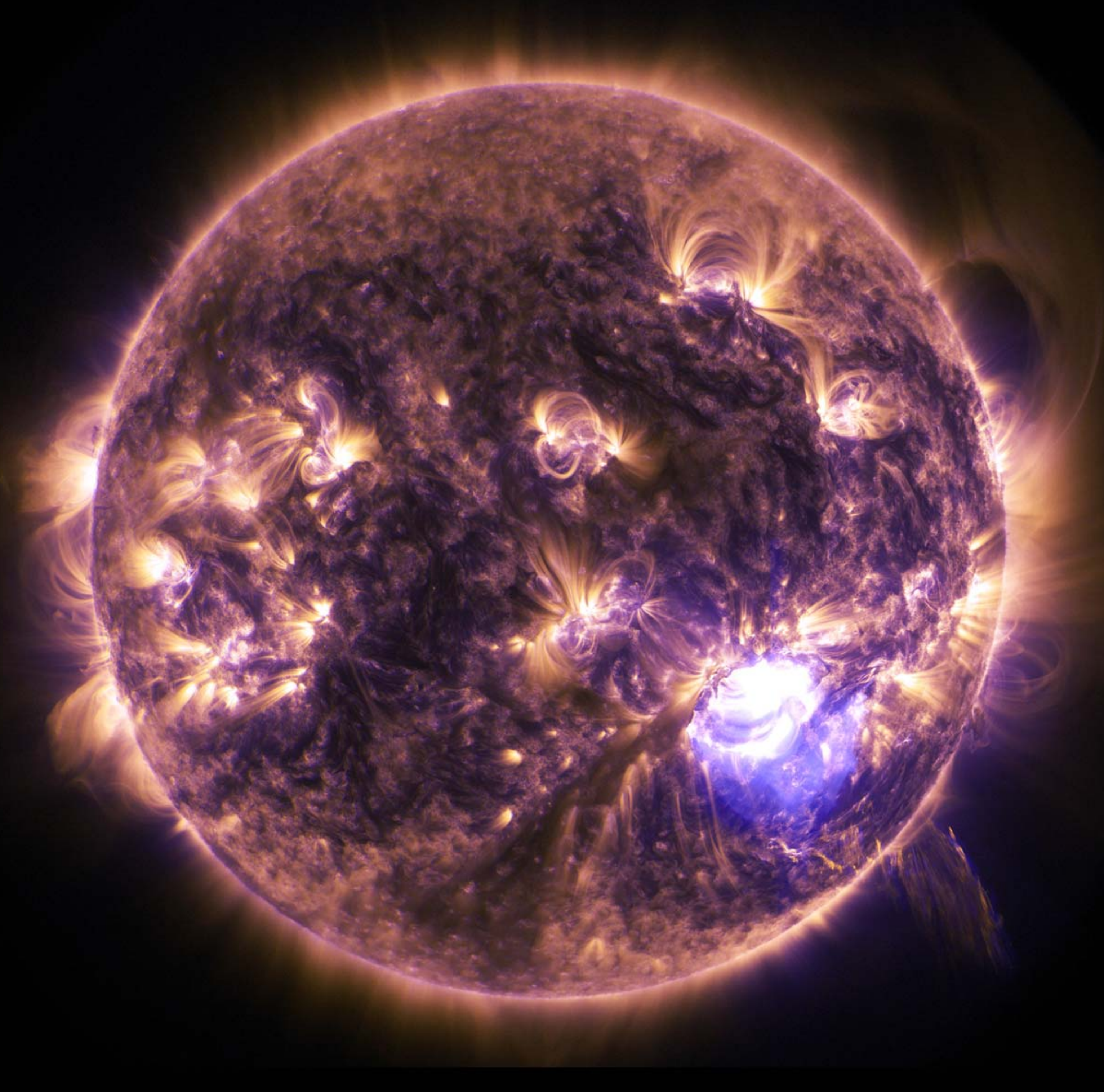
UNIVERSITY COLLEGE LONDON
DEPARTMENT OF SPACE AND CLIMATE PHYSICS

Building Space Weather Resilience in the Finance Sector



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Foreword

When developing business continuity planning for the finance sector, the Sun might not feature on your list of considerations.

But there are consequences of living near a dynamic star because the eruptions and explosions that it produces can have a very real effect on us. They create stormy conditions known as space weather and this natural hazard can severely disrupt the technologies that underpin the finance sector including timing information, communications and power supply. In the 21st century, space weather is a risk that you cannot afford to ignore. To help develop an approach to including space weather in business continuity planning, UCL and Richard Deighton have worked together.

Richard Deighton (FRAS) is an experienced risk professional with over 20 years experience in investment banking, operational risk and business resilience. During this time he has played a major role in business resilience programmes for Goldman Sachs and Morgan Stanley. Richard has also been seconded to the Financial Services regulator in London to develop their market wide exercise (2010) and has led internal teams in participating in these events and those of the SEC in the USA. As a previous co-chair of the Securities Industry Business Continuity Management Group in London he has advised the Tripartite committee (specifically the FSA (now PRA) and Treasury) on many areas of resilience and crisis management. Richard is currently studying astrophysics and cosmology at Cambridge University ICE and is a fellow of the Royal Astronomical Society.

We wanted to bring together our collective expertise from the space weather research and the finance communities to discuss where the vulnerabilities are concentrated. So that, in turn, space weather risks and their likely impact on different aspects of financial organisations can be understood. Developing business continuity and resiliency capabilities begins with this.

