Science & Technology Facilities Council

Technical Report

RAL-TR-2016-006

Summary of space weather worst-case environments. Revised edition.

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May 2016

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ISSN 1358-6254

Summary of space weather worst-case environments (revised edition)

Version 2.3: 25 April 2016, coordinated by Mike Hapgood (mike.hapgood@stfc.ac.uk)
on behalf of the UK Space Environment Impacts Expert Group

Scope of this document

Space weather may be described as disturbances of the upper atmosphere and near-Earth space that disrupt a wide range of technological systems – and, in a few cases, poses a direct threat to human health. The systems at risk are very diverse and include power grids, many aspects of spacecraft and aircraft operations, many types of radio communications and control systems. This note lists a number of these different systems and outlines what we currently know of:

- The space weather environment parameters that best summarise the threat to those systems
- A reasonable worst case for those parameters, together the quality of the knowledge underpinning that estimate of the worst case and the formal provenance of that knowledge, e.g. in the peer reviewed literature.
- What can be done to improve the quality of that knowledge
- Other useful information

This information is presented in a series of tables below – with each table focusing on a specific class of space weather threat to each particular system.

Caveats

1. This is a revision of the summary published in December 2012 (http://tinyurl.com/zwpb3za) to support the Royal Academy of Engineering report “Extreme space weather: impacts on engineered systems and infrastructure” (http://tinyurl.com/oavbwux). The changes reflect advances in understanding over the past three years, e.g. the very active research area around the AD774 atmospheric radiation event.
2. This summary has been assembled fairly quickly to meet a short-term request for information. It will be reviewed further in the course of 2016 and 2017.
3. While this document provides separate descriptions of different space weather risks, it must be remembered that many of these different risks will present themselves close together in time – because they have a common origin in phenomena on the Sun. The associations between the different risks are illustrated in the figure at the end of this document.
4. This document focuses on the environmental aspects of space weather and does not discuss measures that can be taken to provide resilience against space weather, e.g. combined use of complementary technologies with different responses to space weather.

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With additional inputs from Clive Dyer (U. Surrey) and Cathryn Mitchell (U. Bath).

Summary of environments

Target risk: Power grid	
Environmental risk parameter:	Time rate of change of magnetic field (dB/dt), specified in nano-Tesla per minute). The background, slowly varying, UK magnetic field strength is around 50,000 nT for reference.
Rationale:	dB/dt is key driver in fundamental equation for geomagnetically induced currents (e.g. Watermann, 2007, Cagniard, 1953)
Suggested worst case:	5000 nT/min (one single event), broadly consistent with >95% upper confidence level in the Thomson et al (2011) 1-in-100 year event
Worst case duration	Single event, or 'spike', of 1-2 minutes duration. Lesser spikes in dB/dt (1-2 minutes each) will be observed throughout the extreme event duration (hours to days). Magnitudes of >500nT/min have been correlated with enhanced risk to the UK grid (e.g. Erinmez et al, 2002)
Worst case spatial extent	Growing evidence that intense GIC events have spatial scales of a few hundred km (Ngwira et al., 2015; Pulkkinen et al., 2015).
Anticipated effects	• Tripping of safety systems potentially leading to regional outages or cascade failure of grid • Transmission system voltage instability and voltage sag • Damage, e.g. insulation burning, to a number of transformers, through transformer magnetic flux leakage • Premature aging of transformers leading to decreased capacity in months/years following event.
Quality of case:	Kappenman paper: Based on single measurement of earth currents on railway circuit in central Sweden during May 1921. Calibrated by linear extrapolation from similar but smaller earth currents observed in Sweden during 2500 nT/min event in 1982. Thomson et al paper: Published extreme event value statistical analysis of 1982-2010 digital magnetometer data from northern Europe.
Provenance:	Peer-reviewed papers by Kappenman (2006) and Thomson et al. (2011).

