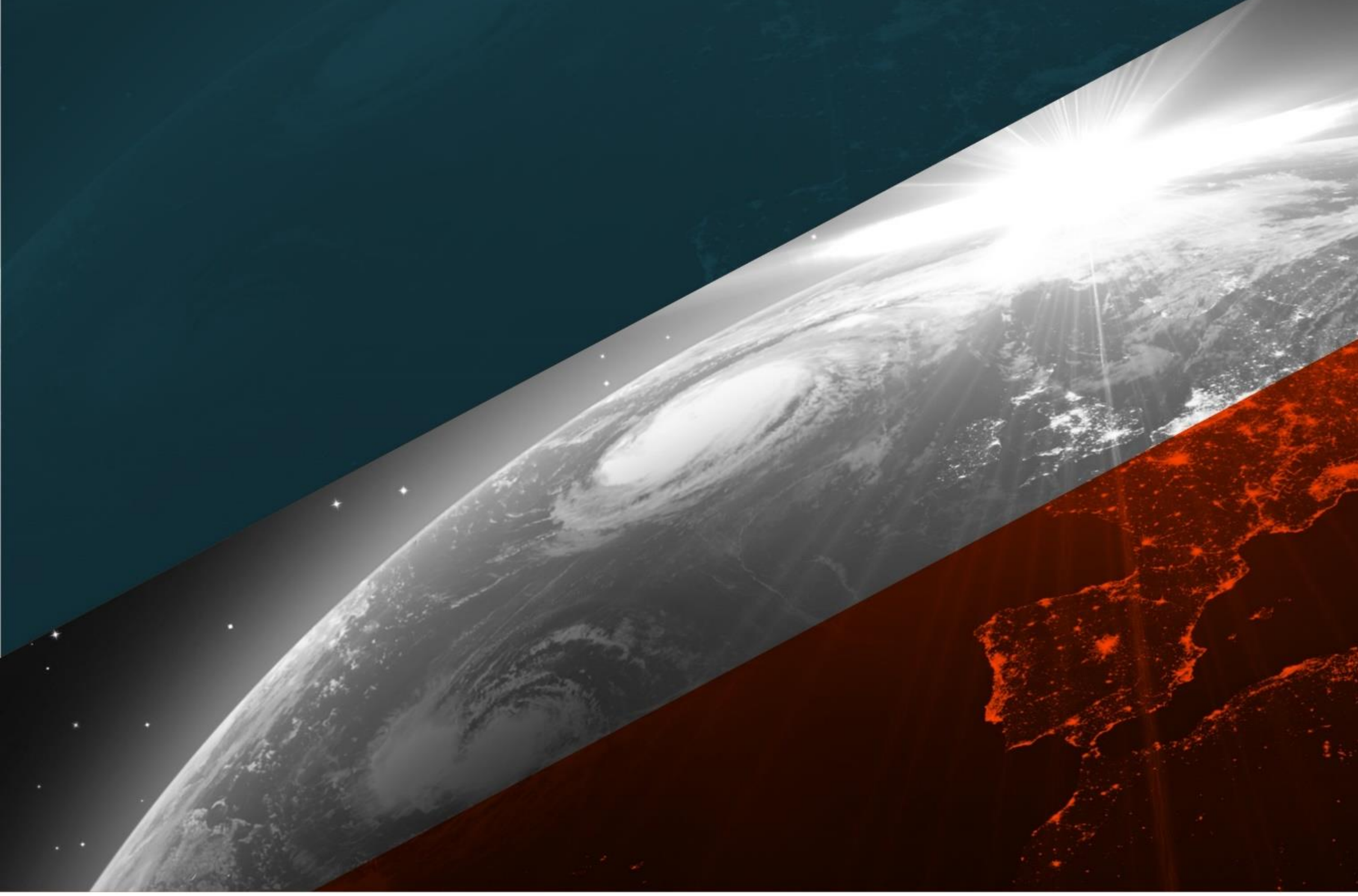
Severe Space Weather Impacts on UK Critical National Infrastructure

A SWIMMR Project Report

Technical Annex



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Technical Annex

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Contents

1 Introduction to the Technical Annex

This document provides additional technical and programmatic detail to supplement the main published report of the SWIMMR S6 project.

The material in this supplementary report was gathered from the engagements in 2022-2024 with over 100 industry, government and academic stakeholders in critical national infrastructure (CNI) and space weather preparedness. The engagements were in the form of interviews and workshops, with verification, where appropriate, through synthesis of published scientific and industry literature.

Some of this material was externally reviewed as part of the intermediate document of the SWIMMR S6 report. Some was included on the basis of consultations and workshops conducted since the intermediate report (September 2023) and has not been externally reviewed.

This annex is structured as follows. Section 2 provides programmatic details about the SWIMMR S6 project, including the consultations and workshops held to gather information for the project.

Section 3 provides a high-level description of the solar and heliospheric physical mechanisms that drive the space weather phenomena that can impact CNI technologies. This section should be seen as a companion of Section 2 of the main report, providing a description of the underlying mechanisms that lead to the space weather hazards outlined there.

Sections 4, 5, 6 and 7 cover the Space, Energy, Communications and Transport CNI sectors, respectively. They provide additional context about the sectors that was deemed by the project team to be of secondary importance compared to the content of the main report. These sections should be read as providing additional reference details for specific CNI technologies, rather than as a narrative section.

Section 8 provides case studies of how downstream entities could be affected by the severe space weather scenario outlined in Section 3 of the main report. These case studies illustrate the cross-sectoral impacts due to the dependencies of downstream entities on potentially vulnerable CNI technologies.

2 SWIMMR S6 Project Details

2.1 Consultations

114 organisations related to UK CNI were interviewed over the course of this project between 2022 and 2024, mostly through online video call. These and account for approximately 44% of the total number of organisations contacted. The remainder either did not respond or declined the consultation invite. Some organisations we interviewed more than once, or with multiple people from the same organisation. Additionally, we interviewed approximately 20 academics about space weather risk more broadly. The appendix in Section 0 provides a list of the organisations that we consulted with.

2.2 Workshops

The project team hosted a total of seven formal workshops, two of which were held in person and five online. Details of the workshops held are provided in Table 1. The aims of the five only workshops were:

1. To disseminate the preliminary results of the project for each sector.
2. To facilitate discussion on the key points of uncertainty around space weather impacts on each sector

In addition, the aims of the in-person workshops were:

3. To disseminate the 40 space weather recommendations for policymakers across the Space, Energy, Transport and Communications CNI sectors.
4. To facilitate discussion on how these recommendations could be implemented by government, academic, and industry stakeholders.
5. To facilitate discussion on the future of space weather activities after the SWIMMR programme.
6. To bring together multiple CNI sectors to discuss cross-sectoral approaches to space weather preparedness.

The CNI sector-specific workshops covered an introduction to the space weather hazards to the technologies used within the sector, a presentation of the initial results identified in this project, and 'deep-dive discussions' into open questions of space weather resilience in the specific sector that were identified in the first round of consultations. They also covered potential impacts of the severe space weather event outlined in the timeline in Section 3 of the main report.

The cross-sectoral workshop was designed to be a more free-flowing agenda, with ample time for whole-room and small-group discussions. The focus was on cross-sectoral considerations, including dependencies on technologies between sectors, UK policy strategy, and socio-economic impacts (know.space presentation and discussion). This in-person workshop also facilitated time for direct engagements with key stakeholders, including representatives of the UK Government Department for energy Security and Net Zero, Department for Transport and the UK Space Agency.

Finally, the consultations with stakeholders concluded with the final in-person workshop in October 2024. This project focussed on disseminating the findings and recommendations that are in the final report and allowed for the final feedback on wording to be received. We also hosted a panel discussion on the future of space weather in the UK after the completion of the SWIMMR programme.

Table 1: Details of the workshops hosted as part of the SWIMMR S6 project.

Workshop Theme	Date and time	Primary Audience	Style
Space Weather Impacts on the Space Sector	11/07/23, 13:00-15:00	Space industry stakeholders	Online
Space Weather Impacts on the Energy Sector	12/07/23, 13:00-15:00	Energy industry stakeholders	Online
Space Weather Impacts on the Communications Sector	20/07/23, 13:00-15:00	Communications industry stakeholders	Online
Space Weather Impacts on the Aviation Sector	21/07/23, 13:00-15:00	Aviation industry stakeholders	Online
Space Weather Impacts on the Rail Sector	07/08/23, 13:00-15:00	Rail industry stakeholders	Online
Cross-sectoral Space Weather Impacts	20/09/23, 10:00-16:30	Policy makers and industry stakeholders	In person
Space Weather Impacts on Critical National Infrastructure: SWIMMR S6 Findings and Recommendations Workshop	04/10/24, 10:00-16:30	Policy makers and industry stakeholders	In person

3 Solar and Heliospheric Drivers of Space Weather Hazards

This section provides additional context of this complex system to highlight the sources of and the interconnectedness of the hazards, presented in a non-technical way where possible. This section should be seen as a complement to Section 3 of the main report, providing details about the physical mechanisms that drive the space weather hazards described there.

3.1 Solar Activity

Regions of strong magnetic field on the surface of the Sun are called active regions and typically contain dark areas called sunspots. Active regions are complex structures of magnetic field that allow for the storage of magnetic energy; the more tangled and stretched the magnetic field the more energy is stored. This stored energy can be released explosively by a process called magnetic reconnection, causing both solar flares and coronal mass ejections (CMEs), the main drivers of extreme space weather.

Active regions appear on the Sun in an approximately eleven-year cycle, with more sunspots and active regions appearing at the maximum of the cycle and fewer at the minimum. Both flares and CMEs are driven by active regions and so both are more likely to occur, and be more intense, closer to solar maximum, as the available energy is larger. An individual active region can be the source for hundreds of flares and CMEs during the 14 days that it takes to rotate across the Earth-facing side of the Sun. The most intense flares and CMEs come from the most frequently flaring active regions. At solar maximum there are often multiple active regions visible at once and increasing the chance of extended periods of high space weather activity.

3.2 The Background Solar Wind

The solar wind is a continuous source of plasma flowing outwards from the Sun, consisting of mainly protons and electrons, and carrying with it the Sun's coronal magnetic field that extends out into space. Different regions on the Sun produce solar wind with different speeds and the exact sources and mechanisms that generate the solar wind are not fully understood. However, open magnetic field regions termed coronal holes produce higher speeds (>500km/s), and the slow solar wind (<500km/s) largely emanates from equatorial regions. The particles, energy and magnetic field that make up the solar wind are part of the chain transmitting solar conditions to the Earth. The solar wind is constantly and dynamically driving the magnetosphere, acting as the background to sporadic, high-energy solar flare and CME events, described below.

