Science & Technology Facilities Council

Technical Report
RAL-TR-2012-022

Summary of space weather worst-case environments

M Hapgood, R Horne, D Kerridge, B Jones, P Cannon, K Ryden, M Gibbs, D Jackson, A Rodger, A Thomson, C Dyer, L Cander, A Senior

December 2012

Enquiries about copyright, reproduction and requests for additional copies of this report should be addressed to:

RAL Library
STFC Rutherford Appleton Laboratory
R61
Harwell Oxford
Didcot
OX11 0QX

Tel: +44(0)1235 445384
Fax: +44(0)1235 446403
email: libraryral@stfc.ac.uk

Science and Technology Facilities Council reports are available online at: http://epubs.stfc.ac.uk

ISSN 1358- 6254

Summary of space weather worst-case environments

Original version: 30 November 2010
Updated for publication: 18 December 2012
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 summary has been assembled fairly quickly and has been subject to very limited peer review. It should be treated as a guide, but not yet a definitive document.
2. 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.
3. 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.

Contributors

Members of the UK Space Environment Impacts Expert Group: Mike Hapgood (RAL Space) (Chair), Richard Horne (BAS), David Kerridge (BGS), Bryn Jones (Solarmetrics), Paul Cannon (QinetiQ), Keith Ryden (QinetiQ), Mark Gibbs and David Jackson (Met Office)

With additional inputs from Alan Rodger (BAS), Alan Thomson (BGS), Clive Dyer (QinetiQ), Lili Cander (RAL Space) and Andrew Senior (Univ. Lancaster), 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 UK magnetic field strength is around 50,000 nT for reference.
Rationale:	dB/dt is key driver in fundamental equation for geomagnetically induced currents (Waterman, 2007, Cagniard, 1953)
Suggested worst case:	5000 nT/min (single event)
Worst case duration	Single event 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)
Anticipated effects	• Tripping of safety systems potentially leading to regional outages or cascade failure of grid • Damage to a number of transformers, through transformer magnetic flux leakage • Transmission system voltage instability and voltage sag • Premature aging of transformers leading to decreased capacity in months/years following event.
Quality of case:	Kappeman 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 statistical analysis of 1982-2010 digital magnetometer data from northern Europe.
Provenance:	Peer-reviewed papers by Kappenman (2006) and Thomson et al. (2011).
How to improve case quality:	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.
Other notes:	The largest recorded disturbance of the last 30 years was around 2700 nT/min, measured in Sweden in 1982. The largest UK disturbance was 1100 nT/min in March 1989.

