Drayton Tyler Ltd

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Severe Space Weather

A Drayton Tyler 'Future Risks' report

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Contents

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He has worked as a Special Adviser in the British Parliament, advising on defence and homeland security (including some of the early planning for pandemic influenza), and in the prestigious Conservative Research Department as defence adviser and speech writer to the leader of the Conservative Party. He was the founding editor of Jane's Intelligence Review, launched in 1989.

Abbreviations used in this report

BEIS	The UK's Department of Business, Enterprise, Industry and Science.
CME	Coronal Mass Ejection.
ESA	European Space Agency.
GCSA	The UK's Government Chief Scientific Adviser.
GIC	Geomagnetically induced current.
GMD	Geomagnetic disturbance.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning Satellite.
MOSWOC	The UK Met Office Space Weather Operations Centre.
NASA	National Aeronautics and Space Administration, the part of the US Government responsible for space activities.
NERC	The UK Natural Environment Research Council.
NOAA	National Oceanic and Atmospheric Administration, a US agency responsible to the US Government for understanding and predicting changes in climate, weather, oceans and coasts.
SAGE	The UK's Scientific Advisory Group for Emergencies, responsible for scientific advice in support of decisions taken in the Cabinet Office Briefing Room.
SEIEG	The UK Space Environment Impacts Expert Group, which advises SAGE.
SEP	Solar Energetic Particles.
STFC	The UK Science and Technology Facilities Council.
SWPC	The US Space Weather Prediction Centre, part of NOAA.
SWIMMR	The UK Space Weather Instrumentation, Measurement, Modelling and Risk program.

1. Summary

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A solar superstorm is a 'when not if' event. In the worst case, the direct and indirect costs are likely to run into trillions of dollars with a recovery time of years rather than months. The probability of an event of that size happening is estimated by the UK's Royal Academy of Engineering as one in ten in any decade.

The seriousness of the risk is not being matched by government action other than in the USA (even there, more spending is needed) and to a reasonable extent in the UK.

The cascade of infrastructure failures that could result from a severe solar storm hitting Earth is not properly appreciated by governments. The societal consequences of prolonged disruption to power supplies and satellite-based timing and navigation services are worrying.

There is a growing risk that existing capabilities for space weather monitoring will degrade in this decade, leaving the world much less able to observe and understand major solar storms.

The US stands out as the country with the greatest expertise and understanding across government of the risks posed, the importance of preparedness and the many benefits of making relevant information publicly available.

Close behind the US, the UK has superb scientific and technical expertise and the support of an actively engaged government department in the form of the Department for Business, Energy and Industrial Strategy (BEIS). Given the magnitude of the risk we were surprised to learn that BEIS does not carry out regular rehearsals of a severe space weather event, however.

To be properly prepared for the worst effects of severe space weather countries need to combine a strong scientific and technical base with the right level of political and governmental involvement, along with an active partnership with the private sector. This last element is too often forgotten.

Greater transparency is needed with regards to space weather preparedness and governance. Whereas the US Government freely publishes relevant information, this is less so in the UK (although the situation is quickly improving). In the EU the situation is opaque.

There is a commendably high level of collaboration at the scientific level, in particular within the UK and between the UK, USA, and European Space Agency, and also between the member states of the International Space Environment Service.

There is a growing risk that the EU's ambitions for control of space projects will interfere with the workings of the more open and collaborative European Space Agency.

Severe space weather contingency plans must be regularly rehearsed, including worst case assumptions with regards to power and communications. The involvement of the private sector in this is vital.

Increasing space weather preparedness is likely to be a powerful catalyst for promoting interest and teaching in science, technology, engineering and maths throughout the educational system. This will bring with it significant economic benefits.

The UK has a tremendous opportunity to increase its global relevance as a space nation. We wait with interest to see whether 'Global Britain' has what it takes to be a Tier 2 player in space.

In conclusion, severe space weather is an ever present risk with short warning times of a kind not experienced since the Cold War. The downside societal and economic risks are significant; the world is not yet properly prepared for it.

Focus and a sense of urgency are needed. This is serious.

2. Recommendations

The Covid-19 pandemic illustrates the importance of actively mitigating risks rather than simply identifying them. We recommend action in the following areas:

2.1 General

2.1.1 Recognise the risks from severe space weather

There is a natural tendency to ignore esoteric risks such as space weather – but that is a mistake. Space weather needs to be taken seriously in both the public and private sectors, particularly in terms of governance and risk management. In the worst case the time to react may be measured in days; once the warning of a severe space storm comes the plans and preparations made now are the ones that will be put into effect. This is not something you can muddle your way through.

2.1.2 Political oversight

We recommend that time be spent by parliamentary or congressional committees on space weather risks and their mitigations, ensuring that organisations and individuals working on space weather receive the acknowledgement, funding and direction they need.

2.1.3 Plan for the worst and rehearse regularly

It's important for national and regional authorities to identify now the teams they need to manage a severe space weather event where this hasn't already been done, and to rehearse those teams every two to three years.

2.1.4 National Risk Councils

There is a good case to be made for countries to form National Risk Councils. These bring several benefits, including providing a point of focus for risks and risk management, as well as offering visibility and transparency in a way that is often lacking currently. Risk councils also allow the right groups of experts to be assembled well before a risk materialises, independent of the priorities of government departments, and co-ordinate responses with other countries.

2.1.5 Economic

We recommend that sufficient, multi-year funding be provided at national/regional level for space weather science, scientific collaboration and space weather funding and that funding is reviewed regularly.

2.1.6 Collaboration

We recommend closer collaboration between the private, public and academic circles in investigating space weather and developing solutions to the challenges of space weather.

2.1.7 Financial Services

We recommend that central banks and financial regulators are alert to the impact on the stability of their financial systems of severe space weather, particularly in relation to GNSS based timing and trading systems and potential market volatility, and prepare mitigation strategies with market participants. We recommend that market participants include space weather in their risk management and business continuity thinking.

2.1.8 Analyse reliance on GNSS position, timing and navigation

We recommend that all developed countries follow the lead of the US and analyse their dependencies on GNSS position, timing and navigation signals and maintain a national register of those dependencies and mitigation strategies where appropriate. This register and mitigation strategies should cover both the public and private sectors.

2.2 Science and technology

2.2.1 Maintain existing satellite-based surveillance capabilities

Existing satellite capability should be maintained and enhanced. We recommend even closer cooperation between the UK, US, Canada, Australia and New Zealand, and between the UK and the Latin American space programmes. Given its ambitions for 'Global Britain' the UK should be prepared to take a leadership role where this would be welcomed by its partners – it should be aspiring to be a Tier 2 space nation and not resigning itself to only ever being Tier 3.

We strongly urge decision makers to guarantee funding for the Lagrange L5 mission so as to ensure its launch in or before 2027.

2.2.2 Add new satellite capabilities
New capabilities are needed to further our understanding of the Sun and to improve the timeliness and accuracy of space weather forecasting, such as the development and launch of small satellites for measuring particles and fields in the magnetotail-to-ionosphere region.

2.2.3 Exploit existing opportunities in space
The growing number of spacecraft launches offers opportunities for increased space weather monitoring, as well as producing more clients for space weather warning services including 'nowcasting' of live space weather conditions.

2.2.4 Ground-based programmes
We recommend that countries with relevant sensors look for synergies, both with respect to their own sensors and by collaboration with other countries, to derive more space weather observations. For example, cosmic ray detectors for soil moisture measurement can be used to measure radiation from space; lightning detectors can be used to detect solar flares and ionospheric changes.

2.2.5 Increase aircraft borne radiation monitors
There are benefits to increasing the number of radiation monitoring instruments on civilian aircraft if suitable commercial terms can be agreed on.

2.3 UK specific

2.3.1 Political
In the UK we recommend that the UK National Strategic Risk Register and the National Space Weather Strategy are reviewed by the Science and Technology Committees in the House of Commons and the House of Lords when they are published.

2.3.2 Economic
In the UK we recommend that a review of funding of the UK space weather community over and above the SWIMMR funds announced in 2019 is carried out to assess whether funding is proportionate to the risk to the UK, and adjusted as appropriate. This is a good time for the UK to invest in space.

2.3.3 Research and development
Strategic Research Programme
We recommend that the Department for Business, Energy & Industrial Strategy (BEIS), as the Lead Government Department for space weather (if necessary in partnership with the Department for Education), funds a strategic research programme to supply research into the operations pipeline represented by SWIMMR. This should be at all stages of the academic cycle: undergraduate, post-graduate and post-doctoral.

Astrophysics
We recommend that BEIS prioritises research and education in origins of space weather, propagation through the heliosphere and the impact on geospace.

Engineering
We recommend that BEIS prioritises the development of the relevant engineering skills required to design and build new space weather instrumentation.

Data modelling skills
We recommend that UK Research and Innovation prioritises funding for the development of innovative approaches to model/forecasting space weather e.g. data assimilation/incorporation, physics-based modelling, model coupling.

2.3.4 User education
We recommend that BEIS funds a rolling programme of user education within all parts of the Critical National Infrastructure in order to educate and inform organisations about the primary and secondary impacts of space weather, building on the 2018 'Public Summary of Sector Security and Resilience Plans'.

3. The problem

3.1 Understanding the Sun

Relative to the Earth the sun is big - its diameter is about a hundred times greater than Earth. It's four hundred times further away from us than the Moon – around 149 million kilometres. Like other stars the Sun is a ball of gas, called plasma. Light from the Sun takes a little over eight minutes to reach Earth.[1]

The Sun accounts for 99.8pc of all mass in the solar system. 91pc of its atoms are hydrogen and 8.9pc helium. The process by which hydrogen fuses into helium releases energy, some of which is eventually released in the form of light.

Different regions of the Sun rotate at different rates – about once every 27 days at the equator but only once every 31 days at its poles. This contributes to the complex nature of the Sun's magnetic field, one effect of which is to heat the outer layer of the sun's atmosphere (the corona) to be many times hotter than the photosphere (the Sun's outer shell which emits light).

Dark spots, known as sunspots, are sometimes seen on the Sun's surface. They form at areas where solar magnetic fields are relatively strong. The number of sunspots increases and decreases throughout the eleven year solar cycle. We are currently at a period of low sunspot activity near the start of the current solar cycle. The previous cycle, which ended at the end of 2019, marked a period of relatively low sunspot activity across the whole cycle compared with other cycles. It's important to note that severe space weather can occur at any part of the solar cycle, with major solar storms having occurred at or near sunspot minima.

Severe space weather can occur at any part of the solar cycle but is more likely to occur at the peak or declining phase of the cycle

3.2 The Sun as an enormous emitter

The Sun is sometimes described as being like a huge nuclear fusion bomb. That's certainly true in that the enormously dense core of the Sun drags down hydrogen atoms, causing them to fuse into helium and release energy in doing so.

But that simple explanation fails to capture everything else that is going on with the Sun, including the Sun's magnetic field and its interaction with the Sun's atmosphere, in particular the outer layer, or corona.

The end result of this vast turmoil of physical and chemical processes is emissions of different types which travel at different speeds across and out of the solar system. At extreme levels these emissions can all have negative effects on Earth and the systems and machines we have created.

Space weather experts categorise these emissions into three groups:

- *Electromagnetic radiation*, travelling at the speed of light.
- Particles emitted from the Sun, including protons, neutrons[2], oxygen ions, helium ions, known as *Solar Energetic Particles*, or SEPs.
- Large expulsions of plasma and magnetic field from the Sun's corona, known as *Coronal Mass Ejections,* or CMEs. The orientation of the magnetic field of the CME as it impacts the Earth's magnetic field is critical to the outcome of the encounter, as it affects the resultant geomagnetic disturbance (GMD) and geomagnetically induced currents (GIC).

Electromagnetic radiation

Solar Energetic Particles

Coronal Mass Ejections

3.2.1 Electromagnetic radiation

A solar flare is an intense burst of electromagnetic radiation coming from the release of magnetic energy associated with sunspots. This electromagnetic radiation from the Sun travels to Earth at the speed of light, across the whole spectrum from Gamma radiation and X-Rays to visible light and radio waves, taking just over eight minutes to make the journey. It can affect the Global Navigation Satellite Systems (GNSS) network[3], ground and spaced based systems, and radar (including early warning radar).

There are numerous instances of sudden bursts of electromagnetic radiation coming from the Sun, which can overwhelm GNSS and jam ballistic missile early warning systems. This is inconvenient (and potentially dangerous) for anyone using satellite navigation and alarming for military operators on the lookout for a missile attack. It can also lead to disruption of high frequency radio communications for several hours and lead to the closure of polar air space.

3.2.2 Solar energetic particles (SEPs)

Solar energetic particles are high-energy charged particles, primarily thought to be released by shocks formed at the front of coronal mass ejections and solar flares. SEPs can travel at up to a third of the speed of light and hence make the journey from the Sun to the Earth in as little as twenty-five minutes.

They can cause damage to satellites, including lasting degradation of micro-electronics, optical components and solar cells. They can also cause data corruption, systems shutdowns and circuit damage, as well as power drains and false instrument readings.[4] They also lead to disruption to HF radio and can increase radiation exposure for aircraft passengers and astronauts, potentially to multiples of normal safe limits.

SEPs can damage satellites and shorten satellite life

Highly energetic SEPs will make their presence felt at the surface of Earth. All latitudes are vulnerable although the worst effects are more likely in more northerly/southerly latitudes. For a 1-in-100 year event the estimated increase in surface radiation in London is a factor of 120. The 1-in-1000 year worst case would see a 1000-fold increase in the surface radiation in London and 5000-fold for the north of Scotland.[5]

This presents challenges for designers and operators of autonomous vehicles and quantum computing systems, not least because of the short time between the observation of a solar flare and the arrival of SEPs about fifteen minutes later.

What happens to a convoy of autonomous vehicles hit by a burst of SEPs?

3.2.3 Coronal Mass Ejections (CME)

This giant blob of magnetic matter, weighing a billion tonnes or more, can be problematic if it hits Earth. This can occur in as little as fifteen hours after it's ejected from the corona, which translates into a speed of over 2500 kilometres *per second*. The frequency of CMEs has been shown to match sunspot activity over the last two solar cycles[6] but CMEs can also occur when there are no sunspots visible. CMEs are sometimes associated with solar flares but can occur independently.

It's important to note that there is no consensus on precisely what causes a CME.[7]

CMEs impact the earth's magnetic field and have a magnetic field orientation. If the CME magnetic field is oriented north (like the earth's magnetic field) then the impact is limited. However, a southwards oriented magnetic field disrupts the Earth's magnetic field to a much greater extent and is more likely to affect vulnerable systems. The resultant fluctuations in the Earth's magnetic field generate electric fields on earth. These geomagnetically induced currents (GICs) can flow into power lines and transformers, leading to transformer saturation and over-heating, voltage drops, transformer damage and grid collapse.

The magnetic orientation of a CME hitting Earth makes an important difference to the outcome

Significant grid problems from CMEs occurred in March 1989 in Montreal in Canada and Salem in the US, and Sweden and South Africa in October 2003. Following the March 1989 storm there were 12 nuclear plant transformer failures in the US over the next 25 months, mostly on the eastern seaboard.[8] Grid failures in one region can, under some circumstances, catalyse grid failures in another, connected, region.

Extreme space weather is thought to be associated with fast CMEs (ie travelling faster than 800 kilometres per second). Typically, the first, fast, CME fired out from the Sun compresses the normal solar wind plasma and associated magnetic field by a factor of four. This accelerates the solar wind speed and introduces a sharp deflection in the direction of the magnetic field. This shock also generates a meaningful increase in SEPs.

CMEs can occur at periods of low sunspot activity – and there's no consensus on what causes them

During periods of high solar activity the Sun can launch several CMEs towards earth. The first CME, having pushed the solar wind away from it but being slowed in the process, may then be caught up by the next CME, producing more complex changes in the interplanetary magnetic field.

Multiple CMEs can occur during periods of high solar activity

When CMEs hit the Earth's magnetic field (magnetosphere) the magnetosphere is compressed while the CME flows around behind the Earth, causing the magnetosphere to extend and magnetic flux lines to join up (releasing further energy). It then returns in time to its normal state but this fluctuation leads to a series of geomagnetic events over a period of days.

Scintillation effects from space weather have been observed in the frequency range from about 10MHz to 12GHz – that's from the 25 metre band and downwards for short-wave radio, FM radio, digital TV and radio, and emergency services' radio in the UK and elsewhere. This will make it hard for governments to communicate properly with their citizens during the aftermath of a severe storm.

