

Impacts of space weather on aviation

CAP 1428

A large, abstract graphic composed of overlapping, semi-transparent blue shapes. The shapes are primarily circular and semi-circular, creating a layered, geometric effect. The colors range from a bright, light blue to a deep, dark navy blue. The graphic occupies the lower two-thirds of the page, starting from the left edge and extending towards the right, with a slight gap from the right edge.

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Contents

Contents	3
Revision history	5
Foreword	6
References	8
Glossary of definitions	10
Abbreviations	12
Chapter 1	13
Introduction	13
Chapter 2	14
Scope	14
Chapter 3	15
What is space weather?	15
Chapter 4	17
Space weather impacts	17
Introduction	17
Electrical power distribution and generation	17
GNSS	17
HF communications	18
Satellite communications	19
Unexpected consequences on RF systems	19
Aircraft passengers and crew	20
Aircraft electronic systems	22
Satellite vulnerability	23
Mitigation against space weather impacts	23
Impacts experienced during previous space weather events	25

Chapter 5	27
Probability of occurrence	27
Introduction	27
Solar flares (radio blackouts – X-ray flares)	28
Solar radiation storms	28
Geomagnetic storms	29
Chapter 6	31
Observing and forecasting space weather	31
Observing space weather events	31
Forecasting space weather events	32
Met Office Space Weather Products and Services	32
ICAO Space Weather Information Service	33
Chapter 7	35
Safety Risk Assessments for Space Weather	35
Introduction	35
Guidelines for Completing a Safety Risk Assessment	36
CAA Oversight of Safety Risk Assessment	37
Chapter 8	42
Summary	42
Chapter 9	43
Recommendations	43
Appendix A	44
ICAO Space Weather Advisories	44
Appendix B	48
Further Reading	48

Revision history

Issue 1

September 2016

CAP1428 is introduced to provide guidance to flight operators and other industry stakeholders on the likely impacts of space weather on aviation. Mitigation strategies through company Safety Management Systems are strongly encouraged.

Issue 2

October 2020

CAP1428 is revised to add details relating to ICAO Space Weather Advisories and Met Office Space Weather Products and Services, and to provide guidance on Safety Risk Assessments for industry when considering the threat of a severe space weather event.

Foreword

Civil Aviation Authority (CAA) Civil Aviation Publications (CAPs) are based upon national and European Union (EU) legislation and non-legislative regulatory material, such as ICAO Standards and Recommended Practices. They are published to provide UK industry with:

- a) guidance and clarification on the means of achieving compliance with global, UK and European regulatory requirements, and where applicable:
- b) details of United Kingdom (UK) 'Alternative Means of Compliance', and
- c) details of any additional national requirements, including CAA administrative procedures.

Details of appropriate supporting administrative procedures are also included where necessary.

In publishing CAPs, the CAA satisfies the obligations placed upon it by the Transport Act 2000¹, Chapter 1 Article 2 'CAA's general duty', which in paragraph 2(a) requires the CAA to exercise its functions under the Act in the manner it thinks best calculated, to further the interests of operators and owners of aircraft, owners and managers of aerodromes, persons travelling in aircraft and persons with rights in property carried in them. The only interests to be considered under subsection (2)(a) are interests regarding the range, availability, continuity, cost and quality of air traffic services.

Publication of CAPs additionally satisfies the requirements set out by the Civil Aviation Authority (Chicago Convention) Directions 2007² to ensure that it acts consistently with the obligations placed on the UK under the Chicago Convention. The CAA is obliged to consider whether it is necessary to amend United Kingdom aviation legislation to ensure appropriate implementation of an ICAO provision.

Where (a) the CAA considers it inappropriate to transpose an ICAO provision into domestic legislation and (b) the CAA has discretionary power to enforce the requirements of such a provision through a certificate, licence, or other means of approval, the Civil Aviation Authority (Chicago Convention) Directions 2007 obliges the CAA to develop and publish such requirements as are necessary to implement the ICAO provision and shall ensure that it is able to verify adherence to those requirements.

CAPs are subject to periodic revision to take account of changes to source regulatory material, feedback from industry, and recognised best practice.

¹<http://www.legislation.gov.uk/ukpga/2000/38/contents> or <http://www.legislation.gov.uk/ukpga/2000/38/data.pdf>

²[https://webarchive.nationalarchives.gov.uk/20100422174722/http://www.caa.co.uk/docs/286/CAA\(ChicagoConvention\)Directions2007\(asamended\).pdf](https://webarchive.nationalarchives.gov.uk/20100422174722/http://www.caa.co.uk/docs/286/CAA(ChicagoConvention)Directions2007(asamended).pdf)

CAP 1428 provides applicable guidance relating to the impacts of space weather to the aviation industry and is to be read in conjunction with the regulatory material referenced in the Scope section of this document. ***Non-inclusion of source regulatory material within this CAP does not preclude the end user from either the need to be aware of, or the need to comply with, the requirements contained within the source regulatory materials unless otherwise exempted from those requirements.***

It is the policy of the UK government that, unless a Difference (from an ICAO requirement) or 'Alternative Means of Compliance' (AltMoc) (related to an EASA 'Acceptable Means of Compliance' (AMC)) has been established, compliance with relevant international (i.e. ICAO and applicable equivalents such as International Telecommunications Union) and European regulatory material is required to the extent mandated in law. Additionally, compliance with national requirements that are not addressed by international or EU regulations is also required.

The words 'must', 'shall' and 'will' indicate that compliance with applicable regulatory requirements is necessary. In the case of AMC, the word 'should' indicate that compliance is required, unless complying with an approved AltMoC.

References

The following references are provided for convenience and are not exhaustive, and in view of the timescales involved in updating a Civil Aviation Publication (CAP), may not be up to date. It is therefore advised that readers take note of all applicable Regulations and of any amendments to the Regulations listed below that are implemented after publication of this document.

- Civil Aviation Act 1982
- Transport Act 2000
- The Civil Aviation Authority (Air Navigation) Directions 2001
- UK Air Navigation Order. www.caa.co.uk/CAP393
- [Statutory Instrument Air Navigation \(Cosmic Radiation: Protection of Air Crew and Space Crew and Consequential Amendments\) Order 2019](#)
- The Civil Aviation Authority (Chicago Convention) Directions 2007
- CAP 493 Manual of Air Traffic Services Part 1
- ICAO Annex 3 – Meteorological Service for International Air Navigation
- ICAO Annex 6 – Operation of Aircraft
- ICAO Annex 8 – Airworthiness of Aircraft
- ICAO Annex 11 – Air Traffic Services
- ICAO Procedures for Air Navigation Services – Air Traffic Management (Doc 4444, PANS-ATM)
- ICAO ATM Operational Contingency Plan – North Atlantic Region (Doc 006)
- ICAO Manual on Space Weather Information in Support of International Air Navigation (Doc 10100)
- ICAO Manual of Aeronautical Meteorological Practice (Doc 8896) to provide guidance on the provision and use of space weather information.
- ICAO Safety Management Manual (SMM) (Doc 9859)