What began as a dialogue developed into a workshop, which was then followed with a symposium held at the Royal Society in London. This symposium brought together those involved in the study of space weather with stakeholders in the London offices of investment banking, regulatory authorities and Government to identify realistic space weather scenarios and evaluate their probability and impact. This guide summarizes what was discussed and we hope that it acts as a useful source of information that can support your approach to incorporating space weather risk into your business continuity planning.

Left to right: Professor Lucie Green and Richard Deighton.

Executive summary

Space weather is the phrase used to describe disturbances in the Earth's upper atmosphere and local space environment that are capable of disrupting a wide range of technological systems, including electricity distribution networks, communications and global navigation satellite systems (GNSS).

These are all technologies that underpin the finance sector. In recent years, awareness of the impact of the natural hazard known as space weather has been building. We know that space weather changes continuously and is multifaceted (as is terrestrial weather) and is driven by bursts of solar activity. The direct impact of space weather on our lives and economies has led to the creation of space weather forecasting centres. In the UK, this is the responsibility of the Met Office's Space Weather Operations Centre.

A few years ago the risks posed were acknowledged at a national level when space weather was included in the National Risk Assessment in 2011, and in the publically available National Risk Register in 2012. Now space weather risk is finding increased focus at a sectorial level. A wealth of scientific research means that developing a strategy to build resilience to space weather can be evidence-driven and based on data gathered during historical space weather events. Although each business within the finance sector will have a unique set of needs, a common framework and set of data can be utilised.

Continuity of high-tech systems is vitally important for the finance sector and loss of systemically important operations could have a serious knock-on effect to the UK economy and economies around the world. The symposium brought together a range of experts to discuss the practical steps that can be taken to develop an approach to managing space weather risk. This report lays out a framework that can be followed and makes the following recommendations in order to continue to build resilience in the future.

Theme 1: business continuity planning

- Firms should consider activities in-house to understand and evaluate the global impact of space weather risk for their business and build or extend their business resilience and crisis management processes accordingly.
- Consideration should be given to using a space weather scenario in a market-wide business resilience test e.g. the Bank of England's financial sector exercises.

Theme 2: research

- Historical data on system "glitches"/downtime should be used to investigate the impact of space weather activity and determine at what scale of event the sector could be impacted.
- Financial companies should start gathering information on component and data failures for future analysis.
- With data, more tailored forecasting services can be developed for the Finance industry.

Introduction: Space weather origins

For centuries humans have been studying the Sun using special telescopes and observing techniques that allow its glare to be reduced and safely revealing the surface of our local star.

It was immediately seen that the surface is marked with black spots, known as sunspots, the number of which fluctuates during an 11-year solar cycle. In 1908 it was realised that regions of strong magnetic field at the solar surface cause the spots, and that the changing number of spots indicates we are living in the proximity of a star with a very dynamic magnetic field. At the start of the space age, another significant discovery was made. The first spacecraft to leave the Earth and head out into the space between the planets detected a million degree electrically charged gas that is actually the very extended atmosphere of the Sun – extending out far beyond what the human eye can see. NASA's Voyager 1 spacecraft, launched in 1977, found the edge of the Sun's atmosphere in 2012 after a 38-year journey past the outer planets. The edge is 15 billion km away, around 40 times more distant than the dwarf planet Pluto. We are living within the atmosphere of the Sun and this is the reason why we have space weather.

The Sun's atmosphere has some characteristics that are analogous to the Earth's. For example, gusty solar winds blow outwards, all the way to the edge of the Sun's atmosphere. These winds blow at millions of km per hour. Less familiar aspects are events called solar flares - bursts of electromagnetic radiation including radio waves, ultraviolet waves and X-rays that happen mostly in the atmosphere above sunspots. This electromagnetic radiation travels at the speed of light and takes 8 minutes and 20 seconds to get to us. When we see a flare in progress, its electromagnetic radiation is already here. Then there are sporadic and dramatic eruptions of gas and magnetic field known as coronal mass ejections. These bubbles of magnetic field and gas expand as they move outwards and rapidly become much bigger than the Sun itself. If they head toward the Earth, which they often do, we become completely engulfed for many hours until they blow over. Their interaction with the Earth's magnetic field can trigger what is known as a geomagnetic storm.

Coronal mass ejections normally take around one to three days to reach us, so we have some time to prepare. The Sun is also capable of creating showers of very fast moving electrically charged particles, either when a solar flare occurs or when a fast moving coronal mass ejection pushes its way through the solar wind. These are known as energetic particle events and the particles begin to arrive at the Earth very quickly, after around 30 minutes.

The shower can last for many hours, even days. The frequencies of these solar activity phenomena vary over the solar cycle being most frequent at cycle maximum. But the very intense storms can happen at any phase of the solar cycle.

Space weather keywords

- **Solar flare:**
  a sudden burst of radiation including X-rays and UV from a localised region in the Sun's atmosphere.
- **Solar wind:**
  a constant but gusty outward flow of material into the Solar System.
- **Coronal mass ejection:**
  an ejection of electrically charged gas and magnetic field.
- **Solar energetic particles:**
  high-energy electrically charged particles that can travel with speeds close to the speed of light.
- **Geomagnetic storm:**
  temporary disturbance to the Earth's magnetic field.
- **Solar cycle:**
  the rise and fall of solar activity levels over an (approximately) 11-year timescale. Large space weather events can occur at any phase of the cycle.

Space weather effects on technological systems

It is useful to draw an analogy with terrestrial weather, which raises the question of conditions that could be deemed to be ‘good’.

