EXTREME SPACE WEATHER; impacts on engineered systems and infrastructure

Professor Paul S Cannon FREng
Royal Academy of Engineering

IMPACT

Infrequent 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.

Explosive eruptions of energy from the Sun which cause minor solar storms on Earth are relatively common events. By 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 remains 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.

How often superstorms occur and whether the above are representative of the long term risk is not known and is the subject of important research. The 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%.

Mitigation of solar superstorms necessitates a number of technology-specific approaches which implies reducing 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 from its early stages as enhanced activity on the Sun through to its impact on Earth. Forecasting a solar storm is a challenge, and current techniques deliver limited advice.

. . . superstorms occur very occasionally . . .

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 separate and linked risks over the long term is a challenge for government, for asset owners and for managers.

ELECTRICITY GRID

A plausible 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.

SATELLITES

Some satellites may be exposed to environments in excess of typical specification levels, so increasing microelectronic upset rates and creating electrostatic charging hazards. Fortunately the

> . . . some satellite designs would prove more vulnerable . . .

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. It is unlikely that these outages will be spread evenly since some satellite designs and constellations would 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.

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. This 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. This must be considered in the context of the lifetime risk of cancer, which is about 30%. No practicable 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. There is very little evidence regarding the impact of solar energetic particles on ground infrastructure and it is consequently difficult to extrapolate to a solar superstorm. More evidence of normal and storm time impacts is available in respect to avionics. During a solar superstorm the avionic risk will be ~1,200 times higher than the background level and this could increase pilot workload. Avionics are designed to mitigate functional failure of components, equipment and systems and consequently they are also robust to solar energetic particles.

> . . . increase pilot workload . . .

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

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 meet this requirement. There will be specialist applications where the loss or reduction in GNSS services cause operational problems. These include aircraft and shipping. Today, the aircraft navigation system is backed up by terrestrial navigation aids; it is important that alternative navigation options remain available in the future.

CELLULAR AND EMERGENCY COMMUNICATIONS

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. The UK implementation of the Terrestrial European Trunked Radio Access (TETRA) emergency communications network is dependent on GNSS. Consequently, mitigation strategies, already in place, are necessary.

HIGH FREQUENCY (HF) COMMUNICATIONS

HF communications are likely to be inoperable for several days during a solar superstorm. HF communications are used less than hitherto. However, it does provide the primary long distance communications 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 well-defined procedures in the event of a loss of communications. 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 is no defined mechanism for closing or reopening airspace once communications have recovered.

> . . . well-defined procedures in the event of a loss of communications . . .

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.

RECOMMENDATIONS

The Royal Academy of Engineering study [Cannon et al., 2013a; b] makes a number of technical recommendations.

In order to ensure a space weather resilient infrastructure the Academy recommends that a UK Space Weather Board be set up with cross-government department responsibilities.

References

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SPACE WEATHER: A space insurance perspective

David Wade
Space Underwriter, Atrium Space Insurance Consortium

Since the Space Age began 55 years ago, approximately 6,500 satellites have been launched. Approximately 1,000 of these satellites are still active[1]. Society has become increasingly reliant upon the services provided by satellites. Space weather is known to pose a peril to satellites and in extreme events it is likely that a number of satellites will suffer temporary outages, and a small number may be permanently lost.

Whilst satellites have so far demonstrated their resilience to space weather, a true stress test of an extreme space weather event has not occurred during the Space Age. Are we prepared for such an event?

RELIANCE

The prominence of satellite services has increased significantly over the past ten years. Forty per cent of UK households now receive their television service via satellite [2] and satellite navigation has spawned a vast number of new services and efficiency gains. Delivery companies, for example, have reduced fuel consumption by 13% whilst increasing fleet utilisation by 27% through the use of satellite navigation[3] and precision agriculture has improved crop yields and reduced the use of fertiliser and pesticide. In the years to come, new satellite-based services will allow shipping to be tracked worldwide to the benefit of national security and safely allow a reduction in the separation of aircraft to cater for the increasing density of air traffic.