Target risk: Power grid	
How to improve case quality:	• Further analysis of UK geomagnetic observatory data running from 1850s to 1982 (digitised paper records) and 1983-2012 (measured digital data). • Industry GIC measurements and their correlation with changes in the geomagnetic data would stimulate development and validation of models of the hazard. • Characterisation of the spectrum of dB/dt during extreme storms, e.g. to determine magnitudes and numbers of lesser spikes
Other notes:	• The largest recorded disturbance of the last 35 years was around 2700 nT/min, measured in southern Sweden in 1982. The largest UK disturbance was 1100 nT/min in March 1989. • Modelled GIC and surface electric fields suggest a per substation GIC of 10s to 100s of Amps and electric fields of ~25 V/km for Carrington scale events is possible (e.g. Pulkkinen et al, 2015; Ngwira et al, 2013; Beggan et al, 2013) • For context, the Dst index (an equatorial measure of the magnetospheric ring current) reached -589 nT in March 1989. The Carrington event has been estimated at -900 to -1760 nT (e.g. Cliver and Dietrich, 2013; Tsurutani et al, 2003), with a recurrence likelihood of 6-12% per decade (e.g. Riley, 2012; Love, 2012) and theoretical considerations suggest -2500nT as a maximum possible Dst (Vasyliunas, 2011)

Target risk: Satellite operations – power	
Environmental risk parameter:	Solar energetic particle fluence (> 1 MeV)
Rationale:	Loss of electrical power from solar arrays is related to fluence accumulated over spacecraft time in space.
Suggested worst case:	3×10^{15} m^{-2} (with energy spectrum possibly as in August 1972 or ESP model (Xapsos et al., 2000))
Worst case duration	Single event lasting 2 days or series of events lasting 1 week
Worst case spatial extent	Most satellite orbits are exposed; the magnetosphere will provide shielding for some orbits, especially equatorial LEO.
Anticipated effects	Premature aging of spacecraft power systems leading to decreased capacity in years following event.
Quality of case:	We refer to ECSS-E-ST-10-04C for our current worst case event which is based on extrapolating existing models. Note that recent work by Cliver and Dietrich (2013) estimates that the Carrington event was probably about a factor 2 more intense than any event of the space age but with 1-sigma error bars lying between factor 20 higher and 5 lower. Hence assuming a factor 4 is still a reasonable estimate for 1 in 100 year event.
Provenance:	ECSS-E-ST-10-04C standard. Paper by Cliver and Dietrich (2013).
How to improve case quality:	• Examine how best to extrapolate from the direct observations of solar energetic particles that have been collected since 1968. • Look for other sources of proxy, e.g. recent work by Miyake et al (2012) suggests that C^{14} can be used as a proxy for extreme events. Work by Mekhaldi et al. (2015) combines C^{14} and Be^{10} data to give the high energy end of worst case spectra. However these data do not contain information below 30 MeV. • Needs further work to reconcile with ongoing work at ESA, plus results coming from studies of the AD774 event.
Other notes:	Damage depends on spectrum and, for solar cells, is more severe for soft spectrum. Further investigation of models is needed.

Target risk: Satellite operations – SEE/control	
Environmental risk parameter:	Solar energetic proton flux and fluence (> 30 MeV). Heavy ions also contribute to SEEs and can double the rates calculated from protons alone (Dyer et al., 2005). In addition heavier ions can give hard failures not produced by protons.
Rationale:	The rate at which SEEs occur is related to this flux but depends on the hardness of the spectrum and the amount of shielding. Thus the frequency of service interruptions, and the size of operator workload, in any period will also rise and fall with this flux. The fluence over a day is useful guide to total number of problems to be expected.
Suggested worst case:	Peak Flux 4.4 x 10^9 $m^{-2}s^{-1}$ 1-day fluence: 2 x 10^{14} m^{-2} (both with energy spectrum as in October 1989 or August 1972). Cliver and Dietrich (2013) estimate a fluence between 10^{13} and 10^{15} m^{-2} >30 MeV for Carrington event. For now rates can be doubled to allow for ions.
Worst case duration	1-2 days for each event, but there could be several lasting a week as in October 1989 and October 2003.
Worst case spatial extent	Most satellite orbits are exposed, the magnetosphere will provide shielding for some orbits, especially equatorial LEO. We do not consider the South Atlantic Anomaly here as that is a constant feature that will cause SEEs when satellites cross that region.
Anticipated effects	High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services • Some potential for permanent loss of sub-systems and of whole spacecraft.
Quality of case:	Based on extrapolation from space age measurements. This may be supplemented in future by use of cosmogenic isotopes to estimate historical SEP events; this is an area of ongoing research.
Provenance:	Paper by Cliver and Dietrich (2013).
How to improve case quality:	Improved understanding SEP events as discussed above and inclusion of worst case fluences from ions and their Linear Energy Transfer (LET) spectra. Dyer et al (2005) shows that Creme96 is a reasonable worst-case LET spectrum for the space age, but 1-in-100 year event might well be factor 4 worse as with the proton estimates.
Other notes:	Depends on energy spectrum of the particles. Probably most severe for intermediate hardness. Suggest use October 1989 or August 1972 to enable scaling from existing space standards- maybe by factor 4. Also need to assume worst case composition for heavy ions.