Disruption to TV and radio broadcasts as a result of a severe solar storm is likely

3.3 Challenges of forecasting space weather

The main challenges of forecasting space weather are the difficulties of forecasting events accurately, short warning times, challenges about estimating where on Earth will be impacted, and estimating the related economic and societal effects.

Forecasting space weather is difficult

Space weather forecasting is a more complicated problem than scientific study of the Sun and its weather, requiring more sensors, both in space (in earth orbit and at the Lagrange points – see Annex A) as well as in the air (eg on aircraft) and on the ground. There are now three space weather centres for aviation (four from later in 2021), as well as the many members of the International Space Environment Service (described in more detail in Section 6) providing various levels of monitoring and reporting. There is a need for more observation platforms, both in space and on Earth, not least to provide systems redundancy that doesn't exist currently.

The risks arising from severe space weather have been recognised by the UK Government for a decade but current preparedness does not fully reflect this, although the direction of travel is encouraging. Given some of the worst case estimates produced by credible sources, we should be deeply concerned about the possible impacts and ensure that countries are as well prepared as can be, both in terms of real-time monitoring and forecasting, and risk mitigation.

Governments, including that of the UK, are not properly prepared for the full effects of severe space weather

4. What's happened in the past?

This section describes some of the more eventful solar storms that have occurred. It is by no means an exhaustive list but illustrates the magnitude and complexity of the challenge of understanding and predicting severe space weather.

The first (and biggest) recorded space weather event occurred at the beginning of September 1859. It was witnessed by the amateur British astronomers Richard Carrington and Richard Hodgson and is described in more detail below, along with accounts of some other notable storms.

4.1 The Carrington Event of 1859 and the storm of 1865

In 1859 aurora lasted for two weeks and were reported in the Tropics and in Australia, as well as Europe and the US

In the early hours of 29 August 1859 a 'splendid aurora borealis' was seen in the London night sky shortly after midnight. The celestial display lasted an hour and was visible across half the sky. According to newspaper reports 'from the SW to W, where the rosy brilliancy began, the appearance might frequently have been taken for the reflection of a vast fire; except, perhaps, for a delicacy and softness of the tints, of which no description can give an adequate conception.'[9]

The London Morning Chronicle reported a display of aurora borealis in New York on 28 August, also quoting a conversation between telegraph operators on the Boston and Portland telegraph offices where they were able to pass messages only when they disconnected the power supply from the system.[10]

Frederick W Royce, a telegraph operator in Washington DC, was reported as saying that the system current changed continuously, at one time being so strong that he could not lift the telegraph key as its magnet was being pulled down. Leaning forward towards the 'sounder' that acted as the signal receiver with his hand resting on the metal plate of the transmitter, he was reported as being temporarily knocked senseless by a spark that jumped from his forehead to the sounder.

Carrington's remarkable observations in September 1859

A few days later, before noon on 1 September 1859, the amateur British astronomer Richard Carrington noted an unusually large pattern of sunspots.

At 11.18am he observed that 'two patches of intensely bright and white light broke out' which faded away within five minutes. He noted with surprise that the pattern of sunspots he was observing remained unchanged and formed the impression that 'the phenomenon took place at an elevation considerably above and over the great group in which it was seen projected. Both in figure and position the patches of light seemed entirely independent of the configuration of the great spot, and of its parts…'.[11]

What Carrington observed and recorded so well was also observed and recorded by another British astronomer, Richard Hodgson. In his shorter account Hodgson adds that 'The magnetic instruments at Kew were simultaneously disturbed to a great extent'.[12]

Newspaper reports of displays of the aurora borealis and jammed telegraphy systems continued in the British press until 9 September, a period of thirteen days from the first reported incidents in London and the eastern seaboard of the United States.

4.1.1 The Kew Observatory Records

The 1859 Kew magnetograph records show that there were two significant geomagnetic storms: the first from 10.30pm on 28 August to 7.30pm on 29 August, and the second from 5am on 2 September to 4pm the same day.[13] Interestingly the records also show a disturbance starting at the same time as Carrington was making his observations and lasting for about ten minutes.

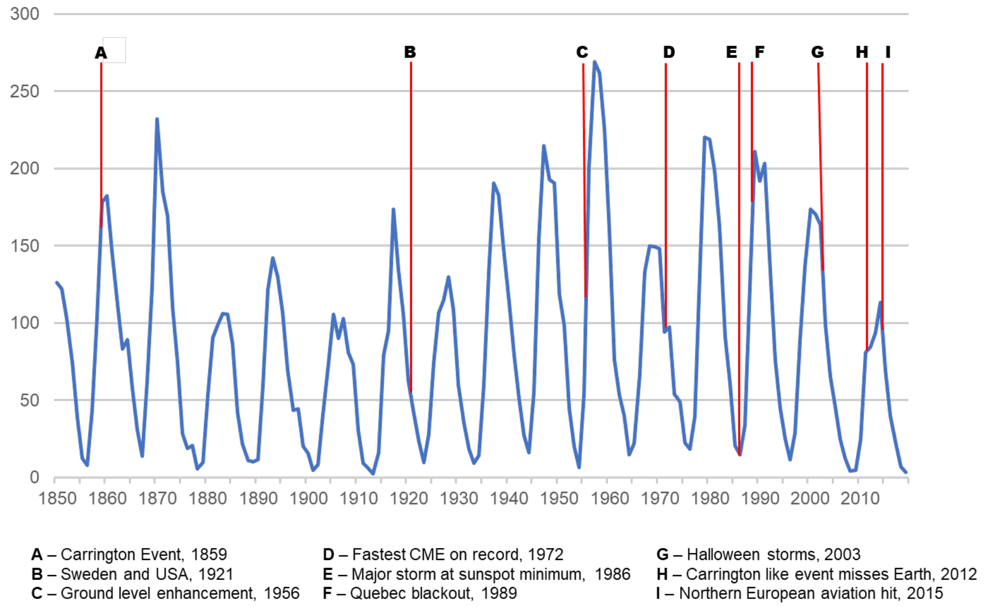
The Kew magnetograph records did not return to normal until 7 September, a period of ten days from the first abnormal observations.

No sunspots were visible in the days leading up to the 1865 storm

Further notable geomagnetic storms were observed at Kew in December 1862 and August 1865. In the 1865 storm major sunspots only appeared on the surface of the Sun on the morning of 3 August, the day the first of the two August storms hit Earth. The observers at the time compare this storm with the 1859 storm in that it consisted of two separate waves.

Figure 2: Mean annual number of sunspots, 1850-2020, with some key storms plotted

There's no simple link between the occurrence of severe space weather and the solar cycle – and a quiet solar cycle is no guarantee of a major solar storm not happening



Source: Drayton Tyler Ltd, Royal Observatory of Belgium

4.2 Sweden and the USA: May 1921

In 1921 a massive sunspot was visible from Earth — subsequent magnetic storms led to fires in New York and Sweden

On 10 May 1921 the US Naval Observatory in Washington DC spotted a large sunspot which they calculated to be 94,000 miles long (about a tenth of the Sun's diameter) and 21,000 miles wide. Shortly before midnight local time on the night of 14/15 May the whole telegraph system out of New York was put out of commission.[14] Excessive currents on telephone lines caused the Union Railroad Station in Albany, New York, to catch fire and there was a fire in the railroad control tower at 57th Street and Park Avenue.[15]

Magnetograph records from the Greenwich Observatory in the UK show the magnetic disturbance lasting from 3pm local time on 14 May to about 2pm the following day.[16] They then picked up again on 16 May.

A few days later the president of the Western Union Telegraph Company announced that the damage to the Transatlantic telegraph cable from the geomagnetic effects of the storm was so great that it might have to be lifted for repair.[17]

On 17 May it was reported that a solar storm had also hit Sweden, leading to a number of fires due to electrical short circuiting, including the complete destruction of the Karlstad Telegraph Station. The telegraph system in Australia was also affected.[18]

4.3 February 1956 – dramatic ground level enhancement

A solar flare in 1956 generated extremely fast SEPs – and was in the ascending phase of the solar cycle

Ground level enhancements (GLEs) – a class of Solar Energetic Particles (SEPs) - are sudden increases in the cosmic ray intensity recorded by ground based detectors. GLEs are invariably associated with large solar flares. [19]

A dramatic increase in ground based measurements of forty-five times background levels was recorded following a solar flare on 23 February. This occurred in the ascending phase of the solar cycle, two years after the minimum of solar activity. Nearly eighty percent of the effect arrived in the first hour, with the peak occurring during the first few minutes.

This event is notable for a number of reasons: firstly, for the high intensity of SEPs that arrived at the surface of the Earth; secondly for the unusually rapid transit time from the Sun (the first protons arrived shortly after the light of the flare was observed)[20], thirdly that it happened during the ascending phase of the solar cycle. This emphasises that the risk from space weather exists at any time of the solar cycle, and not simply around the time of maximum sunspot activity.

4.4 The fastest CME – August 1972

The August 1972 solar storm saw the fastest CME transit time on record, which reached the Earth in under fifteen hours (an average speed of 2700 km per second. The magnetosphere was compressed from its usual 60,000 km from earth to less than 20,000 km.[21] but because the interplanetary magnetic field (IMF) in this case was north aligned little energy entered the magnetosphere. If the IMF had been south aligned the impact on Earth would have been much greater.

1972: the fastest CME on record – 15 hours from Sun to Earth

4.5 Storm at sunspot minimum – February 1986

A major geomagnetic storm occurred on 8-9 February. This is significant because it happened close to sunspot minimum and underlines the importance of being prepared for major solar storms at any part of the sunspot cycle.

The 1986 storm occurred close to sunspot minimum

4.6 The Quebec blackout – March 1989

There were two major solar storms in 1989: a huge geomagnetic storm in March and a major solar radiation storm in October. The March storm caused a nine-hour power blackout in the province of Quebec, affecting six million consumers and caused transformer damage in the UK and other countries.[22]

1989: cascading transformer trips led to transformer burnout. There were also numerous grid anomalies attributed to this storm

What's notable about the effects of the March storm on the Quebec Hydro power system is the speed of grid collapse – a mere 92 seconds from first indications of a problem to the failure of the entire power grid in Quebec. The rest of North America also felt the effects, not least because of the loss of a 2GW power interconnector from Canada to the US. In their post-event analysis, the North American Electric Reliability Council attributed around 200 significant anomalies in their power grids to this storm.[23]

4.7 The Halloween Storms – October 2003

Although a weaker event than 1989, the Halloween Storms of 29-31 October 2003 caused a number of effects which served to highlight the complexity of understanding and mitigating impacts. Polar flights were re-routed, there was transformer damage in South Africa, GPS fails in Europe and widespread HF radio outage across Africa. Japan's ADEOS 2 satellite was lost and the power grid failed temporarily in Malmo, Sweden.[24]

4.8 Direct hit on Mars – July 2012

This huge CME – estimated to be as large as that of the 1859 Carrington Event – was fortunately directed towards Mars and not Earth. Nonetheless there were impacts: Air Canada Flight 003 from Vancouver to Tokyo lost communications while flying over the North Pole, leading to an air traffic alert for a missing aircraft being issued, and the US built Sky Terra 1 satellite (operated by LightSquared) went offline temporarily.

The 2012 CME was as big as the Carrington Event but missed Earth and hit Mars instead

4.9 Northern European aviation hit – November 2015

In November 2015 Sweden was badly hit and its air traffic control systems were knocked out by a moderate solar storm, leading to closure of airspace. There was also disruption in Belgium and Estonia. The incident served to bring the attention of the White House to the vulnerabilities of critical infrastructure to space weather.[25]

5. Assessing the risk

Is the risk of severe space weather too hard to comprehend?

There are a number of hurdles facing governments when looking at risks like space weather.

The first is the psychological one: how do we begin to understand a risk that we have never experienced? Of the current MPs in the UK Parliament only 16pc (106) have an interest or background in science, technology, engineering, maths or medicine. The challenge for space weather experts is to find the language to describe the problem, the opportunities, the risks, and mitigations to those risks to policy makers.

Secondly, we have to find the right risk methodology. The generally accepted risk level of a Carrington level event as 'a one in ten chance in the next decade' catches the attention but we then have to decide whether this is a good starting point for quantifying the impact of an event like this versus other natural risks. Traditional empirical risk methodologies, estimating likely cost and applying a probability factor, aren't adequate.

Thirdly is the question of the funding cycle: the public sector in the UK generally finds itself without all the money it feels it needs so inevitably economies are made. Some of these have undesirable consequences: in the process of researching this report we found evidence of poor procedures relating to coding changes, which in some cases delayed software updates on critical systems.

Finally, the timescales of risks of this kind may be seen to fall outside the normal electoral cycle – money spent preparing for them don't help governments win elections.

5.1 Understanding big risks

There have been some impressive efforts made to prepare for big risks. We look at two: the UN Office for Disaster Risk Reduction Sendai Framework of 2015, and the UK's Blackett Review of High Impact, Low Probability Risks of 2011.

5.1.1 United Nations Office for Disaster Risk Reduction (UNDRR)

The UNDRR introduced the *Sendai Framework for Disaster Risk Reduction* at the third UN World Conference on Disaster Risk Reduction in Sendai, Japan, in March 2015.

The Sendai framework introduced the concept of 'build back better'

The Sendai Framework articulates the following:

- The need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability and hazard characteristics;
- The strengthening of disaster risk governance, including national platforms; accountability for disaster risk management;
- Preparedness to 'Build Back Better'; recognition of stakeholders and their roles; mobilization of risk-sensitive investment to avoid the creation of new risk;
- Resilience of health infrastructure, cultural heritage and work-places;
- Strengthening of international cooperation and global partnership, and risk-informed donor policies and programs, including financial support and loans from international financial institutions.

There is also clear recognition of the Global Platform for Disaster Risk Reduction and the regional platforms for disaster risk reduction as mechanisms for coherence across agendas, monitoring and periodic reviews in support of UN Governance bodies.[26]

While the Sendai Framework provides a useful structure for managing risk on a global basis the risks from space weather or any mention of space weather itself is notable by its absence in UNDRR publications, despite the re-iteration of the Sendai Framework's scope applying to the risk of:

> *"small-scale and large-scale, frequent and infrequent, sudden and slow-onset disasters, caused by natural or man-made hazards, as well as related environmental, technological and biological hazards and risks. It aims to guide the multi-hazard management of disaster risk in development at all levels as well as within and across all sectors."*[27]

5.1.2 Blackett Review of High Impact Low Probability Risks

Understanding high impact, low probability risks is harder than it sounds

One of the more thought-provoking publications to come out of the UK Government Office for Science is the Blackett Review of High Impact Low Probability Risks published in 2011.

In Autumn 2010 the Government Chief Scientific Adviser assembled a group to address the question: 'How can we ensure that we minimise strategic surprises from high impact low probability risks?[28] The Blackett Review was the result.

An insight into risk

According to the Blackett Review, risks can be separated into:

- Those which most people would not necessarily identify and characterise, but about which many experts might have a reasonable understanding. For example, a storm surge overtopping the Thames Barrier protecting London;
- Risks which are identified, but about which little is understood, for example, severe space weather; or
- Risks which most, if not all, experts would struggle to identify.

More generally, there is often a lack of imagination when considering high impact low probability risks.[29] One of the more interesting approaches proposed by the Review for assessing levels of risk – and one which we feel is well suited to comprehending the magnitude of the potential impact of an extreme space weather event – is the Renn Approach.

The Renn Approach

Renn's classical approach to understanding risk

Professor Ortwin Renn, scientific director at the International Institute for Advance Sustainability Studies in Potsdam, identified nine indicators to help to represent risks.[30]

He then distilled these nine indicators into six risk classes, which he gave names from Greek mythology. Each risk brings with it a different mitigation strategy.

1. **Damocles**. Risk sources that have a very high potential for damage but a very low probability of occurrence. e.g. technological risks such as nuclear energy and large scale chemical facilities.
2. **Cyclops**. Events where the probability of occurrence is largely uncertain, but the maximum damage can be estimated. e.g. natural events, such as floods and earthquakes.
3. **Pythia**. Highly uncertain risks, where the probability of occurrence, the extent of damage and the way in which the damage manifests itself is unknown due to high complexity. e.g. human interventions in ecosystems and the greenhouse effect.
4. **Pandora**. Characterised by both uncertainty in probability of occurrence and the extent of damage, and high persistency, e.g. organic pollutants and endocrine disruptors.
5. **Cassandra**. Paradoxical in that probability of occurrence and extent of damage are known, but there is no imminent societal concern because damage will only occur in the future. There is a high degree of delay between the initial event and the impact of the damage. e.g. anthropogenic climate change.
6. **Medusa**. Low probability and low damage events, which due to specific characteristics nonetheless cause considerable concern for people. Often a large number of people are affected by these risks, but harmful results cannot be proven scientifically. e.g. mobile phone usage and electromagnetic fields.