3.3 Solar Flares

Solar flares are an explosive and dynamic phenomenon that result from the release of magnetic energy in the Sun's atmosphere through magnetic reconnection. The twisted solar magnetic field stores and then suddenly releases enormous amounts of energy, producing radiation across the entire electromagnetic spectrum, from decametre radio waves to high-energy X-rays and gamma-rays. Flares can be confined or eruptive and, during an eruptive event, the flare may occur alongside a CME and generate solar energetic particles (SEPs).

Most solar flares exhibit a similar temporal profile, with an impulsive phase where most of the energy is released, related to the production of high-energy particles and extreme localised heating to tens of million Kelvin. While the impulsive phase may only last a few minutes, the flare decay phase can last several hours or even days in extreme long duration flares [1], leading to enhanced radiation and ultra-violet (UV) and X-ray emission for an extended period.

Solar flares drive sudden ionospheric disturbances (SIDs), where increased ionisation in specific layers of the ionosphere change the reflectance of HF radio signals.

3.4 Coronal Mass Ejections (CMEs)

During an eruptive flare, or from a twisted magnetic field structure, plasma and magnetic fields are ejected from the Sun's atmosphere towards the Earth as a CME. CMEs are large-scale structures that rapidly expand as they propagate away from the solar atmosphere into interplanetary space. The leading edge of a fast CME produces a shock wave, like the bow wave of a ship, where SEPs and some types of radio bursts are created.

Those CMEs that are launched either directly towards or away from the Earth are observed as a halo around the Sun from the perspective of the Earth. The Vigil mission, which will place a spacecraft at the fifth Lagrange point (L5) to provide a unique side-view of the Sun, will be able to distinguish between these two types of halos for the first time [2], [3]. Such observations are important for space weather forecasting [4]. CME speeds vary significantly, taking between 1-3 days to reach Earth. The fastest recorded CME transit was under 15 hours for the 4th of August 1972 geomagnetic storm, taking advantage of a previous CME that cleared the interplanetary space of drag-inducing plasma.

3.5 Magnetosphere, Geomagnetic Storms and Substorms

The magnetosphere is the region of near-Earth space controlled by Earth’s magnetic field. It has a bullet-like shape, reaching around 10 Earth radii towards the Sun and stretching hundreds of Earth radii downstream as it is pulled out by the solar wind. The magnetospheric environment consists of a very sparse but energetic plasma. There are two sources of charged particles that create our near-Earth plasma environment: those provided by the solar wind, and those that escape from the upper atmosphere following ionisation by solar radiation and auroral particle precipitation.

During benign space weather, the magnetosphere and solar wind are distinct plasma regions that mix only sporadically when the solar wind magnetic field points opposite to that of the Earth, allowing magnetic reconnection to occur. During periods of increased space weather activity, energy and plasma from the solar wind and incoming CMEs are redistributed throughout the near-Earth space, driving measurable changes to the Earth’s magnetic field at the surface and dynamic aurorae towards the magnetic poles.

The most intense examples of interactions between the solar wind and the magnetosphere are geomagnetic storms. These periods are marked by strong fluctuations in Earth’s magnetic field, as well as large changes in the amount and energy of plasma in near-Earth space that also cause dynamics in the ionosphere. Geomagnetic storms can last several days, and their origins can be traced to transient solar wind features such as CMEs and high-speed solar wind streams.

Substorms are intense periods of disruption which occur in the nightside of Earth’s magnetosphere, called the magnetotail. Like geomagnetic storms, large substorms lead to large energy changes in near-Earth space, drive electric currents in the ionosphere, and heat the upper atmosphere. However, substorms are much more frequent than geomagnetic storms, occurring on average around every 3 hours.

The largest geomagnetic storms are caused by CMEs, and often by multiple CMEs occurring in close succession due to the increased speed of the following CME. When the CME’s magnetic field is in the opposite direction to the Earth’s magnetic field, magnetic reconnection can transfer significant quantities of energy and particles from the CME into the magnetosphere and interact with the Earth's atmosphere much more readily. This is particularly important for forecasting geomagnetic storms as the CME magnetic field direction can be measured only when the CME passes spacecraft permanently located at the first Lagrange point, between the Sun and the Earth. This gives only around 30 minutes of warning about how large the ensuing geomagnetic storm will be.

Large, fast CMEs with favourable magnetic field direction for connecting with the Earth's magnetic field can result in G5 storms, the maximum value in the National Oceanic and Atmospheric Administration (NOAA) G-scale for geomagnetic storm severity. Such large events can occur at any time throughout the solar cycle, although more extreme storms are more likely during the active phase [5].

3.6 Radiation Belts

Some high-energy electrons and protons are trapped in the magnetosphere for a long time, forming the inner and outer radiation belts that encircle the Earth. The inner belt extends from around 300km to 10,000km altitude and is most intense near the equator. It is dominated by high energy protons that have a long lifetime trapped in the inner belt. The outer belt is significantly larger and much more variable in size and in intensity. It extends from around 20,000km altitude as far as the boundary between Earth's magnetic environment and the solar wind. The outer belt is also most intense near the equatorial plane and is dominated by high-energy electrons. The number and energy of high-energy electrons in Earth's outer radiation belt varies by orders of magnitude in response to changes in the solar wind and CMEs as well as internal processes within the magnetosphere such as geomagnetic storms and substorms.

3.7 Extreme Space Weather Events

Much like terrestrial weather, space weather is usually mild. However, occasionally, and particularly during the maximum of the solar cycle, the Sun generates conditions for extreme space weather events. Due to the shared solar and heliospheric drivers of the different space weather hazards, extreme space weather events normally involve a cluster of space weather hazards occurring near-simultaneously over the course of a few days to a few weeks. Although, extreme space weather events associated with a single phenomenon, such as a single extreme solar radio burst without an associated energetic particle event, can also occur.

The international standard for space weather forecasts and alerts, is the G-scale (geomagnetic storm), S-scale (solar energetic particle event) and R-scale (ionospheric radio blackout), introduced by the US NOAA Space Weather Prediction Center (SWPC), which each have discrete magnitudes from 1 (minor) to 5 (extreme). Based on recommendations from the RAEng (2013) Report, the Met Office developed UK specific impact scales (derived from the NOAA scales) which are used in the UK forecasts, alerts and warnings issued by the Met Office Space Weather Operations Centre [6]. They link the G, R and S-scales to expected impacts on UK infrastructure specifically.

The table below lists a selection of historic space weather events and their impacts on infrastructure at the time. The most extreme space weather event, the Carrington event, occurred at the time prior to the development of modern infrastructure, so passed by without major societal impact. More recent severe space weather events were more moderate in their intensity, yet still impacted customers and CNI sector services.

Table 2: Selected historic space weather events and their impacts.

Date	Description	Impacts
1-2/09/1859 "Carrington Event"	The first and largest recorded solar flare released an extremely fast CME which initiated one of the largest geomagnetic storms ever recorded.	Geomagnetically induced currents (GICs) induced in telegraph wires started fires and electrocuted workers. The impacts were not more widespread only because of the absence of modern infrastructure that is more vulnerable. Aurorae were seen as far south as Venezuela [7].
13-14/03/1989 "Hydro-Québec Storm"	Two CMEs following a large solar flare impacted Earth. The same active region that ejected these CMEs also accelerated SEPs that caused GLEs between 29th Sept and 24th Oct.	Impacts include satellite communications disruption and most famously a 9-hour power blackout for over 6 million people in Canada caused by GICs in the electricity transmission network [8]. The associated SEP events are the likely cause of single event effects in spacecraft.
10-11/2003 "Halloween Storms"	A series of large solar flares generated an intense radiation storm and CMEs that impacted Earth across a 3-week period.	An extreme geomagnetic storm drove GICs in power grids globally. Malmo, Sweden, experienced a power blackout for 50,000 customers for an hour [9] and several transformers in South Africa were damaged.
06/12/2006	A series of extreme solar flares generated the largest solar radio burst in recorded history (both in intensity and duration) and caused a moderate geomagnetic storm.	The intense radio noise at GNSS frequencies raised the noise on GNSS signals causing several hours-of-service disruption, particularly to GNSS augmentation systems that are important for commercial airline approaches [10].
23/07/2012 "Near miss"	A CME as large as the Carrington event narrowly missed Earth by 9 days.	Had this CME impacted Earth, the resulting geomagnetic storm would likely be greater than any in recorded history.

Exactly how extreme these historic space weather events are, or in other words how long we might expect to wait before similar or larger events reoccur, is subject of much research. The statistical field of extreme value analysis (EVA) has been used to estimate the return period of space weather events (that is, the number of years over which a certain event severity is expected to occur). It is a technique commonly employed in industries where a precise estimate of the risk from extreme events is required, such as insurance and safety-critical industries like nuclear energy. Using these techniques, the Carrington event geomagnetic storm is considered to be around, or slightly more severe than, a 1 in 100-year geomagnetic storm, the February 1956 event around a 1 in 50-year GLE event, and the December 2006 solar radio burst to be ten times larger than any other event since records began 50 years ago [11], [12].

These return period estimates have significant uncertainty due to the limits of extrapolating EVA models to their extremes. Furthermore, it should be understood that these are statistical occurrence rates giving a probability of occurrence per year, rather than a prediction for how long it will be before the next extreme event.

4 Space Sector

This section covers additional technical details from the consultations with space sector organisations.

4.1 Satellite Operation

4.1.1 GEO Operations and Satellite Communications

Geostationary orbit (GEO) at 35,786km, is very much the domain of large communications and weather satellites, such as Inmarsat's fleet and the UK's Skynet military satellite communications system, and Eumetsat's Meteosat spacecraft. GNSS correction signal services such as GNSS augmentation signals and space-based Precision Point Positioning (PPP) are mostly broadcast through hosted payloads and transponders on satellite communications spacecraft. As such, GNSS signals face impacts in both MEO and GEO.

While perceived likelihood of satellite failure varied significantly during consultations, feared events expressed by interviewees were a severe SEP event overwhelming protection measures with a 'sea of charge' in devices triggering parasitic paths through them, ultimately causing many satellites in GEO to fail, especially if it occurred at a time of a compressed magnetosphere.