Target risk: Satellite operations – internal charging	
Environmental risk parameter:	Energetic electron flux (> 2 MeV)
Rationale:	These very energetic electrons penetrate deep inside spacecraft. Thus electrical charge can accumulate in dielectric (electrically insulating) materials. If this accumulation becomes too large, the dielectric will breakdown resulting in an electrical discharge. This can (a) damage nearby spacecraft systems, and (b) generate false signals that cause the spacecraft to misbehave. The latter will drive up operator workload.
Suggested worst case:	For geosynchronous orbit (e.g. comsats) 24hr average electron flux > 7.7 x 10^5 cm^{-2} s^{-1} sr^{-1} For medium earth orbit (e.g. Galileo) 24hr average electron flux > 7.2 x 10^5 cm^{-2} s^{-1} sr^{-1} (based on paper from SPACESTORM now in review)
Worst case duration	1-2 days
Worst case spatial extent	Peak fluxes vary with longitude around the geosynchronous ring, possibly because magnetic latitude also varies around the ring. Worst case above is for 135° west. Fluxes are lower to east of this position, but maybe even higher further west, possibly peaking around 175º west.
Anticipated effects	Permanent damage to spacecraft systems High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services
Quality of case:	Recent peer reviewed paper by Meredith et al, 2015 gives robust extremes, e.g. 1-in-100 years, for GOES spacecraft longitudes. These fluxes are consistent with earlier theoretical estimates [Shprits, 2011]. Estimates of fluxes in medium Earth orbit are less robust. A statistical analyses of limited data by O’Brien et al. (2007) suggested a 24 hr average electron flux of 5 x 10^5 cm^{-2} s^{-1} sr^{-1} in medium Earth orbit. This was five times the flux of 1 x 10^5 cm^{-2} s^{-1} sr^{-1} derived from similar studies of data from geosynchronous orbit [Koons, 2001]. It remains an open question whether the medium Earth orbit fluxes should also be increased by a factor five from the new GEO estimate by Meredith et al. (2015). It is, however, implausible to have MEO extreme flux lower than the GEO extreme flux.
Provenance:	Peer reviewed papers by Shprits et al (2011) and Meredith et al (2015)
How to improve case quality:	Detailed survey of available datasets and of the published literature, especially new papers that address this issue.

Target risk: Satellite operations – internal charging	
Other notes:	Geosynchronous orbit lies near edge of the outer radiation belt, whereas medium Earth orbit lies in the heart of that belt, especially when enhanced. Thus there are strong reasons to expect a more dangerous environment in MEO than in GEO.

Target risk: Satellite operations – surface charging	
Environmental risk parameter:	Electron flux (1 to 100 keV)
Rationale:	The surfaces of objects in space always acquire some electrical charge. In strong sunlight, this is usually dominated by photoemission from the object, which stabilises the electrical potential at a few volts positive. But in regions of space containing hot plasmas, especially outside sunlight, the surface can go to a negative potential of several thousand volts. If this potential becomes too large it may trigger an electrical discharge. This can (a) damage systems on the spacecraft surface (e.g. solar arrays), and (b) generate false signals that cause the spacecraft to misbehave. The latter will drive up operator workload. Surface charging often occurs: • As a satellite passes out of eclipse into sunlight, due to change in currents to & from the spacecraft • During substorms which inject typically 1 – 100 keV electrons across geosynchronous and medium Earth orbit, usually between midnight and dawn (O'Brien, 2009). • During intense aurora caused by 1-10 keV electrons which affects satellites in polar low Earth orbits crossing the auroral regions Surface charging is determined by the flux of electrons in the hot plasma in these regions.
Suggested worst case:	Typically a peak electron flux of 10^8 cm^{-2} sr^{-1} s^{-1} keV^{-1} between 1 – 10 keV [Fennel et al., 2001]
Worst case duration	Substorms causing plasma injections may last several mins after which the peak flux will decay. However, during active periods multiple substorms occur with an interval of one to a few hours between each substorm. Prolonged periods of multiple substorms can last for 10 days or more during high speed solar wind streams.
Worst case spatial extent	Needs further study
Anticipated effects	Permanent damage to spacecraft systems, particularly solar arrays. High anomaly rates on spacecraft: • High workload by spacecraft operators to restore nominal spacecraft behaviour • Temporary reduction in capacity of spacecraft services
Quality of case:	Surveys of publicly available measurements.
Provenance:	Analysis of GEO data [Fennel et al., 2001]
How to improve case quality:	Detailed survey of available datasets & the published literature, especially new papers that address the issue.
Other notes:	

