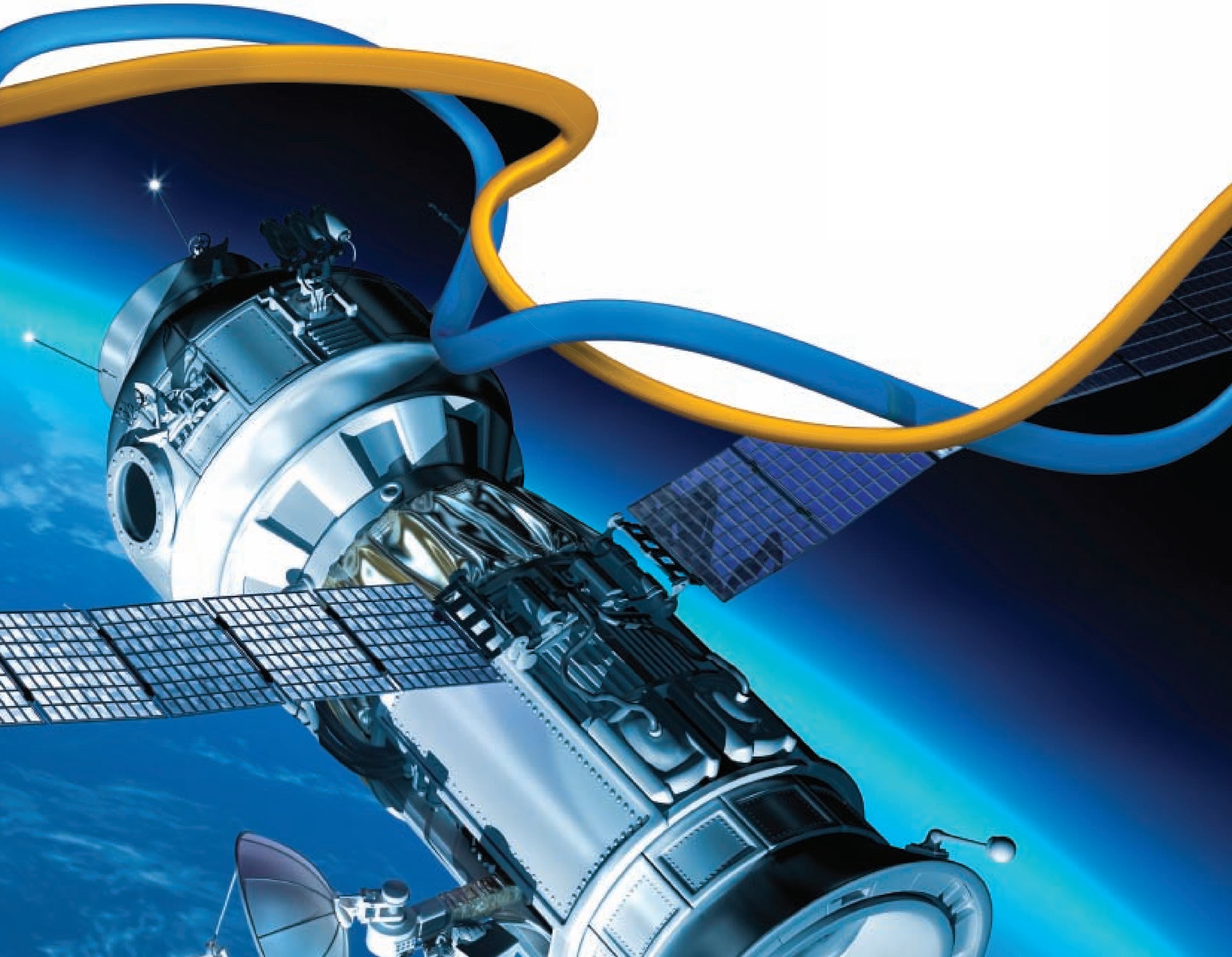
ROYAL ACADEMY OF ENGINEERING

Extreme space weather: impacts on engineered systems and infrastructure

Summary report



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This report is available online at **www.raeng.org.uk/spaceweathersummary**

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Foreword

An extreme space weather event, or solar superstorm, is one of a number of potentially high impact, but low probability natural hazards. In response to a growing awareness in government, extreme space weather now features as an element of the UK National Risk Assessment.

In identifying this hazard, the UK government benefited from the country's world class scientific expertise and from a number of earlier studies conducted in the US. However, the consequential impact on the UK's engineering infrastructure - which includes the electricity grid, satellite technology and air passenger safety – has not previously been critically assessed. This report addresses that omission by bringing together a number of engineering and scientific experts to identify and analyse those impacts. I believe that this study, with its strong engineering focus, is the most extensive of its type to date.

It is my hope that by acting on the recommendations in this report, stakeholders will progressively mitigate the impact of the inevitable solar superstorm.

Professor Paul Cannon FREng
Chair of the study working group

1. Executive summary

Rarely occurring solar superstorms generate X-rays and solar radio bursts, accelerate solar particles to relativistic velocities and cause major perturbations to the solar wind. These environmental changes can cause detrimental effects to the electricity grid, satellites, avionics, air passengers, signals from satellite navigation systems, mobile telephones and more. They have consequently been identified as a risk to the world economy and society. The purpose of this report is to assess their impact on a variety of engineered systems and to identify ways to prepare for these low-probability but randomly occurring events. The report has an emphasis on the UK, but many of the conclusions also apply to other countries.

Explosive eruptions of energy from the Sun that cause minor solar storms on Earth are relatively common events. In contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two. Most superstorms miss the Earth, travelling harmlessly into space. Of those that do travel towards the Earth, only half interact with the Earth's environment and cause damage.

Since the start of the space age, there has been no true solar superstorm and consequently our understanding is limited. There have, however, been a number of near misses and these have caused major technological damage, for example the 1989 collapse of part of the Canadian electricity grid. A superstorm which occurred in 1859, now referred to as the 'Carrington event' is the largest for which we have measurements; and even in this case the measurements are limited to perturbations of the geomagnetic field. An event in 1956 is the highest recorded for atmospheric radiation with August 1972, October 1989 and October 2003 the highest recorded radiation events measured on spacecraft.

How often superstorms occur and whether the above are representative of the long term risk is not known and is the subject of important current research. The general consensus is that a solar superstorm is inevitable, a matter not of 'if' but 'when?'. One contemporary view is that a Carrington-level event will occur within a period of 250 years with a confidence of ~95% and within a period of 50 years with a confidence of ~50%, but these figures should be interpreted with considerable care.

Mitigation of solar superstorms necessitates a number of technology-specific approaches which boil down to engineering out as much risk as is reasonably possible, and then adopting operational strategies to deal with the residual risk. In order to achieve the latter, space and terrestrial sensors are required to monitor the storm progress from its early stages as enhanced activity on the Sun through to its impact on Earth. Forecasting a solar storm is a challenge and contemporary techniques are unlikely to deliver actionable advice, but there are growing efforts to improve those techniques and test them against appropriate metrics. Irrespective of forecasting ability, space and terrestrial sensors of the Sun and the near space environment provide critical space situational awareness, an ability to undertake post-event analysis, and the infrastructure to improve our understanding of this environment.

The report explores a number of technologies and we find that the UK is indeed vulnerable to a solar superstorm, but we also find that a number of industries have already mitigated the impact of such events. In a 'perfect storm' a number of technologies will be simultaneously affected which will substantially exacerbate the risk. Mitigating and maintaining an awareness of the individual and linked risks over the long term is a challenge for government, for asset owners and for managers.

Key points:

Solar superstorm environment

The recurrence statistics of an event with similar magnitude and impact to a Carrington event are poor, but improving. Various studies indicate that a recurrence period of 1-in-100 to 200 years is reasonable and this report makes assessments of the engineering impact based on an event of this magnitude and return time. If further studies provide demonstrable proof that larger events do occur – perhaps on longer timescales - then a radical reassessment of the engineering impact will be needed. The headline figure of 100 years should not be a reason to ignore such risks.

Electricity grid

The reasonable worst case scenario would have a significant impact on the national electricity grid. Modelling indicates around six super grid transformers in England and Wales and a further seven grid transformers in Scotland could be damaged through geomagnetic disturbances and taken out of service. The time to repair would be between weeks and months. In addition, current estimates indicate a potential for some local electricity interruptions of a few hours. Because most nodes have more than one transformer available, not all these failures would lead to a disconnection event. However, National Grid's analysis is that around two nodes in Great Britain could experience disconnection.