4.1.2 MEO Operations and Satellite Navigation (GNSS)

Medium Earth orbit (MEO) extends from 2,000km to GEO (35,786km) and is dominated by the GNSS constellations that mainly orbit between 19,000km and 24,000km, which is within the outer radiation belt that extends from 12,000km to 50,000km at the equator but swells and contracts with space weather. GNSS augmentation and correction signals to MEO signals are re-transmitted from GEO satellites.

In addition to GNSS services, MEO is increasingly being used for satellite communication services. MEO satellites enhance voice, video, and real-time data communications by minimizing round trip latency compared to GEO. Additionally, MEO satcom services require smaller constellations for the same coverage compared to LEO. Deploying systems like Iridium and Globalstar in LEO necessitates intricate design choices based on target markets. Ensuring ubiquitous service globally demands a multitude of satellites in various highly inclined orbits, with inter-satellite communication links reducing latency and simplifying ground infrastructure. This requires precise tracking of moving objects. GEO satellites offer fixed coverage over designated landmasses but incur a high round trip latency of 500-600ms, affecting communication performance. Balancing coverage area and orbital altitude, an initial MEO constellation at 8,000km above sea level in a circular equatorial orbit provides cost-effective, continuous coverage for underserved regions. With eight equatorial MEO satellites, service is maintained within 45 degrees of the Equator, offering high-bandwidth options for emergency responders, disaster relief, and maritime applications.

4.1.3 LEO Operation and Earth Observation

LEO extends from 200km to 2,000km which overlaps the Earth's thermosphere (85 – 690km), an upper layer of the Earth's atmosphere comprised of very low-density atoms, molecules, and ions. However, LEO partially falls within the inner radiation belt, which is comprised of high-energy electrons and protons and extends from 1,000km to 6,000km. For this reason, most of the 3,000 active LEO satellites orbit below 1,000km.

LEO is an increasingly diverse orbit in which Earth observation, broadband (and internet of things) connectivity, synthetic aperture radar (SAR), science missions and crewed missions operate, increasingly from small- or micro- sats and increasingly in large constellations. The cost of these smallsats is kept low by using commercial-off-the-shelf (COTS) components, most of which have little protection from space weather radiation effects. LEO is also where the majority of space debris orbits.

4.2 Satellite Electronics

4.2.1 GEO Satellite Electronics

Satellites in GEO experience less protection from the Earth's magnetic field compared to those in MEO and LEO. The sun-facing side of the magnetic field (magnetosphere) is compressed by this bombardment to between 38,000km and 64,000km. However, in an extreme geomagnetic storm, the magnetosphere can be compressed to within the GEO orbit, at which time satellites in GEO are much more exposed to SEPs which can cause SEEs in the satellites electronic systems.

GEO also sits within the Earth's outer radiation belt, albeit at the outer edge where the effects are much less compared to other areas.

The responses during consultations about the expected extent of damage to GEO satellites during a 1-in-100-year SEP event varied from no damage at all due to the effective and conservative radiation hardening procedures in place, to the permanent loss of most GEO satellites.

4.2.2 MEO Satellite Electronics

GNSS orbits are more protected than GEO from cosmic rays (protons and heavy ions) and energetic solar particles (mostly protons) due to the greater strength of the Earth's magnetic field. However, the most intensive radiation in the outer radiation belt (mostly trapped electrons) is strongest at lower altitudes.

In much the same way as in GEO, satellites in MEO suffer single event effects (SEEs), and therefore radiation protection is a strong design criterion. During severe space weather, the density and energy of particles in the radiation belts increases resulting in vulnerable electronics being more likely to be hit by a charged particle and disrupting its operation.

4.2.3 LEO Satellite Electronics

LEO orbits are highly protected from cosmic rays and energetic solar particles (except in polar regions) due to the strength of the Earth's magnetic field and are therefore in a much more benign environment than MEO and GEO and less affected by radiation from SEP events. However, the radiation hardening of LEO satellites tend to be less extensive, and non-radiation hardened electronics designed for terrestrial use is commonplace. Additionally, with many more LEO satellites than any other orbital regime, and increasing use for CNI purposes, even a lower radiation flux could well still damage more LEO satellites than in MEO or GEO.

The inner radiation belt is strongest over the South Atlantic Anomaly (SAA) where it dips to an altitude of only 200km between Brazil and the South Atlantic, and where the proton flux can increase SEEs by up to 40% [13]. Some operators power-cycle electronics before/after passing through the SAA thus avoiding some of the SEE impacts.

Whilst satellites in an equatorial or low inclination orbit are more exposed to SEEs from the SAA than those in polar orbits, as they pass through it more often, satellites in a polar orbit are at a higher risk from non-trapped protons during solar maximum.

4.2.4 Use of COTS in Satellite Electronics

Software is now an essential element all satellites supporting a wide range of onboard functions, requiring more powerful processors, networks and onboard data storage which is driving the use of COTS devices for many commercial missions.

Although fully depleted silicon-on-insulator (FDSOI) devices show promise for radiation tolerance for 28nm devices, 20nm devices are used in some ESA programmes and Xilinx are producing a 7nm Field Programmable Gate Arrays (FPGA) which is being investigated for use in space applications. Some cubesats and constellations are using non-space qualified commercial-off-the-shelf (COTS) devices.

The longevity of satellites makes it desirable that they can be periodically updated with new software to enhance functionality, fix bugs or workaround onboard failures, including space weather induced failures.

Given these factors, satellite manufacturers assume that SEEs will happen and design for system-wide resilience and mitigations such as error detection and correction, and modular redundancy, though it is not evidenced during the interviews that such mitigation methods are sufficient for robustness during an extreme SEP event.

4.3 Satellite Radio Signals

4.3.1 GNSS Signals in GEO and MEO

Signals from MEO to Earth, such as GNSS signals in L-band (1-2GHz) suffer the same scintillation effects as from GEO.

GNSS services are provided by large satellite constellations with several satellites visible in the sky at any one time. This provides some redundancy and has the effect of reducing the impact of localised scintillation. However, during a particularly intense geomagnetic disturbance, scintillation over much larger portions of sky can occur, even over mid-latitudes, so GNSS services would likely be temporarily unavailable or otherwise severely disrupted, especially in locations with a restricted view of the sky such as urban canyons.

On 30th October 2003, during the Halloween geomagnetic storms a particularly intense plume of plasma from the high atmosphere rose into the magnetosphere and caused rapid changes in the total electron content along paths to GPS satellites. This meant that the US GNSS augmentation system (WAAS) could not provide corrections that ensured GPS-derived positions were accurate enough for aviation use for 11 hours. This condition was detected by WAAS and flagged as a loss of system integrity, thus warning users that it should not be used.

All technologies that use C-band or lower frequencies are vulnerable to solar radio noise during daytime solar radio bursts, which may last minutes to several hours. On 6th December 2006, the largest solar radio burst since measurements began (1 million solar flux units at 1.4GHz radio frequency), decreased carrier-to-noise ratio by ~17dB, enough to impair GPS receivers across the sunlit hemisphere for approximately 30 minutes. This 2006 event was likely the most significant impact of solar radio bursts on GNSS services (although ionospheric scintillation is more commonly disruptive). More recent solar radio bursts have been substantially lower power than the December 2006 event and GNSS technology has developed significantly with multichannel transmission and other innovations that have likely reduced the likelihood and impact of radio noise.

4.3.2 GNSS Signals in LEO

For many satellites in LEO, especially constellations and earth observation missions, knowing their exact position is essential. The attitude and orbit control system (AOCS) of some use GNSS as one element of a redundant system (others include star trackers, gyroscopes etc). As they receive GNSS signals direct from GNSS satellites, they would not pass through the ionosphere, and therefore not be impacted by scintillation. It is noted that some attitude sensors such as star tracker cameras that use charge coupled devices (CCDs) for imaging are sensitive to the highly energetic particles in the radiation belt. This is relevant to all orbits.

GNSS signals are also used by some LEO satellites for radio occultation (uses refraction of GNSS signals in the ionosphere to measure atmospheric characteristics) and GNSS reflectometry (uses GNSS signals reflected off the Earth’s surface to measure characteristics such as ocean surface height, wind speed and direction, humidity, and ice-layer density). Both would be impacted by scintillation.

4.3.3 Multi-Channel Receivers

GNSS receivers are now invariably multi-channel, and many system-on-a-chip (SoC) semiconductors have GNSS capabilities in-built. GNSS technology evolutions are looking to include integrity and greater accuracy. Spacecraft use GNSS receivers for orbit determination and some constellations include payloads such as radio occultation and GNSS reflectometry.

Multi-channel receivers are a significant improvement for resilience to ionospheric scintillation.

4.4 Crewed Missions

In 2017, the USA announced the NASA ARTEMIS programme to land people back on the Moon. This presents an emerging risk to astronaut health as they will travel beyond the protection of the magnetosphere.

In August 1972, between the Apollo 16 and 17 moon landings, there was an ultra-fast coronal mass ejection and huge radiation storm which had it occurred whilst astronauts were walking on the Moon, might have been very damaging to their health if not ultimately fatal. With estimates of radiation dose of 1-5greys, this would be in the fatal range for humans. Neither the Moon nor Mars offer significant magnetic field or atmospheric protection, but they do shield approximately 2% of the incident radiation, depending on the position of the astronauts relative to the planet or moon.

Different space agencies set acceptable limits for radiation exposure based on various factors such as 30-day, yearly, or career totals. The aim is to minimise the risk of effects such as acute radiation syndrome and carcinogenesis. Cancer risk is approached differently as it is stochastic in nature. For instance, NASA sets its acceptable limits based on no more than a 3% increased death risk for astronauts, with a 95% confidence interval. Research on radiation types for longer missions suggests that additional cognitive impairments must also be considered as they may have mission-critical effects as well as permanent impairments.

4.5 Ground Infrastructure

Aside from the antennas and associated transceiver electronics, most of the ground infrastructure supporting satellites is no different from a complex IT system, consisting of physical or virtual machines deployed in servers, or in recent years increasingly on a private or public cloud, connected to the ground stations and end-users via internet connections.

Since 2020, ground stations as a service have started to be introduced by Amazon, Azure, Leaf-Space, K-SAT, and others where the satellite data is delivered directly to a public cloud for processing and product dissemination from a ground station. In some cases (e.g., AWS), the antenna can feed a digital stream into the cloud and a Software Defined Radio (SDR) running in the cloud acts as the front-end and vice-versa for transmit.