Target risk: Satellites – Thermospheric Drag	
Environmental risk parameter:	Change in thermospheric neutral density at LEO satellite orbit altitude
Rationale:	Density changes affect satellite orbital determination, since they lead to changes in the drag on the satellite
Suggested worst case:	Relative density enhancements of up to 750% , and absolute density changes of up to 4 x 10^{-12} km m^{-3} (at 490 km altitude).
Worst case duration	Large changes described above take place within 1 day.
Worst case spatial extent	Effects likely all over the world. Further study needed to assess regional responses.
Anticipated effects	• Satellite loses altitude, or satellite raising manoeuvres need to be carried out to counteract this. Impacts depend on size of the satellite. Nwankwo et al (2015) showed that for selected typical LEO satellites, the altitude may drop by 48-62 km a year at solar maximum, and by 25-31 km at solar minimum. NOAA SWPC estimated the ISS would drop by 200 m in a day during the October 2003 Halloween storm, but by 45 m in a day on a non-stormy day during the same month. • Issues with orbital determination – in extremis satellites have crashed into each other • Tracking of space debris is made significantly more problematic
Quality of case:	Worst case based on observations from 2003 to 2010.
Provenance:	Krauss et al (2015) – density fluctuations observed by GRACE during geomagnetic storms from 2003-2010. Sutton et al (2005) - density fluctuations in October 2003 geomagnetic storms. Pawlowski and Ridley (2008) – thermospheric response to solar flares.
How to improve case quality:	Further exploitation of satellite accelerometer data, including assimilation of such data into models
Other notes:	Density changes of ~20% can also occur during small geomagnetic storms and solar flares. Integrated effect of many such small storms, or flares, on satellite orbit may also need to be examined. Impact of anticipated effects is likely to increase in future due to increasing space debris and proposed constellations of hundreds of nanosatellites. We need to better understand implications for satellite survey and tracking.

Target risk: Terrestrial Electronics	
Environmental risk parameter:	Cosmic ray neutron flux (>10 MeV) at Earth's surface
Rationale:	Secondary neutrons are dominant source of single event effects below 60000 feet and are produced by energetic protons and ions interacting in the upper atmosphere. The flux > 10 MeV is used in the standards but allowance must be made for lower energy neutrons, especially thermal.
Suggested worst case:	50-fold increase in surface radiation environment for latitudes such as UK, based on measurements at Leeds on 23 Feb 1956. This would have been about factor 2.5 times worse at higher (Arctic) latitudes where geomagnetic shielding is weaker ("0 GV cut-off"). Maybe factor 4 higher than Feb 56 for 1-in-100 year event and factor 60 higher for 1-in-1000 year event.
Worst case duration	1-12 hours for a single event but maybe longer for a series of events.
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth's magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles.
Anticipated effects	Greatly enhanced error rates in unprotected digital electronic systems, burnout in high voltage devices
Quality of case:	This is based on observations of the radiation event of 23 Feb 1956. May be 4 times greater for Carrington event and 60 times higher for 1 in 1000 year as evidenced by the analysis of cosmogenic nuclides from AD 774 event (Mekhaldi et al. 2015). This gives 1×10^8 m^{-2} for 1in100 years and $2x10^9$ m^{-2} for 1 in 1000 years
Provenance:	Research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart(2009), Tylka and Dietrich (2009), Mikhaldi et al. (2015).
How to improve case quality:	Full review of observed GLEs in conjunction with work on cosmogenic nuclides.
Other notes:	Feb 56 is hardest event observed (since observations commenced in 1942). The spectral hardness of Carrington event is not known and worst case assumption should be made. Evidence from AD774 event suggests that that event was very hard. Duration is probably worst for short events that give high rates. Event durations are typically 1-12 hrs.