THE REPORT EXPLORES A NUMBER OF TECHNOLOGIES AND WE FIND THAT THE UK IS INDEED VULNERABLE TO A SOLAR SUPERSTORM, BUT WE ALSO FIND THAT A NUMBER OF INDUSTRIES HAVE ALREADY MITIGATED THE IMPACT OF SUCH EVENTS.

Satellites

Some satellites may be exposed to environments in excess of typical specification levels, so increasing microelectronic upset rates and creating electrostatic charging hazards. Because of the multiplicity of satellite designs in use today there is considerable uncertainty in the overall behaviour of the fleet but experience from more modest storms indicates that a degree of disruption to satellite services must be anticipated. Fortunately the conservative nature of spacecraft designs and their diversity is expected to limit the scale of the problem. Our best engineering judgement, based on the 2003 storm, is that up to 10% of satellites could experience temporary outages lasting hours to days as a result of the extreme event, but it is unlikely that these outages will be spread evenly across the fleet since some satellite designs and constellations would inevitably prove more vulnerable than others. In addition, the significant cumulative radiation doses would be expected to cause rapid ageing of many satellites. Very old satellites might be expected to start to fail in the immediate aftermath of the storm while new satellites would be expected to survive the event but with higher risk thereafter from incidence of further (more common) storm events. Consequently, after an extreme storm, all satellite owners and operators will need to carefully evaluate the need for replacement satellites to be launched earlier than planned in order to mitigate the risk of premature failures.

Aircraft passenger and crew safety

Passengers and crew airborne at the time of an extreme event would be exposed to an additional dose of radiation estimated to be up to 20 mSv, which is significantly in excess of the 1 mSv annual limit for members of the public from a planned exposure and about three times as high as the dose received from a CT scan of the chest. Such levels imply an increased cancer risk of 1 in 1,000 for each person exposed, although this must be considered in the context of the lifetime risk of cancer, which is about 30%. No practical method of forecast is likely in the short term since the high energy particles of greatest concern arrive at close to the speed of light. Mitigation and post event analysis is needed through better onboard aircraft monitoring. An event of this type would generate considerable public concern.

Ground and avionic device technology

Solar energetic particles indirectly generate charge in semiconductor materials, causing electronic equipment to malfunction. Very little documentary evidence could be obtained regarding the impact of solar energetic particles on ground infrastructure and it is consequently difficult to extrapolate to a solar superstorm. More documentary evidence of normal and storm time impacts is available in respect to avionics – no doubt because the operating environment has a higher flux of high-energy particles. Our estimate is that during a solar superstorm the avionic risk will be ~1,200 times higher than the quiescent background risk level and this could increase pilot workload. We note that avionics are designed to mitigate functional failure of components, equipment and systems and consequently they are also partially robust to solar energetic particles.

Global navigation satellite systems (GNSS)

Assuming that the satellites – or enough of them – survived the impact of high energy particles, we anticipate that a solar superstorm might render GNSS partially or completely inoperable for between one and three days. The outage period will be dependent on the service requirements. For critical timing infrastructure, it is important that holdover oscillators be deployed capable of maintaining the requisite performance for these periods. UK networked communications appear to meet this requirement. There will be certain specialist applications where the loss or reduction in GNSS services would be likely to cause operational problems; these include aircraft and shipping. Today, the aircraft navigation system is mostly backed up by terrestrial navigation aids; it is important that alternative navigation options remain available in the future.

Cellular and emergency communications

This study has concluded that the UK's commercial cellular communications networks are much more resilient to the effects of a solar superstorm than those deployed in a number of other countries (including the US) since they are not reliant on GNSS timing. In contrast, the UK implementation of the Terrestrial European Trunked Radio Access (TETRA) emergency communications network is dependent on GNSS. Consequently, mitigation strategies are necessary but already seem to be in place.

High frequency (HF) communications

HF communications is likely to be rendered inoperable for several days during a solar superstorm. HF communications are used much less than they used to be; however, they do provide the primary long distance communications bearer for long distance aircraft (not all aircraft have satellite communications and this technology may also fail during an extreme event). For those aircraft in the air at the start of the event, there are already well-defined procedures to follow in the event of a loss of communications. However, in the event of a persistent loss of communications over a wide area, it may be necessary to prevent flights from taking off. In this extreme case, there does not appear to be a defined mechanism for closing or reopening airspace once communications have recovered.

Mobile satellite communications

During an extreme space weather event, L-band (~1.5GHz) satellite communications might be unavailable or provide a poor quality of service, for between one and three days owing to scintillation. The overall vulnerability of L-band satellite communications to superstorm scintillation will be specific to the satellite system. For aviation users the operational impact on satellite communications will be similar to HF.

Terrestrial broadcasting

Terrestrial broadcasting would be vulnerable to secondary effects, such as loss of power and GNSS timing.

Recommendations

A number of detailed recommendations are included in each chapter. Some of the most important are set out below. It is vital that a lead government department or body is identified for each of these recommendations.

Policy

The report makes two key policy recommendations. These are that:

1. A UK Space Weather Board should be initiated within government to provide overall leadership of UK space weather activities. This board must have the capacity to maintain an overview of space weather strategy across all departments.
2. The Engineering and Physical Sciences Research Council (EPSRC) should ensure that its own programmes recognise the importance of extreme space weather mitigation and EPSRC should be fully integrated into any research council strategy.

Solar superstorm environment

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

Electricity grid

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

Satellites

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

Aircraft passenger and crew safety

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

Ground and avionic device technology

7. Ground-and space-derived radiation alerts should be provided to aviation authorities and operators. The responsible aviation authorities and the aviation industry should work together to determine if onboard monitoring could be considered a benefit in flight. Related concepts of operation should be developed to define subsequent actions; this could even include reductions in altitude if deemed beneficial and cost-effective.

Global navigation satellite systems (GNSS)

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

Terrestrial mobile communication networks

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

High frequency (HF) communications

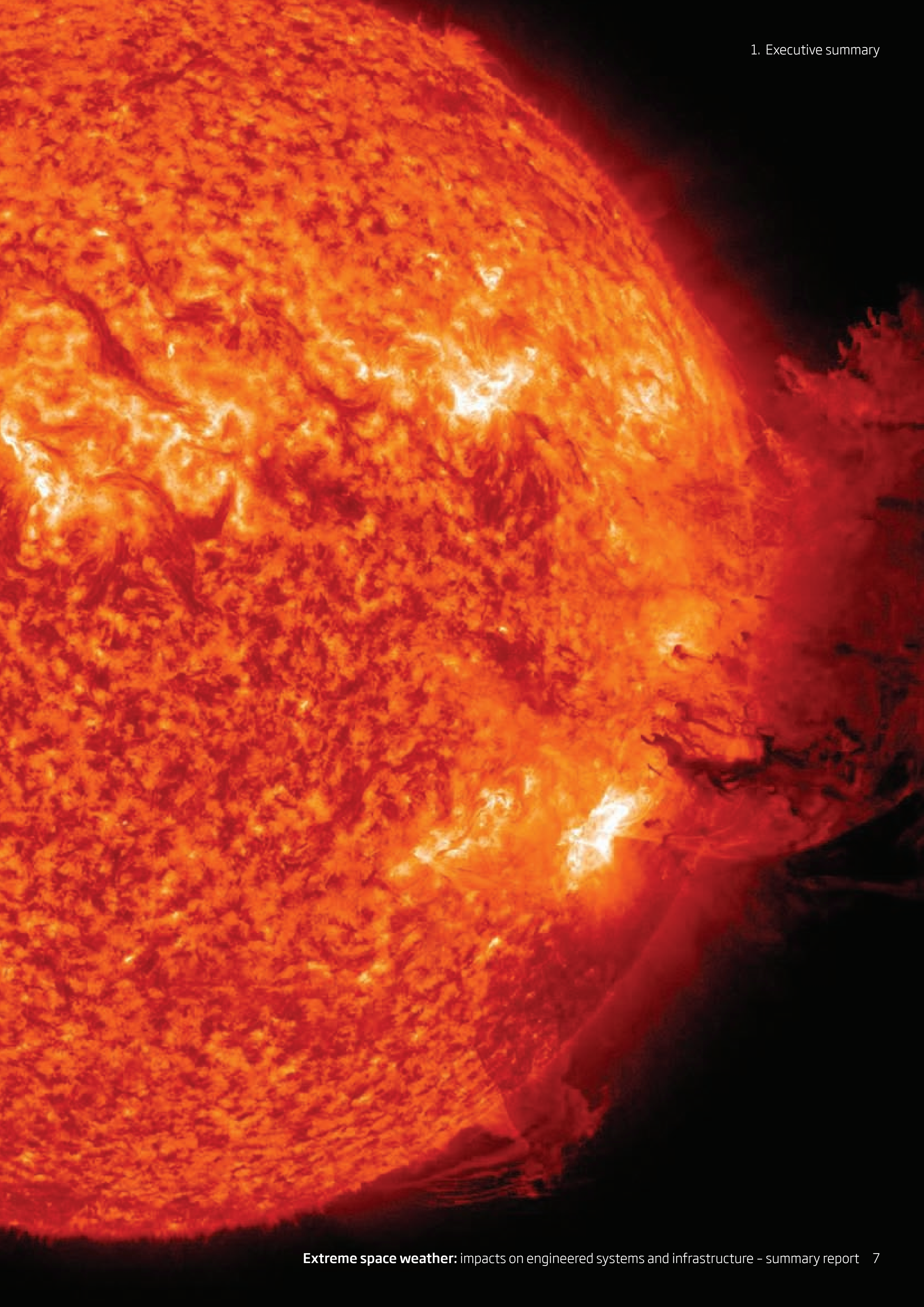
10. The aviation industry and authorities should consider upgrades to HF modems (similar to those used by the military) to enable communications to be maintained in more severely disturbed environments. Such an approach could significantly reduce the period of signal loss during a superstorm and would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