Target risk:	**Satellite operations – power**
Environmental risk parameter:	Solar energetic particle fluence (> 30 MeV)
Rationale:	Loss of electrical power from solar arrays is related to fluence accumulated over spacecraft time in space.
Suggested worst case:	3×10^{14} m^{-2} (with energy spectrum possibly as in October 1989 or ESP model (Xapsos et al., 2000))
Worst case duration	Single event lasting a few days
Anticipated effects	Premature aging of spacecraft power systems leading to decreased capacity in years following event.
Quality of case:	This case was originally based on analysis of nitrate concentrations in ice cores to provide proxy data for SEP event fluences. Recent work by Wolff et al (2012) has shown that this method is flawed. Thus we lack data that can put a good upper bound on the worst case. We therefore refer to ECSS-E-ST-10-04C for our current worst case event which is based on extrapolating existing models.
Provenance:	ECSS-E-ST-10-04C standard. The original SEP event fluences were from a peer-reviewed paper by Shea et al. (2006)
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. Also to analyse event data using engineering approaches (model extrapolations)..
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 – SEU/control**
Environmental risk parameter:	Solar energetic particle flux and fluence (> 30 MeV)
Rationale:	The rate at which SEUs occur is proportional to this flux. 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:	Flux .4.4 x 10^9 $m^{-2}s^{-1}$ 1-day fluence: 1.9 x 10^{14} m^{-2} (both with energy spectrum as in October 1989 or August 1972)
Worst case duration	1 day
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:	This case was originally based on analysis of nitrate concentrations in ice cores as discussed above. It therefore suffers from the flaws discussed there.
Provenance:	The original SEP event fluences are from a peer-reviewed paper by Shea et al. (2006)
How to improve case quality:	Improved understanding SEP events as discussed above.
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 > 1 x 10^5 cm^{-2} s^{-1} sr^{-1} For medium earth orbit (e.g. Galileo) 24hr average electron flux > 5 x 10^5 cm^{-2} s^{-1} sr^{-1}.
Worst case duration	1-2 days
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:	Preliminary survey of US data from geosynchronous orbit shows 1-5 min average fluxes of 1 x 10^5 cm^{-2} s^{-1} sr^{-1} rising to 1 x 10^6 cm^{-2} s^{-1} sr^{-1} during magnetic storms for a Dst index of -200 nT. The risk depends on the duration of the flux and the orbit type. Previous statistical analysis of limited data suggests a 24 hr average electron flux of 1 x 10^5 cm^{-2} s^{-1} sr^{-1} in geosynchronous orbit [Koons, 2001] and 5 x 10^5 cm^{-2} s^{-1} sr^{-1} in medium Earth orbit [O'Brien et al. 2007]. It is possible that these fluxes might be exceeded by up to a factor ten in an extreme storm based on theoretical considerations [Shprits, 2011] but this is a matter for on-going research.
Provenance:	Surveys of publicly available measurements. Analysis of Geo data [Koons, 2001] and other satellite data [O'Brien et al., 2007]
How to improve case quality:	Detailed survey of available datasets and of the published literature, especially new papers that address this issue.
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.
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:	**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. 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 high latitudes such as UK
Worst case duration	3 hours
Anticipated effects	Greatly enhanced error rates in unprotected digital electronic systems, burnout in HV 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. This gives 7×10^{7} m^{-2},
Provenance:	Research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart(2009)
How to improve case quality:	
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. Duration is probably worst for short events that give high rates. Event durations are typically 3-12 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 can 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
Anticipated effects	Loss of signal on wireless systems, especially GNSS and mobile phones. Impact on WiFi and short range control systems is unclear.
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 GPS 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:	Review statistical data on solar radio bursts. Collect additional data and compare with performance of wireless systems.
Other notes:	The lower threshold of 10^{-17} W m^{-2} Hz^{-1} should be detectable by 3G phones, but the likely impact requires expert assessment. Impact on mobiles may 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 – TEC correction**
Environmental risk parameter:	Rate of change of TEC (total electron content)
Rationale:	The ionospheric range correction on GNSS positions is directly proportional to TEC, e.g. a TEC value of 6 $\times 10^{16}$ m^{-2} gives a range correction of 1m. Most accurate GNSS systems use augmentation systems, such as 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 rate of change of TEC is too large, the corrections will not be accurate (as happened over the US during the October 2003 event).
Suggested worst case:	Unknown
Worst case duration	Several days
Anticipated effects	Inaccurate TEC corrections, errors in GNSS positions.
Quality of case:	
Provenance:	
How to improve case quality:	TEC real-time monitoring and modelling.
Other notes:	• The most promising developments in TEC modelling involve new data assimilation methods (see Schunk et al., 2004). • Use of dual-frequency GNSS receivers will allow direct measurement of TEC corrections without need for augmentation systems.

Target risk:	**GNSS & satcom – scintillation**
Environmental risk parameters:	1. Amplitude scintillation as measured by the S4 index. 2. Phase scintillation as quantified by the P_{rms} index (These are related to the standard deviation of the signal intensity and phase over 60 seconds. S4 is normalised to mean signal intensity)
Rationale:	Small-scale spatial irregularities in the ionosphere can diffract 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 (e.g. GPS, satellite links). • Phase scintillation may lead to cycle slips and loss of lock for receivers as they track the signal.
Suggested worst case:	S_4 >greater than ~0.6 P_{rms} > 1 degree
Worst case duration	Several days
Anticipated effects	Widespread loss of GNSS signals for location and timing.
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 Scone (2000)
How to improve case quality:	S4 and P_{rms} real-time monitoring and modelling, especially over the UK, during strong geomagnetic storms. Use of historical geomagnetic data to extrapolate to UK 1-in-200 year worst case.
Other notes:	Worst case above is threshold for strong scintillation. It probably should be higher to reflect a real worst case. Note that strong scintillation is rare over mid-latitude regions such as the UK, but may be expected during severe geomagnetic storms. It is more common in auroral regions (e.g. over ocean areas North of Scotland) and in equatorial regions.

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	A few minutes (tbc)
Anticipated effects	Additional currents flowing in track circuits
Quality of case:	
Provenance:	
How to improve case quality:	
Other notes:	Space weather interference with track circuits has been reported in Sweden and Russia, e.g, see Eroshenko et al., 2010.

Target risk:	**Aviation – avionics**
Environmental risk parameter:	Neutron fluence > 10 MeV
Rationale:	Secondary neutrons are dominant source of single event effects below 60000 feet. The flux > 10 MeV is used in the standards but allowance must be made for lower energy neutrons, especially thermal.
Suggested worst case:	300-fold increase in radiation environment at 12 km
Worst case duration	3 hours
Anticipated effects	High failure rates in unprotected 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. This gives a fluence integrated over a high latitude flight (e.g. LHR-LAX) at 12 km of 1.6×10^{11} m^{-2}.
Provenance:	Peer-reviewed papers by Dyer et al (2007) , Dyer et al (2003), Lantos and Fuller (2003). 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 develop and validation of improved models of radiation exposure.
Other notes:	Assumes near worst case altitude (12km) and route (e.g. high latitude such as LHR-LAX or polar). However 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 3-12 hrs.