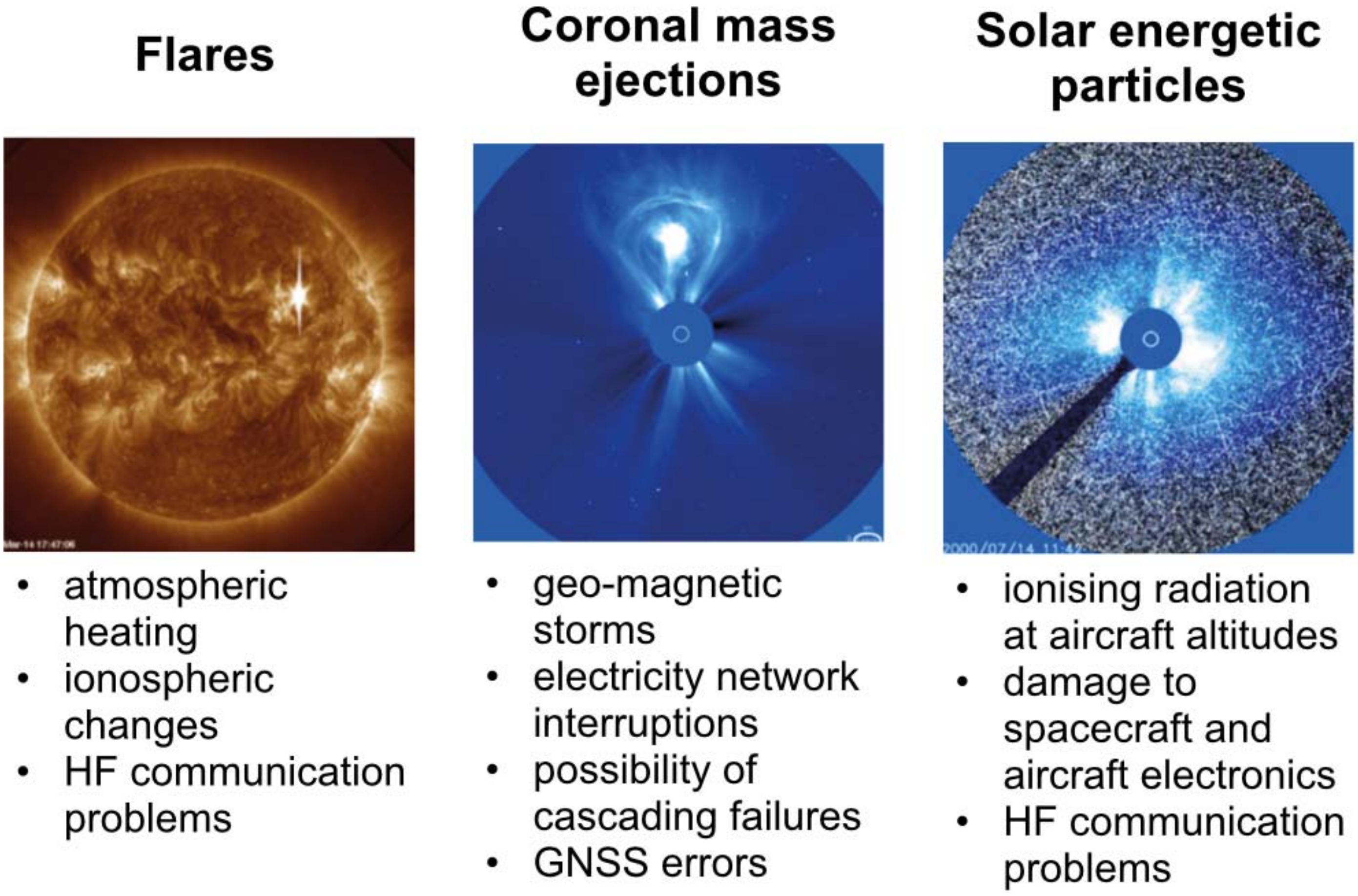
What would a fair/fine space weather day entail? Conditions that are good correspond to quiet conditions on the Sun when solar activity is infrequent and of low intensity, and when the solar wind blows more slowly. The Earth responds with its atmosphere shrinking – leading to a longer lifetime for some satellites – and no disturbances to its magnetic field.

What constitutes bad space weather includes times when the Sun is producing intense solar flares, coronal mass ejections and energetic particle events. The Earth’s magnetic field or atmosphere, or both, can be significantly disturbed at these times. The physical processes involved are complex and interlinked and the impact can vary sector by sector. Even so, the impacts from these three forms of solar activity can be broadly distilled into the following.

Solar flares: the bursts of radiation produced during these events include a broad range of frequencies. The X-ray radiation reaching us is absorbed by the Earth’s upper atmosphere (a layer known as the ionosphere), changing its conditions. This can cause a brief HF radio blackout on the sunlit side of the Earth. The radio waves of the solar flare burst itself can also jam the signal from communication and navigation systems.

Coronal mass ejections: the arrival of the cloud of magnetic field and electrically charged gas can create disturbances to the Earth’s magnetic field. This in turn sets up series of electrical currents above the Earth’s atmosphere, within the atmosphere and through the Earth’s surface. Electric currents induced in power networks and voltage fluctuations can cause protection devices to trip. They can potentially damage high voltage transformers on the electricity transmission network and voltage fluctuations can potentially lead to widespread blackouts. The disturbance to the Earth’s magnetic field also accelerates particles that are already trapped within it, sending them cascading down to the Earth’s atmosphere, possibly damaging satellites en route.

Solar energetic particles: during some solar flares and coronal mass ejections, electrically charged particles close to, or at, the Sun are accelerated to speeds approaching the speed of light. When they reach the Earth, they can damage spacecraft electronics. They are guided by the Earth’s magnetic field toward the poles where they can change the conditions in the upper atmosphere leading to the loss of HF radio communications in these regions.