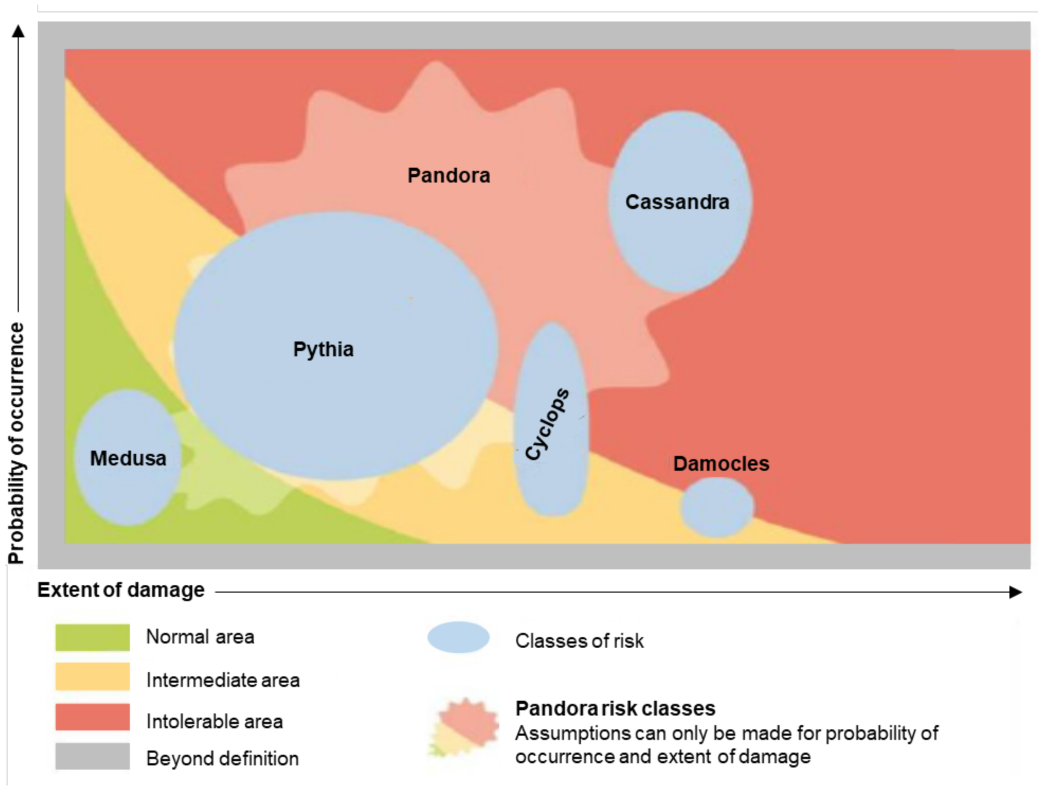
Assessing space weather using Renn's approach

Severe space weather poses an intolerable risk – so why aren't we better prepared?

Severe space weather falls into the group of intolerable risks when we use Renn's method. Whether you put space weather into the 'Pythia' category of risks (highly uncertain and where the probability of occurrence, extent of damage and the way in which the damage manifests itself is also highly uncertain) or categorise it as a 'Cassandra' risk (the probability of occurrence and the extent of damage are known but there is no immediate societal concern because damage will only occur in the future), severe space weather poses a significant risk.

How Renn's risk categories overlap

The chart shows the extent of damage from a risk against the probability of that risk occurring, with severe space weather falling into either the Pythia or Cassandra categories



Source: Blackett Review, UK Government Office of Science, 2011.

Can the UK's National Strategic Risk Assessment process be improved?

The National Strategic Risk Assessment (NSRA) is a classified assessment of the risks facing the UK and is the basis for the publicly available National Risk Register.

The ranking of risks is done on an empirical basis, with Government Ministers being asked to make a risk-based judgement on high impact, low probability risks such as severe space weather.[31]

Considerable thought and effort goes into the production of the NSRA and the unclassified National Risk Register, which was updated in December 2020. We see two flaws in the process though. The first is that the question asked when assessing risks is 'how likely is it that this type of emergency will happen, somewhere in the country, sometime over the next five years'.[32] For severe space weather the answer, absent any signals to the contrary when the re-assessment is made, is always going to be 'not very likely'.

The second flaw is with regards to the NSRA's approach to what is known as 'epistemic risk', or the risk (for anyone doing a scientific assessment) of being proved wrong. Blackett flags up the risk inherent in this approach thus:

> *...the academic empirical scientific tradition has generally taken a stance of strong aversion to epistemic risk, and research is needed into how this impinges on science-informed and risk-informed decision-making, especially in the context of low probability, high consequence 'black swan' events.*

He continues:

> *... if opinions on the probabilities of very rare or unprecedented events are sought from experts, then these should be obtained from the 'right' type of expert — i.e. those not afflicted by acute epistemic risk aversion. Whether this is an appropriate precept to adopt in the current context, and how to determine whether a person 'suffers' from this trait are relevant open questions.*

Trust in government is vital but it seems at the time of writing that this has been badly eroded by the effects of the Covid-19 pandemic and the perceived failure of the State in many countries to handle the situation properly.

Trust in government has been damaged by Covid-19

In the event of a space weather crisis, in the UK SAGE (the Scientific Advisory Group for Emergencies) would drive the response as we explain in more detail in section 6 but we believe with significant support from the 27 person strong Space Environment Impacts Expert Group (SEIEG). Our analysis of the background of the 86 members of SAGE shows only seven with directly relevant scientific experience but this is more than compensated for by the breadth and depth of expertise in SEIEG.

5.1.3 Cascading risks

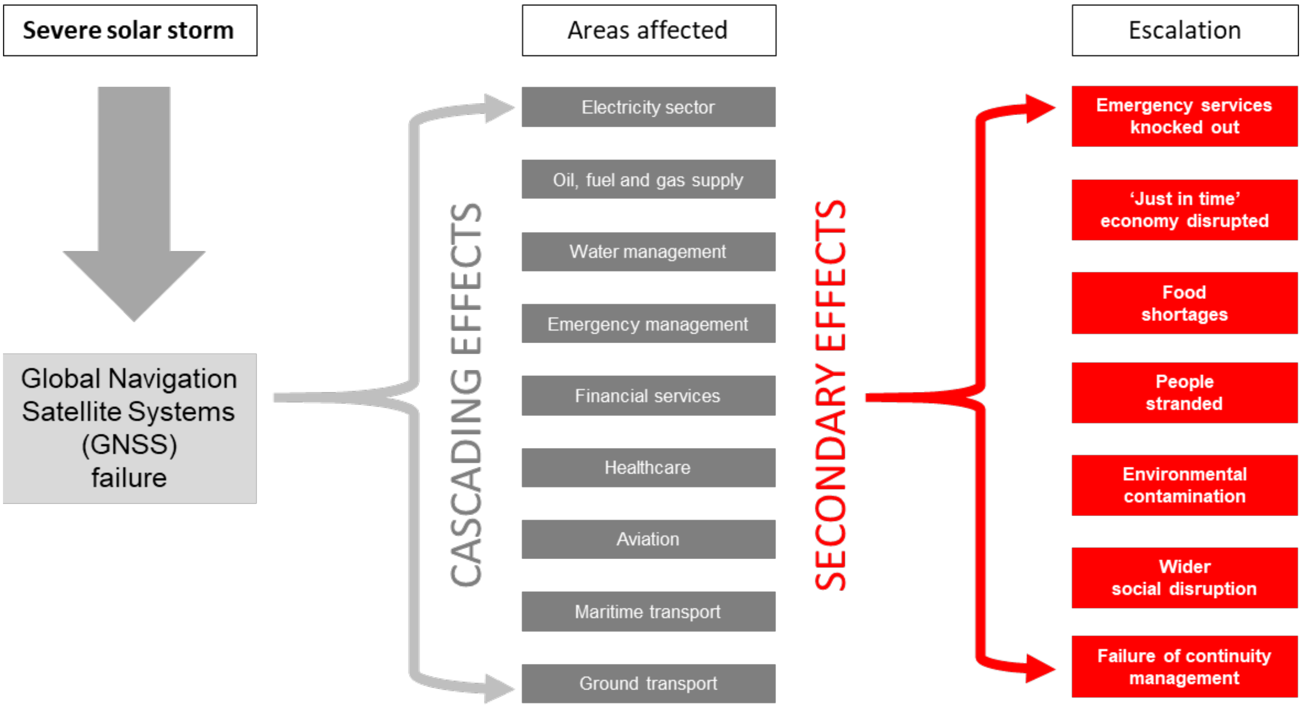
Risks cascade

In our interconnected, globalised world, risks cascade. UCL in the UK, through its Institute for Risk and Disaster Reduction, has done useful work categorising and describing cascading risks. They stress the importance of proper business continuity planning (BCP) preparations in preparing for technological failures as well as those originating from severe space weather and provide a checklist which any organisation would do well to include in its BCP thinking.[33]

The chart below illustrates how one effect – the failure of GNSS satellites – can quickly lead to other significant problems.

'When sorrows come, they come not single spies but in battalions'

An example of how cascading effects can produce secondary emergencies. Crisis managers not properly prepared and rehearsed run the risk of being quickly overwhelmed.



Source: Pescaroli et al, UCL Institute for Risk and Disaster Reduction [34]; Drayton Tyler Ltd

5.2 The challenges of space weather events

The main challenges faced in planning for severe space weather events[35] include:

- The difficulty of forecasting events accurately;
- The short warning time to prepare once there is certainty about the speed and size of events;
- Understanding potential impacts;
- Lack of capability to monitor the effects of severe events since they start.

5.3 Quantifying space weather risks

The probability of a severe solar storm hitting Earth is estimated at between 10pc and 12pc in any given decade – in simple terms once every 79-100 years.[36] However this doesn't mean that severe solar storms follow a regular cycle; we might only wait two years for a superstorm, or we might not see one for three hundred years. Taking 10pc as an acceptable level of risk means that any system with a design life of more than 8.25 years needs to consider the risk from severe space weather events.[37]

Any system with a design life of more than 8.25 years needs to consider the risk of space weather

5.3.1 Warning times

There is no guarantee that severe space weather will only happen during a period of intense sunspot activity although statistically severe space weather is most likely at the peak or declining phase of the solar cycle. One planning scenario from the UK's Met Office suggests being able to highlight an increased risk with only 4-5 days' notice; other sources suggest seven days.

Worst case: four days' notice that something could happen, 12 hours' notice that it has; 15 minutes' notice that it's bad

Solar Energetic Particles

The US Space Weather Prediction Center produces three-day proton forecasts as well as current proton alerts, using a combination of solar image analysis and X-Ray and proton data from the GOES satellites. More details on solar observation satellites can be found at Annex B.

Coronal Mass Ejections

CMEs typically take between one and three days to travel from the Sun to the Earth but can make the journey in as little as fifteen hours. Generally speaking, the faster the CME the greater the impact. Allowing for data processing time, in the worst case the warning time that a CME is on its way could be as little as twelve hours.

The magnetic field of a CME is measured as it passes the ACE satellite described in Annex B, giving between fifteen and thirty minutes notice of the impact of the CME and if it has a southward orientation.[38] ACE data is currently used by the British Geological Survey for its geomagnetic activity alerting service; the ACE satellite will go out of service by 2025.

Research is being carried out at the University of Helsinki and elsewhere to predict the magnetic field profile of CMEs based on observation and modelling of the Sun's corona but it is too early to anticipate when or if this might become a viable process for an early warning system.[39]

6. Governance

Good governance of space weather preparedness at all levels is essential, including at the government level, within the national science establishment, and between government, academia and the private sector. Enablers for success are simple structures, the right level of political oversight, a willingness to collaborate and a culture of clear and open communication. In this section we examine these factors and how different countries and organisations approach them.

6.1 Space weather command and control

A country's ability to come through a severe space weather storm depends on a number of things, including:

- Properly identifying the risks;
- Putting in place all necessary mitigations;
- The strength of its own scientific base;
- International cooperation;
- Contingency planning;
- Communication plan to private as well as state sectors;
- Rehearsal and refinement of contingency plans.

The US has clear lines of responsibility which are reinforced by the PROSWIFT Act

6.2 USA

The current (March 2019) US National Space Weather Strategy and Action Plan 'identifies strategic objectives and high-level actions necessary to achieve a space-weather-ready Nation.'[40]

Each action includes a timeline for completion, from short-term (six months to two years), medium-term (two to five years) and long-term (five to ten years), and ongoing (expected to be repeated within the ten-year horizon). Each action includes a list of relevant agencies, with the recommended lead agency first.

The Action Plan has three objectives:

- **Objective I**: Enhance the Protection of National Security, Homeland Security, and Commercial Assets and Operations against the Effects of Space Weather (eight tasks).
- **Objective II**: Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts (eleven tasks).
- **Objective III**: Establish Plans and Procedures for Responding to and Recovering from Space Weather Events (five tasks).

Objective III includes exercising to rehearse the Federal response, recovery and operation plans and procedures for space weather events – in our view an essential component of space weather preparedness.

Space Weather Operations, Research and Mitigation (SWORM) working group

SWORM is where the work really gets done. It includes members from eight US government departments, fifteen Agencies and Service Departments and four offices from within the Presidential Executive Office. SWORM meets the requirements of the recently passed PROSWIFT Act (see below) for a *Space Weather Interagency Working Group*.

SWORM makes its officially released documents available on its website, including identifying R&D needs, concepts of operations for impending space weather events, and (crucially important) space weather benchmarks.

NOAA Space Weather Prediction Center

The civilian Space Weather Prediction Centre sits under the National Oceanic and Atmospheric Administration and produces a range of space weather forecasts, reports, observations and models.

USAF Space Weather Observation Center (SpaceWOC)

Military space weather forecasting in the US

The military side of space weather forecasting is provided by the 2d Weather Squadron (2WS) of the 557th Weather Wing (557WW) of the US Air Force. Operating from seven sites around the world the headquarters of 557WW is at Offlut Air Force Base in Nebraska, while 2WS operates a radio solar telescope network with detachments in Australia (Learmonth), the US (Sagamore Hill, Massachusetts and Holloman AFB, New Mexico), Italy (San Vito) and Hawaii (Kaena Point). Solar Optical Observatories are in Australia and New Mexico.

2WS provides the US Department of Defense with its only 24/7 Space Weather Operations Center (SpaceWOC) and its mission is to:

> *…ensure the timely provision of operational space weather observations, analyses, forecasts, and other products to support the mission of the DOD including the provision of alerts and warnings for space weather phenomena that may affect weapons systems, military operations, or the defense of the United States.*

US military space weather users include:

- Air Force Space Command (Spacelift, Space Control, Space ops)
- Joint Space Operations Center (Space Situational Awareness)
- NORAD-NORTHCOM (Early Warning Radar)
- Sister services and combatant commands (HF/UHF comms; scintillation)

557WW is facing a number of challenges, including inadequate infrastructure for data sharing and acquisition, ageing equipment on the ground and in space, insufficient secure processing capability for dealing with data from classified sources, limited data sharing (even with allies) and a limited archive of space weather data.[41]

That said, it's hard not to be impressed with the US's thorough and professional approach to the business of space weather preparedness.

6.2.1 Political awareness in the US

There are impressive levels of political awareness in the US

The US political system is commendably aware of the risks to the US from severe space weather as well as the need for improved space situational awareness. Since 2019 there have been twelve congressional committee meetings at which space weather has been discussed. There is a clear understanding in the US political system of the importance – and commercial benefits – of involving the private sector in challenges of this kind, rather than simply leaving things to the public sector. This is reflected in the legislative framework.

6.2.2 Enabling legislation in the US

Executive Order 13744 of 13 October 2016

Presidential Executive Order 13744 laid out US policy for space weather preparations and defined Federal Agency roles and responsibilities in relation to delivering the 2015 Space Weather Action Plan.

Executive Order 13905 of 12 February 2020

Regular audits of national GPS dependencies are required in the US

Presidential Executive Order 13905 recognises the importance of the GPS system in providing positioning, navigation and timing (PNT) to the national resilience of the US and mandates the US Department of Commerce, in conjunction with the private sector in the US, to identify 'systems, networks and assets dependent on PNT services'. It then requires Federal agencies to review these PNT profiles every two years.