Target risk: Wireless systems	
Environmental risk parameter:	Solar radio flux
Rationale:	The Sun can produce strong bursts of radio noise over a wide range of frequencies from 10 MHz to 10 GHz. These bursts may interfere with wireless systems operating at these frequencies if the solar signal is stronger than the operational signal.
Suggested worst case:	10^{-17} to 10^{-16} W m^{-2} Hz^{-1} over a broad range of frequencies.
Worst case duration	1 hour
Worst case spatial extent	Whole dayside of the Earth.
Anticipated effects	Loss of signal on wireless systems, especially GNSS and including mobile phones.
Quality of case:	Statistical studies show that radio bursts up to 10^{-17} W m^{-2} Hz^{-1} are fairly common. A burst of 10^{-16} W m^{-2} Hz^{-1} was recorded in Dec 2006 and disrupted GNSS systems across the sunward side of the Earth.
Provenance:	Statistics in peer-reviewed paper by Nita et al., 2004. Dec 2006 event in peer-reviewed paper by Cerruti et al., 2007.
How to improve case quality:	Conduct extreme value analysis to determine reasonable worse case and assess in light of wireless system operating parameters.
Other notes:	The lower threshold of 10^{-17} W m^{-2} Hz^{-1} should be detectable by mobiles, but the likely impact is small. Impact on mobiles will be greatest at sunrise/sunset when Sun in line of sight of base station antenna beams. There are no reports of impacts on mobiles from the large radio burst in Dec 2006. However, the terminator (sunset/sunrise line) on Earth's surface did not cross any significant inhabited areas, so the potential for interference with base stations was not tested.

Target risk: GNSS – Total Electron Content (TEC) correction	
Environmental risk parameter:	TEC and related gradients
Rationale:	The ionospheric range correction on GNSS position and time estimates is directly proportional to TEC, e.g. an uncorrected TEC value of 6×10^{16} m^{-2} gives a range correction of 1m. Most contemporary accurate GNSS systems use augmentation systems (e.g. EGNOS), that measure TEC and send corrections to receivers. This assumes that TEC does not change significantly between the measurement and delivery of the correction. If the spatial or temporal rate of change of TEC is too large, the corrections will be inaccurate (as happened over the US during the October 2003 event).
Suggested worst case:	Defining a TEC of 1×10^{16} m^{-2} = 1TECu Vertical TEC: 500 TECu based on double the measured value of 250 TECu on 30 Oct 2003 (Mannucci, 2010). TEC spatial range gradient: 80cm/km, based on double the measurements from (Datta-Barua, 2004) for the same event. TEC temporal range gradient of 30cm/s, based on double the measurements from (Datta-Barua, 2004). for the same event
Worst case duration	Several days
Worst case spatial extent	Effects likely all over the world. Further study needed to assess regional responses.
Anticipated effects	Inaccurate TEC corrections, leading to errors in GNSS position and timing.
Quality of case:	Measurements are good. Extrapolation unsubstantiated.
Provenance:	Vertical TEC: (Mannucci, 2010) TEC spatial range gradient: (Datta-Barua, 2004). TEC temporal range gradient (Datta-Barua, 2004). Duration: Expert assessment.
How to improve case quality:	Real-time monitoring and modelling.
Other notes:	• Use of dual-frequency GNSS receivers will allow TEC corrections without need for augmentation or differential systems. • Vertical TEC values given – multiply by 2-3 to adjust for oblique paths.