Flares

- atmospheric heating
- ionospheric changes
- HF communication problems

Coronal mass ejections

- geo-magnetic storms
- electricity network interruptions
- possibility of cascading failures
- GNSS errors

Solar energetic particles

- ionising radiation at aircraft altitudes
- damage to spacecraft and aircraft electronics
- HF communication problems

Figure 1: The image on the left-hand side shows an image of the Sun taken in ultraviolet light. The bright region in the upper-right is the result of a solar flare taking place. The middle image shows the Sun's extended atmosphere (the size of the Sun is indicated by the white circle). The light bulbed shaped feature leaving the Sun to the north is a coronal mass ejection. The image on the right-hand side shows the arrival of energetic particles, which creates a 'snow-storm' effect as the particles strike the camera. Images courtesy of ESA and NASA.

Space weather scales

Several scales are in common use to describe the intensity of the solar activity phenomena and the degree to which the Earth's magnetic field and atmosphere are disturbed. This in turn is then used to estimate the level to which various technologies will be affected. Listed below are some of the scales and measurements that you might see when space weather is being discussed.

Solar flares: the scale for measuring the size of a solar flare is based on how bright the flare is in its X-ray emission. The scale runs through A, B, C, M and X with the X-class flares being of the highest intensity, but lowest frequency (between 2009 and 2015 there were 32 X-class flares).

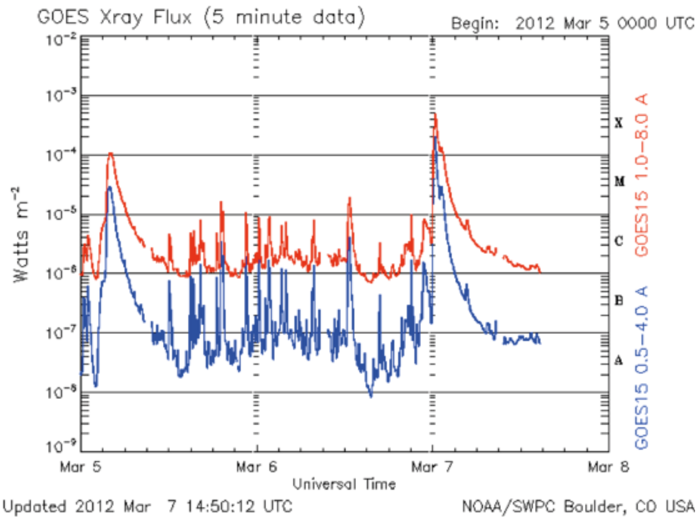


Figure 2: The X-ray emission from the Sun over a 3-day period as measured by the GOES spacecraft. The spikes in intensity are caused by solar flares. The classification of the flare is read from the right-hand vertical axis. Figure courtesy of NOAA/SWPC.

Radio blackouts – the R-scale: the R-scale is used to signal the level to which the ionosphere is affected by a solar flare, and the resultant impact on radio communications. The scale runs from R1 to R5 and is determined from the flare intensity. See Appendix 1 for the Met Office scale for radio blackouts.

Geomagnetic field disturbances – the Disturbance Storm Time index (Dst): Dst indicates the level to which the Earth's magnetic field has been disturbed following the arrival of a coronal mass ejection. Dst is derived from a network of instruments close to the equator that make measurements of changes to the Earth's magnetic field. Hourly Dst values provide a measure of geomagnetic activity. The value of Dst is an average of the magnitude change in the Earth's magnetic field at the station locations and is given in units of nano Telsa.

Geomagnetic field disturbances – the auroral electrojet index (AE): The AE index is created from observatories that are located at high latitudes underneath the auroral zone. AE is given in units of nano Tesla.

Geomagnetic field disturbances – the Kp index: the Kp index is derived from a network of instruments at mid-latitudes that make measurements of changes to the Earth's magnetic field. The Kp index provides a measure of global geomagnetic activity. Its value ranges from 0 to 9 and is given every three hours.

Geomagnetic storms – the G-scale: the G-scale is used by space weather forecast centres to indicate the level to which the Earth's magnetic field is disturbed. The scale runs from G1 to G5 and is set by the Kp index. A G1 storm corresponds to Kp 5, G2 corresponds to Kp6 and so on to G5, which corresponds to Kp9. See Appendix 2 for the Met Office scale for geomagnetic storms.

Solar energetic particle storms – the S-scale: the affect of solar energetic particles on the Earth's atmosphere is indicated with the S-scale. This runs from S1 through to S5 and is determined by the measured flux of energetic particles at Earth. See Appendix 3 for the Met Office scale for solar radiation storms.

Preparation times

A combination of space weather event forecasting and type of event will determine the lead-time available to Business Resilience teams to prepare for any impact and execute business continuity plans.

The probability of solar flare occurrence and magnitude is forecast on a daily basis. However, once a flare is seen to be in progress the electromagnetic radiation is already here. Solar energetic particles take longer to arrive at the Earth, but again, they are only known about once they start to be detected. In some cases the particle flux ramps up over several hours so that the initial detection acts as the alert that the conditions are deteriorating. Coronal mass ejections are detected when they are seen leaving the Sun, they are not yet forecast in advance, and so their transit time dictates the time available for preparations. This is typically between one and three days, although it can be as little as 12 hours due to time delay in obtaining and analysing the data. And there are large uncertainties in the level of impact the coronal mass ejection will have on the Earth's magnetic field.

Solar flares and coronal mass ejections often happen together and in extreme cases there will be a solar flare, coronal mass ejection and solar energetic particle event affecting the Earth over different timescales.