- ICAO International Airways Volcano Watch Operations Group - Space Weather Information:
<http://www.icao.int/safety/meteorology/iavwopsg/Space%20Weather/Forms/AllItems.aspx>
- ICAO Circular 126 Guidance Material on Supersonic Aircraft Operations
- Single European Sky (SES) Framework Regulation (EC) No. 549/2004
- EU Regulation 2018/1139 – The Basic Regulation
- IR (EU) 923/2012 Standardised European Rules of the Air (SERA)
- IR (EU) No. 2017/373 laying down common requirements for providers of air traffic management/air navigation services and their oversight
- EASA (2012) Single event effects (SEE) on aircraft systems caused by cosmic rays, SIB 2012-10. <http://ad.easa.europa.eu/ad/2012-10>
- COMMISSION REGULATION (EC) No 859/2008 of 20 August 2008 amending Council Regulation (EEC) No 3922/91 as regards common technical requirements and administrative procedures applicable to commercial transportation by aeroplane (see OPS 1.390)
- EC (1996), Ionizing Radiation, Directive 96/29/Euratom, Official Journal of the European Communities 39, L159. 29 June 1996.
<https://osha.europa.eu/en/legislation/directives/73>
- EU (2013), Protection against ionizing radiation, Directive 2013/59/Euratom.
<https://ec.europa.eu/energy/sites/ener/files/documents/CELEX-32013L0059-EN-TXT.pdf>
- [European Commission. Radiation Protection No 173. Comparison of codes assessing radiation exposure of aircraft crew due to galactic cosmic radiation. 2012.](#)
- EASA (2012), Effects of space weather on aviation, SIB 2012-09.
<http://ad.easa.europa.eu/ad/2012-09>

Glossary of definitions

1. In CAP1428, where a term is used, which is defined by ICAO in a relevant Annex or PANS document, that definition will apply unless:
 - the contrary is indicated; or
 - there is a different definition in the Air Navigation Order or European Regulations.

2. The terms in the table below have been listed for convenience or have been defined to avoid ambiguity or misunderstanding, or to provide definition of words or phrases which have specific meanings within this document. In some cases, they may be slight modifications of definitions in other documents.

Term	Definition
Air Traffic Services Unit	A generic term meaning variously, air traffic control unit, flight information centre or air traffic services reporting office
Carrington event	The largest solar storm on record. It took place from 1-3 September 1859 and is named after British astronomer Richard Carrington.
Coronal Mass Ejection (Solar Flare)	An ejection of material from the sun into interplanetary space. If the material is directed towards the Earth the event may result in a geomagnetic storm.
Geomagnetic Storm	A temporary disturbance in the Earth's magnetic field caused by interaction with the solar wind and coronal mass ejection which interferes with the Earth's magnetic field
HF Comms	Communication systems relying on the use of high frequency (HF) radio waves
Ionosphere	The region of the Earth's atmosphere exposed to ionising radiation. It ranges from around 60km to 1000km in altitude
L1 Langrangian point	The point where the gravitational forces of the Sun and Earth balance
Millirem (mrem)	A rem is a large dose of radiation, so the millirem (mrem), which is one thousandth of a rem, is often used for the commonly encountered doses
Millisievert (mSv)	A sievert is a very large unit of dose so often millisieverts (mSv) or microsieverts (μ Sv) are used.
Moderate (<i>as used in ICAO Space Weather Advisories</i>)	Guidance on the definition of "Moderate" as used in ICAO Space Weather advisories is provided in the Manual on Space Weather Information in Support of International Air Navigation (Doc 10100).

Term	Definition
NOTAM	A notice distributed by means of telecommunication containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.
Radio Blackout	During a large space weather event the ionosphere may absorb high frequency radio waves instead of reflecting them. This causes problems with communication systems
<i>Severe (as used in ICAO Space Weather Advisories)</i>	Guidance on the definition of “Severe” as used in ICAO Space Weather advisories is provided in the Manual on Space Weather Information in Support of International Air Navigation (Doc 10100).
Sievert (Sv)	The sievert (Sv) is the SI derived unit of radiation dose. Quantities that are measured in sieverts are designed to represent the stochastic biological effects of ionising radiations.
Solar Cycle	The 11-year periodic change in the sun’s activity including changes in the levels of radiation and solar wind emitted
Solar Flare	A brief powerful eruption of particles and intense electromagnetic radiation from the Sun’s surface
Solar Radiation Storm	Interactions between charged particles (predominantly protons and electrons) and the Earth’s magnetic field. The charged particles originate from the sun following a solar flare or coronal mass ejection, and travel at 1/3 the speed of light
Solar Wind	The outward flow of charged particles (primarily electrons and protons) from the sun
Space Weather	Describes conditions in space that can have an effect on earth
Space Weather Advisory	An advisory issued by an ICAO Space Weather Centre providing information regarding the extent, severity and duration of space weather phenomena that have a potential impact on high frequency (HF) radio communications; communications via satellite; GNSS-based navigation and surveillance; and radiation exposure at flight levels
Space Weather Centre	<p>A centre designated by ICAO to monitor and provide advisory information on space weather</p> <p>phenomena expected to affect high-frequency radio communications, communications via satellite, GNSS-based navigation and surveillance systems and/or pose a radiation risk to aircraft occupants.</p> <p><i>Note: A space weather centre is designated as global and/or regional.</i></p>

Abbreviations

Abbreviations	
ATS	Air Traffic Services
CME	Coronal mass ejection (Solar Flares)
ESA	European Space Agency
HF Comms	High Frequency communications
MOSWOC	Met Office Space Weather Operations Centre
mrem	Millirem
mSv	Millisievert
NOAA	National Oceanic and Atmospheric Administration
SWPC	Space Weather Prediction Centre (NOAA)
SWX	Space Weather
SWXC	Space Weather Centre
UKSA	UK Space Agency

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 and space weather impacts are managed routinely by relevant industries such as the communications industry. But generally, the day-to-day variation in space weather has a negligible impact to users of technology or to humans generally. However, on average several times in each solar cycle of 11 years space weather can have an 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 were placed on the UK National Risk Register (NRR) in 2015 [latest version Cabinet Office, NRR 2017] 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 aviation sectors 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 aviation sectors 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 ([Statutory Instrument Air Navigation \(Cosmic Radiation: Protection of Air Crew and Space Crew and Consequential Amendments\) Order 2019, issued July 2019, refers](#)).

This document replaces IN 2013/089 following the publication of several 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; with space weather more dynamic on some days than others. Minor space weather is relatively common, whereas severe events due to solar superstorms are rare, occurring 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 and depending on the source location on the Sun can take as little as 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.

Space weather forecasts can provide a probabilistic estimate of its likelihood, severity and impact a few hours to a few days in advance.

During minor space weather events impacts can be experienced at all latitudes but are likely to be more intense at high and equatorial latitudes. During stronger events more intense impacts may also be experienced at mid-latitudes.

Very rarely (currently estimated to be between 1 in 100 or 200 years) severe space weather occurs. Severe space weather has the potential to significantly disrupt the air

transport systems over the entire globe. It is not possible to deterministically predict when the next event will occur.

The largest recorded example of space weather is known as the Carrington Event which occurred in 1859. It was associated with a large solar flare and the associated CME took only 17.5 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 was that the telegraph systems across the world misbehaved with operators able to receive messages despite having disconnected their power supplies. In our increasingly technologically dependent world the contemporary impact is likely to be wide ranging with impacts on various critical systems.

Chapter 4

Space weather impacts

Introduction

Space weather affects a plethora of systems important to the aviation industry and some of the consequences of a severe 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 a severe event both HF and satellite communications may be lost simultaneously with degraded or lost GNSS derived timing and navigation.