Target risk:	**Aviation – aircrew radiation exposure**
Environmental risk parameter:	Radiation dose
Rationale:	Legal requirement for radiation workers (20 mSv/year but limit kept to 6 mSv/year in practice for aircrew)
Suggested worst case:	2-5 mSv for Feb 56. Possibly factor 4 worse for Carrington event. May be 10 to 20 mSv for Carrington event.
Worst case duration	4-10 hours
Anticipated effects	Many aircrew exceed their annual exposure recommended limits and become unavailable for flight duties for many months. Pregnant crew exceed legal limit.
Quality of case:	This is based on observations of the radiation event of 23 Feb 1956 and calculations.
Provenance:	Papers by Dyer et al. (2007) and Lantos and Fuller (2003). 1956 ground level 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 develop and validation of improved models of radiation exposure.
Other notes:	Assumes 12 km altitude, high latitude flight. During a geomagnetic storm lower latitudes could be equally exposed.

Target risk:	**Aviation – passenger radiation exposure**
Environmental risk parameter:	Dose on any specific flight < half annual exposure for high-risk groups in general public (children and pregnant women) ;i.e. <0.5 mSv. 1 mSv is the legal limit for a planned exposure
Rationale:	It would be invidious (also impracticable) to bar air travel by high-risk groups, so the risk should focus there. The limit should be at a level such that exposed persons can make a return flight and then not fly for some period (e.g. one year). Would have to travel home during guaranteed quiet period or by land/sea!
Suggested worst case:	2-5 mSv for Feb56 event but Carrington event could be factor 4 worse. May be 10 to 20 mSv for Carrington event.
Worst case duration	3 hours
Anticipated effects	Passengers exposed to radiation doses above limits prescribed for general public.
Quality of case:	This is based on observations of the radiation event of 23 February 1956.
Provenance:	Papers by Dyer et al. (2007) and Lantos and Fuller (2003). 1956 ground level observations in research note by Marsden et al (1956), Quenby and Webber (1959), Rishbeth, Shea and Smart(2009).
How to improve case quality:	Need to calculate safe altitude, latitude to keep below limit.
Other notes:	Assumes near worst case altitude (12 km) and route (e.g. high latitude such as LHR-LAX or polar). However any existing geomagnetic storm could expose lower latitude routes to similar doses. Duration is probably worst for short events that give high dose rates and little time for avoidance. However longer duration could affect more flights and/or expose more passengers. Event durations are typically 3-12 hrs. More investigation needed.

Target risk:	**Satellites – Thermospheric Drag**
Environmental risk parameter:	Change in thermospheric neutral density at LEO satellite orbit height
Rationale:	Density changes affect satellite orbital determination, since they lead to changes in the drag on the satellite
Suggested worst case:	Density enhancements of 200-300% - associated with this a LEO satellite orbital altitude dropped by 30km over the same time period.
Worst case duration	~ few hours
Anticipated effects	• Satellite loses altitude, or satellite raising manoeuvres need to be carried out to counteract this • Issues with orbital determination – in extremis satellites have crashed into each other • Tracking of space debris is made more problematic
Quality of case:	Worst case based on observations during October 2003 geomagnetic storms.
Provenance:	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.

Glossary

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

References

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting, *Geophysics*, **18**, 605–635

Cerruti,, A.P., Kintner, P.M., Gary, D.E., Mannucci, A.J, Meyer, R.F, Doherty, P., and Coster, A.J. 2008. Effect of intense December 2006 solar radio bursts on GPS receivers. SPACE WEATHER, VOL. 6, S10D07, doi:10.1029/2007SW000375.

Doherty, P., 2000. Ionospheric Scintillation Effects in Equatorial and Auroral Regions, ION GPS 2000, Salt Lake City, Utah, p. 662-671.

Dyer, C.S., Lei, F., Hands, A., Truscott, P., 2007, "Solar Particle Events In The QinetiQ Atmospheric Radiation Model, " IEEE Trans. Nuc. Sci., Vol. 54, No. 4, pp 1071-1075.

Dyer, C. S., Lei, F., Clucas S. N., Smart, D.F., Shea, M. A., 2003, "Solar particle enhancements of single event effect rates at aircraft altitudes," IEEE Trans. Nuc. Sci., Vol. 50, No. 6, pp. 2038-2045.

ECSS-E-ST-10-04C: European Cooperation for Space Standardization, 2008, Space engineering - Space environment, download from http://www.ecss.nl/.