S.881 – PROSWIFT Act

The US PROSWIFT Act: joining the public and private sectors with academia to create a virtuous circle

This act, for 'Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow', is a good piece of cross-party legislation. The act identifies the national need for good space weather forecasting and the research to support it, and recognises the benefits of the partnership between Federal departments, academia, the commercial sector, and international partners.

The act recognises the importance of clear roles and accountability of Federal departments and lists those departments with their responsibilities. It commits the Federal departments involved in the newly created Space Weather Interagency Working Group to increase engagement with the international space weather community, academic community and commercial space weather sector.

We understand that SWORM (see above) meets the requirement for a Space Weather Interagency Working Group and that the Space Weather Advisory Group is seen as improving coordination with industry and academia.

6.3 UK

In the UK, the Lead Government Department for space weather is the Department for Business, Enterprise, Innovation and Science (BEIS). Space weather forecasting is provided by the Met Office Space Weather Operations Centre, MOSWOC, which operates around the clock.

BEIS plans to produce a new space weather strategy in 2021

The Cabinet Office, in conjunction with BEIS, published its latest space weather preparedness strategy in July 2015.[42] While the Met Office operates the UK's space weather forecasting centre the UK Space Agency and the Natural Environment Research Council also have a role in developing operational capability.

In June 2020 the National Space Council (previously a lower level government committee) became one of the UK Cabinet committees, a moved welcomed by the UK space industry body, UKspace.[43] In September 2020 the UK Government announced a new Space-Based Positioning Navigation and Timing Programme (SBPP) to 'explore new and alternative ways that could be used to deliver vital satellite navigation services to the United Kingdom' while at the same time announcing the conclusion of its own GNSS programme.[44]

The National Space Council has political support at the highest level

BEIS has told us that the Government plans to publish an updated Space Weather Strategy in 2021 which will include details of exercises to be held with stakeholders. BEIS declined to give any further details of what these might entail.[45]

6.3.1 Met Office Space Weather Operations Centre (MOSWOC)

MOSWOC is one of three space weather prediction centres. It operates around the clock 365 days a year and was officially opened in October 2014. In 2016 it had 14 forecasters, one of whom was dedicated to space weather.

The Met Office continues to show its technical excellence with MOSWOC

It provides forecasts to key stakeholders including National Grid, the Ministry of Defence and others. One of its tasks is to identify precursors to a significant space weather event, which in a 2017 presentation was suggested as being 4-5 days before a CME.

If a major storm is predicted (or has just been detected), MOSWOC alerts BEIS and the Cabinet Office and begins to issue specific briefing documents. The Scientific Advisory Group for Emergencies (SAGE) meets, chaired by the Government Chief Scientific Advisor (GCSA) and is advised by the Space Environment Impacts Expert Group (SEIEG). The Government Chief Scientist may brief ministers including the Prime Minister; if the threat is serious then a COBRA meeting can be convened.

6.3.2 UK Space Operation Centre (UK SpOC)

UK SpOC is the hub of defence-approved space weather information products, working closely with MOSWOC. UK SpOC works closely with the ballistic missile radar at RAF Fylingdales in a number of areas, including space weather.

6.3.3 The Blackett review into satellite derived time and position dependencies

In January 2018, the UK Government Office for Science published a review with recommendations into the UK's critical dependencies on satellite derived time and position (two out of three of the PNT functions of GNSS, the remainder being navigation).

This led to the formalisation of an existing cross government PNT working group into the Position, Navigation and Timing (PNT) Technology Group, as well as the Blackett Review Implementation Group, or BRIG. The latter didn't survive Brexit preparations and many of the teams engaged in the BRIG were deployed to work on no-deal preparations.[46]

6.3.4 Forecasting challenges in the UK

Challenges…

The UK is facing a number of challenges with regards to space weather forecasting[47], in particular:

- A lack of real-time UK monitoring capability, either ground, aviation or satellite based;
- A need for improved modelling for 'nowcasting' and forecasting for space, aviation and ground-based systems
- Greater understanding of ionospheric effects (for both HF comms and GNSS);
- Analysis of satellite drag from atmospheric heating;
- Data for geoelectric field modelling.

… and areas for investment

Areas for improvement could include:

- Better CME arrival predictions, including for a second, fast CME;
- Better predictions of the evolution of the solar wind, particularly post CME arrival;
- Processes and procedures in the research to operations (R2O) pathway, particularly with regards to software change control and funding to ensure development and production environments for IT platforms are similar;
- Investment in user interface/user experience design for space weather dashboards.

6.3.5 SWIMMR

GBP20m is a good start

SWIMMR – the Space Weather Instrumentation, Measurement, Modelling and Risk programme – is a GBP20m, four year programme led by the Science and Technology Facilities Council (STFC) with the Natural Environment Research Council (NERC). The aim is to improve the UK's capabilities for space weather monitoring and prediction.

SWIMMR has three high level objectives:

1. Mitigate the potential radiation hazards of space weather to satellites and aviation operations;
2. Mitigate potential space weather effects on communication and global positioning;
3. Mitigate the potential risks of space weather to electric power distribution.

The SWIMMR consortium (led by Birmingham University) draws together the UK's principal experts in upper atmosphere modelling from Lancaster, Bath, Leicester, Leeds and Southampton universities and the British Antarctic Survey.

In July 2020 UK Research and Innovation announced funding for five projects, worth just under GBP9m. Grants went to the British Antarctic Survey, the British Geological Survey, and the Universities of Surrey and Birmingham (two projects funded).[48] Grants worth GBP3.7m had been awarded to Lancaster University in June 2020.

6.3.6 Civil Contingencies Act 2004

UK resilience, according to the Cabinet Office 2015 Space Weather Preparedness strategy, builds upon the role played by what are called Category 1 and Category 2 responders in an emergency as defined in the 2004 Civil Contingences Act. Those in Category 1 are organisations at the core of the response to most emergencies and include the emergency services, local authorities and NHS bodies; Category 2 organisations include the Health and Safety Executive, transport and utility companies and, according to Government guidance 'are less likely to be involved in the heart of planning work'.[49]

The message on space weather risk is not making it out from the centre to the regions

Given the above we were therefore surprised to find that at least two county's major emergency plans (Kent and Northumberland) make no reference to space weather, suggesting a failure in passage of information from the centre of government to the regions. We could find only passing acknowledgement of space weather as a risk on the website of the Scottish National Centre for Resilience and no understanding of the increased risk faced by Scotland by dint of its geography and geology.

6.3.7 BEIS Space Weather Risk Working Group

The 2015 Cabinet Office strategy document provides information on a working group on assessing the risks to the UK from space weather, under the Department for Business, Innovation and Skills (now BEIS – Department for Business, Energy and Industrial Strategy).

Government Departments and agencies represented are[50]:

- Department for Business, Energy & Industrial Strategy
- The Met Office
- UK Space Agency
- Government Office for Science
- Department for Transport
- Cabinet Office
- Ministry of Housing, Communities and Local Government
- Ministry of Defence
- Department for Digital, Culture, Media & Sport
- HM Treasury
- Civil Aviation Authority
- Public Health England
- Department for Environment, Food and Rural Affairs
- Northern Ireland Office

Leading academic experts are also represented, as are the Devolved Administrations.

The working group's point of escalation is to the committee of officials that supports the National Security Council Threat's Hazards, Resilience and Contingencies Committee (NSC (THRC(R)(O)) but any final decisions are taken jointly by the Civil Contingencies Secretariat and BEIS. The Space Environment Impacts Expert Group (SEIEG) acts as adviser to the Government, with the Government Office for Science taking the lead on liaising with SEIEG while working closely with BEIS.

UK's accountabilities for space weather planning are muddled

SEIEG includes MOSWOC, academic and industry experts. It is tasked with identifying space weather environment parameters most related to each space weather impact, agree the worst case events for critical national infrastructure and assist less well-informed.

SEIEG should publish its critical national infrastructure assessments

BEIS has never carried out a full rehearsal of a major space weather event with stakeholders from the private and public sectors[51], nor has it organized space weather related exercises since 2015. The UK Government's Scientific Advisory Group (SAGE) has carried out a number of 'tabletop' rehearsals with input from scientific research teams.[52] The Space Weather Risk Working Group is 'expected to meet each quarter' but 'the frequency of meetings can vary if required by circumstance'.[53]

6.3.8 Table-top exercises

The Met Office has run space weather exercises for SAGE and the Government Chief Scientific Adviser with the aim of exposing them to a severe space weather scenario. Key findings were:

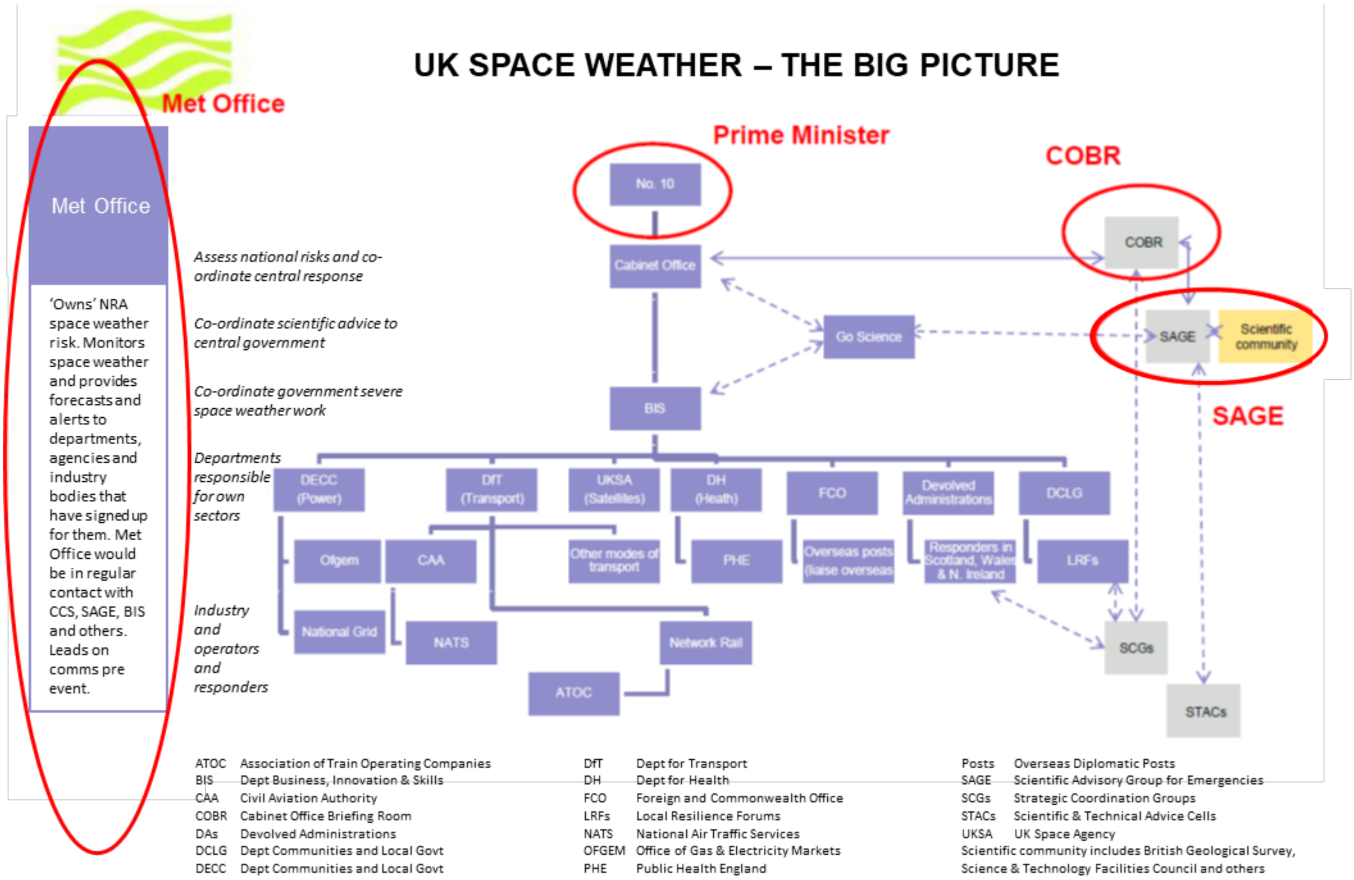
Table-top exercises have been run with impressive imagination

- Level of understanding of space weather, and its impacts, varied widely;
- Some areas were well prepared (e.g. National Grid), but others not;
- There were differences of opinion as to the potential impact on Critical National Infrastructure;
- No clear responsibility for capability relevant to multiple areas e.g. SATCOM;
- Due to a lack of familiarity with space weather amongst those being tested there was some difficulty in interpreting the data to explain the effects.[54]

Table-top exercises run in Ireland in October 2016 produced similar results, as well as 'lots of I thought organization XX [*sic*] would take care of this'.[55]

Who's in charge round here?

Command and control for a major space weather event in the UK looks too complicated to work well in a crisis



Source: Met Office[56]

6.4 Canada

6.4.1 Natural Resources Canada

Natural Resources Canada, a government body, operates the Canadian Space Weather Forecasts Center which was established in 1974 and currently has nine staff. With a broad range of expertise the Canadian team is notable for its work on space weather effects on pipelines and railways and works closely with the US Space Weather Prediction Center. National Resources Canada operates an impressive network of geomagnetic observatories throughout Canada.

6.4.2 Space Weather Socioeconomic Impact Study

In September 2017 the Canadian Space Agency issued a request for proposal (RFP) for a 'Space Weather Socioeconomic Impact Study on Canadian Infrastructure'. The work was awarded to a Canadian consulting firm, Hickling Arthurs Low.

The 105 page study was published in March 2019 and recommended the development of a Canada Space Weather Strategy (CSWS) with the following goals:

- Improve understanding of space weather impacts [in Canada];
- Increase forecasting services tailored to Canadian latitudes;
- Promote greater awareness of the risks and impacts of space weather events;
- Create a space weather preparedness plan;
- Continue and enhance international engagement.

The study, one of the best we've seen with respect to both public and private sectors, provides an extremely good assessment of the impacts and risk mitigation strategies of space weather. The economic impact analysis is particularly thorough, while particular emphasis is given to a lack of space weather emergency preparedness planning at federal and state level. Encouragingly, most infrastructure sectors in Canada are reported as having adopted effective mitigation strategies.

6.4.3 Public Safety Canada

Public Safety Canada is the federal government body with the broad remit of protecting Canadians. It has responsibility for national security, border enforcement, countering crime and emergency management. It operates the impressive 'Canadian Disaster Database', with space weather falling under the category of geomagnetic storm.

6.5 NATO

Despite appearances to the contrary, NATO probably hasn't gone to sleep on space weather

NATO was represented at the 2016 *Space Weather as a Global Challenge* summit held in Washington DC in April of that year. In the presentation given by the NATO speaker one slide – 'Why does NATO care about Space Weather' – stated:

> *Recognition that the effects of an extreme space weather incident on communications and power and the resultant cascading effects on dependent critical infrastructures and services* ***may be beyond catastrophic.*** *(Emphasis added).*

Despite this promising start it's not apparent from unclassified sources that NATO has followed through to develop any kind of space weather forecasting, either within its Civil-Military Planning and Support organisation or in its Meteorological and Oceanographic Military Committee Working Group.

We were told by a NATO military official that: "We, along with our other NATO members, are in the very early stages of establishing a NATO technical panel to address space weather into NATO operations, to include the new NATO Space Centre that is being stood up at Allied Air Command in Ramstein, Germany."

6.6 EU

The EU has a policy of disaster risk management and operates an online Disaster Risk Management Knowledge Centre (although with no sign of papers dealing with space weather).

Good work by the European Commission

In 2016 the European Commission arranged a two-day summit to consider the topic of *Space Weather and Critical Infrastructures*. The resultant publication is well written and provides a good overview of the topic for policy makers.[57] Among the conclusions reached were the need to understand inter-dependencies between critical infrastructures, the importance of a good governance structure to address cascading effects from space weather while managing multiple stakeholders, and that a Pan-European assessment of the power grid was necessary.

Four EU countries (Finland, Hungary, Netherlands, and Sweden) plus the UK and Norway include space weather as a risk in their national risk assessments.

6.6.1 2016 table-top exercise

As part of the 2016 Summit the organisers carried out a table-top exercise to consider various stages of a space weather event, from early warning and preparedness to response and recovery.