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

The sections below provide an overview of the potential effects of space weather on key aviation systems as well as potential effects to aircraft passengers and crew. At the end of the chapter there are summaries of real space weather events and the impacts that were experienced.

Electrical power distribution and generation

Ground electrical power generation and distribution networks are at risk during severe events, as a consequence of the geomagnetic storm, through 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 GNSS supports. [The Blackett Review](#) published by the Government Office for Science provides further reading on the dependency on GNSS of many critical services including aviation.

However, while GNSS is often the primary means of navigation, it is generally not the sole means and consequently if the GNSS signal is lost other systems (conventional navigation aids or inertial reference systems) or procedures maintain continued safe operation, albeit with reduced air traffic management (ATM) efficiency. Where inertial reference systems are not available it is recommended that procedures to follow in the event of loss of GNSS signal are reviewed (for example it is noted that inertial reference systems are not widely used in business jets).

Space weather globally modifies the ionospheric electron density and gives rise to spatial and temporal gradients. At low and high latitudes small irregularities are also formed that cause amplitude and phase signal variations, known as scintillation. During major events the irregularities may extend over a substantial part of the globe for several days. Electron density gradients and the scintillation give rise to GNSS navigation and timing errors and during strong scintillation the signal may be lost and the navigation and timing prejudiced.

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 thereby improving accuracy and these include integrity monitoring to reduce the likelihood of hazardous misleading information. However, 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 during major or severe space weather events.

For systems that use integrity monitoring, disruptions caused by space weather (or any other unintentional interference) normally result in loss of service rather than possibly hazardous misleading information. If the temporal or spatial gradients are too great they may not be detected by the integrity systems. However, integrity monitoring system providers have invested significant effort to minimise this risk.

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.

It is further noted that ATS Authorities may allow minimum aircraft separation levels to be reduced depending on the surveillance systems used and potential impacts to GNSS during a space weather event should be considered in the context of reduced separation levels which have been approved based on the use of systems that rely on GNSS information (for example surveillance systems that utilise ADS-B rely on information derived from GNSS).

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 because 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. Therefore, 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 and it is anticipated that these effects 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 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 have been mandated since 2017 for aircraft operating on the North Atlantic tracks at flight levels 350-390 and from January 2020 were mandated for aircraft operating above FL 290. Around 95% of aircraft operating across the North Atlantic are now equipped with data link capability.

The exceptions 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 have been launched into a polar earth orbit to provide whole Earth coverage.

For operators that adopt satcom through Inmarsat and Iridium this is not however a panacea for HF problems. 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 RF systems and this was apparent in 2015 (see Chapter 5, 2015 solar radio burst). On this occasion equipment unexpectedly malfunctioned during a space weather event, while other similar

equipment continued working. In this case a long duration solar flare caused enough interference to overwhelm ground-based ATC equipment in Southern Sweden for several hours.

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 an altitude of about 18 km and are then progressively attenuated by the atmosphere so that only the most penetrating component can be measured on the ground.

A significant space weather event may cause people on the ground to receive an unusual radiation dose, though it would be far too small to produce an observable health effect. Those flying in planes during a space weather event would be likely to receive a higher radiation dose – typically, at aircraft cruising altitudes the flux of ionising radiation is ~300 times higher than at sea level but it is extremely unlikely to produce adverse health effects for individuals who are exposed. The radiation doses people receive will be dependent on where they are on the planet, how big an event it is, how long it lasts and other factors, with altitude and proximity to the magnetic poles being key factors. For example, for flights operating further north or south, and for those flying polar routes, there is more exposure to ionizing radiation due to the Earth's magnetic field directing solar particles toward the North and South poles. However, during stronger events increased exposure may also be experienced at mid-latitudes. It should be noted that the radiation doses people receive in-flight may only be able to be determined after the event.

Note: The potential health effects of ionising radiation exposure are well known (see Appendix A for further reading), and operators are already required to monitor the occupational exposure of aircrew to cosmic radiation ([Statutory Instrument Air Navigation \(Cosmic Radiation: Protection of Air Crew and Space Crew and Consequential Amendments\) Order 2019](#)), and additional requirements for measuring dose rate of cosmic radiation by aircraft operating above 49 000 FT are included in ICAO Annex 6 Operation of Aircraft, Part 1).

[UK Government guidance on space weather and radiation](#) also notes that it is possible that a solar storm could produce higher than usual radiation dose rates with increased doses sometimes measurable at sea level. These so-called ground level enhancements (GLE) are not uncommon, but when an elevated dose rate is measured at ground level the increase at aircraft altitude is more marked. Since 1942, when records began, there has been on average about one GLE per year, with most occurring around solar maximum. However, only a few of these would have produced significantly increased dose rates for aircrew and passengers and for example, none would have significantly altered individual's lifetime risk of cancer. Government notes that the direct impact on public health from an increased radiation environment is assessed to be small (Cabinet Office 2015, Space Weather Preparedness Strategy).

Note: Radiation doses to people that might cause chronic (long-term) effects such as cancer, are measured in units called sieverts (Sv), though exposures are normally at thousandths of this level (mSv) or even millionths (μ Sv). Public Health England and its predecessor bodies have produced regular reviews of the average dose of radiation to which the UK public is exposed. The average is about 2.7 mSv per year – and some 14 per cent of that is attributed to exposure to cosmic radiation.

The table below shows the mean effective radiation dose in mSv for selected air routes and altitudes for the period January 1958- December 1997 (Baily, S. Air crew radiation exposure-An overview. Nuclear News, January 2000.)

Origin- Destination (one way)	Highest Altitude (ft/1000)	Air Time (h)	Block Hours	Effective dose (mSv)	mSv per 100 block hours
New York NY – Tokyo JP	43	13	13.4	.067	0.50
Athens GR – New York NY	41	9.4	9.7	.058	0.60
Los Angeles CA – Tokyo JP	40	11.7	12	.038	0.32
London GB – Dallas/Ft. Worth TX	39	9.7	10.1	.039	0.38
Lisbon ES – New York NY	39	6.5	6.9	.027	0.40
Tokyo JP – Los Angeles CA	37	8.8	9.2	.030	0.33
Los Angeles CA – Honolulu HI	35	5.2	5.6	.0129	0.23
Miami FL – Tampa FL	24	0.6	0.9	0.00034	0.04
Seattle WA- Portland Or	21	0.4	0.6	0.00014	0.02

Public Health England (PHE)³ are leading a group of experts (The Cosmic Radiation Advisory Group⁴ - CRAG) on the development of a report on the public health implications of severe space weather and the report will advise on measures to protect the public from radiation hazards. CRAG have 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 risk of developing cancer of about one in two (50%), and the fact that more than one in four (28%) of all annual UK deaths are caused by cancer [<https://www.cancerresearchuk.org/health-professional/cancer-statistics/mortality/all-cancers-combined>]. In conclusion CRAG considers that an individual dose of 20 mSv experienced during a reasonable worst case extreme space weather event to be an insignificant additional risk.

³ In August 2020 the UK Government announced that Public Health England would become part of the new National Institute for Health Protection which is to be formalised and operational from Spring 2021.

⁴ CRAG includes: British Airways, British Airlines Pilots Association, Cabinet Office, CAA, Department for Transport, Department of Health, Health and Safety Executive, independent experts, Met Office, NATS, National Physical Laboratory, SolarMetrics, Science and Technology Facilities Council RAL Space, University College London, University of Surrey.