5 Energy Sector

This section covers additional technical details from the consultations with energy sector organisations.

5.1 Microgrids

A microgrid is a localised energy system that can generate, distribute and manage electricity within a small geographic area. It typically includes distributed energy resources like solar panels, wind turbines and battery storage, along with control systems to manage the energy flow. In the UK, there are several long-standing microgrids, such as the Channel Islands and Scottish Islands like Orkney [14], as well as mainland microgrid projects like Knoydart Renewables in Scotland and industrial complexes [15]. While they are connected to the national grid, for example through high-voltage DC links to the mainland, they provide capabilities to operate independently, if needed.

Microgrids can improve the resilience of electricity transmission systems in several ways:

- Islanding: By isolating themselves from the main grid, microgrids can continue to provide electricity to critical facilities like hospitals, emergency response centres, and water treatment plants, even when the main grid is down.
- Redundancy: Microgrids can switch to alternate energy sources without interruption.

This means that microgrids can limit the spatial extent of the impact of a severe space weather event that impacts the national grid infrastructure.

The concept of microgrids has been developed further in the USA, whose transmission network has particularly low resilience due to their dependency on a small number of long isolated powerlines. There are now 160 microgrids in the US, which are used to integrate distributed renewables into the electricity network as well as to limit the scale of blackouts caused by natural disasters [16].

5.2 GICs in Transmission Network Transformers

GIC's are quasi-direct current, meaning that the frequency of variation is much lower than the AC frequency used in electricity transmission. When GICs flow through a transformer, they can cause a phenomenon known as half-cycle saturation. Half-cycle saturation occurs when the transformer flux is offset by the quasi-DC nature of the GIC, forcing the transformer to operate in the nonlinear region of the saturation curve for half of every cycle [17].

This build-up of magnetic flux can cause an increase in the core loss, which is the power dissipated in the core due to hysteresis and eddy currents. This can lead to heating of the transformer, degradation of insulation, and shorten the lifespan of the transformer. It can cause the transformer to go into magnetic saturation, which occurs when the core reaches a magnetic flux density that is so high that it cannot accept any additional flux. When this happens, the transformer's output voltage can become distorted and additional frequency harmonics can be created in the output waveform.

Modern transformers have automatic protection systems that disconnect it from the power grid in response to a fault or abnormal condition. Such tripping procedures can be initiated by various protective relays that are designed to detect specific fault conditions.

GIC magnitude depends on latitude, transformer type, age, grid topology effects, and resistivity of the underlying geology. Additionally, regions on or near geological boundaries between rock types of different resistivities are more susceptible to higher GICs. The same is true for coastal parts of the grid, where the boundary is between the land and sea.

While there are strategic spares for some transformers, a culture of sharing across transmission operators during times of crisis, and a "spares club" for shared components, these measures remain insufficient to rapidly replace damaged transformers. One reason cited in stakeholder interviews for the lack of sufficient spares to rule out the possibility of long-term blackouts is the lack of financial coordination between network operators, asset owners, and associated stakeholders, with each not wanting to bear the whole cost. While unlikely, long-term power cuts in the UK still cannot be ruled out during a 1-in-100-year geomagnetic storm.

5.3 GICs in Distribution Networks

Scientific papers such as AbuHussain et al. 2018 "Impact of Geomagnetically Induced Current on Distributed Generators" recently ignited some concern over the vulnerability of distribution networks in the UK [18]. They modelled the impact on a distribution network of a 100A GIC induced during an extreme geomagnetic storm, suggesting that the impacts could be enough to disrupt the electricity service to customers. However, such modelling results tend to be taken at face value by industry stakeholders who are not aware that the assumption of a 100A induced current in their distribution network is farfetched due to the shorter length and higher resistance of their power lines.

Distribution network GIC modelling should ideally be undertaken as academic-industry partnerships to ensure that the complexities of specific distribution networks are considered. Modelling assumptions must be made clear so that interpretation by industry stakeholders matches the applicability of the results.

5.4 Impacts on Nuclear Power Stations

The potential impacts of space weather on nuclear power stations are becoming an increasingly important consideration for this heavily regulated industry. Unlike other industries that tend to focus on more likely events, the nuclear industry focusses on extreme risks up to 1-in-10,000-year events, known as the design basis event, and, following the 2011 Fukushima Daiichi nuclear power station disaster, "beyond design basis events" are also considered, to avoid a "cliff edge" effect where risk dramatically increases beyond the threshold designed against. This takes statistical extrapolation of space weather events into extremely uncertain territory and pushes the limits on our knowledge of extreme space weather.

Under this regulation, nuclear power station operators are expected to build resilience into their systems to ensure they can withstand extreme events, rather than relying on external entities for protection. While space weather forecasting is being explored for making operators aware of possible causes of issues on plant in power stations, it is not something that can be relied upon for protection. Instead, built-in resilience and passive protection is strongly preferred.

Safety cases are developed to define the understanding of the hazard, vulnerabilities on plant, and mitigations to make the risk As Low as Reasonably Practicable (ALARP). Regulators strongly emphasize Relevant Good Practice (RGP) based on what has worked well in similar cases in the past. However, there is limited RGP available in the context of space weather, so much of the relevant research must be carried out internally or in collaboration with academic partners.

The main nuclear energy risks associated with space weather are GICs causing damage to onsite transformers or transformers in the national transmission system, and GLEs causing single-event effects in critical electronics. Based on stakeholder interviews in the UK nuclear industry, the GIC hazard, while generally better understood than GLE impacts, is perceived to have a bounded impact, where the worst possible event is one in which the plant experiences an extended loss-of-offsite-power (LOOP) event. On the other hand, GLEs can, in principle, cause direct malfunctions of important microelectronics with error rates increasing potentially without bound as the flux of incident neutrons increases in more and more extreme events. Furthermore, the SEE rates in common microelectronic components in unshielded systems at ground-level can potentially reach above 50% for an estimated 1-in-10,000-year GLE [19]. Shielding from structural concrete, redundancy in electronics systems, and error correction can reduce the risk, but resilience to such high severity events may require equipment testing at a neutron bombardment facility.

Small Modular Reactors (SMRs) are considered to be more resilient because they are more passive systems that do not rely as heavily on incoming electricity as traditional nuclear power plants. Space weather risk to SMRs is an unexplored area for the industry.

5.5 Impacts on Windfarms

No published research has been conducted into the space weather risk to renewable generation. Potential concerns were raised in consultations about GICs in the long subsea high-voltage cables connecting large offshore wind farms with the mainland transmission network which can be over 100km for some windfarms. This is a sufficient cable length for GICs of tens or potentially hundreds of Amps during extreme storms. However, such events are unlikely to cause any infrastructure impacts as the increase in voltage induced is negligible compared to the several hundreds of kV used for normal operation of high-voltage DC cables between the mainland substations and the windfarms.

5.6 Dependency on Earth Observation

Earth observation satellites used to assess coastal erosion and landslips, exposed pipes, trees on power lines. Such satellite services are vulnerable to major SEP events, but the impact on the energy of even a prolonged service disruption is expected to be very small as Earth observation services are not critical for safety.

6 Communications Sector

This section covers additional technical details from the consultations with communications sector organisations.

6.1 Mobile Communications

The UK has begun the phasing out of 2nd Generation (2G), GSM, and 3G (UMTS) by 2033 [20]. 4G (LTE) systems were introduced in 2012, and the use of high data rate permitting Orthogonal Frequency Division Multiple Access (OFDMA) schemes makes it versatile, with 4G making up 82% of all connections used to access the internet in 2023 in a mobile context [21]. Growth of the 4G network is expected to continue even further, as Ofcom, the frequency spectrum regulator, expects 95% of the UK landmass to have good outdoor 4G coverage by 2025 [22]. Almost all applications of terrestrial mobile communications utilise frequencies between 600MHz to 4GHz.

The most recent generation of mobile communications, 5G (LTE-A), like 4G also utilises OFDMA. 5G however utilises a broader array of frequencies ranging from 700MHz to 6GHz defined as 'sub-6 GHz' frequencies, with Ofcom releasing spectrum for 'mmWave' applications up to 100GHz [23]. The long range, lower data rate, lower frequency end of the spectrum, twinned with the low range, higher data rate, higher frequency end of the spectrum, means 5G can support a variety of applications, with a significant focus on the industrial implications of the technology, for example the facilitation of self-driving cars and commercial robotic applications.

6.1.1 4G

The 4G network is continuing to expand, with the expected total UK coverage to amount to 95% of the landmass by 2025. As with other generations, the technology associated with 4G is constantly upgraded. The addition of the Minimisation of Drive Testing (MDT), which automatically logs network performance indicators, such as downlink signal strength and signal quality [24]. This provides a significant amount of data and allows for performance changes in the network to be seen without manual testing, which could be utilised for correlational studies with SRB data to fill the existing gap in understanding about the degree to which base stations are vulnerable to space weather.

6.1.2 5G

Release 18, otherwise known as 5G advanced, is currently being developed for 5G systems. It features an increased focus on the industrial implications of the technology, capitalising on the low latency nature of the 5G architecture and improves upon the previous releases to facilitate self-driving cars and industrial automation [25], in addition to standard generational upgrades in data rate and availability. 5G is also expected to be used to facilitate cellular positioning, ranging from centimetre to metre positioning accuracies in indoor and outdoor environments respectively [26].

At the 'Why 6G?' conference in 2023, the first 6G conference in the UK, industry leaders stated that 5G was 'nowhere near being used to its full potential' and that we will see 5G technology begin to reach its full potential from release 18. The use of higher frequencies, and investigation into mmWave technology further increases the data rate and the breadth of applications this generation is applicable in. In terms of physical infrastructure 5G has highly directional beam-steering capabilities, effectively meaning the antenna acts as an array of beams and the beam is steered towards the user, or group of users. Additionally, 5G has provisions for massive multiple input multiple output (MIMO), improving the capacity, and making use of multipaths to provide a heightened level of connectivity.

6.1.3 6G

At the 'Why 6G?' conference, Ofcom stated that a major change for the generation will be dynamic spectrum allocation throughout the entire useable spectrum. Researchers at the University of Surrey suggested that the physical technology between 5G and 6G will remain largely the same, save for improvements to jitter, which would enable higher precision industrial applications.