The scenario used and the responses given are the best unclassified account we have seen on the realities of dealing with severe space weather. Concerns expressed by the participants include:

- How and what to communicate to the public in the hours before the arrival of CME(s);
- The need for more detailed analysis of the risks to the power grid on a Pan-European basis, in particular cascading effects;
- Impact of disruption to GNSS signals, in particular in relation to timing and navigation;
- The potential for food shortages and civil unrest;
- Disruption to communications hampering the emergency service response and the ability of governments to communicate to the general public;
- Damage to, and shortage of spares for, Large Power Transformers (also known as Supergrid Transformers);
- A lack of impact analysis of the loss of GNSS on other systems;
- The absence of protocols at an EU level to coordinate response and recovery.

Recommendations for scientists, infrastructure operators and policy makers are useful and are shown at Annex F.

6.7 European Space Agency (ESA)

ESA's Space Situational Awareness programme, which was launched in 2009, morphed into the Space Weather Office in 2019. Space Weather falls under the 'Safety & Security' remit of ESA, which includes asteroid detection and deflection and space debris monitoring.

ESA lacks the ability or structure to be nimble in its decision making

The ESA Space Weather Service Network is located in Brussels, Belgium and has five supporting expert centres in Brussels (two), Harwell in the UK, Neustrelitz in Germany and Tromsø in Norway. The Network is currently in a pre-operational state with live support available only during normal working hours. ESA has twenty-two member states (most are EU members with Switzerland and the UK the exceptions). Canada, Latvia and Slovenia participate in ESA Education Office programmes.

6.7.1 The EU and ESA

In July 2020, the European Commission cut its space budget for the period 2021-26 from a planned EUR16bn to EUR13.2bn.[58] The majority of the budget will be spent on the Galileo global navigation satellite system and Copernicus environmental monitoring satellites. This will put further strain on the L5 mission budget discussed in more detail in Annex B.

EU cut its space budget in July 2020

The EU continues to grow its own Space Agency, somewhat confusingly known by the acronym EUSPA. The European Commission in 2012 highlighted issues of governance and budget control between the EU and the ESA and set a goal of 'rapprochement' with ESA, to take place in a timescale of 2020-2025. Quite what form that rapprochement might take isn't clear but could lead to ESA being subsumed into EUSPA, giving the European Commission control over the activities of ESA. That would provide challenges for non-EU members of ESA, in particular the UK as it seeks to distance itself from the European Union orbit. The UK's budget contribution to ESA is about 9pc of the total budget – useful in itself but not a game changer in terms of giving the UK much of a voice at the table.

EUSPA – the EU answer to ESA?

6.8 The World Meteorological Organisation (WMO)

The WMO acts as a coordinating body for all weather forecasting. In June 2008, the WMO Executive Council noted the impact of space weather on meteorological infrastructure and important human activities.

In May 2010, WMO established the Interprogramme Coordination Team on Space Weather (ICTSW) with a mandate to support Space Weather observation, data exchange, product and services delivery, and operational applications. As of May 2016, ICTSW involved experts from 26 different countries and 7 international organizations.

In May 2011, the World Meteorological Congress acknowledged the need for a coordinated effort by WMO Members to address the observing and service requirements to protect society against the global hazards of space weather.

In July 2014 potential space weather services to international air traffic navigation were discussed at a joint session of the WMO Commission for Aeronautical Meteorology (CAeM) and the Meteorological Division of the International Civil Aviation Organization (ICAO).

In May 2015, the World Meteorological Congress took note of the Four-year Plan for WMO Coordination of Space Weather Activities developed by ICTSW in consultation with CAeM and the Commission for Basic Systems (CBS). Congress agreed that WMO should undertake international coordination of operational space weather monitoring and forecasting with a view to support the protection of life, property and critical infrastructures.

Though the mills of the WMO grind slowly, yet they grind exceeding small…[59]

The 68th session of the executive Council in 2016 approved the Four-year Plan for WMO's Coordination of Space Weather Activities 2016-2019 (FYP2016-19) and asked CAeM and CBS to establish an Inter-Programme Team on Space Weather Information, Systems and Services (IPT-SWeISS). This team is continuing with the work of ICTSW initiated to fulfil the tasks identified in the FYP2016-19.

A Four-year Plan for WMO's Coordination of Space Weather Activities 2020-2023 (FYP2020-23) was drafted by IPT-SWeISS and approved by the Eighteenth World Meteorological Congress (Cg-18) in 2019. The implementation of space weather services and applications aligned with the FYP2020-23 is expected to provide significant benefits to WMO Members, in terms of more precise observations and improved accuracy.[60]

6.9 International Space Environment Service (ISES)

ISES and ICAO (the International Civil Aviation Organisation) exist to provide centres of excellence in space weather science.

ISES has been coordinating space weather services since 1962, although prior to 1996 it was called the International URSIgram and World Days Service (IUWDS). Its objectives are[61]:

- Provide real-time forecasting and monitoring of space weather to reduce and mitigate the risk of space weather impacts on technology, critical infrastructure, and human activities.
- Facilitate international communication and service coordination regarding space weather, particularly during periods of enhanced activity and in the event of extreme space weather.
- Improve space weather services and promote the understanding of space weather and its effect for users, researchers, the media, and the general public.

ISES is comprised of:

- Regional Warning Centres (RWC);
- Associate Warning Centres (AWC); and
- Collaborative Expert Centres CEC.

ISES REGIONAL WARNING CENTRES			**National space weather interest ranking, 2004-2021 ***
Australia	IPS Radio and Space Services	Sydney	13
Austria	University of Graz, Austria	Treffen	17
Belgium	Royal Observatory of Belgium	Brussels	23
Brazil	National Institute for Space Research	São José	61
Canada	Natural Resources Canada	Ottawa	3
China	Space Environment Prediction Center	Beijing	55
China	National Astronomical Observatories of China	Beijing	55
Czech Republic	Institute of Atmospheric Physics	Prague	42
India	National Physical Laboratory	New Delhi	57
Indonesia	Space Weather Information and Forecast Services	Bandung	63
Japan	National Institute of Information and Communications Technology	Tokyo	10
Korea	Korean Space Weather Center	Jeju	34
Mexico	Space Weather Service Mexico	Morelia	33
Poland	Space Research Centre	Warsaw	39
Russia	Hydrometeorological Service	Moscow	52
South Africa	Space Weather Prediction Center	Hermanus	20
Sweden	Lund Space Weather Center	Lund	14
UK	Met Office Space Weather Operations Centre	Exeter	12
USA	Space Weather Prediction Center	Boulder	7
Norway	Norwegian Centre for Space Weather	Tromso	6

ISES ASSOCIATE WARNING CENTRES			
France	Collecte Localisation Satellites	Toulouse	44
China	National Space Science Center – China Academy of Sciences	Beijing	55
China	Ionospheric Disturbance Prediction Center	Beijing	55
China	Geomagnetic Storm Prediction Center	Beijing	55

ISES REGIONAL COLLABORATION CENTRE			
ESA	European Space Agency	Darmstadt	-

**The space weather interest ranking is derived from the number of searches done for 'space weather' since 2004. The two countries generating the most Google searches in the world – Iceland and Finland – between them account for four times the number of searches of Canada, in third place. This is, we assume, more to do with aurora tourism than a particular fixation with heliophysics.*

6.9.1 Rationale and advantages of ISES membership

ISES provides a clearing house and focal point for space weather expertise, irrespective of the size of the contributing nation.

By opening up the field of space weather science it allows countries to find niche opportunities to which they can contribute expertise – Brazil and South Korea are just two examples of countries making an impact. Countries don't even need their own space programmes to make a valuable contribution since the provision of ground-based data (for example from magnetometers or GNSS receivers) is inherently useful.

As the field of space weather matures it isn't clear how the role of ISES will change since space weather often doesn't fit comfortably within the structure of governmental organisations in many countries. Is it a weather service or a space service? The science of meteorological services traditionally hasn't extended to the high frontier of space but providing operational, environmental services is typically not the focus of a space agency. This doesn't matter at the national level when there is political commitment but it certainly matters at the international level – severe space weather presents a global challenge and hence calls for greater global collaboration.

ISES membership can also help to give visibility to space weather expertise within a country's own political system and hence underpin financial support for the development of that expertise, as well as providing broader situational awareness within the space weather community as a whole.

6.9.2 Relationship with other bodies

ISES is a Network Member of the International Council for Science (now International Science Council) World Data System (ICSU-WDS) and collaborates with the World Meteorological Organization (WMO) and other international organizations, including the Committee on Space Research (COSPAR), the UN Committee on the Peaceful Uses of Outer Space (COPUOS), the International Union of Radio Science (URSI), and the International Union of Geodesy and Geophysics (IUGG).

6.9.3 International collaboration

ISES is an example of international collaboration in action, with Officers from Belgium, Tokyo, Australia, Canada and the Republic of Korea and twenty-one members from around the world providing warning centres as shown in the table below. Staffing and research expertise varies significantly from country to country, at least some of which have space weather portals that simply serve up US NOAA data feeds.

We note the particular expertise that exists in countries and regions in more northerly latitudes, in particular Canada, Russia and Scandinavia. The Belgium Royal Observatory provides a centre of excellence (as well as the current director of ISES) and other European countries, including France, Germany, Austria and Italy are active in space weather science (amongst others).

In the southern hemisphere Australia has a number of geomagnetic observatories (partly in partnership with the US), New Zealand has an active space physics team at the University of Otago while Chile has a laboratory for space and astrophysical plasmas in Santiago. South Africa carries out space weather research through the South African National Space Agency, including at its Antarctic base, SANAE IV.

7. Vulnerabilities and preparedness: UK and elsewhere

Severe space weather was added to the UK National Risk Assessment (now National Strategic Risk Assessment) in 2011 and the subsequent National Risk Register in 2012. We highlight below the key areas of vulnerability in the UK and elsewhere.

7.1 Global Navigation Satellite Systems (GNSS)

Interruption to, or loss of, GNSS is likely to be highly disruptive

GNSS includes the Global Positioning System or GPS (US), GLONASS (Russia), Galileo (EU) and BeiDou (China) systems. All operate in Medium Earth Orbit.

GNSS provide signals for position, navigation and timing (PNT) globally, with dependencies that are probably now not completely understood. GNSS time signals are used widely, from grid synchronisation to mobile phone communications (in some systems), computer network control and financial transactions.

These signals are vulnerable to disruption from ionospheric scintillation resulting from a solar superstorm and although dual frequency civilian navigation systems are increasingly available these are unlikely to mitigate the effects of scintillation.

GNSS satellites are themselves vulnerable to space weather effects, in particular from solar energetic particles and increased drag resulting from atmospheric heating.

It's estimated that 13pc of UK GDP is directly underpinned by GNSS and loss of GNSS would cause a daily economic impact in the UK in excess of GBP1bn.

The value of the GNSS enabled economy in the EU in 2018 was estimated[62] as:

- Telecoms: EUR46bn
- Utilities: EUR11bn (direct) and EUR3.5-4.8bn (indirect)
- Financial services: EUR680bn

7.2 Power

7.2.1 Great Britain

National Grid operates the power grid in England, Wales and Scotland (GB Power Grid), as well other parts of the world (including the US). (It's a public company; its largest shareholder with around 7pc of the voting rights is the US fund management company Blackrock.)

GB power grid seems more resilient than most

We believe that the GB Power Grid is more resilient than the power grids in some other countries because of its overall system design with shorter power lines, a mesh-like grid system and a more robust design for new and replacement transformers. Risk factors in the UK include its relatively high latitude, long coastline and geology. We believe the risk factors are higher in Scotland, particularly with regards to recovery due to challenges with transport and mobile communications in remote areas.

Are there enough Supergrid transformer spares to go round?

There are a number of Supergrid, or Large Power Transformers in the system. Roughly the size of a house (and weighing around 170 tonnes) they require specialist transportation skills, equipment and time to replace.

In 2015 it was estimated that only two substations would experience lasting damage in the event of a major solar storm, leading to up to four months of disruption to power supplies. (In 2012 the GB Power Grid had 710 transformers with 1269 connections; the 400 kV network had 252 nodes with 379 connections.[63])

Geomagnetically induced currents (GIC) can cause saturation of the magnetic circuit of transformers in a power system. This saturation in turn can lead to voltage control problems (generating significant harmonic currents) and cause heating of the internal components of the transformer itself, leading to alarms as well as possible damage, shortened service life, or complete failure.[64] Older transformers are more susceptible to damage from heating than newer designs.

While the National Grid still has a dependency on GNSS for its time signal, work is underway at the time of the writing of this report to engineer out any reliance on GNSS; nuclear clocks are available within the National Grid as a back-up. The vulnerability of grid synchronisation to issues with GNSS is recognised by the power industry internationally.

Vulnerabilities in the Grid to loss of time signal from GNSS are being mitigated

Interconnectors to Northern Ireland, France and the Netherlands operate as High Voltage Direct Current Links and are therefore not susceptible to GIC effects. However the systems at either end of the interconnectors that convert DC to AC may be subject to disruption, leading to loss of supply through these interconnectors.

7.2.2 Ireland

Power supply in Northern Ireland is independent from that of the rest of the UK, with EirGrid acting as Transmission Systems Operator in Northern Ireland and the Republic of Island. EirGrid is wholly owned by the Republic of Ireland's Minister for the Environment, Climate and Communications. EirGrid has owned SONI, the System Operator of Northern Ireland, since 2009. In Northern Ireland the grid is operated by NIE Networks, which is itself owned by the Irish state-owned company ESB Energy.

Northern Ireland electricity supply is ultimately managed from Dublin and is independent from the rest of the UK

There's an East West Interconnector linking the electricity grids of Great Britain with Ireland. This is a High Voltage Direct Current connection, capable of providing capacity of 500MW in both directions.

Other Interconnectors are planned including the 1500MW North South Interconnector between Northern Ireland and the Republic of Ireland and the 700MW Celtic Interconnector between the Republic of Ireland and France.

7.2.3 Mitigating space weather effects on the Grid

If a severe space weather event is detected then the National Grid says it has a number of well-established and rehearsed procedures for mitigating the effects. These include bringing all transformers on-line so as to reduce the individual neutral current through any one transformer and instructing all generators to produce power.

The National Grid also has a procedure known as 'Black Start' to bring the Grid back up in the event of an intentional or non-intentional switch-off of part or all of the system. The Black Start procedures are under review by National Grid ESO in light of the migration of power generation from fossil fuels to renewables. The move to renewable power generation – particularly away from coal – means there is less base load generation ticking away and an increase in the number of companies generating power and the means by which power is generated (covered by the term 'Distributed Energy Resources', or DER.[65]).

'Black Start' procedures in the UK assume a situation may exist where the Grid goes dark

One of the significant challenges that this presents is communications in the event of Black Start being invoked. An Energy Networks Strategic Telecommunications Group (ENSTG) has been created to address this and to ensure resilient telecommunications, including power resilience and resistance to cyber or physical attack. The second stage of the organisational, systems and telecommunications design was published in December 2020 – it's comprehensive and well thought out and includes different technology types, thereby improving resilience.

Good levels of resilience in communication systems

Project definition is due to be completed by the end of 2021 with the delivery of future services starting by the end of 2024. A review of Codes, Regulations, Policies and Standards has not identified any significant gaps or blockers to the commencement of Distributed ReStart services.

There is also a human factors challenge: to design systems and procedures that are not overly complicated to follow, given the stress levels facing operators from both a personal and professional perspective if Earth has just been hit by a major solar storm.

Understanding human factors in the event of a severe event is important

7.3 Telecommunications (UK)

7.3.1 Mobile

The UK's mobile phone network relies on power but doesn't require timing synchronisation from Global Navigation Satellite Systems (GNSS) to function. (This is unlike the North American mobile phone networks which require both power and GNSS time signals to be available.)

Don't rely on anything other than the most resilient communications networks being available

7.3.2 Transoceanic communications

While the fibre optic cables used for transoceanic communications are unaffected by geomagnetically induced currents there is a potential vulnerability in the electric power cables that run alongside, which are used to power repeater stations.

7.3.3 Mobile satellite communications

Satellite communications tend to use high frequency signals in the Ultra High Frequency (UHF – 300MHz to 3 GHz) and Super High Frequency (SHF – 3 to 30 GHz) bands. During an extreme space weather event, satellite communications are likely to be disrupted or even completely interrupted for at least three days and possibly longer.

7.3.4 Digital television and radio

Digital television uses the 470MHz to 800 MHz band and is likely to be disrupted by severe space weather making public information announcements harder. Digital and FM radio may also be affected.

7.3.5 Emergency services communications

Emergency services communications using any form of radio network are not guaranteed in the aftermath of a severe space weather event, both with respect to scintillation effects and disruption to GNSS time signals.

