasting from hours to days. Some Global Positioning Satellite (GPS) users observed errors and some users had to cancel operations e.g surveyors. The US Wide Area Augmentation System (WAAS) was affected. For a 15 hour period on the 29 October and an 11 hour period on the 30 October, the ionosphere was so disturbed that the vertical error limit was exceeded and WAAS was unusable for precision approaches.

2006 radio burst

In 2006, during a quiet phase of the solar cycle, the Earth was exposed to the largest radio burst ever recorded. It was also the first recorded incident of a radio burst affecting GPS reception. In some instances GPS navigation was unavailable for approximately 30 minutes, with some aircraft reporting loss of lock.

Observing space weather events

Ground-based and satellite instrumentation are used to observe and monitor space weather events.

The solar surface and atmosphere can be observed in near-real time using ground based and satellite based telescopes to detect any new active regions that may become the source of large events. Flares can be monitored and can be related to their impact. These measurements inform Governments and responsible organisations that they should be prepared for a major solar storm.

The effects of the radiation storm can also be monitored on the ground and on satellites. Satellite measurements enable the spectrum and intensity of the solar energetic particles to be measured and ground based monitoring enables the products of these particles to be measured leading to the declaration of a ground level event. Again, these measurements are important because they enable government agencies to advise airlines on the risk. (It should be noted that it is very difficult to extrapolate from satellite measurements to aircraft altitudes. The most reliable approach is to employ on-board (aircraft) sensors.)

Perhaps the most important observations are velocity, density and magnetic field observations of the incoming CMEs (geomagnetic storms) using satellites. The CME is important because it has a direct consequence on the electric grid. Observational satellites orbit the L1 Lagrangian point between the Earth and Sun where the gravitational forces of Sun and Earth are balanced. L1 observations help determine whether a CME is earth directed and are used as inputs to forecast models which predict the CME arrival time and also whether the embedded magnetic field will couple with the Earth's magnetic field to produce system impacts. Not until this measurement is made can an imminent emergency be declared by Government. Unfortunately at this point there is only 15-30 minutes of notice.

The effects of the solar flares, the radiation storm and the geomagnetic storm on the ionosphere are monitored using networks of ionosondes, total electron content monitors and other instrumentation. This enables government agencies to understand over what regions of the globe HF, satellite communications, GNSS and eLoran navigation are prejudiced.

Forecasting space weather events

The Met Office have developed, in cooperation with overseas agencies, academia and industry, a national capability for space weather forecasting of solar flares, solar radiation storms and geomagnetic storms.

The current forecasting capability is still in its infancy and forecast skill is low. For example, based on measurements just after the CME launches, the estimate of the arrival time at the Earth is at best ± 6 hours. Therefore, forecasts have to be used with care and understanding. In the event of an incoming Carrington level CME no definitive forecast can be made more than 15-30 minutes ahead of its impact.

Further information can be found from the Met Office Space Weather Operations Centre Website. For information on how to access a range of forecasts visit: www.metoffice.gov.uk/publicsector/emergencies/space-weather/forecasts or email moswoc@metoffice.gov.uk.

International cooperation and initiatives

Space Weather forecasting is necessarily an international exercise requiring ground and space based observation cooperation. The NOAA Space Weather Prediction Center and the Australian Bureau of Meteorology provide two services with many decades of heritage. More recently a number of other services have been initiated reflecting growing national and international needs. This includes space situational awareness services by the European Space Agency.

International aviation activities to establish a global space weather observations and forecasts service are centred on ICAO. An ICAO working group is developing a service to provide space weather observations and forecasts tailored to aviation communications and navigation systems and radiation risks to flight crew, passengers and avionics.

Chapter 6

Space weather impacts

Introduction

Space weather affects a plethora of systems important to the aviation industry and some of the consequences of an extreme space weather event are summarised below.

Current contingency arrangements mitigate some of the individual effects but further consideration is required of common failures. For example during an extreme event both HF and satellite communications may be lost along with severely degraded or lost GPS derived timing and navigation.

It is also important to recognise that aviation's vulnerability to the effects of space weather continues to increase due to the greater use and continued miniaturisation of microelectronics, and due to increasing reliance on signals from satellite based systems. The full range of effects and their likelihood is a topic of significant research interest.

Electrical power distribution and generation

Ground electrical power generation and distribution networks are at risk during extreme events, as a consequence of the geomagnetic storm, though a process of induction into the long transmission lines. This can cause damage to switchgear and transformers.

GNSS

The use of GNSS within the aviation sector is increasing, not only in the number of users but also in the number and type of operations that the system supports.

Solar storms increase the electron density in the ionosphere and give rise to ionospheric irregularities at low and high latitudes. During an extreme event the irregularities may extend over a substantial part of the globe for several days. Increased electron density may give rise to navigation and timing errors and the irregularities will cause signal scintillation (fading and signal Doppler shifts). If the scintillation is sufficient then the signal will be lost and the corresponding navigation and timing prejudiced.

While GNSS is often the primary means of navigation, in most cases it is not the sole means and consequently if the GNSS signal is lost other systems (conventional navigation aids or inertial reference systems) or procedures are available to allow continued safe operation, albeit with reduced air traffic management (ATM) efficiency.