The annual worldwide revenue of the satellite services sector has grown from US$ 46.4 billion in 2001[4] to US$ 107.7 billion in 2011[1]. This only accounts for the direct sale of satellite services. Revenue from downstream services, such as the use of the Global Positioning System (GPS) are not included within this figure, yet satellite navigation services already account for between 6% and 7% of the gross domestic product of Western countries; approximately €800 billion in the European Union alone[5].

EFFECTS ON SATELLITES

The near-Earth space environment is characterised by two toroidal radiation belts girdling the Earth, known as the Van Allen radiation belts. Low Earth Orbiting (LEO) satellites in Sun-synchronous or polar orbits such as those used for imaging purposes and Medium Earth Orbit (MEO) satellites used for navigation are exposed to the inner radiation belt. The design of satellites operating in these orbits needs to account for the significant radiation dose such satellites will receive over their lifetimes. The 400 or so geostationary satellites, such as those used for communication services, reside in geostationary orbit, 36,000 km above the equator. At this location the satellites orbit within the outer radiation belt and are exposed to solar events which can significantly enhance the background radiation levels.

Charging, both on the surface of the spacecraft, as different regions, perhaps with different materials, charge to different levels, and internal charging, as high energy electrons penetrate into the body of the spacecraft can occur and can damage sensitive microelectronic components. Energetic protons will reduce the efficiency of solar cells which may, for example, require communications channels to be turned off to compensate for the loss of power. Ions will produce single event effects (SEE's) which are often temporary in nature, but which can cause permanent physical damage in a minority of cases. During an extreme space weather event a satellite may also receive sufficient radiation to exceed its specified lifetime dose. Whilst this rarely leads to losses, it does age the satellite which may require plans to replace the satellite to be brought forward[6].

Little can be done to reduce the risk posed to a satellite by an extreme space weather event once the satellite is in orbit, although satellite operating companies may choose to

> . . . satellites have demonstrated resilience to space weather . . .

suspend manoeuvres, or call in extra satellite controllers to cope with any anomalies that do result.

SPACE INSURANCE EXPERIENCE

With little chance to react once a satellite has been launched it is essential that the satellite has been designed to withstand the environment within which it is expected to operate.

Satellites are affected by the space environment and 19%[7] of satellite anomalies are deemed to be, at least in part, attributable to space weather. An anomaly however can be as simple as a device suffering a spurious switch off which can be reset. In many such cases the end user of the satellite service would not even be aware that an anomaly had taken place. In other cases, where a satellite loses its ability to point, for example, an anomaly may result in a temporary outage which would require ground intervention. Only in a small number of incidents, where permanent physical damage is caused to the satellite and the value of the asset is impaired will an insurance claim be payable.

Over the past 25 years, space insurance claims due to space weather have amounted to US$ 275 million; just 2% of the total claims of US$ 12.3 billion. Does this mean that the space insurance community can ignore the effects of space weather? Absolutely not! Claims due to space weather may be a small proportion of the total claims paid, but an extreme space weather event still poses the ultimate low frequency, high severity risk that the space insurance community faces.

. . . an anomaly may result in a temporary outage . . .

REALISTIC DISASTER SCENARIOS

For insurance underwriting purposes, realistic disaster scenarios (RDS's) are defined[8] so that estimates can be maintained of the worst case loss that may result from a particular event. The space RDS's are being revised, but two RDS's related to space weather are currently included in the updated definitions.

In the first of these scenarios an anomalously large solar proton event is envisaged. The event would last long enough that all satellites, particularly those in geostationary orbit, would be exposed to the proton stream. The increased flux of protons would degrade the efficiency of the satellite's solar arrays. Many satellites have power margins in excess of that required, and space insurance policies include minimum power margins that must be maintained. Other policies cover satellites on a total loss only basis. Such policies will not be triggered by an attritional loss of power. Taking these factors into account, and based on the US$ 23.5 billion of insured exposure in-orbit as of January 2013, an insurance loss of approximately US$ 1 billion would be expected under this scenario.

. . . degrade the efficiency of the satellite's solar arrays . . .