In the UK the current 'Airwave' network is being replaced by the new 'Emergency Services Network' (ESN). ESN, which was originally scheduled to enter service in 2017, is running seriously late and may not now enter service until 2024 or 2025.[66] There is no out-of-service date for Airwave. Although the Airwave network had a dependency on the GNSS time signal we believe that this risk has now been mitigated.[67]

7.3.6 High Frequency (HF) communications

During an extreme space weather event, HF communications might be disrupted for several days. This is likely to require airspace over the poles to be closed and then re-opened once normal comms are re-established, since HF radio is often used by commercial aviation when flying polar routes. However, as airlines upgrade their fleets, newer satellite communication systems are being introduced which are said to be less susceptible to space weather effects, making HF communications obsolescent.[68]

7.4 Financial services

7.4.1 Precision time

The financial services sector depends on accurate and precise timestamping, which is heavily dependent on GNSS signals and therefore liable to disruption from severe space weather. The degree of precision required is defined in the second EU *Markets in Financial Instruments Directive,* or MiFID II. More details can be found at Annex C along with the weakness of current mitigation methods.

7.4.2 Market volatility

A major solar storm is likely to lead to significant market volatility in all financial instruments. We would expect a general market sell-off on the announcement of an impending superstorm, combined with a flight to (financial) safety.

Volatility in financial markets is inevitable – and will bring winners and losers

The impacts of a severe storm are likely to be felt in waves, with the first effects being noticed on satellite systems with the arrival of solar energetic particles. Significant satellite or satellite related failures will lead to another sell off in the markets as a harbinger of worse to come; thereafter the markets will wait for announcements relating to the speed and polarity of coronal mass ejections (CMEs). The distributed working practices adopted during the Covid-19 pandemic may facilitate increased market volatility.

If the CME is fast and the polarity is damaging then the markets are likely to tip down further; conversely if the news is good then the markets could be expected to recover quickly. But if news reports show that aurora are widespread and power and communication systems are failing, sellers will continue to dominate. The risk of markets – particularly in more northerly and southerly latitudes – being closed due to volatility or technical reasons is present. Banks would be well advised to have active trading desks and liquidity in the Middle East or Far East, which, being closer to the equator are less likely to be affected by severe space weather.

There's no evidence that the FCA is on top of space weather – but they've told us they're looking into it

The severity of the storm is likely to be known relatively quickly – in the matter of a day or so – but since one CME is likely to be followed by a second or third, investor nerves will continue to fray. The extent of damage to critical infrastructure and second order effects – of which the one that worries us most is satellite orbital displacement and the potential for a sudden increase in space debris – is unlikely to be known for weeks rather than days.

Thereafter governments will turn their thoughts to stimulus (which will now be limited because of the costs of dealing with the Covid-19 pandemic), institutional investors to opportunities (as infrastructure and systems damaged in the storm are repaired or replaced, and the impact on countries becomes clear), and sovereign wealth funds to taking the opportunity to make strategic investments. As ever, there will be winners and losers.

7.5 Rail

In 2014 the UK Department for Transport (DfT) commissioned the engineering consultancy firm Atkins to produce a study entitled 'Rail Resilience to Space Weather'.[69] The 2014 report was deemed to be the 'Final Phase 1 Report'. A Phase 2 report was never produced.[70]

Does anyone in the UK care about rail anymore?

The Atkins report (produced in cooperation with RAL and York EMC Ltd) highlights a number of vulnerabilities in the UK rail system from solar weather effects, including:

- **Power**: Transformer failure and secondary effects in terms of geographical area and passenger safety.
- **Signalling**: Power supply failure leading to a lack of availability of the signalling and telecoms system and severely degraded operation of the railway and track circuit interference by geomagnetically induced currents (GIC) resulting in loss of train detection.
- **Train traction**: DC current flowing in the Overhead Line Equipment affecting the rolling stock main transformer which may result in overheating and train shut down; similarly interference with onboard line current (fault) monitoring could stop train movement.
- **GNSS failure**: A number of railway systems were identified as being vulnerable and whilst these are not thought to be safety critical, they would lead to disruption.
- **Radio communications**: GSM-R (2G mobile phone system used on railways) may all be affected by solar radiation bursts.
- **Track-side staff**: those carrying out maintenance activities on the rail system during a solar weather event are vulnerable to GICs generating voltages in cables.[71]

We made repeated requests to Network Rail for clarification as to their preparedness for severe space weather but received no satisfactory response, other than a vague acknowledgement of the issue and possible technical solutions and the statement: 'our work in this area is under way but is in its relatively early stages'. Nothing we have seen persuades us that Network Rail is anything other than poorly prepared.

Network Rail shows no sign of being properly prepared for severe space weather

Responsibility for the resilience of the UK's transport infrastructure, including rail, rests with the Department for Transport National Security Science and Research Division.

7.6 Pipelines

The problem of corrosion in metal pipelines has been known for some time, with the cost of effective corrosion control under normal conditions being about 1-2pc of the total cost of laying the pipeline.[72] The principal factors in pipeline corrosion are:

Pipelines can corrode faster when there's a major solar storm – but more research is needed to understand the scope of the problem

- The nature of the soil the pipeline is buried in;
- The composition of the groundwater;
- Any external electrical influences (stray currents);
- The effectiveness of the protective system.

The impact of geomagnetically induced currents on pipelines resulting from severe space weather depends on a number of factors including the pipeline's proximity to the Earth's magnetic poles (it's worse the closer to the poles you get), soil resistivity and proximity to a seacoast.[73]

According to the US Pipeline and Hazardous Materials Safety Administration while there are still some cast and wrought iron pipelines in use for natural gas distribution (some up to sixty years old), by the end of 2019 the majority (97pc) of gas distribution pipelines were made of plastic or steel.

Modelling geomagnetic induction in pipelines – and therefore understanding the risk – is complicated, although good work has been done by space weather scientists in Canada and elsewhere.[74] It's probable that the risk is material – in particular at pipelines joints – and that pipeline lives will be shortened by a severe solar storm. It will require studies such as the UK's Space Weather Impacts on Ground-Based Systems (SWIGS) study to quantify this (see para 7.9, below), along with data analysis of major pipeline incidents over the last twenty years relative to CMEs hitting Earth.

7.7 Satellites and satellite drag

As at the end of 2019 there were 2218 operational satellites in Earth orbit, of which 1468 are in low Earth orbit (LEO), 562 in geosynchronous orbit (GEO), 132 in medium Earth orbit (MEO), and 56 in elliptical orbit. The number of LEO satellites in particular will increase markedly in coming years. 2018 revenues from the satellite industry were USD277bn.

Severe space weather can lead to atmospheric heating, which in turn leads to increased satellite drag and shortens mission times

As a result of the 2003 major solar storm ten percent of the satellite fleet experienced anomalies and the joint US/Japanese Midori 2 satellite, costing USD640m, was lost.[75]

The impact of coronal mass ejections (CME) on the Earth's magnetosphere causes the atmosphere to expand, increasing atmospheric drag on satellites, particularly those in low earth orbit (LEO). When the Sun is quiet, LEO satellites have to boost their orbits about four times a year. When solar activity is at its greatest – even without the effects from a CME – satellites may have to be manoeuvred every 2-3 weeks.[76]

Interactions between the solar wind and the Earth's magnetic field during geomagnetic storms can produce dramatic short-term increases in upper atmosphere temperature and density, increasing the drag on satellites (with a resultant change in their orbit) as well as leading to space junk being 'lost' until it can be identified by radar and new orbits calculated.[77] In the March 1989 solar storm thousands of space objects were lost, taking many days for North American Defence Command to re-acquire them in their lower, faster orbits.

We seem to have lost some space junk…

During a major space weather event, there are likely to be multiple occurrences of atmospheric warming with cumulative effects. Satellite operators will be kept very busy during this period and may be overwhelmed by the workload.

7.7.1 Space situational awareness (SSA)

The US is the world leader in tracking Earth-orbiting objects and has signed over a hundred space situational awareness agreements, most recently with Romania. Space surveillance network sensors are found in the US and around the world, including at RAF Fylingdales in the UK, Diego Garcia, Ascension Island, Chile and the Marshall Islands.

The 18th Space Control Squadron (18 SPCS — part of the US Combined Force Space Component Command) tracks space debris and since September 2020 has been releasing debris-on-satellite predictions. 18 SPCS monitors around 3200 active satellites for close approaches with about 24,000 pieces of space junk. It issues on average 15 high interest warnings for active near-Earth satellites and ten high interest warnings for active deep-space satellites a day.[78]

It's important to know what's in orbit around the Earth – and more sophisticated modelling is needed to do this

The US Space Surveillance Network (SSN) is only able to track objects more than 10 cm in size. Debris between 1 cm and 10 cm in size, referred to as the 'lethal population' (of which it is believed there are around half a million in orbit) can't be tracked or catalogued but can cause catastrophic damage to satellites and other spacecraft. However, there is considerable room for improvement in tracking and modelling of objects in space, which will allow better forecasting of potential collisions.[79]

Maintaining space situational awareness during and after a major space weather event will be hard, both because of the amount of data processing required, and because of the degradation of ground based and orbiting radar systems from space weather effects. Situational analysis, communication to satellite operators, and communication from ground control to satellites will be put under significant strain during a severe solar storm.

7.8 Aviation

In November 2019 the International Civil Aviation Organisation (ICAO) announced the creation of a 24/7 service to provide real-time and worldwide space weather updates for commercial and general aviation. [80] The service went live that month.

There are three – and soon to be four – space weather centres providing advisories for the aviation industry

There are currently three (four from later in 2021) global space weather centres able to provide advisories for the aviation industry.

- NOAA Space Weather Prediction Service (USA);
- Pecasus consortium (Finland, Cyprus, Germany, Italy, Netherland, Austria, Belgium, South Africa, Poland, UK);
- ACFJ consortium (Australia, Canada, France) Japan;
- CRC consortium (Russia and China) – believed to be going operational in 2021.

Each consortium takes it in turns in two week shifts to provide advisory validation and dissemination, although all centres continue with data collection and analysis at all times.

The first advisory was provided to the industry on 28 September 2020.[81]

7.8.1 Case study: NATS (North Atlantic Air Traffic Service)

In 2019 there were 508,000 flights over the NATS area. While this has dropped significantly in 2020, NATS expect (perhaps optimistically) that flights will return to pre-2020 levels in the next few years.

Once over the Atlantic aircraft depend on GNSS navigation over the Atlantic with fixed waypoints and coordinates but with no ground based equipment. While aircraft have inertial systems as backup these aren't guaranteed to maintain aircraft separations properly.

Comms is primarily HF with backups provided by CDPLC (a two-way data link system) and satellite communications.

Aircraft use satellite navigation to determine their position which is then broadcast to air traffic control and other users through the ADS-B system.

A nasty surprise in 2018

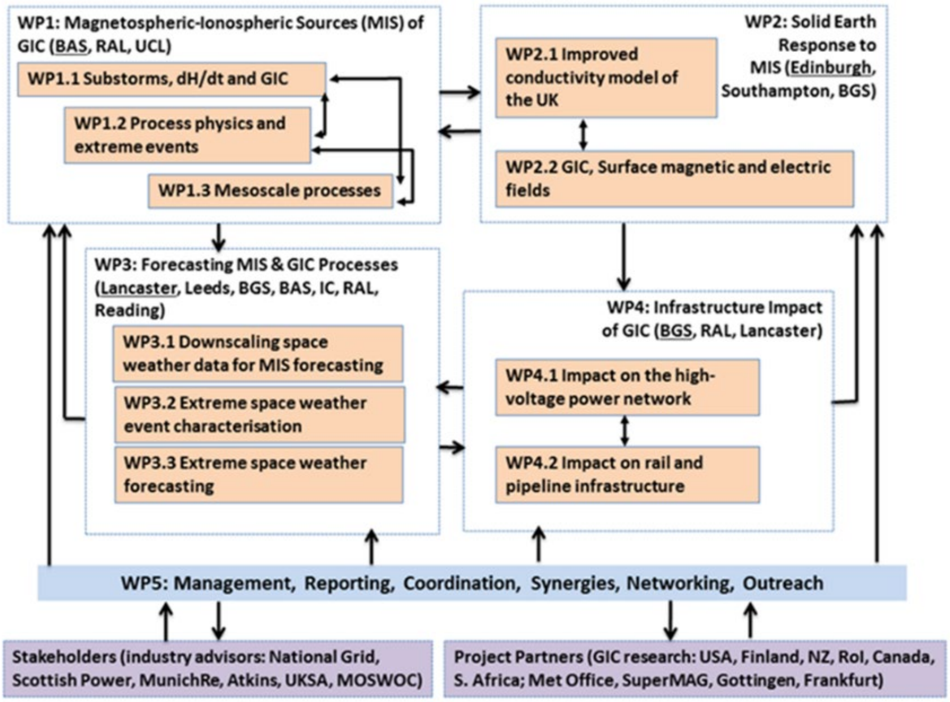
During a Space Weather Workshop in Prestwick in Scotland in July 2018 it was found that in the event of loss of communications and satellite interference a number of airlines had the same operating procedure: to return to base at the same flight level as other airlines. It is believed that this has now been remedied but this serves to illustrate the importance of detailed analysis of the primary and secondary effects of severe space weather.

7.9 Space Weather Impacts on Ground-Based Systems (SWIGS)

UKRI (UK Research and Innovation) has commissioned a consortium of ten institutes in the UK to gain a better understanding of the effects of space weather on ground-based technologies such as electrical transmission systems, pipelines and railways. The funded period is from May 2017 to April 2022, at a modest cost of GBP3m.[82]

Cheap at the price: impressive collaboration in the pursuit of knowledge

SWIGS project plan



Source: British Geological Survey

7.10 OneWeb

On 20 November 2020 OneWeb, the low earth orbit satellite communications company, emerged from Chapter 11 bankruptcy protection in the US, with the UK Government and Bharti Global becoming joint majority shareholders acquiring 45pc of the equity each (valuing the company at USD1.1bn), the remaining 10pc being held by existing creditors including SoftBank.

OneWeb: an interesting satellite company partially owned by the British Government… but we still don't understand the logic of the investment

On 15 January 2021 it was announced that SoftBank had invested a further USD350m. According to the London Financial Times the extra investment gives SoftBank roughly 30pc of OneWeb and dilutes the UK Government and Bharti Telecom to about the same level. The UK retains its golden share, allowing it to control access to the system. The other principal investor, Hughes Network Systems, added a further USD50m on top of a USD50m investment last year.

The OneWeb satellite constellation was originally conceived as a 650 satellite constellation in low-earth orbit (LEO) designed to provide remote area internet access. OneWeb satellites will transmit 4G signals in the 14GHz band, which is susceptible to space weather effects.

OneWeb has also been suggested by some commentators as a possible route for the UK to acquire its own GNSS capability. It would be a technical stretch to do so for two reasons: the OneWeb satellites are placed into a low-earth orbit (LEO) whereas all other GNSS satellites are in a medium earth orbit (MEO) – this makes the computation of time and position more complicated given the greater number and higher relative speeds of these satellites. LEO placed satellites are also more susceptible to an increase in atmospheric drag from severe space weather.

OneWeb is an interesting company to watch by dint of its shareholders and its new CEO, Neil Masterson. Masterson, a twenty year veteran of Thomson Reuters, will bring useful skills to the role but whether the company can cut it in a competitive market remains to be seen.

7.11 eLoran

eLoran (E standing for 'enhanced') is the latest iteration of low-frequency LOng RAnge Navigation (LORAN) systems. It provides a land-based system for position, time and navigation and can be used to either supplement GNSS navigation or act as an alternative if GNSS signals are jammed either by severe solar storms or malicious actors on Earth.

The South Korean Ministry of Ocean and Fisheries announced in November 2020 that it is developing eLoran (by improving its Loran-C infrastructure) to be used alongside GPS on South Korean shipping so as to mitigate the effects of GPS jamming by North Korea. Tests have already been carried out on the Aru Waterway.

Norway dismantled its Loran infrastructure in 2017 despite British requests not to

In 2016 the UK Government Office for Science held a seminar on eLoran which was attended by the Norwegian Ministry of Commerce. Earlier in the year the Norwegian side had met with the British Cabinet Office, Innovate UK and the General Lighthouse Authority of the UK (otherwise known as Trinity House). The main discussion point was Norwegian plans to demolish its Loran-C infrastructure, which the UK wanted Norway to keep. In 2017 the Norwegian Ministry of Transport and Communications informed the UK Civil Contingencies Secretariat (CCS) that it had tasked Norwegian Cyber Defence to dismantle the infrastructure, despite earlier pleas from the CCS not to.

India, China, Saudi Arabia and South Korea retain their Loran-C transmitters.