GNSS Required Navigation Performance (RNP) operations are always based on the use of integrity monitoring systems such as RAIM (Receiver Autonomous Integrity Monitoring) and Fault Detection and Exclusion (FDE) techniques for operations down to Non Precision Approach. SBAS (Satellite Based Augmentation System) and GBAS (Ground Based Augmentation System) use differential techniques to minimise residual errors improving accuracy and include integrity monitoring to reduce the likelihood of hazardous misleading information. Thanks to the use of augmentations, disruptions caused by space weather (or any other unintentional interference) will normally result in loss of service rather than possibly hazardous misleading information. However, if the temporal or spatial gradients are too great they will not be detected by the integrity systems. In particular, users of GNSS without integrity monitoring, for example pilots using hand-held receivers which are not RAIM equipped, (as an aid to visual flight rules (VFR) navigation) may get incorrect positional information.

GNSS is also used by many systems as a source of timing and, while fall back timing sources are often available, errors in timing due to degraded or lost signals have been known to cause widespread system failures.

HF communications

HF radio communication in the (3-30 MHz bands) relies on the bouncing of signals from the ionosphere to propagate radio signals beyond the horizon. During low solar activity flares and relatively minor variations in the solar wind produce small changes in the height and density of the ionospheric layers from which the HF signals are reflected. To accommodate this variability, communication service providers select primary and secondary frequencies most appropriate to the aircraft–to-ground receiver skip distance and the ionospheric conditions expected during the flight.

During moderate and above solar storms HF communications on the sunlit side of the Earth are prejudiced through radio blackouts associated with sudden ionospheric disturbances (SIDs) due to the flare. At very high latitudes HF communications can be prejudiced as a consequence of the radiation storm which causes polar cap absorption (PCA), and at auroral latitudes rapid fading and further absorption can occur as a secondary effect associated with the geomagnetic storm. These various events can last for periods of minutes to hours. As a consequence, aircraft crossing the Atlantic have well established procedures for coping with a loss of HF communications which allows aircraft to continue their intended flight plan.

The Royal Academy of Engineering [Cannon et al, 2013a, b] expect that during a superstorm the polar cap and auroral oval will move south so that it includes or is south of the UK. Consequently, HF disturbances will be common on long distance HF communications originating from the UK. It is anticipated that these effects will be worse in the evening but could continue for several days without respite.

Satellite communications

HF is currently the main beyond line of sight communications bearer for aircraft outside of line-of-sight very high frequency (VHF) coverage. However in the North Atlantic there has been a significant progress in mandating the use of satellite data link. ICAO has been instrumental in requiring aircraft operating in the North Atlantic track system to use either Future Air Navigation System (FANS 1/A), Controller-Pilot Data Link Communications (CPDLC) or Automatic Dependent Surveillance Contract (ADS-C) systems. These systems will be required from 2017 for aircraft operating on the North Atlantic tracks at flight levels 350-390 and from 2020 for aircraft operating above FL 290. By 2020 it is expected that 90% of aircraft operating across the North Atlantic will be equipped with data link capability.

The exceptions here are cross polar routes, i.e. those venturing to the poleward side of the 80th parallel, which lose their communication link with the geosynchronous Inmarsat satellites due to the earth's curvature beyond 82 degrees latitude. Currently, in this region, HF radio communication must be employed with all the associated problems already noted. To deal with this, Iridium communications satellites are being launched into a polar earth orbit to provide whole Earth coverage. Plans are in place to provide an operational Iridium satellite service to fill this aviation communications gap by 2018. Operators are expected to increasingly adopt the Iridium satcom service over the coming years.

Satcom through Inmarsat and Iridium is, however, not a panacea for HF. Aircraft satcom operates with low signal margins and the fading and Doppler shift associated with scintillation is likely to result in loss of communications during extreme events (and possibly other lesser events).

Unexpected consequences on RF systems

Operators should be aware that space weather highlights the vulnerabilities in the systems and this has been apparent on at least two occasions during 2014-15. In both cases equipment unexpectedly malfunctioned during a space weather event, while other similar equipment continued working. In one case a solar radio burst caused sufficient interference to overwhelm ground-based ATC equipment.

Aircraft passengers and crew

High-energy cosmic rays, and solar energetic particles associated with the radiation storm spawn a multitude of other high-energy particles through nuclear interactions in the upper atmosphere. These high-energy particles generate secondary particles that reach a maximum flux at about 18 km and are then progressively attenuated by the atmosphere so that only the most penetrating component can be measured on the ground. Typically, at aircraft cruising altitudes the flux of ionising radiation is ~300 times higher than at sea level. The potential health effects of ionising radiation exposure are well known and operators are already required to monitor the occupational exposure of aircrew to cosmic radiation.