There are two main differences between 5G and 6G, as stated by industry leaders. The first is the push for more energy efficient infrastructure, allowing the industry to more easily achieve the net-zero goal, and to ensure the network is sustainable and futureproof [27]. The second difference is the integration of space-based communications within the terrestrial core network, with the University of Surrey, in collaboration with OneWeb successfully connecting LEO communications satellites with the local campus 5G core network [28].

6.1.4 Cellular Connectivity during SRBs

In one of the few papers to explore the impacts of SRBs on cellular networks, Muratore et al. 2022 investigated the use of 4G Minimization of Drive Testing (MDT) technology to assess the impact, with respect to network capacity and the direction of the Sun compared to the cell tower and connecting devices [29]. They found that, even in mild SRB emissions, the base-station was unwilling to make connections with mobiles outside of the sun-facing antenna's main beam, however mobiles within the main beam were largely unaffected. The mobiles that were unable to make connections with the base-station then tried to connect with a different cell tower, meaning the base-station with the sun-facing antenna is operating under capacity, but other base-stations with non-sun-facing antennae are operating over usual capacity. This imbalance would be heightened in a more extreme SRB emission, in which even mobiles in the main beam would not be able to connect. These imbalances degrade service quality, and it has been speculated that the degradation due to imbalance could continue to affect the network even after the SRB has passed.

Despite this probability of impact based on correlational and theoretical studies, and some major SRBs occurring in the past few decades, no major impacts on mobile phone networks have been reported. It is possible that the effects are hard to discern among the many other variabilities in service quality on mobile networks, our ability to isolate SRB events has increased massively over the past decade.

That being said, the provision of massive MIMO in 4G LTE/5G and beam steering technology potentially presents a level of mitigation against SRBs. The use of multipaths may provide means of communicating with other non-sun-facing sectors on a base station with a sun facing antenna, while beam steering technology may be able to overpower the SRBs due to the highly directional nature of each beam and due to it serving only a few users in a small area.

6.2 Internet

6.2.1 Copper Cables

Coaxial copper cables can be affected by GICs, but only when the length of cable is in the order of several tens of kilometres.

One such event occurred in the Mid-Western USA during the major geomagnetic storm in 1972, causing the outage of a coaxial cable system [30]. The Canadian Meanook Magnetic Observatory observed a peak rate change of 2,200nT/min, with an estimated voltage rise of 7.4V/km within the system. This exceeded the threshold 6.5V/km that the system was rated for, resulting in a shutdown.

6.2.2 Network Upgrades

While fibre-optic communications represent 99% of all internet and telephone traffic, some connections that have not yet been upgraded to fibre, or do not require a fibre connection based upon required data rates, still utilise copper cables to connect with the core network.

Old copper-based devices are beginning to be phased out by manufacturers, with support for fibre being the only option. The expansion aims to have connected 25 million homes and businesses to 'UltraFast' fibre by December 2026, which promises to be up to ten times faster than current technologies, and be more robust, experiencing 70-80% fewer faults [31].

The 2020 COVID-19 pandemic required many people around the country to work from home, and to adopt a new hybrid-working scheme when returning to the workplace. This change in requirement has put an increased expectation upon domestic fibre connectivity.

6.2.3 Dependency on Electricity

Although fibre is the most energy efficient form of broadband, networks are still dependent on electrical power from the transmission network [32]. In the event of a GIC induced electricity blackout, networks rely on uninterruptible power supplies (UPS) across all the affected systems to provide holdover while the electricity blackout is rectified. The duration of the UPS holdover is dictated by the criticality of the operation the system supports. Given the potential for long power blackouts during severe geomagnetic storms, contingency for weeks without power to critical network infrastructure should be implemented.

6.2.4 Dependency on GNSS Timing

In addition to the direct risk to data centres from ionising radiation during GLES, data centres are vulnerable to disruptions to GNSS timing services [33]. Data centres primarily rely on GNSS timing services for many functions, depending on the use-case. This includes precise synchronisation of network devices, transaction timestamping, data logging and security protocols. Redundant timing sources like atomic clocks may be used to mitigate potential issues with GNSS accuracy. However, space weather can impact GNSS reliability. Ionospheric scintillation and blackout effects can cause intermittency of service, with periods of signal disruption for lasting for up to several hours. In the reasonable worst case of a 1-in-100-year event, GNSS satellites may be damaged during SEP events, potentially rendering their service lost for extended periods of weeks or months, depending on how quickly the satellite operators can bring satellites back online (e.g., through power cycling) or replacing satellites.

Motivated by this possibility, data centres should use a combination of GNSS and backup timing sources, like atomic clocks, to maintain operational continuity of CNI sector services.

6.3 Satellite Communications

6.3.1 Trends in Satellite Communications

Satellite communications (satcom) have been a significant driver of socio-economic development in recent years, with applications ranging from telecommunication, broadcasting, navigation, and remote sensing to name a few. According to the latest report by the Satellite Industry Association (SIA), the global satcom industry generated $118 billion in revenue in 2022, showing a steady growth trend [34]. Furthermore, the industry supports over 1.5 million jobs globally and contributes significantly to economic growth across the world.

The growth of the internet of things (IoT) and machine-to-machine (M2M) communication has increased the demand for reliable and ubiquitous connectivity. Satcom has become an integral part of this ecosystem, providing connectivity to devices in remote locations where other forms of communication are not feasible.

6.3.2 Preparedness Against Severe Space Weather

The 2017 paper "Impact of space weather on the satellite industry" by Green et al. identified, through interviews with many stakeholders across many applications and nations leading the industry, that while the space industry has made strides in mitigating the effects of space weather on satellites concerns remain about the industry's preparedness for a potentially more intense space weather environment [35]. Stakeholders in the satellite industry acknowledge that advancements in research, awareness, and mitigation strategies have helped to decrease the frequency and severity of anomalies caused by space weather. However, they also note that the current mild space weather conditions may be masking underlying issues that could persist as new technologies emerge, and the industry continues to expand. The authors emphasize the need for improved guidance for satellite operators, better tools, and training for manufacturers to interpret space weather data, and mechanisms for sharing anomaly occurrences to improve anomaly attribution, problem identification, and implementation of fixes. Addressing these issues now will ensure safe and reliable satellite operations in the future.

6.4 Broadcast and HF Communications Systems

6.4.1 Context

Digital television technologies currently operate within the lower end of the ultra-high frequency (UHF) band, which occupies the electromagnetic spectrum from 300MHz – 3GHz, Digital TV occupies the spectrum from 470MHz to 800MHz. Both FM and DAB Radio technologies operate within the very high frequency (VHF) band, which occupies the EM spectrum from 30MHz – 300MHz, with FM using 88MHz- 108MHz and DAB using 215MHz – 230MHz [36]. Between all of these technologies there are very few base stations, in the order of hundreds [37]. This is due to the higher power that the transmitters operate at, meaning fewer resources are required to provide services to the nation, as broadcasting is a one-way transmission system.

Radar has a multitude of uses, and thus utilises a broad range of frequencies to suit all applications, ranging from high frequency (HF) at 3MHz – 30MHz used for coastal radar systems, all the way to W-band at 75GHz – 110GHz used for automotive radar systems and high-resolution meteorological observation.

HF communications systems operate at frequencies in the 3MHz – 30MHz range. Transmissions within this frequency range have the capability of reaching long distances due reflection from certain layers of the ionosphere. This 'skywave' permits beyond line-of-sight communications. Signals above 30MHz penetrate the ionosphere and are not refracted whereas signals under 3MHz are absorbed or refracted by the lowest layer of the ionosphere, the D-layer. HF communications have a multitude of uses including military and governmental communications systems, aviation air-to-ground communications, amateur radio, shortwave international and regional broadcasting, maritime sea-to-shore and ship-to-ship services and over-the-horizon radar systems. In terms of critical national infrastructure, the most vital applications are the military, maritime, and aviation use of HF communications. In an aviation context, HF communications perform 'CNS ATM' – communication, navigation, surveillance, and air traffic management [38]. Disruption to any one of these services could result in significant repercussions.

6.4.2 Dependency on Power

Broadcast, radar and HF communications systems all rely upon electricity sources to operate. Unlike mobile cellular networks these systems may rely upon receiver power being available in addition to transmitter power.

In the event of a GIC induced power cut, operators rely on uninterruptible power supplies (UPS) across all of the effected systems to provide holdover while the electricity blackout is rectified. The level of UPS protection for these technologies depends on the application and is at the discretion of the service provider. Based on stakeholder interviews, the confidence in the UPS systems is high, but extended loss of power events beyond a week have been analysed.

6.4.3 Disaster Relief

Severe space weather events can have a significant impact on disaster relief efforts. These events can disrupt critical communication systems, complicate rescue missions, and hinder the ability to provide essential aid to affected communities.

An example of such disruption seen during hurricane response efforts in the Caribbean [39]. In September 2017, the Caribbean was hit by a series of powerful hurricanes, including Hurricanes Irma, Jose, and Maria. At the same time, the Sun was highly active, releasing multiple X-class solar flares on 6th, 7th, and 10th September, which caused disruptions in HF communications and created challenges for emergency managers in providing critical recovery services. The Hurricane Weather Net (HWN) and the French Civil Aviation Authority (DGAC) reported issues with HF communication, and ground operators experienced a blackout for nearly 3 hours, adding further difficulties to relief efforts. Additionally, the French Civil Aviation authorities reported that HF radio contact was lost with one aircraft for approximately 90 minutes, triggering an alert phase. In stakeholder interviews, the South African National Space Agency (SANSA) described similar issues with relief efforts in Africa during the moderate geomagnetic storms of early 2023.

7 Transport Sector

This section covers additional technical details from the consultations with transport sector organisations.

7.1 Road

7.1.1 Road-side Infrastructure Adoption

The first smart motorway was introduced on the M42 in 2006 in a trial to increase capacity. Since then, about 10% of the motorway network include them. However, in 2023 the scheme has been paused due to safety concerns. Smart motorways use cameras and vehicle detection equipment linked to a Motorway Incident Detection and Automated Signalling (MIDAS) system which analyses the data and provides lane and speed limit control, and incident warnings, to drivers via overhead gantries. The detection equipment includes verge mounted radar and inductive-loop traffic detectors in the road. In total, 30,000 road-side devices are connected to 7 regional control centres by the IP-based dual-fibre National Roads Telecommunications Service (NRTS) [40].

The National Highways Digital Roads 2025 initiative takes this a step further [41]. It will utilise data from sensors, technology, and connectivity to enable greater automation and network adaptability, not least to facilitate the introduction of connected and autonomous vehicles, and to introduce connected services providing information direct to vehicles and between vehicles (cooperative intelligent transport systems). Data will be stored on cloud servers and provided direct to motorists. AI will be used to forecast potential issues.