Target risk: Ionospheric Scintillation: GNSS, satcom and other satellite systems	
Environmental risk parameters:	Scintillation is caused by small scale irregularities which can be quantified by the strength of turbulence parameter, CkL. Amplitude scintillation is often quantified by the S4 index. Phase scintillation often quantified by the sigma-phi index
Rationale:	Small-scale spatial irregularities in the ionosphere can diffract and refract radio signals. This causes rapid fluctuations in signal intensity and phase, known as amplitude and phase scintillation respectively. • Amplitude scintillation can reduce radio signal intensity below a receiver's lock threshold, thereby causing loss of signal on GNSS and other satellite links). • Phase scintillation may lead to cycle slips and loss of lock for receivers as they track the signal.
Suggested worst case:	Scintillation which is characterised by a Rayleigh intensity distribution and random phase.
Worst case duration	Several days, intermittent
Worst case spatial extent	Covering globe down to latitude of 30 degrees.
Anticipated effects	Widespread loss of GNSS signals for location and timing. Loss of communications links for L-band systems and below Loss of operation of other satellite systems using frequencies below L-band.
Quality of case:	Studies by international Satellite-based Augmentation Systems (SBAS) Ionospheric Working Group with representatives from the European, Japanese and US systems (EGNOS, MSAS and WAAS).
Provenance:	Peer-reviewed papers by Doherty (2000) and Skone (2000)
How to improve case quality:	Better understand issues of intermittency.
Other notes:	

Target risk: Railway signal systems	
Environmental risk parameter:	Rate of change of magnetic field (dB/dt, specified in nano-Tesla per minute) – as for power grids.
Rationale:	Track circuits are widely used to detect the presence of trains on specific sections of railway track. The presence of the train changes the flow of electricity in the circuit, compared to an unoccupied track. If GIC from space weather also enters a track circuit, it may confuse the operation of that circuit.
Suggested worst case:	Unknown
Worst case duration	Single event, or 'spike', of 1-2 minutes duration. Lesser spikes in dB/dt (1-2 minutes each) will be observed throughout the extreme event duration (hours to days).
Worst case spatial extent	Growing evidence that intense GIC events have spatial scales of a few hundred km (Ngwira et al., 2015; Pulkkinen et al., 2015).
Anticipated effects	Additional currents flowing in track circuits
Quality of case:	
Provenance:	
How to improve case quality:	Needs better understanding of GIC impact on rail systems including different types of track circuits. Also analysis of databases of rail system anomalies.
Other notes:	Space weather interference with track circuits has been reported in Sweden and Russia, e.g. see Eroshenko et al., 2010. Space weather risks to rail systems are gaining more attention, e.g. an international workshop was held in London in September 2015 (Kraussmann et al., 2015).

Target risk: Aviation – avionics	
Environmental risk parameter:	Neutron fluence > 10 MeV
Rationale:	Secondary neutrons are dominant source of single event effects below 60000 feet. At altitudes above 60000 feet ions make a significant contribution to SEEs and dose-equivalent for humans. The flux > 10 MeV is used in the standards but allowance must be made for lower energy neutrons, especially thermal, which can increase rates in certain components by a factor 10.
Suggested worst case:	1000-fold increase in radiation environment, compared to solar minimum conditions, at 40000 feet (12 km), based on 23 Feb 1956 event. 4000-fold increase for 1-in-100 years event, and 60000-fold increase for 1-in-1000 years. Fluxes 4.4 times higher again at 60000 feet. Above this altitude ions must be considered.
Worst case duration	1-12 hours for a single solar event but maybe longer for a series of events.
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth’s magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles.
Anticipated effects	High upset rates and possible high failure rates in inadequately protected digital avionic systems
Quality of case:	This is based on ground-level observations of the radiation event of 23 Feb 1956 and calculations. May be 4 times greater for Carrington event consistent with Cliver and Dietrich (2013). This gives a fluence integrated over a high latitude flight (e.g. LHR-LAX) at 40000 ft (12 km) of 7 $x10^{10}$ m^{-2} for Feb56, $2.8x10^{11}$ $m^{-2}$for a Carrington event and 4.4x 10^{12} m^{-2} for a 1-in-1000 year event.
Provenance:	Peer-reviewed papers by Dyer et al (2007), Dyer et al (2003), Lantos and Fuller (2003), Tylka and Dietrich (2009), Mekhaldi et al.(2015). 1956 observations in research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart (2009).
How to improve case quality:	More measurements on board aircraft, and by ground-based neutron monitors, to stimulate development and validation of improved models of radiation exposure. Review of GLEs and cosmogenic nuclides. Further modelling of radiation in the upper atmosphere for UAVs, buoyant stratospheric balloons and space tourism.