Terrestrial broadcasting

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

A copy of *Space weather: impacts on engineered systems* is available online at **www.raeng.org.uk/spaceweather**.

The Sun unleashed an M-2 (medium-sized) solar flare, an S1-class radiation storm and a spectacular coronal mass ejection (CME) on 7 June, 2011 © NASA



2. Background

The April 2010 Icelandic (Eyjafjallajökull) volcano eruption and resulting ash cloud and the March 2011 Japanese earthquake and tsunami demonstrated how devastating rarely occurring natural hazards can be to society and national economies. Natural events have no respect for national boundaries and *in extremis* the whole world can suffer.

In 2011 the UK recognised extreme space weather events (also referred to as solar superstorms and sometimes simply as superstorms) as one of these rare, but high impact, hazards. Space weather was for the first time included as part of the UK National Risk Assessment (NRA) – an unclassified version of which can be found at: **www.cabinetoffice.gov.uk/resource-library/national-risk-register**. However it quickly became apparent that the engineering impact is poorly understood especially in a UK context.

This report seeks to describe the effects, evaluate the impact and advise on suitable mitigation strategies. We have not deliberated on societal or economic impacts. Above all the report seeks to be realistic in terms of the engineering impacts so that solar storms can be better placed in the context of other natural hazards.

The report makes recommendations intended to improve the understanding of extreme events and to help to mitigate the effect of extreme events when they occur. The report does not consider high altitude nuclear explosions or any other man-made modifications of space weather.

3. Space weather – an introduction

Introduction

Space weather is a term which describes variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere, which can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety. Many of the systems affected by space weather are illustrated in Figure 1. Just like terrestrial weather, space weather is pervasive and compensating for its impact is a challenge.

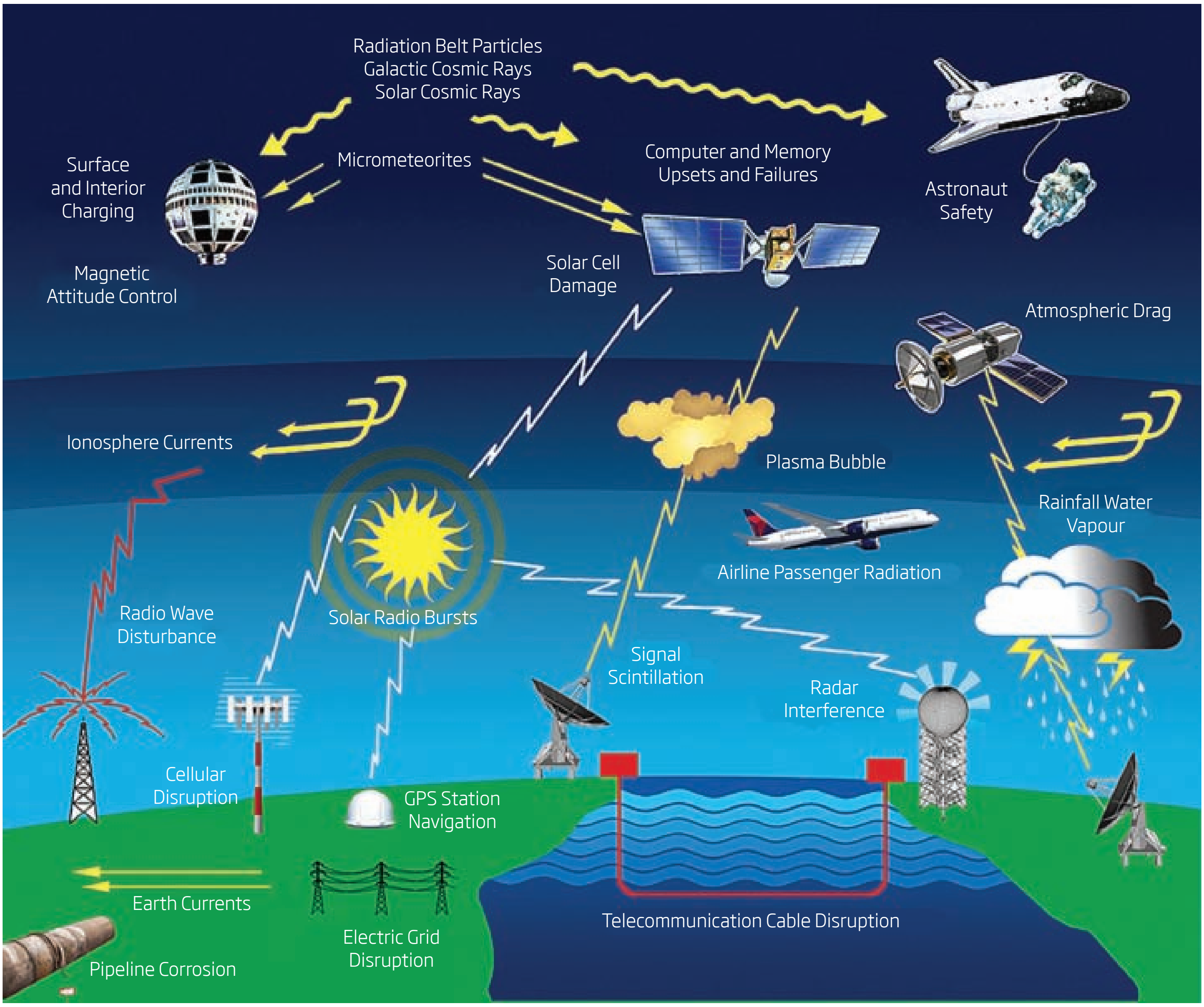
Space weather exhibits a climatology which varies over timescales ranging from days (ie diurnal variations due to the rotation of the Earth) to the 11-year solar cycle and over longer periods such as grand solar maxima and minima.

Superimposed on this climatology are weather-like variations; on some days space weather is more severe than on others. Minor solar storms are relatively common events; in contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two.

Causes of space weather

Although there is some influence from outside the solar system, most space weather starts at the Sun. The elements of the integrated Sun-Earth space weather system consist of Sun, solar wind, solar magnetic field, magnetosphere and ionosphere, as displayed in *Figure 2.*

Figure 1: Impacts of space weather © L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.