Longer term future technologies being looked at include under-road inductive charging coils for in-travel charging of vehicles.

7.1.2 In-Vehicle Technologies and Services Adoption

Whilst initially limited to anti-lock braking and then cruise control, the last decade has seen a proliferation of technologies designed to enhance the safety of driver and passengers. These include driver monitoring, forward collision warning and avoidance, intelligent speed adaptation, lane departure warning, adaptive cruise control, emergency call (eCall) systems and head-up displays. These use a range of sensors including LIDAR, radar, cameras, image processing and GNSS. AI is starting to be considered so systems can learn car and driver behaviours and identify anomalies. Systems are increasingly networked via a car management system.

European regulation has mandated the use of eCall in new cars and vans since 2018 [42]. This automatically connects a driver with an emergency response centre in the advent of a serious crash and sends data such as location (from GNSS), car model, direction of travel, fuel type etc. to the responder as the driver might be unconscious or not know where they are. The UK has adopted this.

The use of Smart Tachographs has been mandated by European regulation since 2019. The UK has adopted this. They use GNSS positioning and short-range communications for road enforcers and telematic applications.

7.2 Rail

7.2.1 GICs in Electric Rail Infrastructure

The rail network has long lengths of electrically uninterrupted track, overhead electrification, and trackside wiring. Overhead Line Equipment (OLE) carries 25 kV AC, and the third rail carries 750V DC. Both low voltage AC lines (due to their higher resistance) and DC lines are not likely to be directly affected by GICs.

7.2.2 Dependency on Electricity

It was reported during rail industry engagements that some of the new trains are "precious about voltage" and the train management system will switch off to protect from out of specification voltages. an interview with a major rail sector stakeholder described a lightning strike that disabled several substations, briefly unbalancing the load on the grid. The frequency dip caused trains to stop and certain Govia Thameslink trains shut down and became stranded due to the configuration of their on-board automatic safety systems [43].

If this happens, then the train will stop and will need to be re-started. It will then be possible to move it (assuming the over-voltage condition has ceased), but only with the signaler's permission (as the train won't know where it is), and the procedure says to do so without passengers, although in an emergency situation, the driver can make expeditious decisions. Note that as the power will still be on, a lot of effort may be needed in isolating power to the various stretches of track should the delay be considered long enough that passengers might decide to get off the trains.

Some trains cannot be re-started by the driver and require an engineer to be present. Should multiple trains come to a halt, then this might be a lengthy procedure.

Localised power failures are not new to the rail sector. The 2018 power cable cut at York station and a frequency "wobble" in 2019 which caused all Thameslink trains to stop have given operators experience in quickly identifying clever workarounds, often using current technology such as social media to communicate with passengers.

7.3 Maritime

7.3.1 Use of Space-Based Services

The International Maritime Organization (IMO) introduced an e-Navigation Strategy Implementation Plan in 2014, updated in 2018, setting out tasks to address the five e-navigation solutions it felt were required [44]. In July 2022, the UK Hydrographic Office announced it was looking at ways to move away from paper charts to digital solutions by end 2026 [45].

7.3.1.1 GNSS Use on Vessels

As well as for navigation, GNSS signals are used elsewhere on vessels, to provide timing to all ships clocks, for satellite broadband and entertainment systems, and for stabilising helidecks on some vessels. GNSS is one of the key sources of information for the Automatic Identification System (AIS) transponders mandatory since 2004 on the larger cargo vessels. Fully autonomous vessels are in the planning stage. The world's first electric autonomous cargo ship, the Yara Birkeland, was launched in Norway in Nov 2021. Rolls Royce are heavily involved in this initiative.

7.3.1.2 GNSS Use in Port Infrastructure

Most ports have a dependence on GNSS although 5G positioning and hybrid 5G / GNSS are being introduced. Some ports are looking at installing their own 5G network to facilitate this.

The gantry cranes which load, and unload containers are increasingly automated and work on GNSS. Autonomy in warehouses is being explored. The goal of the industry, solicited from stakeholder interviews is, cars that drive themselves to the port from the production line and load themselves onto freight carriers.

7.3.1.3 Satellite Communications

Use of satcoms has increased since 2013 as vessels become increasingly digitised and many larger freight vessels have multiple communications devices which can include C-band and/or Ku-band satcoms, Inmarsat voice and IP satcoms, Iridium Openport (often as an emergency line from the engine room in case of pirates), and the automated global maritime distress and safety system (GMDSS). Ships must monitor a specific frequency for specific alerts to them from vessel traffic systems. These are typically VHF frequencies. Currently, communications in port remains low tech VHF and voice transmissions.

Use of Starlink LEO satellites is being explored. Starlink uses Ku and Ka band and so is likely to be unaffected by scintillation although the satellites themselves might suffer electronic failures which might disrupt the communications' electronics. Communication from a vessel to an engineer on a wind turbine is often by Tetra radio which operates at UHF frequencies and is therefore susceptible to solar radio bursts near sunrise or sunset.

7.3.1.4 Aids to Navigation (AtoNs)

In 2019, the GLA published an 'Aids to Navigation Review 2020 to 2025' which states that "Across all classes, there is an overwhelming reliance on GPS with its inherent vulnerabilities to man-made interference and space weather. The GLA have concerns that lessons have not been learned from over reliance on electronic navigation." [46]

The impact on AtoNs of the loss of GNSS is negligible, even if they all report being off station. They will still function and anomalies in large numbers of them will be noticed. Sequencing of some buoys might suffer but this will not impact safety as they have sufficient holdover from internal clocks. The only impact is if a buoy becomes detached concurrently with a severe space weather event, and it is relied on by a vessel in adverse conditions. Radio Navigation Warnings are published stating where GPS is not operating (e.g., jamming, or spoofing exercise), which AtoNs are malfunctioning, and where AIS might be inoperative [47].

Virtual AtoNs rely on AIS and AIS tracks have been noticed to fail during G3 and G4 geomagnetic storms. AIS operates on two VHF frequencies - 161.975MHz and 162.025MHz. AIS signals sent via VHF links to satellites (i.e., to shore stations when out of line-of-sight range to shore) are vulnerable to ionospheric scintillation. During a severe event it's likely that shore stations will lose track of positions of many ships in North Atlantic and up into the Arctic.

7.3.1.5 HM Coastguard Rescue Centres

HM Coastguard operates a single network of UK maritime operations centres with an integrated maritime radio infrastructure. It comprises 10 Maritime Rescue Coordination Centres (MRCC) and Sub-Centres (MRSC) around the UK's coastline plus a Joint RCC / Mission Control Centre at Southampton. As most emergencies will be at sea, the emphasis is on coordinating with local search and rescue, passing vessels and foreign coastguards. As such, communications are essential, and away from coastlines, Inmarsat services, VHF and satcoms are relied upon, both for receiving distress calls and for coordinating with vessels and other agencies.

7.3.1.6 Coordination Centres

The Maritime Rescue Coordination Centres and Sub Centres rely heavily on communications to receive distress calls and to coordinate a response, and GNSS to determine locations of vessels in distress and those responding. Coordinating is via VHF and satcoms, both of which are vulnerable to severe space weather, although together provide a more robust system due to the different vulnerabilities of each.

Offshore construction vessels are tracked from mainland operations centres by AIS which as it uses GNSS, is susceptible to severe space weather. Whilst vessels can stop operations during a space weather event, should it be accompanied by un-forecast loss of VHF and satcoms, then any personnel on wind turbines would be more at risk. Under such circumstances, a vessel's captain would use manual navigation to extract personnel. In adverse weather conditions such as fog, everyone would have to hunker down and wait. This would not be a problem unless it coincided with an emergency health situation such as an engineer having an accident.

When constructing offshore wind farms, a process which can take 2+ years, two forms of temporary communications channels to the mainland are required for safety purposes before more permanent fibre can be collocated with the export power cables (long runs underwater require a repeater). This usually comprises VHF and VSAT[1] terminals unless a nearby site can be linked to by 4G LTE. VSAT terminals are most often designed to operate in the 6/4GHz[2], 14/11-12GHz, and 30/20GHz (Ka) frequency bands and hence are unlikely to be susceptible to scintillation effects but might suffer radio blackouts if the antenna is pointing at the sun during an event [48]. In the UK, for safety reasons, work is stopped if communication is lost.

7.3.1.7 Drones

Air and water drones are being investigated for security and maintenance patrols, possibly initially by remote control by later autonomously. Autonomous operation would likely use GNSS.

The use of air and water drones using GNSS to navigate raises the question of what happens to them, especially aerial drones, should GNSS be lost or a threshold event cause incorrect position data to be used. Even if they try and land slowly, they might still injure somebody. Similarly with autonomous land vehicles, a feared event is them crashing into somebody should GNSS be lost, or worse giving out false signals due to space weather.

7.3.2 Radar

The most common maritime radars are S-band (3 GHz) and X-band (10 GHz) although there are also high-frequency high-resolution radar using K-Band (24 GHz) and E-band (76 GHz). The technology of radars has advanced since 2013 with solid-state and high-speed rotation radars offering improved resolution.

Many larger ports have vessel traffic systems (VTS) which track ships in their area by radar, provide alerts to specific vessels, and provide pilotage, surveying, and dredging services. Maritime radar operates in the 3, 5 and 9 GHZ bands.

Maritime radar operates in the 3, 5 and 9GHz frequency bands. These radar systems are not vulnerable to ionospheric effects like scintillation or radio blackout because they are line-of-sight systems. However, should the radar antenna be pointed towards the sun, which might happen at sunrise or sunset, then they might suffer noise from solar radio bursts. This will show up on the radar screen. it has in the past been misconstrued as intentional jamming [49]. A ship's ultimate mitigation is to drop anchor until the problem resolves, although this would only be necessary in coastal waters and when radar was needed. In mid-ocean, the ship would just continue its heading.

7.3.3 Magnetic Compass

Geomagnetic storms can cause deviations in magnetic compasses. These are more pronounced at more northerly latitudes and during severe storms. During the Halloween storms of 2003, deviations of up to 7° were observed in Lerwick, Scotland [50]. Magnetic compass navigation is now only ever a complementary technology, used as part of a system-of-systems to provide diversity and redundancy in navigation.