Target risk: Aviation – avionics	
Other notes:	Assumes near worst case altitude (40000ft/12km) and route (e.g. high latitude such as LHR-LAX or polar). Fluxes would be factor 4.4 worse at 60000 feet and ions must be considered above this altitude. Any existing geomagnetic storm could expose lower latitude routes to similar fluxes. Duration is probably worst for short events that give high rates. Event durations are typically 1-12 hrs.

Target risk: Aviation – human radiation exposure	
Environmental risk parameter:	High radiation dose rates at aviation altitudes require GOES solar proton fluences > 100 cm^{-2} s^{-1} sr^{-1} in the >100 MeV channel. Northern hemisphere increases in ground level monitor count rates by a factor of 1.5. Secondary neutrons are the main contribution below 60000 feet but above this ions make a significant contribution to SEEs and dose-equivalent for humans.
Rationale:	**Air crew**: are occupationally exposed. Airlines operate to a limit of 20 mSv per year and seek to keep doses below a constraint of 6 mSv per year. **Pregnant air crew:** airlines are expected to limit the dose received to 1 mSv, once they have been informed that their employee is pregnant. **Passengers including frequent business fliers**: not covered by legislation so no dose limits or constraints apply.
Suggested worst case:	**1 in 100 year event**: 2-5 mSv for Feb 1956. Possibly factor 4 worse for Carrington event, may be 10 to 20 mSv for Carrington event. This 20 mSv value may be taken as a precautionary worst value. **1 in 1000 year event**: if due to a single solar event, the 774 AD event may have been a factor 60 worse than the Feb 1956 event.
Worst case duration	1-12 hours for a single event, but perhaps longer in a sustained series of events with several large X-class flares and fast CMEs.
Worst case spatial extent	Considerable variations across the world due to radiation from the Sun being directed by the interplanetary magnetic field, and the shielding effects of Earth's magnetosphere. The former can lead to variations with longitude, whilst the latter can lead to greater fluxes at high latitudes – but with marked differences between the northern and southern poles.
Anticipated effects	**Aircrew:** could exceed 6 mSv and airlines would seek to limit further doses by changes to flight duties. This may be logistically problematic. **Pregnant crew:** may exceed 1 mSv limit if they are still undertaking flight duties. However, airlines routinely change the flight duties of pregnant crew once they are notified of the pregnancy. **Passengers**: will need information on exposures received.
Quality of case:	This is based on observations of the radiation event of 23 Feb 1956 and calculations. Data for a Carrington scale event are speculative, but there is real evidence of very high radiation levels for 774 AD.

Target risk: Aviation – human radiation exposure	
Provenance:	Papers by Dyer et al. (2007), Lantos and Fuller (2003), and Tylka and Dietrich (2009). 1956 ground level observations in research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart (2009). 774 AD event: Mekhaldi et al (2015).
How to improve case quality:	More measurements on board aircraft, and by ground-based neutron monitors, to stimulate development and validation of improved models of radiation exposure. Better solar proton data with storm levels based on > 100 MeV flux or better still > 500 MeV flux. Need to determine the thresholds for considering restrictions to take off and rerouting or changing altitude.
Other notes:	Assumes near worst case altitude (12 km) and route (e.g. high latitude such as LHR-LAX or polar). However, a simultaneous geomagnetic storm could produce similar doses for lower latitude routes. Doses are probably worst for short events that give high dose rates and little time for avoidance. Longer duration events could affect more flights and/or expose more passengers.

Glossary

BGS	British Geological Survey
EGNOS	European Geostationary Navigation Overlay Service (European SBAS)
GEO	Geosynchronous orbit
GIC	Geomagnetically induced currents
GLE	Ground Level Enhancement
GNSS	Global Navigation Satellite System
HV	High voltage
LEO	Low Earth Orbit
MEO	Middle Earth Orbit
MeV	million electron-volts
MSAS	Multi-functional Satellite Augmentation System (Japanese SBAS)
mSv	milliSievert – unit of radiation dose
SBAS	Satellite-based Augumentation System (for GNSS)
SEE	Single event effect
SEP	Solar energetic particle
Tbc	To be confirmed
Tbd	To be done
WAAS	Wide Area Augmentation System (US SBAS)

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Interrelationships between effects

Many space weather effects will occur close together in time as they have a common origin in solar phenomena such as coronal mass ejections. The figure below outlines many of the most important associations between space weather effects.