Erinmez, I. A., J. G. Kappenman, and W. A. Radasky (2002), Management of the geomagnetically induced current risks on the national grid company's electric power transmission system., Journal of Atmospheric and Solar-Terrestrial Physics, 64, 5-6, 743-756.

Eroshenko, E.A., A.V. Belov, D. Boteler, S.P. Gaidash, S.L. Lobkov, R. Pirjola, L. Trichtchenko. 2010. Effects of strong geomagnetic storms on Northern railways in Russia, Adv. Space Res. 46, 1102-1110.

Fennell, J. F. ; Koons, H. C. ; Roeder, J. L. ; Blake, J. B. (2001) Spacecraft Charging: Observations and Relationship to Satellite Anomalies, Aerospace Report TR-2001(8570)-5

Feynman, J., G. Spitale, J. Wang, and S. Gabriel (1993), Interplanetary proton fluence model: JPL 1991, J. Geophys. Res., 98(A8), 13,281–13,294, doi:10.1029/92JA02670.

Kappenman, J.G., 2006, Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921, Adv. Space Res. 38, 188-199. doi: 10.1016/j.asr.2005.08.055

Koons, H. C. (2001), Statistical analysis of extreme values in space science, *J. Geophys. Res.*, 106(A6), 10,915–10,921, doi:10.1029/2000JA000234.

Lantos, P., Fuller, N., 2003, "History of the solar particle event radiation doses on-board aeroplanes using a semi-empirical model and Concorde measurements," Radiation Protection Dosimetry, , 104, 3, 199-210.

Miyake, F., K. Nagaya, K. Masuda, and T. Nakamura (2012), A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan, Nature, 486, 240-242, doi: 10.1038/nature11123.

O'Brien, T. P., J. F. Fennell, J. L. Roeder, and G. D. Reeves (2007), Extreme electron fluxes in the outer zone, *Space Weather*, 5, S01001, doi:10.1029/2006SW000240.

O'Brien, T. P., 2009, SEAES-GEO: A spacecraft environmental anomalies expert system for geosynchronous orbit, Space Weather, 7, S09003, doi:10.1029/2009SW000473

Pawlowski, D.J. and A.J. Ridley, Modeling the thermospheric response to solar flares, J. Geophys. Res., 113, A10309, doi:10.1029/2008JA013182, 2008

Schunk et al., 2004. Global assimilation of ionospheric measurements (GAIM), Radio Sci., 39 RS1S02, doi:10.1029/2002RS002794.

Quenby, J. J., Webber, W., 1959, "Cosmic-ray geomagnetic cut-off rigidities and the Earth's magnetic field," Phil. Mag., 4, 90-112.

Rishbeth, H., Shea, M. A., Smart, D. F., 2009, "The solar-terrestrial event of 23 February 1956," Advances in Space Research, 44, 1096-1106.

Shea M.A., D.F. Smart, K.G. McCracken, G.A.M. Dreschhoff, H.E. Spence., 2006, Solar proton events for 450 years: The Carrington event in perspective. Adv. Space Res. 38 232–238. doi:10.1016/j.asr.2005.02.100
Shprits, Y., D. Subbotin, B. Ni, R. Horne, D. Baker, and P. Cruce (2011), Profound change of the near-Earth radiation environment caused by solar superstorms, *Space Weather*, 9, S08007, doi:10.1029/2011SW000662.
Skone, S., 2000, Impact of Ionospheric Scintillation on SBAS Performance, ION GPS 2000, Salt Lake City, Utah, 284-293.
Sutton, E.K, J. M. Forbes, and R. S. Nerem, 2005, Global thermospheric neutral density and wind response to the severe 2003 geomagnetic storms from CHAMP accelerometer data, J. Geophys. Res., 110, A09S40, doi:10.1029/2004JA010985
Thomson, A. W. P., E. B. Dawson, and S. J. Reay (2011), Quantifying extreme behavior in geomagnetic activity, Space Weather, 9, S10001, doi: 10.1029/2011SW000696.
Waterman, J. 2007. The Magnetic Environment – GIC and other ground effects, in: Lilensten, J. (Ed.), Space Weather – Research towards applications in Europe. Springer, Dordrecht, pp. 269-275, 2007.
Wolff, E. W., M. Bigler, M. A. J. Curran, J. E. Dibb, M. M. Frey, M. Legrand, and J. R. McConnell (2012), The Carrington event not observed in most ice core nitrate records, Geophys. Res. Lett., 39, L08503, doi: 10.1029/2012GL051603
Xapsos, M. A., G.P. Summers, J.L. Barth, E. G. Stassinopoulos and E.A. Burke, "Probability Model for Cumulative Solar Proton Event Fluences", IEEE Trans. Nucl. Sci., vol. 47, no. 3, June 2000, pp 486-490.

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.