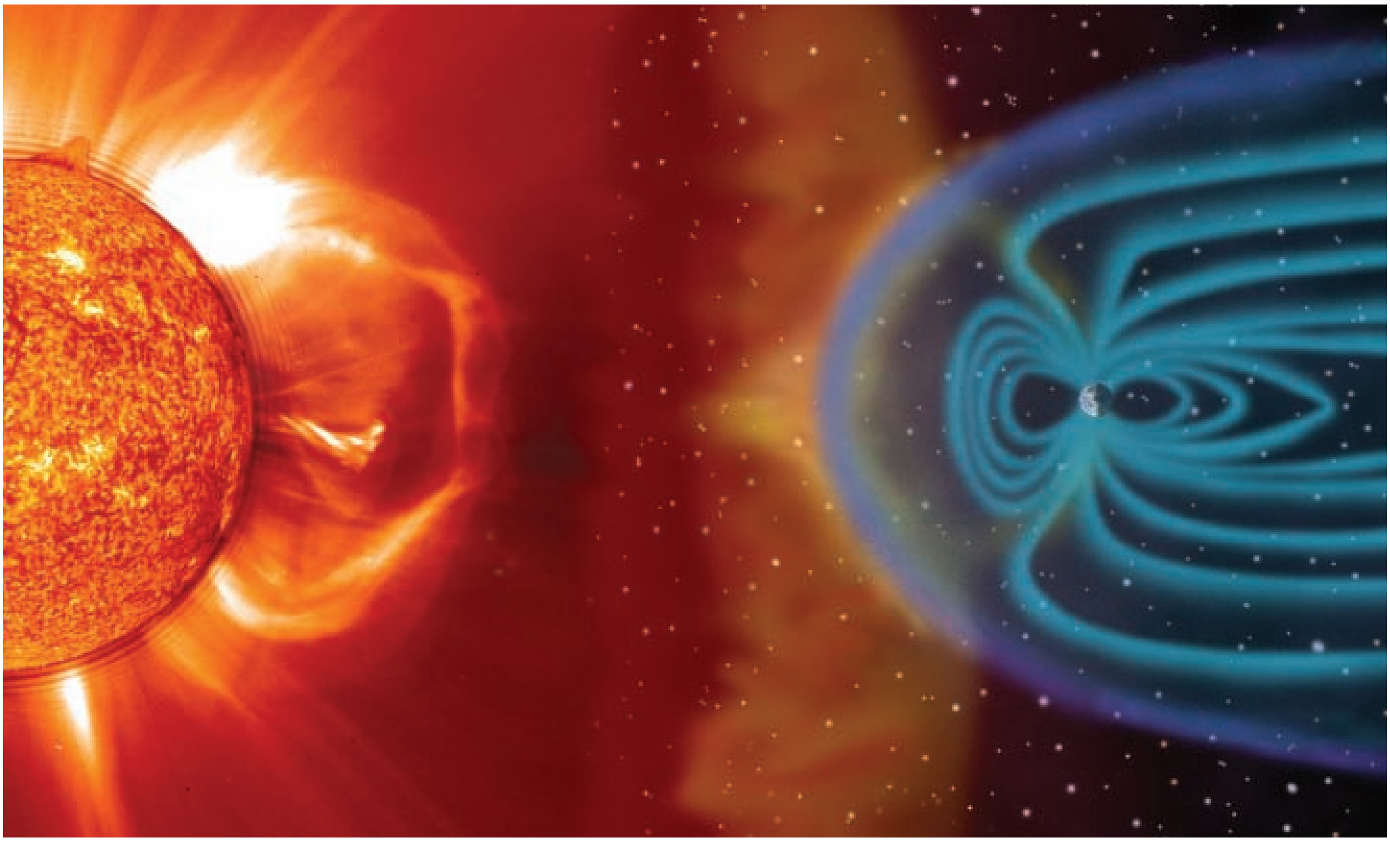


Figure 2: The space weather environment ©NASA

The Sun is a nearly constant source of optical and near-infrared radiation. However, there is considerable variability during storm periods at EUV, X-ray and radio wavelengths. During these periods, the Sun is also more likely to generate high-energy solar energetic particles (SEPs) and the solar wind plasma speed and density, forming part of the solar corona, can increase substantially. Coronal mass ejections (CMEs) are one manifestation of the latter and stream interaction regions (SIRs), formed when fast streams in the solar wind overtake and compress slow streams, also occur. Directly or indirectly, the ionising radiation, the ionised particles and the plasma interact with the magnetosphere and the ionosphere below it to cause a variety of effects on engineered systems.

Monitoring and forecasting space weather

Space weather monitoring is critical to forewarning of solar events that could generate severe space weather at Earth. It enables engineering teams to go on standby and it helps provide the context against which scientific advice and political decisions can be made.

Forecasts also provide a useful capability which, given sufficient accuracy, could change how space weather is mitigated. Currently neither flares nor SEPs can be forecast but there are techniques in research that may improve this situation. Operational provision of such a service would necessitate the appropriate instrumentation including monitoring of the far side of the sun.

CME arrival time can be forecast with an arrival time accuracy of ±6-8 hours which, although far from precise, is useful for putting the engineering teams on standby; this can be expected to improve over the next few years. To be geoeffective the CME magnetic field must be oriented southward. This cannot be judged, and definitive forecasts issued, until the CME reaches the L1 point satellite sensor, thereby providing only 15-30 minute notice.

Recommendations

- The UK should work with its international partners to ensure that a satellite is maintained at the L1 Lagrangian point, and that data from the satellite is disseminated rapidly.
- The UK should work with its international partners to explore innovative methods to determine the state of the solar wind, and its embedded magnetic field upstream from L1.
- The UK should work with its international partners to ensure the continued provision of a core set of other space-based measurements for monitoring space weather.

4. Solar superstorms

The geomagnetic, satellite, atmospheric radiation and ionospheric environments all react to increased solar activity. However, each environment reacts differently depending on the energy spectrum of the electromagnetic and particle radiation.

Solar storms all differ, yet we understand their basic chronology and their consequences (*Figure 3*):

1. The storm starts with the development of one or more complex sunspot groups which are observed to track across the solar surface.
2. From within these active regions, one or more solar flares occur and are detected on Earth at radio, optical and X-ray wavelengths just eight minutes later.
3. Highly solar energetic (relativistic) particles are released and detected just a few minutes later both on satellites and on the ground. These continue to arrive over a period of hours and even days if further eruptions occur.
4. A CME of plasma occurs which travels outwards at many hundred kilometres per second, taking ~15-72 hours to arrive at the orbital distance of the Earth. The level of impact on Earth is dependent on the speed of the CME, how close it passes with respect to Earth, and the orientation of the magnetic fields in the CME and in the compressed solar wind ahead of the CME.

The history of large solar storms and their impact

The effects of solar storms can be measured in a number of ways but the longest series of measurements (since the 1840s) have been made by ground-based magnetometers. These records have demonstrated that there have been many solar storms of which a very small number are severe. The storm of 2-3 September 1859 is the largest event on record and is known as the Carrington event after Richard Carrington, the distinguished British astronomer who observed a huge solar flare on the day before the storm. During this