The Met Office Space Weather Operations Centre issues the following information, available freely to all critical national infrastructure providers, including the Finance sector:

- Space weather forecasts are issued twice daily describing current conditions and giving forecasts for up to 4 days ahead
- Warnings give advance notice of when an event may impact and how long it may persist for
- Alerts are issued following the impact identifying the scale of the event

The above are available via email by contacting MOSWOC@metoffice.gov.uk. or see the Met Office website: www.metoffice.gov.uk/space-weather

Space weather risks to the finance sector

The financial sector includes investment/retail banks, exchanges, investment funds, insurance and real estate companies. Their clients can be other institutions or private individuals.
For example, pension companies are typically clients of investment banks. Almost all of us will have a retail bank account and frequently use an ATM for cash or have insurance policies, savings or other forms of financial investment.

Behind the scenes, financial sector organisations have a complex array of processes and technology to support their activities. Typically their locations are determined by the proximity of clients, employee talent pools and are global in operation.

The use of mobile phones is prevalent and imperative for many aspects of business, particularly those highly mobile senior executives out with clients or organising complex transactions. The global nature of business opportunities can mean extensive travel between locations. In recent years, significant changes in working practices mean more employees work from home regularly.

A firm may have large processing or technology centres located in high value locations with significant numbers of employees located on a campus of buildings. In addition, there may be a large front office location in New York or London and large purpose built technology centres known as data centres close to low cost power and away from hazards such as earthquakes or flood-planes.

Where local regulation allows, processes can be multi locational, starting in one time zone and moving to others in a continuous never ending processing cycle. Locations often share work between them.

Execution and processing of extremely high volumes of transactions between organisations is absolutely reliant on technology systems and accurate timing.
Volumes of transactions are triggered by events; some anticipated, others driven by corporate actions or communication. In order that markets can operate effectively, the synchronized timing of transactions is imperative.

This time stamping is reliant on timing devices and increasingly on GNSS.

Continuous uninterrupted power for all of these operations is essential. Where possible firms use power from separate grids and substations but different geographies have different arrangements and this is not always possible

Space weather events by their scope and nature pose a number of risks to operations. These risks range from the more common travel and service disruption for a single institution, to the more unlikely widespread systemic event impacting several market participants and the knock-on effect to the wider financial sector requiring the intervention of authorities and governments.

Probability data suggest a major geomagnetic storm affecting a large area of the globe is a 1 in 100 year event and therefore potentially at the extreme end of business continuity planning. The more frequent 1 in 10 year severe geomagnetic and solar radiation storms have serious enough impact and frequency to be considered by financial risk and business continuity professionals.

Disruptions to GNSS services may impact time stamping but can also affect commuter rail networks that rely on GNSS technology. Solar geomagnetic storms may cause flights to be disrupted, diverted or cancelled. Although firms cope with these service interruptions on a daily basis, it is important whenever possible to have advanced information for informed decision-making.

Financial sector organisations have complex supply chains, leveraging time sensitive pricing and news information from market data providers, technology/technologists from 3rd party organisations and fibre optic cabling for networking from a complex array of providers to ensure continuity of service. Breaks in vendor services can, in the worst cases, lead to reputational damage for a firm.

Historical case studies of space weather impact

Space weather scenarios based on historical cases illustrate that global space weather has localized pockets of intense impact. In addition, case studies reveal how you may get very little notice that stormy space weather is on its way. Listed below are events that act as examples of severe to extreme space weather and its consequences.

September 1859 – the reasonable worst-case scenario?

Probably the most frequently mentioned historical space weather event is the one that took place on 2nd September 1859. In fact, this was one event of many that occurred over several days between 28th August and 8th September. It is notable though because it was the most intense and caused the skies around the world to light up with an intense display of the aurora. In early September, the aurora was visible much closer to the equator than normal and this generated an interest in both the general public and the scientific community. In London, the world's first underground railway was under construction, the electric telegraph network had been developed and the Reuters News Agency was in its eighth year. The electric telegraph was the key technology at the time for gathering news items and during this space weather event the operators reported that they could use their systems without the need for a battery – powered instead by the electric currents set-up in the atmosphere as a result of the geomagnetic storm. One newspaper in 1859 reported that you could light a chemical match using the sparks from the telegraph equipment. The newspapers reported the public's sightings of the aurora and on Saturday September 3rd the London Daily News printed, "the electric telegraph communication with all quarters was singularly disrupted and very uncertain, on Friday, owing to some mysterious atmospheric influence. No telegrams were received from France till after the close of the Stock Exchange."

The severe space weather experience on Friday 2nd September 1859 was the worst since the development of the electric telegraph and is known today as the Carrington event, after the British amateur astronomer Richard Carrington. He observed the flare on the Sun that occurred at the same time as the coronal mass ejection, which caused the geomagnetic storm when it arrived at the Earth. The primitive observations of the solar flare make it difficult to determine its intensity on today's scales however attempts to do this have been carried out.

Flare intensity	X15 to X42 [1,2]
Coronal mass ejection transit time	17.5 hours
Geomagnetic storm intensity	Dst = - 850 nT[3]

Table 1: Properties of the 1859 Carrington flare, coronal mass ejection and geomagnetic storm.

This geomagnetic storm remains the largest on record and in light of this is often referred to as the "reasonable worst-case scenario" and used to inform resiliency planning.

Technological impact	Telegraph system, sometimes inoperable
Onset time	05:00 local-time in the UK
Duration of disruption	Not known

Table 2: Technological impact of the 1859 Carrington geomagnetic storm.