8. Costs, benefits and opportunities

Space weather preparedness shouldn't be seen simply as a cost on governments, particularly in the post-Covid economic era, but rather as a form of economic stimulus with a good fiscal multiplier. Investment in the science and engineering skills needed to design, develop and build satellites and instrumentation will show benefits across country's educational and industrial base. A growth in skills will stimulate private sector activity – as continues to be shown in the US – and spawn need industries and technologies. Accurate and timely space weather forecasting will be needed more and more as space ventures expand, presenting an opportunity for countries with the will and economic might to enter the field.

Space weather preparedness is a catalyst for greater interest in STEM subjects

8.1 Economic impacts

The economic impacts of a Carrington level event depend in part on our ability to forecast major storms. Satellites are vulnerable to a number of risks to their operation, including solar storms and hitting space debris. There is little redundancy in current satellite coverage and, with funding issues appearing, the world's continuing ability to monitor the Sun and accurately predict the scale and timing of solar storms is not guaranteed.

Little redundancy in current satellite coverage is a concern

According to a 2019 research paper GDP loss to the UK is estimated to be as much as GBP15.9bn for a Carrington level event, although this reduces to GBP2.9bn if the existing forecasting capability is maintained and as little as GBP0.9bn if forecasting is enhanced.[83] This is lower than other estimates we have seen.

A 2017 presentation by RAL Space (part of the Science and Technologies Facilities Council) estimated potential direct losses to the UK in a medium worst vase scenario up to EUR5bn with daily economic losses globally of between USD7bn and USD48.5bn.[84] Oughton et al estimate the daily loss to the US economy from severe space weather at USD41.5bn.[85]

In 2010 Lloyds of London produced a 'Risk Insight' report into Space Weather.[86] They didn't pull any punches in their estimation of the seriousness of the risk, writing in the summary: "A very severe outbreak of space weather could create a systemic risk to society." They highlight the risks to many sectors from the potential disruption to the electricity supply, including fuel supply, food storage and distribution, sanitation, communications, transport and financial services. We do not think these concerns are understated.

Severe space weather poses a systemic risk to society, says Lloyds of London

In 2013 Lloyd's of London carried out an assessment of the risks to the North American grid, which included a scenario where 20-40 million people were left without power for up to 1-2 years with costs of USD0.6 to USD2.6trn. Schulte in den Baumen et al in 2014 looked at the effects of a 1989 Quebec-like severe space weather event on East Asia, North America and Europe and concluded that the event could see a global economic impact of USD2.4-3.4trn, leading to a global GDP loss of 3.9-5.6pc.

A trillion dollars here, a trillion dollars there...

8.2 The benefit of space weather spending

In 2016 the consulting firm PwC carried out a cost-benefit analysis of the European Space Agency's (ESA) Space Situational Awareness Programme. This programme included Space Weather, Near Earth Objects and Space Surveillance tracking. This analysis was performed with the assistance of the UK's Met Office and showed an impressive benefit to cost ratio for the whole programme of 6.25 on total benefits of EUR3,137m.[87] Five years on the benefits are likely to be even greater.

8.3 UK space weather priority needs

In order for the UK's space weather efforts to achieve their full potential, focus and investment is needed in the areas described below:

8.3.1 Maintenance of existing capabilities

Firstly, there's a need to maintain existing capabilities at the Lagrange L1 point. Currently the UK uses data from SDO, SOHO, ACE and DSCOVR spacecraft for solar magnetic maps, coronography, solar wind measurements, amongst other data points. The US has plans to send a replacement satellite in the next few years, possibly in conjunction with ESA.

8.3.2 New capabilities

The L5 mission is important – and its funding needs to be secured

The ESA L5 mission is important in order to provide a side-on view of space weather heading to Earth from the Sun and will allow space weather scientists to observe much more of the Sun than currently. The reduction in funding in the November 2019 round is a concern and means that launch will slip at least two years, to 2027. If the UK Government is as ambitious as it says it is with regards to its desire to expand its involvement in space, then one way to do this would be to take over funding of the L5 mission, including more involvement from the UK space industry. However this would probably mean continuing existing partnerships with countries already developing instruments for the mission.

Smaller satellites are needed for measuring particles and fields in the magnetotail-to-ionosphere region.

8.3.3 Exploit new satellites

Subject to payload availability new satellites could be used to enhance space weather observations, for example neutral mass spectrometers on low-earth orbit satellites in order to measure thermospheric density, and radiation monitors in all orbits.

8.3.4 Aircraft-borne radiation monitors

There's a significant gap in real-time radiation monitoring for aviation which could be filled by adding sensors to civil aircraft. As beneficiaries of improved space weather forecasting we would expect this not to be overly controversial to implement but would required consultation with airlines and manufacturers.

8.3.5 Synergies with existing sensor platforms

The opportunity exists to leverage existing sensors. For example, cosmic ray neutron sensors for soil moisture estimation could also be used for measuring solar radiation, and lightning detectors could be used to detect solar flares and ionospheric changes.

8.3.6 Training and education

Driving relevance with the US and ESA

The quality of scientists working in space weather in the UK is high but the pipeline for finding and nurturing talent is limited. Space weather provides a useful economic opportunity for the UK, both in terms of building capability to service the private sector, and to provide better safeguards for the UK against the worst effects of space weather. It also provides opportunities for greater partnership and participation with the US (currently the UK barely gets a mention in US space weather circles) and the European Space Agency.

To succeed, SWIMMR needs post-doctoral, post-graduate and undergraduates with space science skills

The GBP20m SWIMMR programme is developing a research-to-operations pipeline but this requires existing research to feed into it. This pre-supposes a suitable pool of post-doctoral talent which in turn depends on suitable skills development at post-graduate and undergraduate level. Further research and education is required in the origins of space weather, propagation through the heliosphere and the impact on geospace.

An increase in the scientific base for space weather will also pull with it a need for more engineering skills to develop new instruments.

Data scientists needed

There's a role for data scientists as well, for innovative approaches to modelling and forecasting space weather, for example data assimilation/incorporation, physics-based modelling, and model coupling.

More user education

Finally there's a continuing need for user education with regards to the impacts of space weather on critical national infrastructure and Defence.

8.4 Risks inherent in decarbonising the UK

The UK's Clean Growth Strategy increases space weather risks to the UK

The UK Government's Clean Growth Strategy[88] set a target for the UK of reducing greenhouse gas emissions by at least 80pc by 2050. Inherent in this is a continuing migration to electricity produced from low or zero carbon sources and away from gas for domestic and industrial heating.

There is a risk in this: that by increasing the nation's dependency on electricity the disruption from a major space weather event will be magnified. This is exacerbated by the increase in the number of electricity generating organisations (some of which have control rooms outside the UK), which increases the complexity of the Black Start procedures used by National Grid ESO to restore power once lost.

The tension that exists between the Clean Growth Strategy and national resilience in the event of a major space weather event has not previously been recognised and we have seen no evidence that the risk is recognised or that mitigations are being considered.

9. Annex A -- Lagrange points in space

Lagrange points – a good place to park space weather satellites

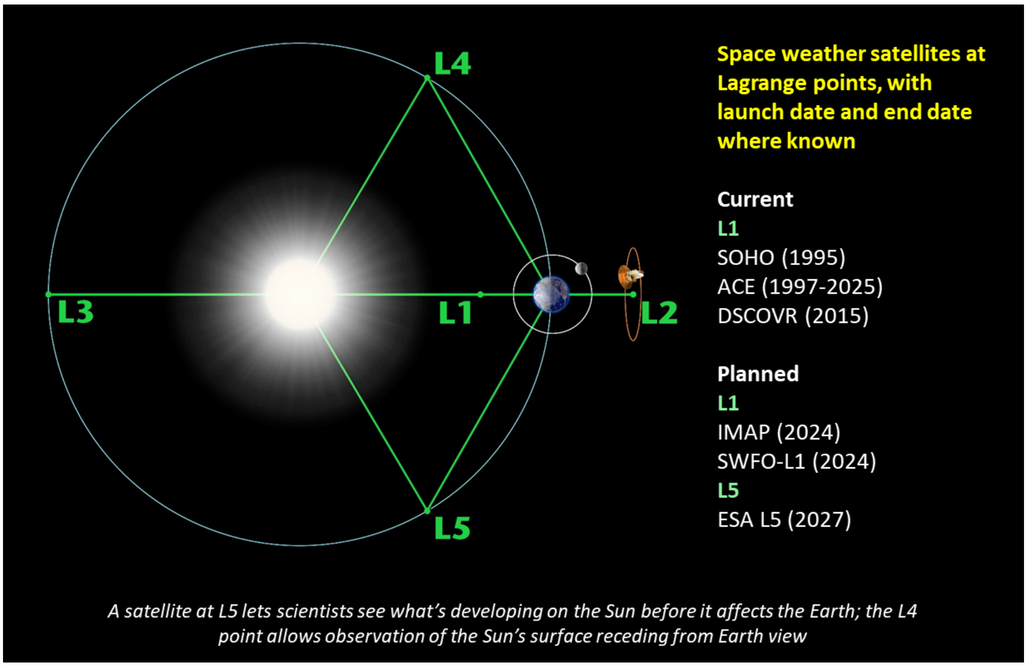
Lagrange points are positions in space where objects tend to stay put once placed there. At Lagrange points the gravitational pull of two large masses – for example the Earth and the Sun – precisely equals the centripetal force required for a small object to move with them.[89]

Lagrange points are named after the eighteenth century Italian-French mathematician Josephy-Louis Lagrange. In his essay 'General Three-Body Problem' he proposed one family of solutions to a question first posed by Isaac Newton in 1687 when considering the interaction of the gravity of three bodies.

Lagrange identified five points, of which three are unstable and two stable. The unstable Lagrange points – L1, L2 and L3 – lie along the line connecting the two large masses (for example the Earth and the Sun). The stable Lagrange points – L4 and L5 – form the apex of two equilateral triangles that have the masses at their vertices.

Lagrange points – useful (but not the only) locations for space weather satellites

The five Lagrange points between the Sun (centre) and the Earth – L1 and L5 are the most useful points to place solar observation satellites. The European Space Agency L5 mission is currently two years behind schedule.



Source: NASA/WMAP Science Team via Met Office; Drayton Tyler

10. Annex B -- Solar observation satellites

There are a number of solar observation satellites in service, some in Earth orbit, three in solar orbit and three at the Lagrange L1 point.

10.1 Earth orbit

10.1.1 Solar Dynamics Observatory (SDO)

The Solar Dynamics Observatory was launched in 2010 and provides ultra-high definition imagery of the Sun in thirteen different wavelengths. SDO studies how solar activity is created and how space weather comes from that activity.

NASA

10.1.2 Geostationary Operational Environmental Satellite (GOES) program

GOES-16, launched in 2016, became operational in December 2019. GOES-16, primarily designed as a weather satellite, also includes instruments for solar observation from the Earth's orbit. GOES-17 was launched in 2018.

NASA/NOAA

10.1.3 COSMIC-2A/FORMOSAT-7

The six COSMIC-2A/FORMOSAT-7 satellites launched successfully in June 2019 into low-inclination orbits. The constellation provides data for meteorology, ionosphere, climatology and space weather research.

NOAA/USAF/UCAR/ Taiwan

10.2 Solar orbit

10.2.1 STEREO – the Solar Terrestrial Relations Observatory

The two STEREO spacecraft (A and B) were launched in 2006. STEREO-B went offline in 2014 and was declared lost in 2018. Although STEREO-A is now past its design life it continues to operate and is currently well placed to give a side view of the Sun-Earth axis, allowing useful views of any CMEs coming towards Earth for the next few years. However its orbit means that from about 2023-25 it will only give astronomers a 'head on' view of the Sun.

NASA

10.2.2 Solar Orbiter

Launched in 2020 the Solar Orbiter will take images of the Sun from closer than any spacecraft before and for the first time look at its uncharted polar regions.[90] The Solar Orbiter is not designed to give real-time reporting on solar activity but will be useful for post-event analysis (if it survives a major solar storm).

ESA

10.2.3 Parker Solar Probe

Launched in 2018, the Parker Solar Probe is designed to fly close to the Sun and to study the Sun's atmosphere (known as the corona). This has already yielded insights into the behaviour of magnetic fields within the corona and the way these magnetic loops might contribute to its heating. The mission calls for seven flybys over nearly seven years.

NASA

10.3 Lagrange L1 point

10.3.1 ACE – the Advanced Composition Explorer

Launched in 1997 and approaching the end of its life with fuel due to run out in 2025[91], the ACE satellite sits at the Lagrange L1 point between Earth and Sun (see Annex A for more on Lagrange orbit points). Real-time data from ACE are used by a number of agencies to improve forecasts and warning of solar storms as they travel between Sun and Earth. ACE will be replaced by SWFO-L1 in 2024 (see below).

NASA

10.3.2 DSCOVR – Deep Space Climate Observatory

Completed in 2001 but not launched until 2015, the DSCOVR mission was designed to succeed the ACE satellite (see above) and provides data on the solar wind. Like ACE it also sits at the Lagrange L1 point.

NOAA

DSCOVR went offline in 2019 because of technical issues but after nine months was brought back into service in March 2020. This wasn't the first technical issue faced by the satellite – it started to go offline intermittently shortly after commissioning in June 2015[92] and it wasn't until four years later, in June 2019, that a software patch was applied which resolved the issue.

DSCOVR will be replaced by SWFO-L1 in 2024 (see below).

10.3.3 SOHO LASCO Coronagraph, at L1

The SOHO (Solar and Heliospheric Observatory), launched in 1995, continues to operate successfully. It sits in an orbit around the Lagrange L1 point and is equipped with the LASCO coronagraph that allows observations of CMEs and solar corona heating. Unplanned loss of SOHO would severely impede space weather monitoring and is a concern to US officials.[93]

NASA/ESA

10.3.4 IMAP

The Interstellar Mapping and Acceleration Probe is scheduled to launch in 2024 and is the fifth mission in NASA's Solar Terrestrial Probes Program. It's designed to provide data on the boundary of the heliosphere (a sort of magnetic bubble surrounding and protecting our solar system) and cosmic radiation entering the solar system from outside. The IMAP instrument suite includes a pair of magnetometers to provide a baseline for space weather applications and to provide real-time space weather monitoring. It will be positioned at the Lagrange L1 point.

NASA

10.3.5 SWFO-L1

In June 2020 NASA awarded a fixed-price contract worth USD96.9m to Ball Aerospace and Technologies to design and build the Space Weather Follow On-Lagrange 1 spacecraft, for launch along with IMAP in 2024. Separate contracts have been awarded for the sensor suite. SWFO-L1 is expected to replace functions currently provided by both ACE and DSCOVR.

10.4 Lagrange L5 point

10.4.1 L5 mission

Originally due to launch in 2025, the launch date has slipped to 2027 [94] following less funding being received than hoped for at ESA's Space 19+ Ministerial Council meeting in November 2019. ESA leadership had asked for EUR900m for its space safety and related programmes but only EUR541m was approved by ESA member states.[95]

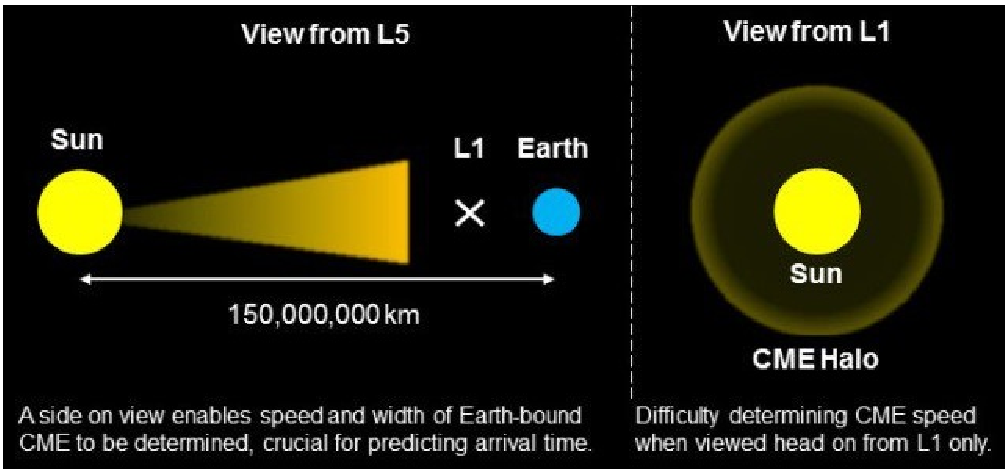
ESA

A solar observation satellite at the L5 point provides a crucial side on view of the passage of a Coronal Mass Ejection from the Sun to the Earth, giving vital data on speed and arrival time at Earth. A satellite at L1 detects that a CME is on its way but only when (or if) the CME arrives at the satellite itself can an accurate estimate of arrival time at Earth be given, which could be as little as fifteen minutes.