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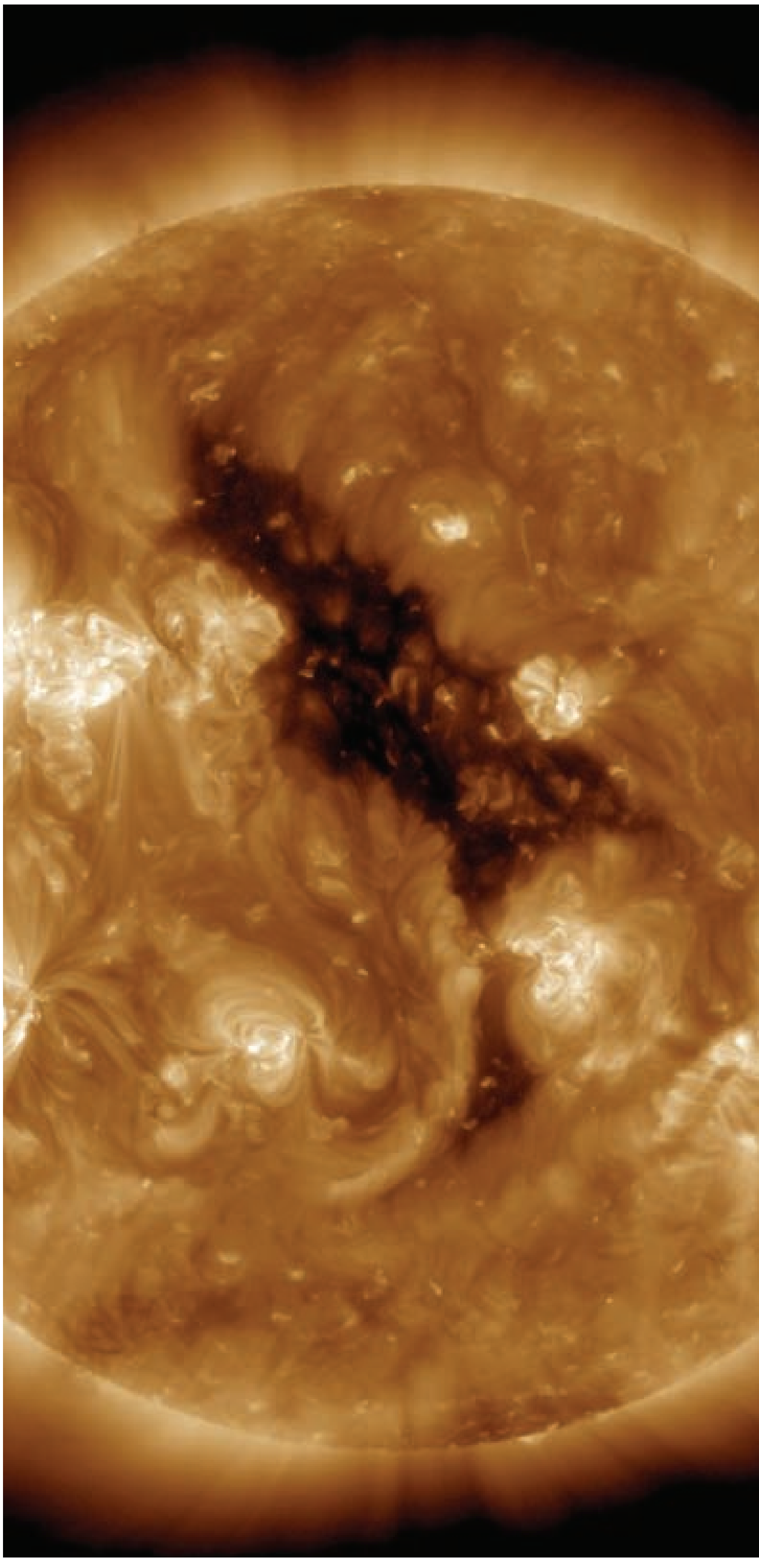
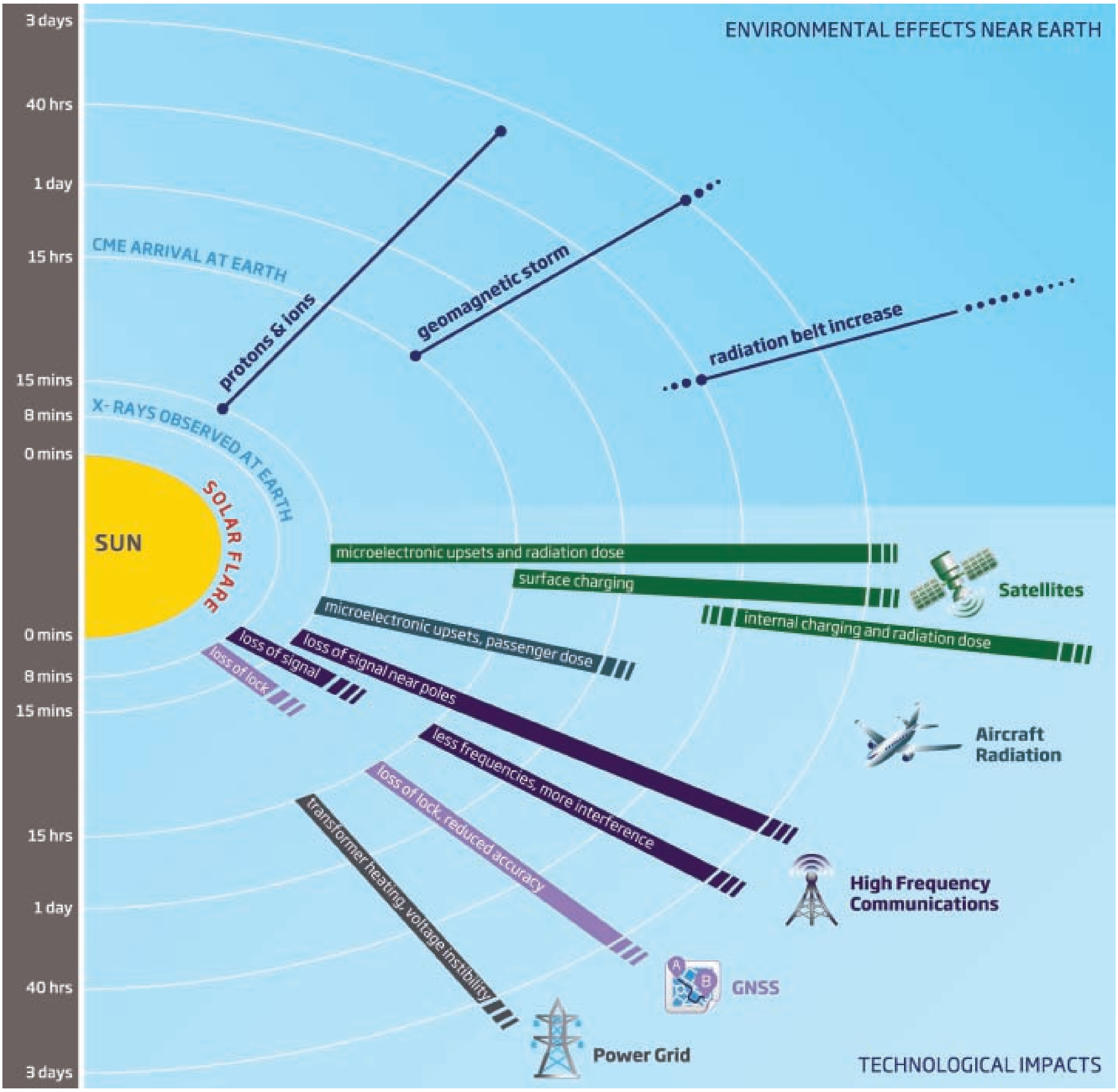


Coronal holes are regions where the sun's corona is dark. These features were discovered when X-ray telescopes were first flown above the Earth's atmosphere to reveal the structure of the corona across the solar disc. Coronal holes are associated with 'open' magnetic field lines and are often found at the sun's poles. The high-speed solar wind is known to originate in coronal holes © NASA period, aurora were seen all over the world, rather than just at high latitudes, with contemporary reports of aurora in the Caribbean. The Carrington event serves as the reference for many studies and impact assessments.

We now believe that this flare was associated with a very fast CME that took only 17.6 hours to travel from the Sun to the Earth. The Carrington event has been widely studied in the past decade and we now have a wealth of published data and analyses. These suggest that the Earth was hit by a CME travelling at about 1,900 km s^{-1} and with large southward-pointing magnetic field (100 to 200 nT) in the sheath of compressed plasma just ahead of the CME (but behind its shockwave). It is this combination of high speed and strong southward magnetic field that generated such a severe geomagnetic storm because it allowed the energy of the CME to enter the Earth's magnetosphere. The location and duration of the impact region depends on processes in Earth's magnetosphere and upper atmosphere, in particular the substorm cycle. This extracts energy

Figure 3: A summary of space weather effects on technology © Royal Academy of Engineering 2012



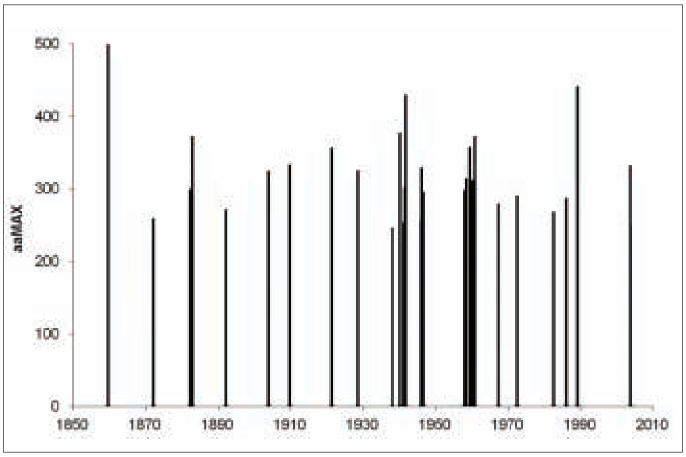


Figure 4: The top 31 geomagnetic storms since 1850; storm sizes based on the geomagnetic index, aa*MAX index developed at the US National Geophysical Data Center. The Carrington event is the large peak on the left © Rutherford Appleton Laboratory

from the solar wind, stores it as magnetic energy in the tail of Earth's magenetosphere and then explosively releases it back towards the Earth. During a severe geomagnetic storm, such as the Carrington event, lasting one or more days there will be many substorms at intervals of one to three hours. Each substorm will produce severe conditions that will often be localised in space and time.

Figure 4 shows one measure of the most severe geomagnetic storms that have occurred over the past 170 years with the Carrington event on the far left of the figure.

There have been many large space weather events since Carrington, the most frequently referred to being events in March and October 1989, 14 July 2000 (known as the Bastille Day event) and October 2003 (the Halloween event). We also note that on 4 November 2003, a few days after the Halloween event, the Sun produced the largest X-ray solar flare observed since the advent of space measurements and one that was probably similar in strength to the flare associated with the CME that caused the Carrington event . Fortunately this flare occurred on the west limb of the Sun, as the region that caused the Halloween event rotated to the far side of the Sun.