Once published, PHE have indicated that public communication plans may need to be revised in line with the report's recommendations. Although PHE would issue public information relating to an event, industry should also consider their own communication plans for an event given the potential concerns about the health implications of radiation, especially from those who are considered to be at greater risk, such as pregnant passengers and crew. Consideration should be given to the fact that the ability to assess the level of exposure to crew and passengers is severely limited, for example, it is very difficult to accurately extrapolate from satellite measurements to aircraft altitudes and the most reliable approach for measuring on-board radiation is to employ on-board (aircraft) sensors.

Aircraft electronic systems

The same particles which cause radiation to effect 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 avionics systems are 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. As it is currently not possible to state that full protection against all solar energetic particles can be assured, because of the low frequency of events and insufficient data being available to accurately model such an event, 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 [SIB No 2012-09 Effects of Space Weather on Aviation].and a Certification Memorandum (CM No.: CM-AS-004 Issue 01 issued 08 January 2018 - Single Event Effects (SEE) Caused by Atmospheric Radiation Certification Considerations and an

Analysis Method to Demonstrate the Acceptability of Effects on Aircraft, Engine, APU and Propeller Systems and Equipment, caused by Atmospheric Radiation).

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 because of ageing effects.

Mitigation against space weather impacts

Although space weather forecasting skills and capabilities are continuously improving, the current scientific and monitoring capability does not yet allow reliable forecasts or real-time alerts and the limited ability to accurately predict the time, duration and intensity of events precludes effective operational mitigation based on space weather forecasts. This means that the only feasible in-flight protection is to reduce altitude when an extreme event starts, and this approach is considered in further detail below. Mitigation also needs to be considered for flights not yet airborne, and for aircraft that were operational during a space weather event. It is recommended that operators clarify with manufacturers what, if any, checks may need to be carried out if aircraft have been operational during a Space Weather event, similar to the checks that may be required following a lightning strike incident.

The consequences as well as the benefits of mitigation strategies should be weighed as part of the risk assessment conducted to assess the effectiveness, and safety, of protective actions i.e. actions incorporated during pre-flight planning, actions taken in-flight, and post flight checks.

For example, operational flight level changes mid-flight intended to reduce the risk of exposure during severe solar weather events (approximately 30% reduction in exposure per 1000 m of altitude reduction) must be assessed against the resulting hazards posed by this action, such as potential traffic conflicts arising from descent through busy traffic lanes; the associated risks of which are further compounded if ATC receive requests from multiple aircraft to descend, which could be expected during a severe space weather event. The hazards related to this scenario are further increased if multiple aircraft have lost communication with ATC, which is one of the impacts that is most likely to be experienced during a severe space weather event, and a pilot, or pilots, take a decision to carry out uncleared emergency descents through flight levels which are potentially

occupied by under-flying aircraft (operators should ensure that flight crews are familiar with the guidance contained in their contingency plans for loss of communication with an oceanic ATC facility).

Aircraft Intending to operate above 49000ft

ICAO Annex 6 (Part I, Chapter 6) requires aircraft intending to fly above 49000ft (15000m) to carry equipment to measure and indicate continuously the dose rate of total cosmic radiation being received, and Annex 6, Appendix 2 requires that operations manuals contain information which will enable the pilot to determine the best course of action to take in the event of exposure to solar cosmic radiation and procedures in the event that a decision to descend is taken, covering:

1. the necessity of giving the appropriate ATS unit prior warning of the situation and of obtaining a provisional descent clearance; and
2. the action to be taken if communication with the ATS unit cannot be established or is interrupted.

Appendix 2 notes that guidance material on the information to be provided is contained in Circular 126 — Guidance Material on SST Aircraft Operations. Circular 126 includes guidance to pilots on actions that could be taken should the total on-board radiation reach 50 mrem/h (approximately 0.5 mSv/hr).

One action noted in Circular 126 would be for pilots to request clearance to descend to a level where the total radiation dose would not be greater than that to which the occupants of a subsonic aircraft on the same route could be expected to be exposed, and that they should descend only upon receipt of clearance to do so. To enable pilots to make effective decisions on whether a request for a descent *intended to reduce exposure to radiation* would be justified Circular 126 includes an operational requirement for supersonic aircraft to be equipped with an airborne radiation detection device to indicate readily to the flight crew the dose rate of cosmic radiation (ionizing and neutron) and the cumulative dosage throughout each flight. If pilots of supersonic aircraft were unable to contact ATC, ICAO notes that it is not considered that the risk associated with a dose rate in excess of 50 mrem/h (approximately 0.5 mSv/hr) justifies an emergency uncleared descent to or through a flight level occupied by under-flying aircraft.

Aircraft not Intending to operate above 49000ft

Most commercial aircraft do not operate above 49000ft and do not carry equipment to measure and indicate the dose rate of total cosmic radiation. For aircraft without the ability to measure on-board radiation a pilot would need to consider on what basis a request to descend *for the purposes of reducing radiation exposure* would be made e.g. for aircraft operating without a radiation detection device the pilot would not have access to an accurate indication of radiation levels on-board on which to inform a decision to descend (*for the specific purpose of reducing radiation exposure on-board*). For example, in radiation protection it is very important that the period of time over which a radiation dose

may be received is known and hence it is very important to clearly identify the units of dose per unit time for any exposure situation.

However, if pilots do request a descent to a lower level during a space weather event, air traffic controllers should take all reasonable measures to accommodate such requests, and controllers should be aware that on rare occasions pilots encountering severe space weather may initiate an emergency descent without waiting for a clearance (For further information see Manual on Air Traffic Services - MATS Part 1, ICAO Annex 6 and PANS-ATM). In such cases, pilots are expected to select transponder code A7700 and advise air traffic control units of the action taken as soon as possible. During the emergency descent pilots will be responsible for separation and collision avoidance.

Impacts experienced during 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 approximately seventeen 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 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 worst 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. Typically, less intense CMEs can take several days to reach Earth, but more severe CMEs are likely to reach Earth far more quickly, such as occurred during the Carrington event, meaning that there would be limited notice of a severe event and therefore limited time to implement mitigation measures.

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 because 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 significant 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 also 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 solar radio burst ever recorded. It was also the first recorded incident of a radio burst affecting GPS reception. In some locations GPS navigation was unavailable for approximately 30 minutes, with some aircraft reporting loss of lock.

2015 solar radio burst

On the afternoon of 4 November 2015, an intense solar radio burst caused extensive interference to air traffic control radars in Europe, generating many false echoes in radars in Belgium, Estonia and Sweden. In southern Sweden, these echoes caused the ATC system to shut down for several hours, severely disrupting flights in Swedish airspace.

Chapter 5

Probability of occurrence

Introduction

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

Note: The use of the category “Severe” in the assessment tables below is different to the use of “Severe” as used to indicate the intensity of an event in ICAO Space Weather Advisories. Guidance on the ICAO use of “Severe” can be in the ICAO Manual on Space Weather Information (Doc 10100).

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 3 to 5 years after solar minimum, 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 tends to occur more frequently in the 8 or so years straddling solar maximum, although significant events have occurred near solar minimum.