The modern day impact of an event of this size has been studied by the Royal Academy of Engineering and their report concludes that up to 10% of satellites could experience temporary outages lasting hours to days and GNSS would be rendered inoperable for one to three days due to disturbances to the upper atmosphere (ionosphere) and through solar radio bursts. National Grid's analysis is that the most likely cause of problems would be from some localised power disruptions, lasting a number of hours. In addition, the best estimate is that two small, rural National Grid substations could be sufficiently damaged to disconnect their local communities from the grid. Such disconnections can occur as a consequence of terrestrial weather.

March 1989 – the space weather wake-up call

The most famous space weather event in modern times is the geomagnetic storm of 13th March 1989. The source of the storm was a coronal mass ejection that left the Sun on 10th March, again, from a region that produced several large flares and coronal mass ejections. This time there were telescopes monitoring the Sun and space weather forecasts were available.

Flare intensity	X4.5[4]
Coronal mass ejection transit time	54 hours
Geomagnetic storm intensity	Dst = - 640 nT

Table 3: Properties of the 10th March 1989 solar flare, coronal mass ejection and the geomagnetic storm that then occurred on 13th March.

When the geomagnetic storm was underway, the Hydro-Québec electricity grid experienced strong voltage fluctuations that were so large they caused the grid's protection system to be triggered. This led to the whole network shutting down in under two minutes. Six million people were affected and there was significant knock-on economic cost. It was the 'wake-up call' regarding space weather impacts and led to many lessons learned by electricity operators in geographically at-risk locations. Work on assessing the risk and hardening their respective grids is ongoing in US, Canada, UK, Nordic countries and South Africa, among others.

The consequences of the geomagnetic storm were felt in Quebec over a period of about 30 hours, i.e. from around 02:44 am on 13th March until 09:00 am the following day, although the power was back for most people by 10:00 am 13th March. The impact in the UK was much less severe. National Grid recorded adverse effects on 13th and 14th March 1989 with damage to two transformers that were subsequently repaired, returned and which are still in use today.

Technological impact	Blackout Québec Hydro electricity distribution, Canada
Onset time	02:44 EST
Duration of disruption	Up to 30 hours

Table 4: Impact of the 13th March 1989 geomagnetic storm.

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[1] Cliver, E. W., Svalgaard, L., The 1859 Solar-Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity, Solar Physics, 2004, 224, 407

[2] Thomson, N. R., Rodger, C. J.; Clilverd, M. A., Large solar flares and their ionospheric D region enhancements, Journal of Geophysical Research: Space Physics, 2005, 110, 6306

[3] Siscoe, G., Crooker, N. U., Clauer, C. R., Dst of the Carrington storm of 1859, Advances in Space Research, 2006, 38, 173

Halloween storms 2003 – multiple impacts in the modern era

As we move forward in time and sophistication of technology the risks posed by space weather evolve. In 2003 there was an event that really brought home how many aspects of our lives and business can be affected by severe space weather. The Sun produced a series of flares, coronal mass ejections and energetic particle events in quick succession and the Earth was directly in the firing line. With all three solar activity phenomena happening together, the impacts were widespread and lasted over several days. The most intense impacts at the Earth were felt on 29th and 30th October 2003.

The HF communications blackout and risk of exposure to excessive particle radiation caused aircraft on high latitude routes to reduce altitude or to re-route. Changes to the atmosphere caused problems with the Global Navigation Satellite System culminating in no service between 14:00 and 15:00 GMT on 29th October.

29th October 2003	
Flare intensity	X17 (flare occurred on 28th October)
Coronal mass ejection transit time	19 hours
Geomagnetic storm intensity	Kp 9
Radiation storm intensity	S3 - S4

Table 5: Properties of the solar activity and geomagnetic storm of 29th October 2003

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[4] Feynman, J., and A. J. Hundhausen, Coronal mass ejections and major solar flares: The great active center of March 1989, J. Geophys. Res., 1994, 99, 8451

Technological impact on 29th October 2003			
Technological impact	Air traffic controllers reported minor to severe impact on HF communications[5]	Global Navigation Satellite System	Electricity network
Onset time		14:00 UTC on 29th October	None
Duration of disruption	26th October to 5th November	1 hour	None

Table 6: Impact of the 29th October 2003 storm

And the next day, on 30th October, part of the high-voltage power transmission system in southern Sweden (operated by the Sydkraft company) failed.
The blackout lasted for an hour and left 50,000 people without electricity.

The Global Navigation Satellite System experienced a significant position error between 21:00 and 22:00 UTC on 30th October. Over these days 47 satellites suffered temporary outages.

30th October 2003	
Flare intensity	X10 (flare occurred on 29th October)
Coronal mass ejection transit time	19 hours
Geomagnetic storm intensity	Kp 9
Radiation storm intensity	S3

Table 7: Properties of the solar activity and geomagnetic storm on 30th October 2003

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[5] www.mssl.ucl.ac.uk/~rdb/portal2/docs/SOARS_Final_Report.pdf

[6] Pulkkinen, A. A., Lindahl, S., Viljanen, A., Pirjola, R., Geomagnetic storm of 29–31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, Space Weather, 2005, 3, S08C03

Technological impact on 30th October 2003			
Technological impact	Air traffic controllers reported minor to severe impact on HF communications	GNSS	Electricity network
Onset time		21:00 UTC	21:07 Central European Time (UTC+1)
Duration of disruption	26th October to 5th November	1 hour	1 hour

Table 8: Impact of the 30th October 2003 storm

July 2012 – the perfect storm?