Probability of a superstorm

The key question, critical to placing this natural hazard in context with other natural hazards, is a good estimate of the probability of a superstorm on the scale of or greater than the Carrington event.

In the UK, for planning purposes, a reasonable worse case superstorm with the strength of the Carrington event is currently considered to be a 1-in-100-year event. However, given that our longest geomagnetic data set extends back only ~170 years and satellite particle effects are at best measured only over ~50 years, our understanding of how often an event of this type will affect the Earth is poor.

The Sun is believed to produce several tens of Carrington-class CMEs every century but most miss the Earth or the interplanetary magnetic field (IMF) is oriented North.

Summary and recommendation

The recurrence statistics of an event with similar magnitude and impact to a Carrington event is poor, but improving. Various studies indicate that a recurrence period of 1-in-100 to 200 years is reasonable and this report makes assessments of the engineering impact based on an event of this magnitude and return time. If further studies provide demonstrable proof that larger events do occur – perhaps on longer time scales – then a radical reassessment of the engineering impact will be needed.

Recommendation

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

5. Impacts on the electrical power grid

The reasonable worst case scenario, assumed to be of the order of a one-in-100-year event, will have a significant impact on the national electricity grid. Current estimates are for some local electricity interruptions lasting a few hours. In addition, around six super grid transformers (SGTs) in England and Wales and a further seven grid transformers in Scotland could be damaged and taken out of service.

Because most nodes have more than one transformer available, not all these failures would lead to a disconnection event. However, National Grid's analysis is that around two nodes in Great Britain could experience disconnection. This number of failures is within the capacity of National Grid's transformer spares carrying policy. The time for an emergency transformer replacement, when a spare is available, is normally 8 to 16 weeks, with a record of four weeks. Some generator step-up transformers will be at more risk than SGTs because of their design. Lesser storms, compared to a one-in-100-year event, will have progressively less impact on the system.

In the build-up to a significant space weather event, National Grid would take actions triggered by National Grid's space weather monitoring team following on from advice from the British Geological Survey, Met Office and other forecasting bodies. National Grid would issue warnings and advice to government, customers and third parties to enable them to mitigate the consequences.

Recommendations:

- The current National Grid mitigation strategy should be continued. This strategy combines appropriate forecasting, engineering and operational procedures. It should include increasing the reserves of both active and reactive power to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers.
- There is a need to clarify and maintain a very rapid decision-making process in respect to an enhanced GIC risk.
- Consideration should be given to the provision of transportable recovery supergrid transformers and to GIC blocking devices, which are still in their infancy.
- Further geophysics, transmission network and transformer modelling research should be undertaken to understand the effects of GIC on individual transformers, including the thermal effects, reactive power effects, and the production of harmonics.
- Long-term support for geomagnetic and GIC monitoring should be maintained.
- The National Grid should better quantify the forecasting skill that it requires and assess this in the light of foreseeable improvements following from current and future scientific research.

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6. Other geomagnetically induced current effects

Pipelines and railway networks

GICs can be induced on any long lengths of earthed electrical conducting material such as pipelines and railway networks, during a solar storm but reported effects in the UK are hard to find.

Trans-oceanic communications cables

Optical fibre cables are the backbone of the global communications networks. They carry the vast majority (99%) of internet and telephone traffic and are much preferred to links via geosynchronous spacecraft since neither human voice communications nor the standard protocols can efficiently handle the ~0.3s delay imposed by the long paths to geostationary satellites. Optical fibres are more resilient to space weather than their twisted copper wire predecessor, which was very prone to GIC effects.

However, electric power is required to drive optical repeaters distributed along transoceanic optical fibres and this is supplied by long conducting wires running alongside the fibre. These wires are vulnerable to GIC effects as was demonstrated during the geomagnetic storm of March 1989.

Recommendations

- Government and industry should consider the potential for space weather damage on the optical fibre network through overvoltage on the repeaters and should consider whether appropriate assessment studies are necessary.
- UK railway operators and pipeline operators should be briefed on the space weather and GIC risk and should consider whether appropriate assessment studies are necessary.

OPTICAL FIBRES ARE MORE RESILIENT TO SPACE WEATHER THAN THEIR TWISTED COPPER WIRE PREDECESSOR, WHICH WAS VERY PRONE TO GIC EFFECTS.

7. Satellites

During an extreme space weather event, some satellites may be exposed to environments in excess of typical specification levels. This would increase microelectronic upset and failure rates and also create electrostatic discharge hazards. In addition, significant cumulative radiation doses could be received causing rapid satellite ageing. Because of the multiplicity of satellite designs in use today, there is considerable uncertainty on the overall behaviour of the fleet but experience from more modest storms indicates that some disruption to satellite services must be anticipated. Fortunately the conservative nature of spacecraft designs and their diversity is expected to limit the scale of the problem.

During the superstorm, our best engineering estimate, based on the 2003 storm, is that around 10% of spacecraft will experience an anomaly leading to an outage of hours to days but most of these will be restored to normal operations in due course. It is unlikely that outages will be spread evenly across the fleet since some satellite designs and constellations will inevitably prove more vulnerable than others by virtue of their detailed design characteristics. A few spacecraft might be lost entirely during the storm through a sudden damage mechanism such as electrostatic discharge.

In the months after the extreme storm, old satellites such as those in life extension mode may start to fail as a result of the ageing (dose) effects (we note that as many as one in 10 satellites in geostationary orbit are thought to be in life-extension mode). Recently launched satellites would be expected to survive the event but with higher risk thereafter from incidence of further (more common) storm events. Consequently, after an extreme storm, all satellite owners and operators will need to carefully evaluate the need for replacement satellites to be launched earlier than planned in order to mitigate the risk of premature failures. Obviously such a scenario has potential for creating a bottleneck in the satellite supply chain which will raise questions of priority.

Recommendations:

- Extreme storm risks to space systems critical to social and economic cohesion of the country (which is likely to include navigation satellite systems) should be assessed in greater depth; and users of satellite services which need to operate through a superstorm should challenge their service providers to determine the level of survivability and to plan mitigation actions in case of satellite outages (eg network diversification).
- The ageing effects of an extreme storm across the whole satellite fleet should be modelled to determine if a serious bottleneck in satellite manufacture or launch capacity could be created.
- Research should be actively pursued to better define the extreme storm environments for satellites and consequential effects. Collaboration with the NASA *Living with a Star* programme would be highly beneficial.
- Observations of the space radiation environment and its effects should be maintained and developed. Such measurements enable post-event analysis of satellite problems, the development of improved physical models which can be used in satellite design phases and the development of better warning and forecasting.

8. Ionising radiation impacts on aircraft passengers and crew

Passengers and crew airborne at the time of an extreme event would be exposed to an additional dose of radiation estimated to be up to 20 mSv, which is significantly in excess of the 1 mSv annual limit for members of the public from a planned exposure and is comparable to about three CT scans of the chest. Such levels imply an increased cancer risk of 1 in 1,000 for each person exposed, but this should be considered in the context of a lifetime risk of fatal cancer which is about 30%.

No practical method of forecasting is likely in the short term since the high-energy particles of greatest concern arrive at close to the speed of light. Mitigation and post-event analysis is needed through better onboard aircraft monitoring. An event of this type will generate considerable public concern.

ATMOSPHERIC RADIATION ALERTS SHOULD BE PROVIDED TO THE AVIATION INDUSTRY AND CONCEPTS OF OPERATION SHOULD BE DEVELOPED TO DEFINE SUBSEQUENT ACTIONS BASED ON RISK ASSESSMENT

Recommendations

- Consideration should be given to classifying solar superstorms as radiation emergencies in the context of air passengers and crew. If such a classification is considered appropriate, an emergency plan should be put in place to cover such events. While the opportunities for dose reduction may be limited, appropriate reference levels should be considered and set, if appropriate.
- Atmospheric radiation alerts should be provided to the aviation industry and concepts of operation should be developed to define subsequent actions based on risk assessment (eg delaying take-offs until radiation levels have reduced).
- Consideration should be given to requiring aircraft operating above a specified altitude (25,000-35,000 feet) to carry a radiation sensor and data logger. This would enable post-event analysis to allay public concerns and to manage any health risks.
- Consideration should be given to the sensor being visible to the pilot and to the development of a concept of operations whereby the pilot requests a reduction in altitude (noting that modest reductions can be beneficial) under solar storm conditions.
- Post-event information and advice on the radiation doses received should be available to passengers and crew (especially to pregnant women).

9. Avionics and ground systems

Very little documentary evidence could be obtained regarding the impact of solar energetic particles on ground infrastructure and it is consequently difficult to extrapolate to a solar superstorm.