Solar radiation storms cause an increase in radiation exposure to flight crews and passengers, the principle consequence being an increase in the incidence of cancer. Public Health England led a group of experts which noted that during a solar superstorm aircraft occupants flying at typical cruising altitudes (10 km or higher) could each receive a dose of about 20 mSv in a single flight, a dose that could increase lifetime fatal cancer risk by about 0.1%. However, this value needs to be interpreted in the context of the general population lifetime fatal cancer risk of about 25 %. The reasonable worse case extreme space weather event would not produce doses high enough to produce acute radiation induced health effects.

Poor present and likely future skills precludes operational mitigation based on forecasting. This means that the only feasible protection is to reduce altitude when an extreme event starts. This is not an action that the CAA considers appropriate for aircraft already in flight, but appropriate mitigation needs to be considered for flights not yet airborne.

In the event of a solar superstorm public concern should be expected, especially from pregnant passengers and crew. Information from on board radiation sensors may alleviate some of these concerns.

Aircraft electronic systems

The same particles which cause radiation damage to passengers and crew also cause damage to microelectronic circuitry through single event effect (SEE) interactions with the semiconductor device structure causing equipment failure or malfunction. During an extreme space weather event multiple faults in the operation of avionic systems is possible and this could increase pilot workload and reduce the degree of safety margin provided within the aircraft systems.

Because the first solar energetic particles arrive within a few minutes of recognising the flare no practical forecast of predicted SEE can currently be provided.

Industry working groups have been discussing the mitigation of the currently understood characterisation of solar energetic particles that can cause SEEs, and the level of protection that needs to be afforded at component, equipment and system level. When mitigation is generated by providing component protection, the protection afforded for the average SEE rate, provides a degree of protection against higher peak levels. It is currently not possible to state that full protection against any size of extreme solar flare can be assured because the low frequency of events means that there is insufficient data to accurately model such an event, so a pragmatic approach to the overall threat is taken. This is commensurate with the approach taken for other types of protection against environmental effects such as high intensity radiated fields (HIRF) and lightning, which have been shown to be robust to the resultant environment despite not demonstrating full protection against the highest peak threats.

It is important that work being undertaken to develop international guidelines for mitigation of SEE continues. Ongoing work has been conducted by the International Electrotechnical Commission (IEC) to set out the atmospheric radiation standards for testing electrical components, and SAE / EUROCAE continue to work together to develop an SEE environmental specification which can be used within aircraft system development processes. The European Aviation Safety Agency (EASA) has issued a Safety Information Bulletin [EASA, 2012].

The consequences as well as the benefits of mitigation strategies should be weighed as part of the risk assessment conducted to assess the effectiveness of protective actions. For example, operational flight level changes mid-flight intended to reduce the risk of exposure during severe solar weather events (30% reduction in exposure per 1000m of altitude reduction) must be assessed against the resulting hazards posed by this action such as potential traffic conflicts arising through descending through busy traffic lanes. This is not an action that the CAA would consider appropriate.

Satellite vulnerability

Aircraft operations are increasingly dependent on satellites for communications and navigation. Radiation storms and the secondary effects of extreme geomagnetic storms will cause a number of problems for satellites including single event upsets, electrostatic charging and cumulative (ageing) effects of satellites.

Following an assessment by the Royal Academy of Engineering [Cannon et al., 2013a; 2013b] their best estimate is that during a solar superstorm around 10% of satellites will experience an anomaly leading to an outage of hours to days. Most will be restored to normal operations in due course. It is also anticipated that in the months after an extreme solar event old satellites especially those in life extension mode may start to fail as a result of ageing effects.

Chapter 7

Summary

Our understanding of space weather and the associated risks is improving but our understanding is still in its infancy. Current forecast skills are poor, but are rapidly improving against a backdrop of increasingly sophisticated space weather observations.

The hazard posed by a Carrington type, extreme space weather event is high even though the probability is extremely low.

A number of technologies critical to the aviation industry are vulnerable to extreme space weather and these vulnerabilities are likely to increase with time as technology becomes more sophisticated.

While it is noted that mitigations are in place for many individual technologies, organisations need to note that during an extreme space weather event a number of effects will occur simultaneously. For this reason all UK sectors of aviation should be aware of the possibility that the UK's aviation "system" could be severely compromised. As a global hazard, the UK will not be affected in isolation which may lead to operations being restricted or curtailed with large scale disruption to schedules arising as a result.

The CAA continues to monitor the development of forecasting and mitigating actions, as well as seeking standardisation of actions in response. It will provide updates on developments as and when they occur.

Chapter 8

Recommendations

All UK sectors of aviation should consider how they may be affected by space weather and ensure that they have appropriate procedures in place to mitigate all levels of space weather.

They should especially consider the compounded impact that will be encountered during an extreme space weather incident.

The aviation industry is recommended to initiate educational programmes that provide staff with a greater understanding of the impact of severe space weather events on their operations and to ensure that the risk of extreme space weather is captured in their Safety Management System (SMS). In particular, aircraft operators are reminded of their legal responsibility under the Air Navigation Order to assess and limit air crew exposure to high energy particle radiation from solar and cosmic radiation sources. Effective mitigating actions should be scalable to the severity of the event.

The aviation industry should ensure that the risk has been assessed and mitigations are in place. The issue is, not will a solar superstorm occur, but when will it occur?

Appendix A

References and further reading

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