In July 2012 the Sun produced series of fast coronal mass ejections. This time Earth wasn't in the firing line but the ejections were recorded as they passed over the STEREO Ahead spacecraft. The data collected by the spacecraft showed that one of the coronal mass ejections had the highest speed and magnetic field strength ever measured at the distance of the Earth from the Sun.

Flare intensity	Not observed
Coronal mass ejection transit time	19 hours
Geomagnetic storm intensity	Dst = -600 nT to -1150 nT[8]

Table 9: Properties of the July 2012 coronal mass ejection and estimated geomagnetic storm

They are seen as 'near miss' events because if these eruptions had happened a few days earlier, and been Earth directed, they would have triggered a large geomagnetic storm.

The July 2012 event is viewed as representing the 'perfect storm' because of multiple factors that all aligned:

- Speed of the coronal mass ejections
- Series of ejections in quick succession
- Earth's season (i.e. Earth's tilt with respect to the solar magnetic field)

This scenario has also been used to investigate what a similar coronal mass ejection could do if it differed only in its magnetic field orientation to make it even more hazardous. In this case, a very significant geomagnetic storm could be have been produced perhaps even larger than the Carrington event.

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[7] www.mssl.ucl.ac.uk/~rdb/portal2/docs/SOARS_Final_Report.pdf

[8] Liu, Ying D., Luhmann, Janet G., Kajdič, Primož, Kilpua, Emilia K. J., Lugaz, Noé, Nitta, Nariaki V., Möstl, Christian, Lavraud, Benoit, Bale, Stuart D., Farrugia, Charles J., Galvin, Antoinette B., Observations of an extreme storm in interplanetary space caused by successive coronal mass ejections, Nature Communications, 2014, Volume 5

[9] Baker, D., The Major Solar Eruptive Event in July 2012: Defining Extreme Space Weather Scenarios, American Geophysical Union, Fall Meeting 2013, abstract #SM13C-04

Building resilience to space weather

For many institutions, business continuity plans for technology, process, location, travel and vendor disruptions already exist. A space weather plan should therefore be considered a natural extension of existing arrangements. Increased awareness, monitoring and interpretation of space weather data are an important first step. The following sections lay out five key considerations:

1. **Monitoring** - The inter-connectedness of financial services businesses and the people and technology concentrations mean monitoring space weather events by crisis management centres and planning a response to them by business continuity planners are an important addition to financial sector business response plans.

2. **Technology and Facilities Risk assessments** - Technology and Facilities professionals should consider risk assessments for the most critical application and power infrastructure. Although shielding from solar radiation may be expensive, as systems are demised, replacements systems with appropriate shielding could be considered.

3. **Vendor Risk Assessments** - A careful assessment of vendor risk is generally undertaken during any vendor on-boarding process. Questions relating to a vendor's exposure to space weather could be added to that due diligence.

4. **Space Weather Response Plans** - For many businesses, their response plans are based on a series of "trigger" events driven by planning scenarios. For space weather planning, these triggers might be keyed off the geomagnetic and solar radiation scales (see Appendices). Business should consider the scope of the events (local/global/multi-region) and the impact on their own business and supply chain. In addition, space weather impacts can be felt on multiple systems, with the possibility of cascading failures in the most extreme cases.

   Other considerations might include:
   a) Travel services teams informing travelling staff of forthcoming disruption as a result of space weather.

   b) For the most serious storms, a plan to leverage a firm's global footprint to move work and processes around the globe as and when a space weather event might occur could be undertaken.

   c) At the most severe end of the space weather scale a co-ordinated response may be required particularly where more than one firm is affected and there is potential for systemic risk. Co-ordinated market wide testing could be considered by authorities and inter-bank organisations to prepare the sector for such an event.

5. **Education and Awareness** - Education and awareness of space weather risk could be undertaken by internal risk teams and business continuity planners. This could take the form of crisis management drills or as part of other training. Corporate communication teams could also consider their response to solar weather events, and their implications from a social media perspective. A firm could also consider their response to client requests for space weather preparedness as the sectors' monitoring becomes more mainstream.

	Threat Type													
	Geomagnetic	Solar Radiation	Scope	Description	Street Power	Internal Power	International Travel	Local Travel Disruption	Data / Voice	Mobile	Time Stamps	Social Media	Regulatory	Economic
5	Geomagnetic 5 Storm - Extreme	Solar Radiation Extreme	Global	Satellites Maybe affected, loss of power localised, transformers may experience damage, mobile phones affected, satellite navigation degraded GPS systems interrupted	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
			US	Satellites Maybe affected, loss of power localised, transformers may experience damage, mobile phones affected, satellite navigation degraded GPS systems interrupted	✗	✗	✗	✗	!	✗	✗	✗	!	✗
			UK	Satellites Maybe affected, loss of power localised, transformers may experience damage, mobile phones affected, satellite navigation degraded GPS systems interrupted	✗	✗	✗	✗	!	✗	✗	✗	!	✗
4	G4 Storm - Severe		Global	No significant power interruptions but maybe localised, internal power systems maybe affected. Satellites will be affected, Mobile phone and GPS systems affected	✗	!	✗	✗	!	✗	✗	!	✓	✓
			US	No significant power interruptions but maybe localised, internal power systems maybe affected. Satellites will be affected, Mobile phone and GPS systems affected	✗	!	✗	✗	!	✗	✗	!	✓	✓
			UK	No significant power interruptions but maybe localised, internal power systems maybe affected. Satellites will be affected, Mobile phone and GPS systems affected	!	!	✗	✗	!	✗	✗	!	✓	✓
3	G3 Storm - Strong		Global	Intermittent GPS satellite Navigation and low-frequency radio navigation problems may occur. HF Radio maybe intermittent	!	!	✗	!	✓	!	!	!	✓	✓
			US	Intermittent GPS satellite Navigation and low-frequency radio navigation problems may occur. HF Radio maybe intermittent	!	!	✗	!	✓	!	!	!	✓	✓
			Region	Intermittent GPS satellite Navigation and low-frequency radio navigation problems may occur. HF Radio maybe intermittent	✓	!	✗	!	✓	!	!	!	✓	✓
2	G2 Storm - Moderate		Global	High Latitude power systems may experience voltage alarms, long duration storms may cause transformer damage	!	✓	✓	✓	✓	!	✓	✓	✓	✓
			US	High Latitude power systems may experience voltage alarms, long duration storms may cause transformer damage	!	✓	✓	✓	✓	!	✓	✓	✓	✓
			UK	No impact to UK power grid, mobile phone networks may experience outages	✓	!	✓	✓	✓	!	✓	✓	✓	✓
1	G1 Storm - Minor		Global	Localised power disruptions possible	!	✓	✓	✓	✓	✓	✓	✓	✓	✓
			US	Localised power disruptions possible	!	✓	✓	✓	✓	✓	✓	✓	✓	✓
			UK	No impact to power grid, no impact to internal power systems. Some minor service interruptions possible to mobile and GPS services	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 10: Trigger based impact-planning chart