More documentary evidence of normal and storm-time impacts is available in respect to avionics – no doubt because the operating environment has a higher density of high-energy particles. Our estimate is that during a solar superstorm the avionic risk will be ~1,200 times higher than the quiescent background risk level. We note that the more critical avionics, such as engine control, are designed to mitigate functional failure at component, equipment and system level and consequently they will be partially robust to solar energetic particles.

Solar energetic particles exhibit a wide range of energies and it is currently impossible to forecast the spectrum of particles that might erupt from the Sun. Moreover, because the first particles arrive within a few minutes of the associated solar flare, no practical forecast of an event and its consequences can currently be provided.

Recommendations:

- Ground-and space-derived radiation alerts should be provided to aviation authorities and operators. The responsible aviation authorities and the aviation industry should work together to determine if onboard monitoring could be considered a benefit in flight. Related concepts of operation should be developed to define subsequent actions (eg fastening of seatbelts or reducing altitude if the storm occurs on route or, if still on the ground, delaying take-offs until radiation levels have reduced). This could even include reductions in altitude if deemed beneficial and cost-effective.
- The responsible aviation authorities and the aviation industry should work towards requiring that future aircraft systems are sufficiently robust to superstorm solar energetic particles, including through the appropriate standards in atmospheric radiation mitigation – for example *IEC 62396-1* Ed.1:2012).
- Since the impact of a solar superstorm on ground-based systems cannot be clarified, further consideration is required. Systems with very high safety and reliability requirements (eg in the nuclear power industry) may need to take account of superstorm ground-level radiation on microelectronic devices within the system.

10. Impacts on GPS, Galileo and other GNSS positioning, navigation and timing (PNT) systems

GNSS positioning, navigation and timing are ubiquitous to our lives and important in a number of safety of life applications; their unmitigated loss resulting from a superstorm would have severe social and economic repercussions.

Assuming that the satellites – or enough of them – survived the impact of high energy particles, we anticipate that a solar superstorm would render GNSS partially or completely inoperable for between one and three days. The outage period would be dependent on the service requirements. For critical timing infrastructure, it is important that holdover oscillators be deployed capable of maintaining the requisite performance for these periods. UK networked communications appear to meet this requirement.

With current forecast skills, it is inevitable that aircraft will be flying and ships will be in transit when the superstorm initiated. Aircraft use differential and augmented systems for navigation and in the future possibly for landing. With these applications set to increase, the potential for significant impact from an extreme space weather event will likewise increase. Fortunately, the aviation industry is highly safety conscious and standard operating procedures appropriate to other emergency situations are likely to provide sufficient mitigation to an extreme space weather event. These include other terrestrially based navigation systems. The challenge will be to maintain those strategies over the long term as GNSS become further embedded into operations.

This study has not explored the impact on ship navigation, but recognises that precision and non-precision navigation by GNSS is widespread and standard operating procedures will be needed to educate sailors on how to recognise a solar superstorm and deal with it in the possible absence of HF and satellite communications.

Recommendations

- All critical infrastructure and safety critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.
- Care should be taken to ensure that this requirement extends to cabled and fibre communications systems.
- Backup position, navigation and time services such as eLoran service (which in the UK is broadcast from the Anthorn transmitter) should be considered as an alternative to GNSS for UTC traceable time, timing and location based services. We note that the USA has set-up the Alternate Position Navigation and Time (APNT) programme that is working to reconfigure existing and planned ground navigation aids (e.g. Distance Measuring Equipment) and the ground based transmitters associated with automatic surveillance) so that they can back up GNSS well into the future.
- Since loss of GNSS would have a major impact on lives in general, and on shipping and air travel specifically, warnings of events should be provided through a nationally recognised procedure, possibly involving government crisis management arrangements, NATS, the CAA and the General Lighthouse Authority. Criteria should be established for the re-initiation of flying when it is safe to do so.

THE AVIATION INDUSTRY IS HIGHLY SAFETY CONSCIOUS AND STANDARD OPERATING PROCEDURES APPROPRIATE TO OTHER EMERGENCY SITUATIONS ARE LIKELY TO PROVIDE SUFFICIENT MITIGATION TO AN EXTREME SPACE WEATHER EVENT.

11. Impacts on radio communication systems

Space weather events can affect the operation of radio systems in a number of ways. The effects may be prompt (ie they occur soon after the initial event on the Sun) or delayed (ie some days later).

This section outlines the possible impacts on:

- terrestrial mobile communications networks
- high frequency (HF) communications and international broadcasting
- mobile satellite communications
- satellite and terrestrial broadcasting.

Terrestrial mobile communication

Good quality and reliable mobile (cellular) communications are relied on by the public. Furthermore, mobile communications are also critical for the delivery of effective police, fire and ambulance services and these services are likely to be in high demand during an extreme solar event when other parts of the national infrastructure are under stress.

This study has concluded that the UK's commercial cellular communications networks are currently much more resilient to the effects of a superstorm than those deployed in a number of other countries (including the US) since they are not reliant on GPS. Solar radio bursts have been identified as a potential problem, but only for parts of the network facing the Sun at dawn and dusk. The Academy believes that this is an acceptable risk given that each burst will only last ~20 minutes.

In contrast, the TETRA emergency communications network is dependent on GPS timing and, without mitigation strategies, would be vulnerable. However, a number of mitigation strategies are already in place.

Recommendations

- All terrestrial mobile communication networks with critical resiliency requirements should also be able to operate without GNSS timing for periods up to three days. This should particularly include upgrades to the network including those associated with the new 4G licenses where these are used for critical purposes and upgrades to the emergency services communications networks.
- Ofcom should consider including space weather effects when considering infrastructure resilience.
- The impact of extreme space weather events should be considered in the development of upgrades to emergency services communications networks and GNSS holdover should be ensured for up to three days.
- Further study of radio noise effects on mobile communication base stations should be undertaken to quantify the impact.

HF communications

HF communications are likely to be rendered inoperable for several days during a solar superstorm. HF communications are used much less than they used to be; however, they do provide the primary long distance communications bearer for long distance aircraft (not all aircraft have satellite communications and this may also fail during an extreme event). For those aircraft in the air at the start of the event, there are already well-defined procedures to follow in the event of a loss of communications. However, in the event of a persistent loss of communications over a wide area, it might be necessary to prevent flights from taking off. In this extreme case, there does not appear to be a defined mechanism for closing or reopening airspace once communications have recovered.

Recommendations

- The aviation industry and authorities should consider upgrades to HF modems (similar to those used by the military) to enable communications to be maintained in more severely disturbed environments. Such an approach could significantly reduce the period of signal loss during a superstorm and would be more generally beneficial.
- Operational procedures for closing and reopening airspace in the event of an extended HF and satellite communications blackout should be developed

Mobile satellite communications

During an extreme space weather event, L-band satellite communications might be unavailable, or provide a poor quality of service, for between one and three days owing to scintillation. The overall vulnerability of L-band satellite communications to superstorm scintillation will be specific to the satellite system. For aviation users the operational impact on satellite communications will be similar to HF.

Recommendation

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

Terrestrial broadcasting

Terrestrial broadcasting would be vulnerable to secondary effects, such as loss of power and GNSS timing.

Recommendation

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

12. Conclusion

The report has sought to elucidate the nature and the impact of solar superstorms on contemporary and future high-technology systems with an emphasis on the UK. The breadth of technologies considered is significant and, with the input of a number of domain experts, each has been studied in some depth. Our study is based on an estimate of the environmental impact of events which have occurred in the last 200 years. How representative these are of the longer term is not known, and in any case every solar superstorm is different.

The study has demonstrated that solar superstorms are indeed a risk to the UK's infrastructure. The UK electricity grid, while probably not as susceptible as in some other countries, is at risk and this provides the biggest concern because so much other infrastructure is dependent on it. Many other technologies are also vulnerable and the unmitigated impact is likely to have both safety-of-life and economic impacts. It appears that, in contrast to the USA and some other countries, contemporary UK 2G, 3G and 4G mobile communications networks are not vulnerable – this needs to be maintained. The study has not assessed how the impact of a superstorm might be magnified by the failure of multiple technologies, but the likelihood that this will indeed occur has been noted.

The Academy recommends continuing vigilance of this recently recognised threat. Vigilance will require the maintenance of current mitigation strategies and the development of new approaches in response to new technologies. Mitigation of the effects of solar superstorms requires a balance between engineering approaches and operational approaches – the latter being partly dependent on storm forecasts. The specific technology and the relative costs of mitigation will dictate the best way forward. Technological mitigation tends to be application specific, whereas forecasting has both generic and application specific elements. Reliable space weather forecasting requires a mix of satellite and ground based observations combined with coupled physical models. It is likely to be a grand challenge for the scientific community and requires partnership with the engineering and business communities to be effective.