Research is being carried out to allow the CME magnetic field at Earth to be predicted based on solar observations but this is still at a relatively early stage.[96]

Benefits of an L1/L5 satellite combination

An L1/L5 combination enables accurate speed, width and direction of CME to be determined



Source: Met Office via @MetOfficeSpace on Twitter

11. Annex C – precision time in Financial Services

Current requirements relating to precision time and timestamping in the UK and EU derive from the second Markets in Financial Instruments Directive (Directive 2014/65/EU), or MiFID II. This came into effect on 3 January 2018. Technical standards are given in guidelines published by the European Securities and Markets Authority (ESMA) on 10 October 2016 in ESMA/2016/1452 (and corrected on 7 August 2017) and Commission Delegated Regulation (EU) 2017/574.

High frequency trading depends on highly accurate timestamping

MiFID II requires market participants to timestamp certain activities, from the time of telephone calls to the time a trade is executed. Market participants involved in high frequency algorithmic trading (the highest standard) are allowed to diverge from Coordinated Universal Time (UTC) by up to 100 microseconds in their timestamping and must timestamp with a granularity of one microsecond or better.

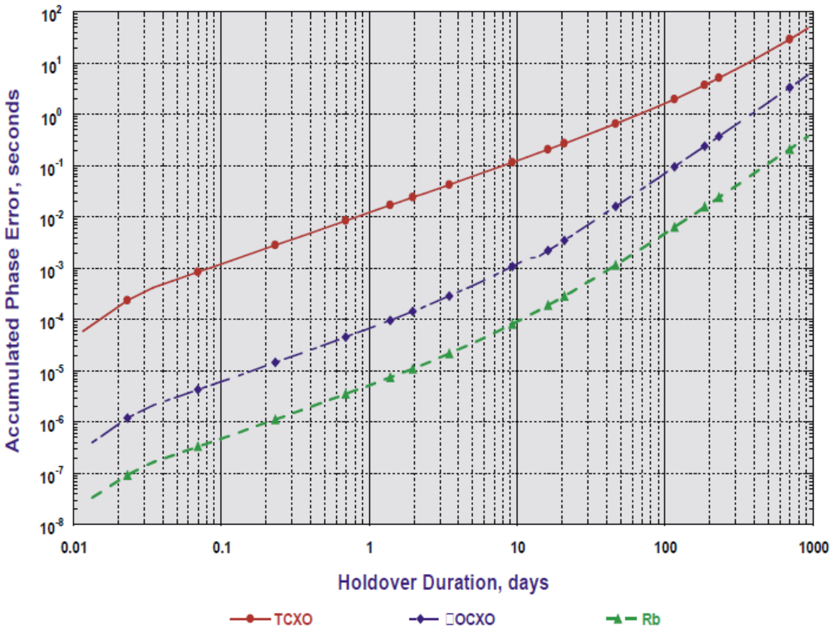
Trading systems derive their time signal from *Network Time Protocol (NTP)* and/or *Precision Time Protocol (PTP)* servers. These in turn take time from one or more different GNSS such as the GPS, Galileo or GLONASS systems.

Even the best atomic clocks drift away from the standard

System design allows for loss of satellite time signal and servers that operate in 'holdover' mode using an internal oscillator – in effect their own internal clock. However, since these internal clocks will slowly drift away from the standard, holdover times can be as little as 24 hours but can be extended with the addition of *oven controlled crystal oscillators (OXCO) or rubidium oscillators* (a type of atomic clock). Anyone involved with high frequency algorithmic trading in a holdover scenario and using the highest performance oscillator will find themselves out of compliance within ten days if the GNSS time signal is not restored.

Holdover performance for different time server oscillator options

For temperature controlled (TCXO), oven controlled crystal (OCXO), and rubidium (Rb) oscillators



Source: EndRun Technologies

12. Annex D – RAE report recommendations, 2013

The RAE report, excellent in all respects, made a number of recommendations which are shown below. These need be reviewed by the UK for relevance, deliverables set and then progress against these deliverables measured and reported.

12.1 Space weather forecasting

a. The UK should work with its international partners to ensure that a satellite is maintained at the L1 Lagrangian point, and that data from the satellite is disseminated rapidly.

b. The UK should work with its international partners to explore innovative methods to determine the state of the solar wind, and its embedded magnetic field upstream from L1.

c. The UK should work with its international partners to ensure the continued provision of a core set of other space-based measurements for monitoring space weather.

12.2 Solar superstorm environment

a. The UK should work with its international partners to further refine the environmental specification of extreme solar events and where possible should extend such studies to provide progressively better estimates of a reasonable worst case superstorm in time scales of longer than ~200 years.

12.3 National electricity grid

a. The current National Grid mitigation strategy should be continued. This strategy combines appropriate forecasting, engineering and operational procedures. It should include increasing the reserves of both active and reactive power to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers.

b. There is a need to clarify and maintain a very rapid decision making process in respect to an enhanced GIC risk.

c. Consideration should be given to the provision of transportable recovery supergrid transformers and to GIC blocking devices, which are still in their infancy.

d. Further geophysics, transmission network and transformer modelling research should be undertaken to understand the effects of GIC on individual transformers, including the thermal effects, reactive power effects, and the production of harmonics.

e. Long-term support for geomagnetic and GIC monitoring should be maintained.

f. The National Grid should better quantify the forecasting skill that it requires and assess this in the light of foreseeable improvements following from current and future scientific research.

12.4 Other geomagnetically induced current effects

a. Government and industry should consider the potential for space weather damage on the optical fibre network through overvoltage on the repeaters and should consider whether appropriate assessment studies are necessary.

b. UK railway operators and pipeline operators should be briefed on the space weather and GIC risk and should consider whether appropriate assessment studies are necessary.

12.5 Satellites

a. Extreme storm risks to space systems critical to social and economic cohesion of the country (which is likely to include navigation satellite systems) should be assessed in greater depth; and users of satellite services which need to operate through a superstorm should challenge their service providers to determine the level of survivability and to plan mitigation actions in case of satellite outages (eg network diversification).

b. The ageing effects of an extreme storm across the whole satellite fleet should be modelled to determine if a serious bottleneck in satellite manufacture or launch capacity could be created.

c. Research should be actively pursued to better define the extreme storm environments for satellites and consequential effects. Collaboration with the NASA Living with a Star programme would be highly beneficial.

d. Observations of the space radiation environment and its effects should be maintained and developed. Such measurements enable post-event analysis of satellite problems, the development of improved physical models which can be used in satellite design phases and the development of better warning and forecasting.

12.6 Aviation: passenger and crew safety

a. Consideration should be given to classifying solar superstorms as radiation emergencies in the context of air passengers and crew. If such a classification is considered appropriate an emergency plan should be put in place to cover such events. While the opportunities for dose reduction may be limited, appropriate reference levels should be considered and set, if appropriate.

b. Atmospheric radiation alerts should be provided to the aviation industry and concepts of operation should be developed to define subsequent actions based on risk assessment (eg delaying take-offs until radiation levels have reduced).

c. Consideration should be given to requiring aircraft operating above a specified altitude (25,000-35,000 feet) to carry a radiation sensor and data logger. This would enable post-event analysis to allay public concerns and to manage any health risks.

d. Consideration should be given to the sensor being visible to the pilot and to the development of a concept of operations whereby the pilot requests a reduction in altitude (noting that modest reductions can be beneficial) under solar storm conditions.

e. Post-event information and advice on the radiation doses received should be available to passengers and crew (especially to pregnant women).

12.7 Avionics and ground systems

a. Ground-and space-derived radiation alerts should be provided to aviation authorities and operators. The responsible aviation authorities and the aviation industry should work together to determine if onboard monitoring could be considered a benefit in flight. Related concepts of operation should be developed to define subsequent actions, eg fastening of seatbelts or reducing altitude if the storm occurs on route or, if still on the ground, delaying take-offs until radiation levels have reduced. This could even include reductions in altitude if deemed beneficial and cost-effective.

b. The responsible aviation authorities and the aviation industry should work towards requiring that future aircraft systems are sufficiently robust to superstorm solar energetic particles, including through the appropriate standards in atmospheric radiation mitigation – for example IEC 62396-1 Ed.1:2012.

c. Since the impact of a solar superstorm on ground-based systems cannot be clarified, further consideration is required. Systems with very high safety and reliability requirements (eg in the nuclear power industry) may need to take account of superstorm ground level radiation on microelectronic devices within the system.

12.8 GNSS

a. All critical infrastructure and safety critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.

b. Care should be taken to ensure that this requirement extends to cabled and fibre communications systems.

c. Backup position, navigation and time services such as eLoran service (which in the UK is broadcast from the Anthorn transmitter) should be considered as an alternative to GNSS for UTC traceable time, timing and location based services. We note that the USA has set-up the Alternate Position Navigation and Time (APNT) programme that is working to reconfigure existing and planned ground navigation aids (e.g. Distance Measuring Equipment) and the ground based transmitters associated with automatic surveillance) so that they can back up GNSS well into the future.

d. Since loss of GNSS would have a major impact on lives in general, and on shipping and air travel specifically, warnings of events should be provided through a nationally recognised procedure, possibly involving government crisis management arrangements, NATS, the CAA and the General Lighthouse Authority. Criteria should be established for the re-initiation of flying when it is safe to do so.

12.9 Terrestrial mobile communication networks

a. All terrestrial mobile communication networks with critical resiliency requirements should also be able to operate without GNSS timing for periods up to three days. This should particularly include upgrades to the network including those associated with the new 4G licenses where these are used for critical purposes and upgrades to the emergency services communications networks.

b. Ofcom should consider including space weather effects when considering infrastructure resilience.

c. The impact of extreme space weather events should be considered in the development of upgrades to emergency services communications networks and GNSS holdover should be ensured for up to three days.

d. Further study of radio noise effects on mobile communication base stations should be undertaken to quantify the impact.

12.10 HF communications

a. The aviation industry and authorities should consider upgrades to HF modems (similar to those used by the military) to enable communications to be maintained in more severely disturbed environments. Such an approach could significantly reduce the period of signal loss during a superstorm and would be more generally beneficial.

b. Operational procedures for closing and re-opening airspace in the event of an extended HF and satellite communications blackout should be developed

12.11 Mobile satellite communications

a. Current and proposed L-band satellite communications used by the aviation and shipping industries should be assessed for vulnerability to extreme space weather.

12.12 Terrestrial broadcasting

a. Where terrestrial broadcasting systems are required for civil contingency operations, they should be assessed for vulnerabilities to the loss of GNSS timing.

13. Annex E – Blackett review recommendations, 2011

The Blackett review of high impact, low probability risks, completed in 2011 but published in January 2012, was produced by the UK and commissioned by the Cabinet Office and the Ministry of Defence. It discussed the thinking at the time on the best approach to identifying, assessing and managing these types of risks.

The Blackett review process is an expert-led, independent study to answer specific scientific or technological questions and to inform policy-makers. These types of review are named after the physicist Patrick Blackett (1897-1974) and are usually of 3-9 months duration with anywhere from 10-20 experts investigating the questions posed.

The recommendations, which are applicable everywhere and not just the UK, are useful. For readers outside the UK the Cabinet Office supports the Executive Office (in the UK the Prime Minister). They are as follows:

1. Government should make greater use of external experts to inform risk assumptions, judgements and analyses.
2. Government should continue to ensure the optimal and efficient balance of resources is used to address high impact low probability risks versus any other risk.
3. Government departments should enhance their warning systems to better detect early signs of low probability high impact risks as a mitigation measure to avoid strategic surprise. In doing this it should make best use of work and capabilities in government, academia and industry.
4. Government should review the means by which it can assess the effectiveness of its risk mitigation strategies.
5. Government should use probabilistic analysis, where it is available, in support of its risk management process to evaluate defined scenarios and inform decision making about significant individual risks.
6. Government should strengthen its mechanisms to review risks and include ‘Near Misses’ (where a significant risk almost materialises).
7. Government should work more closely with risk communication experts and behavioural scientists to develop both internal and external communication strategies.
8. Cabinet Office, working with other departments, should strengthen the scrutiny of the NRA (the National Risk Assessment) by experts drawn from appropriate disciplines in the scientific, analytical and technical fields.
9. Cabinet Office should encourage government departments to develop and maintain a database of appropriate experts for the NRA risks they own and ensure that it is kept under continual review.
10. Cabinet Office should encourage departmental risk owners to consider using supplementary approaches to inform the likelihood and impact assessments for scenarios within the NRA process.
11. Cabinet Office should work with other government departments and experts to consider potentially linked or compounding risks to inform contingency planning appropriately.

14. Annex F – European Commission recommendations, 2016

Based on the conclusions of the impressive Space Weather & Critical Infrastructures Summit held in Italy 29-30 November 2016, the following recommendations for action targeting stakeholders in science, industry and policy were proposed:

14.1 Recommendations for science

1. Physical models should be improved or — where necessary — new models developed to allow a better prediction of CME arrival times, an earlier determination of the interplanetary magnetic field orientation, and an estimate of the probability and size of the likely impacts.

2. Forecasting capabilities should be enhanced to provide regional or local forecasts on the severity and duration of extreme space weather to ensure the most appropriate operator response.

3. Extreme space-weather scenarios should be defined against which operators can benchmark the performance of their infrastructures and develop risk mitigation strategies. This should be accompanied by a reference document for all stakeholders which includes a clarification of terminology.

4. Impact models for different types of critical infrastructures and their components should be developed to facilitate risk assessment. Cooperation with industry should be sought to obtain access to infrastructure-specific data for model verification and scenario building.

5. Methodologies for multi-hazard risk assessment and the modelling of infrastructure interdependencies should be developed for a realistic estimate of extreme space weather impacts on industry and the ripple effects in society.

14.2 Recommendations for operators

1. Operators should be aware that a satisfactory performance of infrastructures during moderate space weather does not guarantee continued operability and lack of damage during Carrington-type geomagnetic storms.

2. Also, operators should be aware that during extreme space-weather conditions, areas normally unaffected by geomagnetic storms are likely to be hit. Response plans should be ready in case of an alert.

3. A comprehensive vulnerability assessment of the European power transmission grid to extreme space weather should be carried out to identify criticalities and the possibility of transboundary effects.

4. Operators should assess if hidden vulnerabilities to space weather are embedded in their systems, for example via dependencies on GNSS.

5. Care should be exercised when modernising technology to ascertain that new vulnerabilities to space weather are not inadvertently introduced into systems.

14.3 Recommendations for policy

1. A strategic plan should be developed to define the roles of the key players in Europe.

This can include the establishment of a centralised European strategic decision making capability tasked with coordinating space-weather risk mitigation (including alerting) and response at a pan-European level.

2. Consistency in forecasting needs to be ensured. Protocols are needed to coordinate forecasts of different space-weather service providers.

3. Protocols should be developed that define responsibilities and ensure good coordination between the stakeholders before, during and after an extreme event. This includes communication of the risks and potential impacts to the public.

4. Emergency plans for extreme space weather should consider the full range of critical infrastructures possibly affected. Once drawn up, these plans need to be tested.

5. The opportunity for organising a joint space-weather exercise at EU level should be explored to test existing response capabilities and identify critical gaps.

6. It should be determined if further measures may be necessary to guarantee the integrity of critical infrastructures and their continued operability in case of a major event.

7. Coordinated strategic investments into developing scientific capability and know-how in the EU should be explored.

ENDNOTES

[1] The Sun has six regions: the core, the radiative zone, and the convective zone in the interior; the visible surface, called the photosphere; the chromosphere; and the outermost region, the corona.

[2] In simple terms: protons and neutrons are the basic building blocks of the nucleus of atoms; protons have a positive charge equal to the electron's negative charge. A hydrogen atom has one electron and one proton; a helium atom has a nucleus of two protons and two neutrons, plus two electrons. Of course, life is never this simple: both hydrogen and helium have isotopes, which are characterised by having different numbers of neutrons in the nucleus.

Ions are formed when atoms loose or gain electrons and hence become charged particles.

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[10] Morning Chronicle, 28 September 1859, p. 7.

[11] Monthly Notices of the Royal Astronomical Society, Volume 20, Issue 1, November 1859, p. 13–15.

[12] Ibid p. 15-16.

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AMENDMENTS

01 – 18 March 2021: minor typographical corrections; minor adjustments to timelines in Figure 2.