Conclusions and Recommendations

We recommend the following actions grouped into two themes.

Theme 1: business continuity planning

- Firms should consider activities in-house to understand and evaluate the global impact of space weather risk for their business and build or extend their business resilience and crisis management processes accordingly.
- Consideration should be given to using a space weather scenario in a market-wide business resilience test e.g. the Bank of England's financial sector exercises.

Theme 2: research

- Historical data on system "glitches"/downtime should be used to investigate the impact of space weather activity and determine at what scale of event the sector could be impacted.
- Financial companies should start gathering information on component and data failures for future analysis.
- With data, more tailored forecasting services can be developed for the Finance industry.

Appendix 1

Space weather scale for radio blackouts

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle=11 years)
Scale	**Descriptor**	**Duration of event will influence severity of effects**			
Radio blackouts				**GOES X-ray peak brightness by class and by flux**	**Number of events when flux level was met; (number of storm days)**
R 5	**Extreme**	**HF Radio:**Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector.	**HF Radio:**Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** : HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time.	**HF Radio:** : HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth.	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes.	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact.	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Other frequencies may also be affected by these conditions.

Appendix 2

Space weather scale for geomagnetic storms

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects			
		Geomagnetic storms		Kp values*	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	**Power systems:** Localised voltage control and protective system problems may occur leading to potential for localised loss of power. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, drag may increase on low-Earth-orbit satellites, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** HF (high frequency) radio communication may be impossible in many areas for one to two days, GNSS(GPS) satellite navigation may be degraded for days with possible effects on infrastructure reliant on GNSS (GPS) for positioning or timing, low-frequency radio navigation can be out for hours, and aurora may be seen across the whole of the UK.	**Power systems:**widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** may experience surface charging and tracking problems, drag may increase on low-Earth-orbit satellites, corrections may be needed for orientation problems. **Other systems:** HF radio propagation sporadic, GNSS(GPS) satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora may be seen across the whole of the UK.	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent GNSS(GPS) satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent. Aurora may be seen in Scotland and Northern Ireland and as low as Mid-Wales and the Midlands	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** No impact on UK power grid. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora may be seen across Scotland.	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** No impact on UK power grid. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Aurora may be seen as low as Northern Scotland.	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle

*The Kp-index used to generate these messages is derived from a real-time network of observatories the report data to SWPC in near real-time. In most cases the real-time estimate of the Kp index will be a good approximation to the official Kp indices that are issued twice per month by the German GeoForschungsZentrum (GFZ) (Research Center for Geosciences).

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (Tips on Viewing the Aurora)

Appendix 3

Space weather scale for solar radiation storms

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects			
Solar radiation storms				Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S 5	Extreme	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** Some satellites may suffer temporary outages due to memory impacts which can cause loss of control, serious noise in image data or orientation problems and permanent damage to solar panels. **Aircraft Operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** Some satellites may suffer temporary outages due to single event effects on electronics which can cause unexpected behaviours, noise in image data or orientation problems and permanent damage to solar panels.*** **Aircraft Operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** A small number of satellites may experience outages due to single event effects, which can cause unexpected behaviours, noise on imaging systems and orientation problems. **Aircraft Operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** No additional risk. **Satellite operations:** Infrequent single-event upsets possible. **Aircraft operations:** Unlikely to have significant effect.***	**Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** none. **Satellite operations:** none. **Aircraft operations:** Unlikely to have an effect***	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2}. Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

*** High energy particle measurements (>400 MeV) are a better indicator of radiation risk to aircraft avionics, passengers and crews. Pregnant women are particularly susceptible.

Further reading and relevant websites

- Cannon, P. S., et al. (2013), Extreme Space Weather: Impacts on Engineered Systems, Royal Academy of Engineering, London, UK

- Space Weather Preparedness Strategy, BIS www.gov.uk/government/publications/space-weather-preparedness-strategy

- Space Weather and Financial Systems: Findings and Outlook, DOI 10.2788/18855

- Space Weather: Its Impacts on Earth and Implications for Business, Lloyd's 360 report www.lloyds.com/~/media/lloyds/reports/360/360%20space%20weather/7311_lloyds_360_space%20weather_03.pdf

- Met Office Space Weather Operations Centre www.metoffice.gov.uk/publicsector/emergencies/space-weather

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