7.3.4 INS and Quantum INS

Inertial navigation systems (INS) rely on accelerometers and gyroscopes to measure changes in position, velocity, and orientation. They do not use GNSS and as such, any space weather influence would only be due to single event effects from ionising radiation reaching ground level. This potential impact on terrestrial electronics needs more research. It is seen extensively in satellites but the impact of a 1-in-100-year ground level enhancement event on modern terrestrial

[1] *A very small aperture terminals (VSAT) is a small-sized earth station used to transmit/receive data, voice, and video signals over a satellite communication network.*

[2] *6/4 GHz means the uplink is 6GHz and the downlink is 4GHz. The separation minimises interference.*

equipment is relatively unknown. Variations in the Earth's magnetic field during geomagnetic storms could affect magnetometers at higher latitudes as they are sometimes used to aid INS systems. Quantum INS uses cold-atom interferometry and might be similarly impacted.

7.3.5 Dockside Power

Docks rely on power from national electricity transmission. In addition, cruise ships, for example, require a lot of power and remain connected to the electricity grid supply when in docks. GICs could cause regional power outages which would thus affect such services, leading to commercial impacts if back-up generators are not available.

7.4 Aviation

7.4.1 Solar Radio Burst Effects on Radio Systems

In November 2015, southern Sweden airspace was closed for two hours for both incoming and outgoing air traffic as many radar systems experienced noise [51]. This was caused by a solar radio burst of around 50,000sfu at GHz frequencies and made radar systems interpret increased radio noise as many additional aircraft, making it unable to identify actual aircraft.

7.4.2 Dependency on GNSS

There is some uncertainty over the severity of space weather event to cause disruptions to GNSS service for aviation. The two main examples of GNSS service disruption are:

- The ~2-days of disruption to the US Wide Area Augmentation System (WAAS) in October 2003 caused by ionospheric scintillation during the Halloween geomagnetic storm. Errors exceeded limits and WAAS was unusable for precision approaches.
- The ~30-minute disruption of GNSS globally during the December 2006 solar radio burst – the largest in recorded history.

Both these events were towards the extreme end of what has been observed in the modern era. More moderate storm conditions were explored by Hospodka and Matějovie 2022, who analysed European ADS-B signals during the September 2017 geomagnetic storm [52]. The found no correlation between the space weather event and ADS-B signals, suggesting that more extreme conditions are required to be disruptive to this service.

7.4.3 Qantas Flight 72

The major example of a likely impact from single-event effects in aviation is the Qantas Flight 72 incident that occurred on October 7, 2008. An Airbus A330-300 aircraft experienced sudden and uncommanded movements during a flight from Singapore to Perth. The incident was caused by a malfunction in the aircraft's Air Data Inertial Reference System (ADIRS) which triggered unexpected and aggressive nose-down pitches, causing everything and everyone not strapped down to be accelerated to the aircraft ceiling. Over a hundred passengers and crew were injured with many needing immediate hospital treatment. An investigation ruled out causes related to hardware and software failures, leaving single event effects in an integrated circuit within the CPU module as the potential cause [53].

This event must be understood in the context of these aircraft types having flown collectively over 40 million flight hours and the consideration of SEE during the design process was consistent with industry practice at the time the inertial reference unit was developed.

7.4.4 Radiation testing

The CAA advises that where necessary, flight operators should clarify with original equipment manufacturers what are the specifications for the operating limitations to which approved equipment has been manufactured in relation to protection against cosmic radiation, for example protection of electronic systems, particularly flight-critical and flight-essential systems, against potential electromagnetic interference, and flight operators should consider how crew would determine when cosmic radiation operating limitations have been exceeded in flight noting that the most reliable approach for measuring on-board radiation is to employ on-board (aircraft) sensors as, whilst space weather forecasting and alerting skills are continuously improving, current scientific modelling and monitoring capability does not yet allow sufficiently reliable forecasts or real-time alerts for ionising radiation events at aviation altitudes and the limited ability to accurately predict the time, duration, and intensity of events precludes effective operational mitigation based on space weather forecasts and alerts.

However, there is large uncertainty in the industry over how vulnerable avionics systems are to single event effects caused by cosmic radiation and as mentioned the CAA advises flight operators to clarify with original equipment manufacturers what are the specifications for the operating limitations to which approved equipment has been manufactured in relation to protection against cosmic radiation. A potential difficulty for manufacturers in providing this information is establishing causality to radiation effects when there are usually other possible factors like hardware and software faults that need to be ruled out. One approach is to correlate so called "no fault found" errors, i.e., errors for which no human or mechanical fault was found, with solar radiation levels. Currently, while these errors are recorded by many airlines, there is no centralised repository to pool data across the industry, no standardised way to record these failures, and a reticence to share these potentially commercially sensitive data. Overcoming such issues would support industry's progress in understanding the SEE risk to avionics systems. Academic stakeholders have indicated that they would be very interested to analyse such data with industry groups should it become available.

7.4.5 SEE Mitigation

Industry working groups have been discussing the mitigation of the currently understood characterisation of solar energetic particles that can cause SEEs, and the level of protection that needs to be afforded at component, equipment and system level. When mitigation is generated by providing component protection, the protection afforded for the average SEE rate, provides a degree of protection against higher peak levels. As it is currently not possible to state that full protection against all solar energetic particles can be assured, because of the low frequency of events and insufficient data being available to accurately model such an event, a pragmatic approach to the overall threat is taken. This is commensurate with the approach taken for other types of protection against environmental effects such as high intensity radiated fields (HIRF) and lightning, which have been shown to be robust to the resultant environment despite not demonstrating full protection against the highest peak threats.

Mitigation techniques to improve the resilience to SEEs include redundancy and dissimilarity, error detection and correction, and shielding. Redundancy and dissimilarity are common practices for modern avionics system design, for example, having several flight control computers of different kinds where outputs from one can verified by the others. Shielding is not taken into account due to the size and weight restrictions in aviation. It is important that when estimating failure rates, whatever materials of the aircraft body are containing critical electronics should be accounted for as they may provide an attenuation and/or moderating effect on incoming particles. Moderating effects can be particularly problematic as fast neutrons can be slowed down into the thermal range, which can, for some devices, increase the SEE rate.

8 Cross-Sectoral Impact Case Studies

While sector-specific impact assessments are crucial to understand, these impacts will not happen in a vacuum. Near-simultaneous impacts to multiple sectors, services, and infrastructure could amplify the impact of a major space weather event across society. To provide an illustration of these intertwining mechanisms, we present two case studies illustrating potential impacts on rural SMEs and emergency services in the following sections.

8.1 Impact Case Study 1 – Rural SME

8.1.1 Rationale

In 2020/21, there were 549,000 businesses registered in rural areas in England, accounting for 23% of all businesses registered across England. These businesses employ 3.6 million people, representing 13% of total employment. Excluding London, predominantly rural areas have more registered businesses per head of population than predominantly urban areas [54]. SMEs, often located in less urbanised areas, heavily rely on modern technology for their operations, including space-based systems for communication, global positioning, and broadband connection. The shift to remote work, especially during the COVID-19 pandemic, has further increased this dependency.

Considering the 14.6% of SMEs in rural areas operating in 'Agriculture, forestry and fishing', a space weather event could disrupt their production, product conservation, transportation, and daily administration. This highlights the need for robust contingency plans to mitigate potential disruptions and helps us visualise a potential scenario of practical impacts.

8.1.2 Scenario

In the context of a farmer running an agricultural SME in a rural area, their business might initially seem unaffected by a space weather event as outlined in the Severe Space Weather Scenario described in the main report. However, after a week, disruptions in connectivity and PNT services could occur due to space weather effects on satellites and affect their business substantially.

Their farming practices heavily rely on GNSS applications, particularly related to precision farming and variable rate application (VRA), contributing to increased yields and cost reduction. The GNSS devices they use for their agricultural activities are often more expensive than those used in other sectors, and typically rely on multiple constellations. Therefore, a potential disruption or intermittent signal could lead to less efficient cultivation practices and planning procedures. Even though a week-long disruption in GNSS services could (it has been estimated) potentially result in a loss of £224 million for the agricultural sector, the impacts of a space weather event would likely be much shorter and intermittent, leading to less substantial losses.

From a productivity perspective, an additional loss could be caused by disruptions in internet connectivity. The loss of internet connection could affect their usual administrative practices and delivery schedules. In addition, increased future reliance on satellite-enabled connectivity (e.g. Starlink) may lead to increased impacts in future for remote businesses such as theirs, especially given the limited availability of alternative connectivity sources.

Around the same timeframe, a week after a severe space weather event, regional blackouts may impact food conservation technologies, particularly in summer months, leading to potential economic losses from spoilage. Moreover, the escalating global temperatures are likely to exacerbate the risk of food spoilage during power outages. Similarly, damage to equipment related to transformer damage could create additional costs for companies like theirs. These impacts might result in property damages and lost output, potentially leading to a range of secondary and tertiary effects, including repercussions on insurance policies, medium- and long-term losses due to reduced efficiency in agricultural production, and reputational impacts of delayed or forgone deliveries.

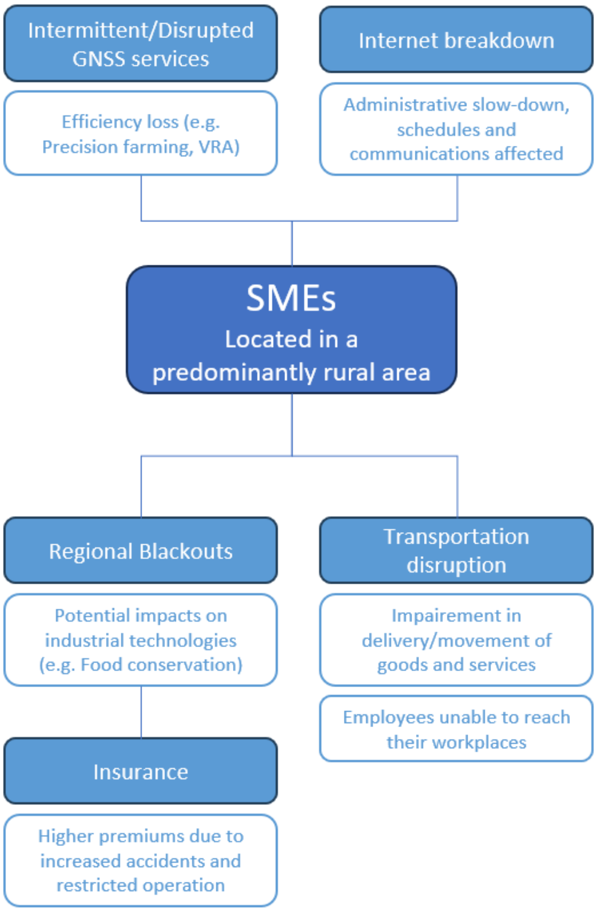

Figure 1: Visual overview of socio-economic impacts for Case Study 1.