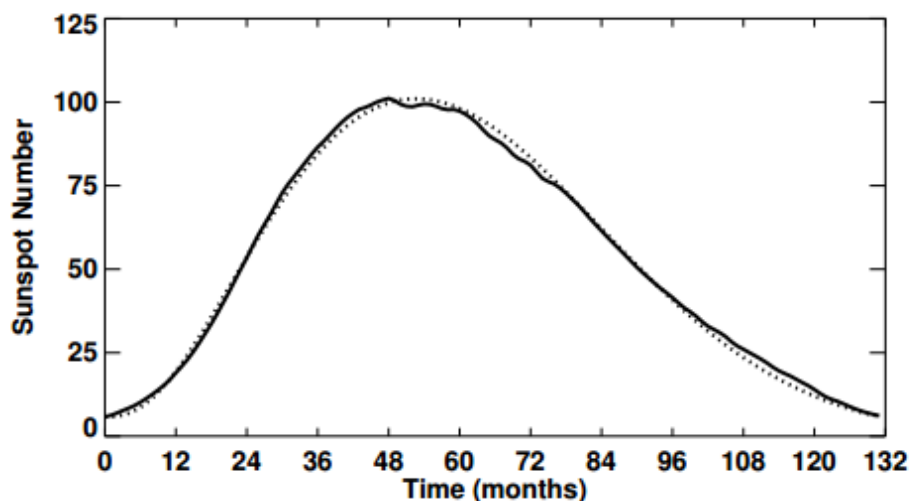


Figure 1: Average solar cycle [Hathaway 2010]

Solar flares (radio blackouts – X-ray flares)

Category	Aviation impact	Probability (outside of solar minimum)
Severe	<ul style="list-style-type: none"> ▪ 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	<ul style="list-style-type: none"> ▪ HF radio communication blackout (due to absorption) on the sunlit side of Earth for one to two hours. 	At least once per year
Minor	<ul style="list-style-type: none"> ▪ 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)
Severe	<ul style="list-style-type: none"> ▪ 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 radiation dose limits for crew and passengers. ▪ HF communications blackout in the polar cap regions. ▪ Contribution to loss of up to 10% of the satellite fleet 	~ 1 in 100 years

Category	Aviation impact	Probability (outside of solar minimum)
Significant	<ul style="list-style-type: none"> ▪ 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 advisable radiation dose limits 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
Minor	<ul style="list-style-type: none"> ▪ No significant effect. 	~ 3 or 4 days per year

Geomagnetic storms

Category	Aviation impact	Probability (outside of solar minimum)
Severe	<ul style="list-style-type: none"> ▪ 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 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. 	~ 1 in 100 years

Category	Aviation impact	Probability (outside of solar minimum)
	<ul style="list-style-type: none"> ▪ Potential disruption to the electricity network due to ground induced currents (GICs), with possible consequences for air traffic control infrastructure. 	
Significant	<ul style="list-style-type: none"> ▪ 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
Minor	<ul style="list-style-type: none"> ▪ HF communications need managing. ▪ Otherwise no significant effect. 	~ 100 days per year

Chapter 6

Observing and forecasting space weather

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. The size and complexity of active regions are used by responsible organisations to inform Governments that they should be prepared for the possibility of a significant space weather event. Flares can be monitored and can be related to their likely impact.

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 enhancement (GLE). Again, these measurements are important because, as previously noted it is very difficult to extrapolate from satellite measurements to aircraft altitudes, and therefore ground based monitoring enables government agencies to advise airlines on the risk.

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 initially whether a CME is earth directed and are used as inputs to forecast models which predict the CME arrival time. L1 observations are critical to understanding the orientation of the embedded magnetic field, as the CME passes through L1, indicating whether the CME's magnetic field will couple with the Earth's magnetic field to produce system impacts, or not. 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 before the potential onset of significant impacts.

The effects of the solar flares, the radiation storm and the geomagnetic storm on the ionosphere are monitored using networks of ionosondes, GNSS receivers 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

CAP1428, Chapter 7 notes that industry should develop Safety Risk Assessments within their SMS covering space weather hazards and provides a list of activities that operators are recommended to review to ensure that effective procedures and mitigations are in place should a space weather event occur. One recommended activity is to consider how the organisation would respond if notification was received of a forecast space weather event, and what action would be taken.

Notification of a space weather event could occur through the receipt of an ICAO Space Weather Advisory or, for those that have registered to receive them, by receipt of a Met Office Space Weather Alert, and/or by reference to the daily Met Office Space Weather forecast service. It is recommended that organisations should review procedures for receiving and, promulgating ICAO Advisories and Met Office Alerts and forecasts.

There are some differences between ICAO Advisories and Met Office products, but both are important tools enabling organisations to better respond to a space weather event. ICAO Advisories are likely to be only issued when an event occurs but will provide detail on where impacts may be experienced. The Met Office will issue similar alerts but also provide a four-day outlook indicating the probability of events occurring supported by comprehensive technical detail.

However, it should be noted that currently global forecasting capability is still largely 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 must 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 arrival.

To make effective use of ICAO Advisories and Met Office products it is necessary for organisations to be able to correctly interpret the information they provide to assess the likely impacts to their operations and it is recommended that operators consider any requirements for general space weather training, provided by the Met Office or other suitable training providers.

Details regarding the ICAO Space Weather Advisory Service and Met Office Products and Services are provided below.

Met Office Space Weather Products and Services

The Met Office has developed in cooperation with overseas agencies, academia, the Ministry of Defence and industry, a UK national capability for space weather forecasting. An overview of the Met Office Space Weather Operations Centre can be found at <https://www.metoffice.gov.uk/weather/learn-about/space-weather, including:>

- What is space weather?

- Space weather impacts.
- Measuring the impact.
- Space weather publications.

Aviation stakeholders wishing to register to receive automated Met Office space weather alerts and warnings and to view specialised forecasts, (including the probability that risks will be exceeded (exceedance risks) of geomagnetic storms, radio blackouts and solar radiation), can do so via the Met Office website.

<https://register.metoffice.gov.uk/WaveRegistrationClient/public/register.do?service=space-weather>

Additionally, public access to daily space weather bulletins are provided at

<https://www.metoffice.gov.uk/weather/specialist-forecasts/space-weather>

ICAO Space Weather Information Service

The provision of space weather advisory information was introduced into ICAO Annex 3 (Meteorological Service for International Air Navigation) following Amendment 78, which established the concept of global weather centres to provide space weather advisories.

Space weather advisories will be disseminated through the aeronautical fixed network in cases of moderate or severe impacts of space weather phenomena, with respect to high-frequency (HF) communications, global navigation satellite system-based (GNSS) navigation and surveillance, satellite communications and potentially increased levels of radiation aboard aircraft.

The global service is provided 24/7 by those States which have accepted the responsibility to provide three, ICAO designated, global space weather centres, namely, the **ACFJ consortium** (comprising Australia, Canada, France and Japan), the **PECASUS consortium** (comprising Austria, Belgium, Cyprus, Finland, Germany, Italy, Netherlands, Poland and the United Kingdom), and **the United States**. The service will be provided by the three centres on a rotating basis.

When necessary, space weather advisory information will be supplied to area control centres, flight information centres, aerodrome meteorological offices, international operational meteorological (OPMET) databanks, international NOTAM offices and aeronautical fixed service Internet-based services.

Additionally, in accordance with Annex 3 (Chapter 9, Service for Operators and Flight Crew Members) space weather advisory information relevant to the whole route shall be supplied to operators and flight crew members as part of their meteorological information used for pre-flight planning, in-flight re-planning, centralized operations centres, and flight crew members before departure.