The second space weather RDS considers a defective satellite design or a workmanship issue which leaves a particular system or component sensitive to space weather effects. With many satellite manufacturers launching numerous examples of the same type of satellite, differences, albeit minor, in workmanship and build quality can affect the sensitivity, thus it is realistic that a small number of satellites could become total losses. With many satellites' insured values exceeding US$ 300m and some exceeding US$ 400m, a loss of up to US$ 1.2 billion for this scenario is feasible.

These figures only represent the loss to the space insurance market. The loss of revenue for the satellite operating company, as well as from downstream services, would make the true economic impact many times greater than the insurance loss. It is impossible to determine an accurate figure, the total loss from a single extreme space weather event would be in the region of tens of billions of dollars.

. . . differences in build quality . . .

NOT ARMAGEDDON

Although we have not experienced an extreme space weather event during the Space Age, experience suggests that satellites have been able to demonstrate a good degree of resilience. An extreme event may be expected to result in a temporary outage of as many as one hundred satellites[6], or 10% of the in-orbit fleet, with a much smaller number permanently disabled by the event. With the ever-increasing reliance we place in satellite services, there is no room for complacency. We need to continue to monitor the space environment, improve our models, learn how to forecast and fully incorporate these models into the design process to make sure we are not caught off guard the next time an extreme event occurs.

. . . no room for complacency . . .

References

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Chris Train
Network Operations Director,
National Grid

National Grid takes the threat of disruption from severe space weather seriously. We work with government, industry, academia and other organisations to understand and combat this threat. National Grid has modelled the impact of an extreme space weather event on the national transmission network and has concluded that widespread damage resulting in decade-long disruption to power supplies is unrealistic. A 1 in 100 year space weather event could cause damage and some short term (on the order of 12-24 hours) disruption, but National Grid's policies and operational procedures would minimise the impact on end users of the electricity network.

National Grid operates the high voltage electricity transmission network in Great Britain, and owns the transmission network in England and Wales. In England and Wales the transmission voltages are 400 KV and 275 KV, and in Scotland 132 KV is also used. The network has over 7900 km of overhead lines and underground cables feeding in to over 900 substations, with approximately 1400 high voltage transformers. In an extreme space weather event, magnetic material that crosses the interplanetary space from the sun to the earth induces electric fields in the interior of the earth. If the local geology is resistant to the flow of electric current, then these geomagnetically induced currents are forced out of the ground, passing through the earthing cables of the high voltage transformers, flow along the transmission lines and cables, returning to earth through transformer earths at the far end of the line. The higher the voltage, the lower the resistance of the transmission lines, so the more likely it is that these induced currents will flow into the system. We are fortunate that, unlike many countries, we do not have voltages above the 400 KV level.

Effects from space weather disturbances have been known for many years, but it was only in the second half of the twentieth century that electricity grids became developed enough for effects to manifest themselves on transmission networks. The first and so far largest space weather event known occurred in 1859. The initial disturbance on the sun was observed by the British astronomer Richard Carrington – hence the Carrington Event. Clearly there was no electricity transmission network in 1859, but there was widespread disruption to the telegraph network in Europe and North America. Estimates put the severity of the Carrington Event at 1% or less. Other storms worthy of note that have occurred during the time period since the development of electric grids include the 1989 Quebec Blackout storm and the 2003 Halloween storm. In 1989 a storm about 10 times less intense than the Carrington Event caused the collapse of the grid in the Canadian province of Quebec, bringing the network down within 90 seconds. Effects were felt much less in the UK, but two transformers on the GB grid were damaged and removed from service.

. . . collapse of the grid in Quebec . . .