8.2 Impact Case Study 2 – Emergency Services

8.2.1 Rationale

A space weather event impacting PNT services and causing blackouts could significantly hinder the ability of UK's emergency units (including the Police Service, Fire Service and Emergency Medical Services) to locate calls and respond promptly to emergencies. As per the Association of Ambulance Chief Executives (AACE), between April and December 2022 the volume of 999-calls answered ranged from approximately 800 thousand to 1 million per month, with the mean call answer time fluctuating between around 20 and 88 seconds, before dropping sharply to 17 seconds in January 2023 [55]. This data underscores the substantial volume and critical nature of these prioritised calls, where even minor disruptions can have significant consequences.

The impact of space weather events on this sector is also influenced by temperature, hence climate change and specific climate conditions are crucial factors. For instance, the UK sees around 2,000 deaths annually due to heatwaves [56], and approximately 3,000 excess deaths each year resulting from inadequate home heating during winter months [57]. These figures could rise if severe space weather events coincide with extreme climate and temperature conditions. Considering the broad societal implications, emergency services serve as a good example to illustrate the effects of space weather on both public services and the wider population.

8.2.2 Scenario

From the viewpoint of a middle-aged person, the immediate effects of a severe space weather event might not be apparent. However, within about a week, potential regional blackouts could lead to rapid food spoilage, thereby increasing the risk of food poisoning. This could happen unnoticed, particularly if occurring at night. Blackouts could also result in the unavailability of heating and cooling systems in homes, posing a health risk, especially for the elderly. The potential inability to charge phones and intermittent internet services could lead to further difficulties in communicating with emergency services, family, and friends. All these factors could become intrinsically more problematic during winter and summer months due to more extreme temperatures, leading to an increased volume of calls to emergency lines.

On the receiver end, emergency calls receivers might experience several difficulties in responding to requests, especially due to road congestion, potential blackouts and, most importantly, intermittent PNT disruptions. Around a week after the beginning of the severe space weather, an emergency call receiver could face difficulties in locating callers while experiencing an increase in the volume of calls, leading to increased response times. Given that internal communication systems are enabled through GNSS time synchronisation functionalities, a loss of efficiency could be experienced by receivers. The GNSS-based navigation systems for emergency service fleets might not function or be intermittent, resulting in inefficiencies that could necessitate additional staff to cover the deficit [58].

While it is unlikely that disruptions would cause social unrest, road congestion could impair the rapid movement of emergency vehicles. Emergency service vehicle drivers might encounter an increased number of vehicles than normal, especially given potential malfunctioning of rail services causing people to switch to alternative forms of transportation.

A middle-aged person in need of support might therefore encounter difficulties in contacting emergency services, and later in being located or reaching support (e.g., hospitals) through public and private transportation means. Public communications to the wider population might not reach everyone, due to intermittency in internet services experienced in coincidence with GNSS disruptions.

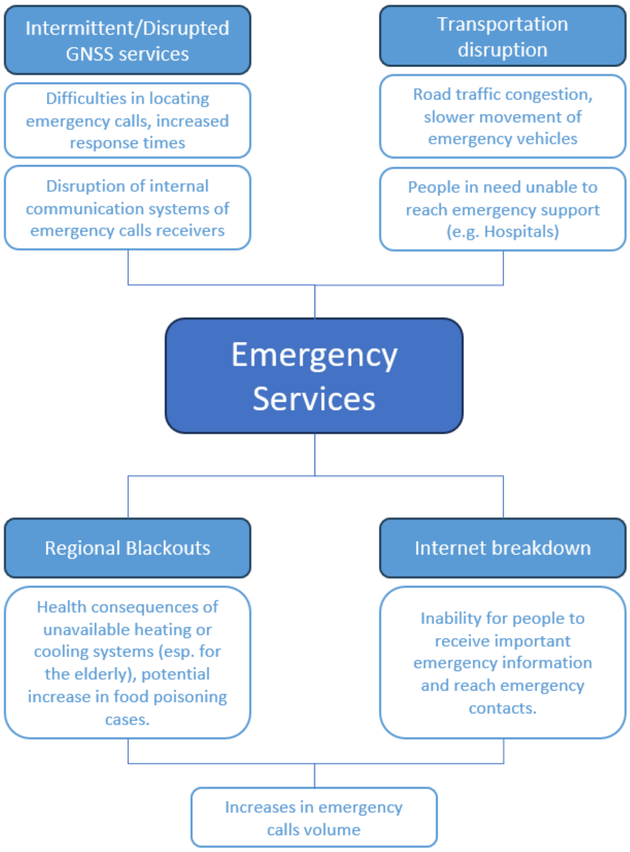

Figure 2: Visual overview of socio-economic impacts of Case Study 2.

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10 Appendix

This section contains a list of organisations related to UK CNI who were interviewed for this project.

Organisation	Relevant CNI sector(s)
Abbott Risk Consulting (ARC)	All
Airbus (Aircraft)	Transport (Aviation)
Airbus (Space)	Space
All.space	Space
Astroscale	Space
Atrium Space Insurance Consortium	Space
British Association of Public-Safety Communications Officials	All
Business, Energy and Industrial Strategy (BEIS), Department of. - Energy	Energy
BEIS - Space	Space, Emerging Technologies
British Geological Survey (BGS)	Energy
BP Shipping	Energy, Transport (Maritime)
British Airways (BA)	Transport (Aviation)
CAA (Air)	Transport (Aviation)
CAA (Space)	Space
Catapult - Connected Places	Transport
Catapult - Energy Systems	Energy
Centre for Connected & Autonomous Vehicles (CCAV)	Transport (Road)
Communications Resilience Group (via DCMS)	Communications
Centre for the Protection of National Infrastructure (CPNI)	All
CPNI - Space Security Information Exchange	Space
CPNI – Network Security Information Exchange	Communications
Czech Technical University, Faculty of Transportation Sciences	Transport (Aviation), Space
Deakin University	Emerging Technologies
Department for Digital, Culture, Media and Sport (DCMS)	Communications
Department for Energy Security and Net Zero (DESNZ)	Energy, Emerging Technologies
Department for Transport (DfT)	Transport
EDF Energy	Energy
Electricity Task Group (ETG)	Energy, Communications
Electricity North West Limited	Energy
European Marine Energy Centre (EMEC)	Energy
Energy Networks Association	Energy
European Space Agency (ESA)	Space
EUMETSAT	Space
Fraser Nash	Space, Transport, Emerging Technologies
Greater Lighthouse Authority (GLA)	Transport (Maritime)
GravitiLab	Space
Health Security Agency	Transport (Aviation), Space
High Speed 2	Transport (Rail)
HM Treasury	All
Imperial College London	All
INCOSE (Int'l Council on Systems Engineering)	All
Inmarsat	Space
Jet2	Transport (Aviation)
Lancaster, University of	Transport (Rail), Energy
LNER	Transport (Rail)
Maritime & Coastguard Agency (MCA)	Transport (Maritime)
Ministry of Justice	All
Mission.space	Space
National Grid ESO	Energy
National Grid Electricity Transmission	Energy
National Grid Telecoms	Energy, Communications
National Highways	Transport (Road)
National Air Traffic Services (NATS)	Transport (Aviation)
National Cyber Security Centre (NCSC) - Aviation Cyber Security Forum	Transport (Aviation)
NCSC - Civil Aviation Information Exchange	Transport (Aviation)
NCSC - Network Security Information Exchange	Communications
NCSC - Energy Systems Information Exchange	Energy
NCSC - Private Sector / Maritime Information Exchange	Transport (Maritime)
NCSC - Smart Systems & Autonomous Vehicles	Transport (Road)
NCSC - Space & PNT	Space

National Physical Laboratory (NPL)	All
National Quantum Computing Centre	Emerging Technologies
Network Rail	Transport (Rail)
Network Rail - Telecom Private Networks	Transport (Rail), Communications
National Oceanic and Atmospheric Administration	All
Nominet	Communications
Northern Gas Networks	Energy
Northumbria University	Emerging Technologies
Natural Resources Canada (NRCan)	Energy, Transport (Rail)
Office of Communications (OFCOM)	Communications
Office for Nuclear Regulation (ONR)	Energy
Orsted	Energy, Transport (Maritime)
Otago, University of	Energy
Port of Tyne	Transport (Maritime)
QinetiQ	Transport (Aviation), Space
Quantum Communications Hub	Communications, Emerging Technologies
Rail Delivery Group	Transport (Rail)
Rail Partners	Transport (Rail)
Rail Safety & Standards Board (RSSB)	Transport (Rail)
RAL Space, Quantum communications	Space, Communications, Emerging Technologies
RAL Space, STFC Rutherford Appleton Laboratory	All
RethinkPNT	All
Rolls-Royce Controls and Data Services Ltd	Space, Transport (Aviation)
Royal Institute of Navigation	All
Seajacks	Energy, Transport (Maritime)

SES Systems	Space
Space Environment Impacts Expert Group (SEIEG)	All
Sky Mobile	Communications
Society of Motor Manufacturers & Traders (SMMT)	Transport (Road)
Solarmetrics	Transport (Aviation)
South Africa National Space Agency (SANSA)	All
SP Energy Networks	Energy
Space Solar	Energy, Emerging Technologies
Spirent Communications	Transport, Communications
SSE	Energy
Subsea 7	Energy, Transport (Maritime)
Sure	Communications
Surrey Space Centre	Space
Surrey Satellite Technology Ltd.	Space
Sygensys	Energy
Thales Alenia Space	Space
Tracsis	Transport (Rail)
Transport for London (TfL)	Transport
UK Atomic Energy Authority (UKAEA)	Energy
UK Chamber of Shipping	Transport (Maritime)
UK Power Networks	Energy
UK Met Office	All
UK Space Agency	Space
US Cybersecurity & infrastructure Security Agency	Communications
Varamis	Transport (Rail)
Wayve Technologies	Transport (Road)
Welsh Government	All
Zentralanstalt für Meteorologie und Geodynamik (ZAMG)	Energy

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