PANS-ATM Doc 4444 contains provisions for the transmission of space weather activity information which requires ATS units to transmit space weather advisories to affected

aircraft and requires information on space weather phenomena that have an impact on high frequency radio communications, communications via satellite, GNSS-based navigation and surveillance systems, and/or pose a radiation risk to aircraft occupants at flight levels within the area of responsibility of the ATS unit, to be transmitted to the affected aircraft by either a direct transmission, a general call, a broadcast or via data link.

ICAO has also now issued the “Manual on Space Weather Information in Support of International Air Navigation” (Doc 10100) and the “Manual of Aeronautical Meteorological Practice” (Doc 8896) to provide guidance on the provision and use of space weather information.

Space Weather Advisories

Background

Since 7th November 2019, under the auspices of ICAO, a global space weather information service in support of international air navigation has been operational. This service provides space weather advisories which, when required to be issued, will be disseminated through the Aeronautical Fixed Service (AFS) including the Aeronautical Fixed Telecommunications (AFTN) and the Aeronautical Message Handling System (AMHS).

The service provides advisories for the following space weather related phenomena; HF Communications, GNSS-based navigation and surveillance, satellite communications and solar radiation that impacts systems, crew and passengers aboard aircraft.

As noted elsewhere in the CAP, disturbances of the ionosphere can be caused through solar flares, coronal mass ejections, high speed solar wind storms and high energy solar particles. Additionally, when the energy is exceptionally high, may also interact with atmospheric particles and trigger secondary ionising particle cascades which can increase radiation levels on board aircraft.

The change from daylight to night can also cause ionospheric disturbances which may affect equatorial or near equatorial regions.

Technical details regarding Space Weather Advisories can be found at Appendix A.

Chapter 7

Safety Risk Assessments for Space Weather

Introduction

ICAO's generic safety risk assessment process is described in the Safety Management Manual (SMM) (Doc 9859). The CAA Publication CAP 795 (Safety Management Systems - SMS) provides guidance on implementing SMS which meet the requirements contained in applicable ICAO Annexes and EU Implementing Regulations. However, an approach aligned with an operator's Safety Management System (SMS) would be equally appropriate. The material in CAP1428 is designed to provide information to support operators in developing their safety risk assessment (SRA) within their SMS, covering the space weather hazard.

When undertaking a safety risk assessment (SRA) each operator should develop its own list of procedures and hazards since these must be relevant to the specific equipment, experience and knowledge of the operator, and to the route profile. For example, an approach similar to the way in which operators developed volcanic ash SRAs following the Icelandic volcanic in 2010 (the Eyjafjallajökull eruption). However, it should be noted that a space weather SRA would need to take in to account the fact that space weather forecasting skills and capabilities are less developed than those for forecasting the presence of volcanic ash.

The operator should complete the SRA as part of the SMS before initiating operations when space weather is present or forecast to be present. During its normal oversight of its operators, the CAA will evaluate the SRA as an identifiable process of the operator's SMS.

An operator should have satisfied the CAA regarding the likely accuracy and quality of the information sources it uses in its SMS and its own competence and capability to interpret such data correctly and be able to reliably and correctly resolve any conflicts that may arise among data sources.

The operator should revise its SRA when changes occur that are material to the integrity of the assessment.

The operator's SRA should take into account data published by the relevant Type Certificate Holders (TCH) regarding the susceptibility of the aircraft to airworthiness effects to space weather especially those relating to increased electromagnetic radiation levels i.e. consideration should be given to potential failure modes for on board systems as a result of electromagnetic interference. The SRA should also include the nature of these effects and the related pre-flight, in-flight and post-flight precautions to be observed by the operator.

The operator should ensure that personnel needing to be familiar with the details of the SRAs receive all relevant information (both pre-flight and in-flight) to be able to apply

appropriate mitigation measures as specified by the SRA, especially when the situation deviates from any scenario that has not previously been contemplated.

In fulfilling its primary responsibility for the safety of operations, operators are dependent on the Type Certificate Holders (TCH) for the equipment it operates. TCH's should ensure that operators have all the information needed to inform their SRA for operations when there is a space weather event in progress or is forecasted.

SRAs sometimes have to use qualitative information (expert judgement) rather than quantitative data due to unavailability of data. Using the safety risk matrix allows the user to express the safety risk(s) associated with the identified hazard in a quantitative format. This enables direct magnitude comparison between identified safety risks. A qualitative safety risk assessment criterion such as "likely to occur" or "improbable" may be assigned to each identified safety risk where quantitative data is not available.

Guidelines for Completing a Safety Risk Assessment

Risk is an assessment of the probability and severity of adverse consequences resulting from a hazard. To help an operator to decide on the probability of a hazard causing harm, and to assist with possible mitigation of any perceived safety risk, all pertinent information available should be considered and relevant stakeholders consulted.

Firstly, the hazards related to space weather should be identified, this includes loss of communications, potential failures of avionics and increased radiation exposure by passengers and crew. An assessment of an operator's crisis management plan should be undertaken to ensure that the significant disruption from such an event is included in plans especially those related to communications of the hazard to employees and passengers.

For the different space weather scenarios, the operator should consider the seriousness of the above effects occurring. This should include evaluating the probability of encountering space weather related phenomena which may be considered harmful to the safe operation of the aircraft and by determining whether the consequent risk is acceptable and within the organization's risk performance. Where necessary the operator should prioritise any actions that will reduce the safety risk to a level that is acceptable to the operator's Accountable Manager.

The process should assess the following:

Hazard Identification

Operators are encouraged to make use of tools and techniques for undertaking this work, it should be noted that aviation is a complex system of technical and human centred systems (Airlines, Airports, ANSPs etc.) and for that reason all hazards including those affecting environment, people, procedures & equipment should all be reviewed for potential space weather impacts.

Note: The CAA publishes guidance on the use of [the bowtie model](#) to build up the risk picture which revolves around a hazard. The CAA worked with industry to create two space weather bowties which may assist operators when assessing space weather hazards. The two space weather bowties can be found on the [CAA public website](#) (1.4 Loss of Control Large Commercial Air Transport and 5.4 Airborne Conflict Large Commercial Air Transport)

Risk Severity and Probability

For each of the different space weather scenarios a risk severity assessment should be undertaken, operators should consider the potential risk and its likelihood of occurrence, noting that risk assessments should include an assessment of risks that are very infrequent but have a potentially large impact on their operation and on the network in general. Work is being undertaken by the Governments Space Environment Impact Expert Group (SEIEG) which is working on detailing the likely impacts of a reasonable worst-case space weather event.

Risk Tolerability

Each operator should assess the level of risk that they are prepared to accept and be able to justify this assessment, this assessment should also consider other stakeholders risk tolerance, i.e. airport operators and air navigation service providers with an understanding of the likely mitigations that they may put in place.

Risk Mitigation

Such an assessment needs to establish the types of mitigation that can be undertaken on a hazard that is relatively poorly understood and has uncertain impacts. Operators should use whatever safety data and safety information is available on this topic especially that provided from original equipment manufacturers, noting that some of the information may not be in the public domain.

CAA Oversight of Safety Risk Assessment

As part of the CAA's oversight activities the CAA will when necessary review Safety Risk Assessments. The bullet points and questions below are provided as guidance on aspects of an organisation's Safety Risk Assessment that are likely to be reviewed during regulatory oversight:

Safety Risk Assessments

- Confirm that all existing procedures for Risk Evaluation have been followed
- Was a comprehensive hazard identification and consequence identification carried out (did the operator use a standard hazard identification process?)