Electricity grids are affected by space weather events because of the effect of geomagnetically induced currents on high voltage transformers. These currents appear to the transformer as direct currents, rather than the alternating currents they are designed to operate with. They cause an enormous

> . . . well developed plans for restoration of power . . .

intensification of the magnetic field inside the transformer. There are three consequences of this saturation of the transformer's internal magnetic field. First, the magnetic energy escapes from the core of the transformer, and along the escape paths there are intense localised heating effects. The transformer's coolant overheats, setting off alarms which disconnect the transformer, and in the worst cases insulation can catch fire causing irreparable damage. Secondly, the transformer is operating outside its design parameters. It becomes a consumer of "reactive power". This causes the voltage on the network in the local vicinity to fluctuate, getting lower, and there is a danger that the voltage can collapse to zero, which leads to a power outage. There are devices on the network to stabilise the voltage against these fluctuations. However, these are sensitive to distortions – harmonics – in the waveform of the alternating current, and are protected by automatic relays. Unfortunately the third effect of the induced currents is to distort the waveform coming out of the transformer, making it more likely that the relays protecting the corrective equipment will trip, and remove the devices from service just when they are most needed. It was a combination of these two latter effects that caused the Quebec blackout in 1989.

In order to understand the effects of an extreme space weather event on today's transmission network, National Grid has modelled the effects of a Carrington-like event. This involves modelling the magnetic field caused by the impact of the coronal mass ejection, the currents generated deep within the earth's crust, the local geology below our feet, down to more than 500 km, the electrical properties of the transmission grid as the current flows up into 7900 km of transmission lines, and the effect of the induced currents on the high voltage transformers, giving their likelihood of failure. The risk that National Grid was most keen to address was the widespread damage to high voltage transformers. This is because these 3 to 4 million pound-worth machines take several years to build, and the worldwide manufacturing capability for them is low. If the UK and other major industrialised countries needed large numbers of transformer replacements it would be many years before electricity grids were as resilient and robust as they are today. National Grid's analysis shows that widespread damage is unrealistic, although some transformer damage would probably occur, on the order of 15 transformers countrywide. However, the electricity grid has more transformers on it than are needed to ensure that it is resilient to multiple failures. National Grid carries a stock of spare transformers. These factors make it unlikely that there would be significant impacts on the public. Where damage does occur the redundant transformers would take up the burden until a replacement could be installed – this is a large scale undertaking, and takes at least 8-16 weeks. It is possible that one or two small substations in relatively unpopulated areas could find their substation out of action, and special measures would have to be taken, in conjunction with the local distribution operators, to minimise the inconvenience.

More likely is the scenario of voltage fluctuations. In areas dependent on the precise structure of the particular event, the induced currents will cause localised problems on the network, which may lead to power outages. While serious for people affected, National Grid has well developed plans for restoration of power, typically within 12 hours. The effects are much more short term than the previous (fortunately unrealistic) scenario of widespread collapse.

National Grid has been preparing for extreme space weather since realising the implications from the experience of the 1989 storm. As time has passed scientific understanding of the phenomenon has increased and understanding of the potential risks has developed. Since 1999 new National Grid transformers have been built to a higher standard to improve their tolerance to geomagnetically induced currents. We have also substantially increased our spares holding. Some aspects of the design of our grid give a natural resilience against space weather: we do not use ultra-high voltages, the line lengths are relatively short, the network is highly connected, substations have extra resilience through the redundancy of operational spares. All these factors help to mitigate the risk.

National Grid continually monitors the state of the sun, looking for signs of impending space weather events. We have close contacts with space weather prediction bodies, and have a bespoke monitoring system designed in conjunction with the British Geological Survey, who also provide us with space weather forecasts. We have carefully rehearsed operational plans for minimising the impact of a space weather event through operational procedures. The operational procedures are similar in many ways to the procedures we employ in times of exceptional terrestrial weather, and National Grid has an exemplary track record in managing these risks.

One mitigating technology we have not yet used are blocking devices. These claim to be able to interrupt the flow of the induced currents while allowing the normal alternating current to flow unimpeded. Such devices are at present in their infancy – only one manufacturer has developed such a device – and there is much testing and trialling of the technology to be done before National Grid decides whether such devices are suitable for our system. We are keeping a close watching brief on these developments.

The science of space weather and its impacts on our technological infrastructure is developing fast, but much remains to be learnt. National Grid is at the forefront of international efforts to understand and prepare for such events. We work closely with partners in government, industry, academia and international partners to develop the knowledge and expertise to protect out customers and our country against this and other threats.

> . . . National Grid has an exemplary track record . . .