Technology specific recommendations are included in each chapter of the report.

The Academy also recommends the initiation of a UK space weather board to provide overall leadership of UK space weather activities: observations and measurements, operational services, research and related technology developments. In regard to the latter the board should, through its leadership, support and facilitate the UK space sector to enable it to respond to ESA and other space environment missions. The board, under the auspices of a nominated government department, should include representatives of all major stakeholders. It should be responsible for advising on proposal development and prioritisation, ensuring coherency of work programmes, avoiding duplication of projects and delivering value for money. Above all, the board should link the research and operations communities so that the science is more clearly focused on delivering useful results and tested against well-defined metrics.

Understanding and mitigating solar superstorms is a subject lying at the interface between science and engineering. The discipline has grown out of the former and, to maintain and extend our understanding and ability to measure and monitor space weather in general, and superstorms more particularly, it is vitally important to maintain the UK science expertise. Space weather research related to impacts on the Earth's environment, from the deep interior to the upper atmosphere and magnetosphere, is primarily the responsibility of the Natural Environment Research Council (NERC) while non-Earth space weather research, including space plasma and solar physics, are the responsibility of the Science and Technology Facilities Council (STFC). However, mitigating space weather and solar superstorms also has an important engineering dimension. Consequently, the Academy recommends that the Engineering and Physical Research Council (EPSRC) should ensure that its own programmes recognise the importance of extreme space weather mitigation and that EPSRC be fully integrated into any research council strategy.

This report presents our best assessment of the impact of a severe space weather event largely based on our experience of previous smaller events and our understanding of modern technology. We caution that the conclusions are subject to a large uncertainty as an extreme event has not been encountered in modern times and if it were there are likely to be many nonlinear dependencies. Therefore, our assessment may understate the impacts.

13. Glossary

Term	Definition
Bastille Day event	Radiation storm that occurred on 14 July 2000 and associated geomagnetic storm on 15/16 July
Carrington event	The largest solar storm on record. It took place from 1-3 September 1859 and is named after British astronomer Richard Carrington.
Coronal mass ejection	A large burst of solar wind plasma ejected into space
Electrostatic discharge	The sudden flow of electricity between two objects caused by contact, an electrical short or dielectric breakdown
eLoran	Enhanced Long-Range Navigation System
Geo-effective	Storm-causing
Geomagnetically induced currents	Electrical currents flowing in earthed conductors, induced by rapid magnetic field changes
Geomagnetic storm	A worldwide disturbance of the Earth's magnetic field induced by a solar storm
Geostationary orbit	A circular orbit 35,900 km above the Earth's surface where most telecommunications satellites are located. Satellites in GEO orbit appear stationary relative to the rotating Earth
Global navigation satellite systems	Generic term for space-based navigation systems of which GPS and Galileo are examples
Halloween event	A solar storm that occurred in October 2003
Harmonics	Electric voltages and currents that appear on the electric power system as a result of non-linear electric loads and are a frequent cause of power quality problems
Interplanetary magnetic field	Solar magnetic field carried by the solar wind to the planets and beyond
Ionosphere	The region of the atmosphere between around 80-600 km above the Earth
L1 Langrangian point	The point where the gravitational forces of the Sun and Earth balance
Magnetosphere	The region surrounding a planet, such as the Earth, in which the behaviour of charged particles is controlled by the planet's magnetic field
Magnetometer	An instrument used to measure the strength and direction of magnetic fields.
Reactive power	Describes the energy in the magnetic component of the alternating current
Relativistic	Having or involving a speed close to that of light
Scintillation	The perturbation of radio signals caused by variations in the ionosphere
Solar corona	The extended outer atmosphere of the Sun
Solar energetic particles	High-energy particles coming from the Sun
Solar flare	A brief powerful eruption of particles and intense electromagnetic radiation from the Sun's surface
Solar wind	The constant stream of charged particles, especially protons and electrons, emitted by the Sun at high velocities, its density and speed varying during periods of solar activity
Substorm	A brief disturbance of the Earth's magnetosphere that causes energy to be released from its "tail"
TETRA	An emergency communications network
Thermosphere	An atmospheric layer lying between the mesosphere and the exosphere, reaching an altitude of ~750km above the Earth's surface

14. Abbreviations and Acronyms

Acronym	Meaning
CAA	Civil Aviation Authority
CME	Coronal mass ejection
GIC	Geomagnetically induced currents
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HF	High frequency
NATS	National Air Traffic Control Service
NRA	National risk assessment
SEP	Solar energetic particle
SGT	Super grid transformer
TETRA	Terrestrial European trunked radio access
UTC	Universal coordinated time

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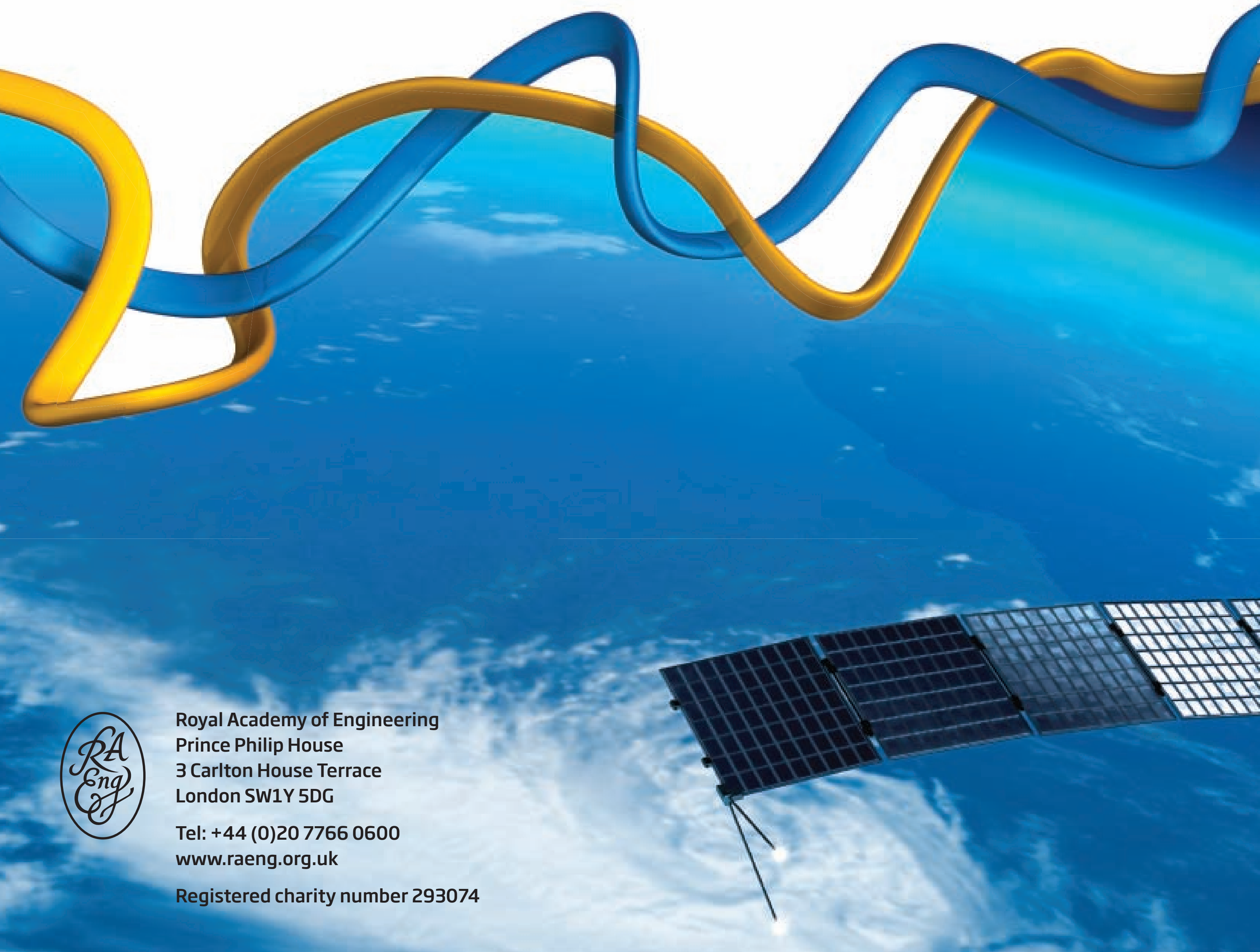

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