- Have all hazards and their consequences been recorded, e.g. in the form of a risk register? (for example, loss of communications, loss of avionics, simultaneous impacts to multiple aircraft, flight plan changes, impacts to the availability of procedures affecting diversion aerodrome suitability, and potential impacts to passenger and crew health)
- Have all indirect impacts been assessed? (for example, impacts at ground level could result in power black outs and back-up power at aerodromes may only be sufficient to 'clear the skies')
- Have the cumulative effects been assessed?
- Have human performance related hazards been included?
- Were all potentially impacted teams assessed during the evaluation (have they all subsequently been involved in mitigation of the risk?)
- Is there a process in place for regularly reviewing the Safety Risk Assessment?
- If/where necessary, has the organisation updated their Safety Management/Management System to include appropriate references to Space Weather? For example:
 - Updated operations and engineering manuals and procedure documents for moderate and severe Space Weather events as required;
 - Updated Operations Control Centre procedures for both dispatch and flight following during Space Weather events as required;
 - Procedures for management of routine Space Weather events (e.g. HF/SBAS impacts).

Note: It is recommended that where relevant procedures consider, and make applicable reference to, NATS planning assumptions and NATS procedures for space weather events.

Contingency Arrangements

- Would existing corporate and/or departmental crisis management plans be effective during a space weather event?
- Do Operators include Space Weather in their potential crisis management scenarios?
- What resources have been allocated to managing crises?

- If applicable, how would operators ensure that flight crews are familiar with guidelines contained in relevant contingency plans? (such as for loss of communication with an oceanic ATC facility e.g. see UK AIP, En-Route section, Failure of Radio Communication and ICAO ATM Operational Contingency Plan – North Atlantic Region (Doc 006).
- If necessary, do flight crew operating procedures include emergency procedures specific to a space weather event?

Staff briefing/training

- Are organisations, and relevant staff, aware of CAP1428 Impacts of Space Weather on Aviation?
- Has the operator reviewed any requirements for general space weather training? E.g. in accordance with The Air Navigation (Cosmic Radiation: Protection of Air Crew and Space Crew and Consequential Amendments) Order 2019.
- Have Operators researched space weather briefings or training courses available from the Met Office or other suitable providers?
- Has the organisation reviewed procedures for receiving, promulgating and responding to Space Weather information? (ICAO Space Weather advisories and Met Office Space Weather alerts and forecasts).
 - Including arrangements to make space weather information relevant to the whole route available to flight crew members, and
 - Suitably informing, or reminding, flight crew of
 - NATS procedures for loss of communication, and
 - ICAO Annex 6 and Circular 126 guidance on requesting a descent with the intention of reducing exposure to radiation

Operations Centres

- What will the operator do when they receive an ICAO Space Weather Advisory? (are they receiving the test messages)
- Has the operator checked that their staff understand how the organisation will respond to a Space Weather event?

- Have Operators discussed with NATS their procedures for loss of communications especially for those who operate North Atlantic flights?
- Have operators suitably informed, or reminded, flight crew of NATS procedures for loss of communications?

Equipment and Maintenance

- If necessary, has the operator clarified with original equipment manufacturers what are the specifications for the operating limitations to which approved equipment has been manufactured in relation to protection against cosmic radiation, for example protection of electronic systems, particularly flight-critical and flight-essential systems, against potential electromagnetic interference.

Note: To make best use of ICAO Space Weather Advisories and Met Office forecast products it would be necessary for organisations to effectively assess and understand this information in relation to equipment specifications and the likely impacts e.g. potential impacts to avionics during a space weather event.

- How would flight crew determine when cosmic radiation operating limitations have been exceeded in-flight? (is this information contained within the flight manual).
- Do existing inspection provisions require any examinations after aircraft have been operational during a severe space weather event (if necessary, has the operator clarified with OEMs what, if any, checks may need to be, or are recommended to be, carried out).
- Does the maintenance procedure manual require that routine full power-down of aircraft is carried out (has the operator considered consulting with OEMs to assess whether it would be recommended to carry out a full power-down of aircraft, or carry out other tasks, on aircraft that have been operational during a Space Weather event e.g. based on any issues highlighted in the technical log)?

Crew and Passenger Welfare

- How would the operator capture the potential increase in radiation levels experienced by crew arising from a solar storm in radiation monitoring systems?

- Have the effects of a severe space weather event related to crew rostering been assessed? (although the assessment of resource levels and rostering is recognised as a business as usual activity there is the potential for specific impacts during a space weather event).
- Are operators aware of the requirements included in The Air Navigation (Cosmic Radiation: Protection of Air Crew and Space Crew and Consequential Amendments) Order 2019, including the requirements to:
 - carry out new risk assessments if the operator has reasonable cause to believe that a crew member has received an overexposure while performing their duties on board an aircraft or space craft?
 - take into account assessed exposure when organising work schedules?
 - ensure that all crew members are given adequate and appropriate training and information about radiation and exposure risks;
 - be aware of the regulations relating to continued working of overexposed aircrew, and
 - to notify the CAA of overexposure.

Chapter 8

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.

Notwithstanding that certain aviation technologies routinely adapt to space weather impacts (e.g. HF Comms and GNSS) a number of technologies critical to the aviation industry are still vulnerable to extreme space weather and these vulnerabilities are likely to increase with time as technology becomes more sophisticated.

The probability of a Carrington type extreme space weather event is extremely low but because the hazard posed, is high industry should consider how to deal with the potential impacts of such an event given the likelihood of little or no warning.

While it is noted that mitigations are in place for many individual technologies, organisations need to note that during an extreme space weather event several 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 9

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), and 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 whether a solar superstorm will occur, but *when* it will occur.

APPENDIX A

ICAO Space Weather Advisories

Space weather effects are classified in Space Weather Advisories as

- HF radio communications (HF COM),
- Satellite communications (SATCOM),
- GNSS based navigation and surveillance (GNSS) or
- Radiation at altitudes (RADIATION).

The intensity of space weather phenomena in the advisories may be moderate (MOD) or severe (SEV). Guidance on the definition of “MOD” and “SEV” as used in Space Weather advisories is provided in the ICAO Manual on Space Weather Information in Support of International Air Navigation (Doc 10100).

Each of the advisories address OBS (Observed) and FCST (Forecast) effects at T, T+6, T+12 and T+24, and will be updated at least every 6 hours until the space weather event is no longer expected to have an impact.

Affected geographic areas are referenced by their latitudes and longitudes and flight levels for radiation. Abbreviations are used as follows

HNH High latitudes Northern Hemisphere (N9000- N6000)

MNH Mid latitudes Northern Hemisphere (N6000- N3000)

EQN Equatorial latitudes Northern Hemisphere (N3000- N0000)

EQS Equatorial latitudes Southern Hemisphere (S0000- S3000)

MSH Mid latitudes Southern Hemisphere (S3000- S6000)

Note, that the horizontal, vertical and temporal resolutions of the advisory are coarse using bands of 30-degree in latitude, 15-degree in longitude, 3,000-foot vertically (for radiation), and 6-hour time intervals. Therefore, the advisories may over or under forecast the affected airspace. For example, a region may be forecast to have MOD or SEV space weather, but this may not cover the entire region or may be intermittent or temporary. Users should refer to the remarks section of the advisory for additional information.

Space Weather Advisory Message:

A Space Weather Advisory Message has the following format:

1. WMO Header (FNXX01, WMO location indicator, UTC date-time of issue of the message)
2. SWX ADVISORY (message type)

3. STATUS (either test (TEST) or exercise (EXER) if required)
4. DTG (Time of Origin - Year/month/date/time in UTC)
5. SWXC (name of Space Weather Centre)
6. ADVISORY NR (advisory number; unique sequence for each space weather effect: HFCOM, GNSS, RADIATION, SATCOM)
7. NR RPLC (number of the previously issued advisory being replaced)
8. SWX EFFECT (effect and intensity of space weather phenomenon)
9. OBS (or FCST) SWX (Date and time (in UTC) and description of spatial extent of observed or forecast space weather phenomenon)
10. FCST SWX +6HR (Date-time (in UTC) of forecast spatial extent of space weather event)
11. FCST SWX +12HR (as above)
12. FCST SWX +18HR (as above)
13. FCST SWX +24HR (as above)
14. RMK (NIL or free text)
15. NXT ADVISORY (Year/month/date/time (in UTC) or NO FURTHER ADVISORIES)

The intensity of the space weather phenomena (field 8, SWX EFFECT) is based on various parameters and thresholds which are detailed in the ICAO Manual on Space Weather Information in Support of International Air Navigation (Doc 10100). For information regarding the potential impacts of space weather effects of varying intensity to aviation refer to the “Impact Tables” in Chapter 4.

EXAMPLES OF ADVISORIES

EXAMPLE 1 – HF COM MOD

```

FNXX01 YMMC 020100
SWX ADVISORY
DTG:                20190502/0054Z
SWXC:               ACFJ
ADVISORY NR:        2019/319
SWX EFFECT:         HF COM MOD
OBS SWX:            02/0054Z DAYLIGHT SIDE
FCST SWX + 6 HR:    02/0700Z DAYLIGHT SIDE
FCST SWX + 12 HR:   02/1300Z DAYLIGHT SIDE
FCST SWX + 18 HR:   02/1900Z NOT AVBL

```

FCST SWX + 24 HR: 03/0100Z NOT AVBL
 RMK: SOLAR FLARE EVENT IN PROGRESS IMPACTING HF COM ON
 DAYLIGHT SIDE. PERIODIC LOSS OF HF COM ONDAYLIGHT
 SIDE POSSIBLE NXT 12HRS.
 NXT ADVISORY: WILL BE ISSUED BY 20190502/0654Z=

Decode

Space weather Advisory issued at 0054 UTC on the 2nd May 2019
 Rostered Operational Space Weather Centre: ACFJ (Australia, Canada, France, &
 Japan Consortium). Advisory number 319 in 2019.

Moderate HF communications impacts have been observed at 0054 UTC on 2 May
 on the daylight side. Impacts are forecast to persist for the following 12 hours.

Detail of impact shows a solar flare event in progress, affecting HF communications
 on the daylight side. Periodic loss of HF communications on the daylight side
 possible for the next 12 hours.

The next advisory will be issued at 0654 UTC.

EXAMPLE 2 – RADIATION MOD

FNXX01 EFKL 190300
 SWX ADVISORY
 DTG: 20190219/0300Z
 SWXC: PECASUS
 ADVISORY NR: 2019/20
 SWX EFFECT: RADIATION MOD
 OBS SWX: 19/0300Z HNH HSH E18000-W18000 ABV FL370
 FCST SWX + 6 HR: 19/0900Z NO SWX EXP
 FCST SWX + 12 HR: 19/1500Z NO SWX EXP
 FCST SWX + 18 HR: 19/2100Z NO SWX EXP
 FCST SWX + 24 HR: 20/0300Z NO SWX EXP
 RMK: RADIATION AT AIRCRAFT ALTITUDES ELEVATED
 BY SMALL ENHANCEMENT JUST ABOVE PRESCRIBED
 THRESHHOLD. DURATION TO BE SHORT-LIVED
 NXT ADVISORY: NO FURTHER ADVISORIES=

Decode

Space weather Advisory issued at 0300 UTC on the 2nd May 2019 Rostered
 Operational Space Weather Centre: European space weather centre. Advisory
 number 20 in 2019.

Moderate radiation increase (effective dose of between 30-80 micro-Sieverts per hour) have been observed at 0300 UTC on 2nd May at high latitudes in the northern hemisphere (between 60-90 degrees North) and high latitudes of the southern hemisphere between (between 60-90 degrees South) and between 18W and 18E, above 37,000ft. Not expected to persist.

Detail of impact shows elevated radiation impacts to aircraft, just above 30 micro-Sieverts per hour, duration expected to be short lived.

No further advisories for this event will be issued.

EXAMPLE 3 – GNSS MOD

```

FNXX01 KWNP 020100
SWX ADVISORY
DTG:                20190502/0100Z
SWXC:               SWPC
ADVISORY NR:        2019/59
NR RPLC:            2019/58
SWX EFFECT:         GNSS MOD
OBS SWX:            02/0100Z HNH HSH E18000-W18000
FCST SWX + 6 HR:    02/0700Z HNH HSH E18000-W18000
FCST SWX + 12 HR:   02/1300Z HNH HSH E18000-W18000
FCST SWX + 18 HR:   02/1900Z NO SWX EXP
FCST SWX + 24 HR:   03/0100Z NO SWX EXP
RMK:                IONOSPHERIC STORM CONTINUES TO CAUSE LOSS-OF-LOCK
                   OF GNSS IN AURORAL ZONE. THIS ACTIVITY IS
                   EXPECTED TO SUBSIDE IN THE FORECAST PERIOD
NXT ADVISORY:       20190502/0700Z=

```

Decode

Space weather Advisory issued at 0100 UTC on the 2nd May 2019 by the United States Space Weather Prediction Center. Advisory number 59 in 2019, replacing advisory number 58.

Moderate Global Navigation Satellite System impacts have been observed at 0100 UTC at high latitudes in the northern hemisphere (between 60-90 degrees North) and 18W to 18E. This event is expected to persist for 12 hours.

Detail of impact shows an ionospheric storm causing loss of lock on GNSS in the Auroral Zone. This activity is expected to subside within 12 hours.

The next advisory for this event will be issued at 0700 UTC.

APPENDIX B

Further Reading

Further information on space weather and its effects may be gained from the following sources:

[Cabinet Office \(2017 edition\), National Risk Register of Civil Emergencies](#)

[Cabinet Office \(2015 Version 2.1\) Space Weather Preparedness Strategy](#)

[UK Met Office Space Weather Operations Centre](#)

[The European Space Agency \(ESA\)](#)

[United States National Oceanic and Atmospheric Administration Space Weather Prediction Centre](#)

Cannon, P. S., et al. (2013), Extreme space weather: Impacts on engineered systems - a summary *Rep.*, ISBN 1-903496-96-9, Royal Academy of Engineering, London, UK

[Government Office for Science: The Blackett Review for Science - provides further reading on the dependency on GNSS of many critical services](#)

[Hathaway D.H \(2010\) "The Solar Cycle", *Living Rev. Solar Phys.* 7.](#)

[British Geological Society.](#)

Clauer, C. R., and G. E. Siscoe (2006), The Great Historical Geomagnetic Storm of 1859: A Modern Look, *Adv Space Res.*, 38, 115-388.