



BRIEFING

# SPACE WEATHER

Its impact on Earth and implications for business



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**BRIEFING**

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# FOREWORD

FROM THE PERFORMANCE MANAGEMENT DIRECTOR, LLOYD'S



Space weather<sup>†</sup> is not science fiction, it is an established fact. When tourists travel to Scotland or Norway to view the Northern lights, what they are really viewing is a spectacular storm in our atmosphere. And these storms, as well as other events, outlined in this report, have an impact on earth.

Nor is space weather a problem that we can consign to the future, it is something we need to consider now. Scientists predict a spike in strong space weather between 2012 -2015. In terms of cycles, we are in late autumn and heading into winter.

Lloyd's are publishing this report so that businesses can think about their exposure to space weather as we move into this period. Space weather is not a new phenomena, but over most of the last few millennia, it has had limited impact on human existence. However, it does affect machines – potentially anything powered by electricity generation, which would affect everything from hospital systems through to banking, and also machines using wireless technologies, such as GPS, which are critical in many types of transport. Some of the impacts of a single event, such as a spectacular geomagnetic storm could be highly dramatic in terms of disabling power grids in a short space of time. But there is also a slower collateral effect of exposure of equipment and systems, and people, to radiation

from space. For example, airlines routinely monitor airline crew for radiation exposure, which is a by product of space weather at high altitudes. But many risks need more exploration, one of the issues highlighted in this report is the exposure of very frequent flyers to radiation from space weather.

Space weather started to have an impact on human life back in the 19th century when early telegraph lines were affected. Since then, we have become increasingly reliant on machines which make us more and more vulnerable to space weather.

It is impossible to say for sure what the impact of the coming Space weather winter will be on earth. It may be a mild affair, or it may be the space equivalent of blizzards and floods. The worst storm on record, the Carrington event of 1859 would, according to a report by the US National Academy of Science cause extensive social and economic disruption if it occurred today.\*

The purpose of this report is for businesses to look at their potential exposure to space weather and plan accordingly, because it is not just the plot of a Hollywood movie, it is a real risk for today's businesses.

## **Tom Bolt**

Performance Management Director  
Lloyd's

<sup>†</sup> Space weather describes disturbances caused by solar activity that occurs in near earth-Earth space.

\* National Academy of Sciences Severe Space Weather Events - Understanding Societal and Economic Impacts.

# EXECUTIVE SUMMARY

## **1. SPACE WEATHER DESCRIBES EVENTS THAT HAPPEN IN SPACE, WHICH CAN DISRUPT MODERN TECHNOLOGIES**

Like weather on the Earth, Space weather comes in different forms and different strengths. However, space weather is governed by an 11-year solar cycle that allows us to predict, at some level, when effects are likely to be most severe. This period is called 'solar maximum' and is next likely to occur between 2012 and 2015.

## **2. THE GROWTH OF TECHNOLOGIES HAS LEFT SOCIETY MORE AT RISK FROM SPACE WEATHER**

Previous periods of solar maximum have varied in their severity. However, as we become more reliant on modern technologies (and as systems become more interconnected) a major space weather event in the next 3 years could disrupt unprepared businesses.

Although we have evidence of space weather existing for centuries, it poses a much greater threat today because of the emergence of vulnerable technologies. The first example of the impact of space weather on technology was the electric telegraph, arguably the Victorian equivalent of the internet. This was followed by the telephone at the end of the 19th century and radio communications in the early part of the 20th century. Since the 1950s there has been a steady growth in the use of advanced technologies by business and government.

## **3. SPACE WEATHER COULD POTENTIALLY CREATE HUGE DISTURBANCES IN THE TRANSPORT, AVIATION AND POWER SECTORS**

Electrical power, in particular, is vulnerable to space weather and is of course of critical importance to modern economies and societies. A number of space weather incidents have already disrupted electrical transformers and grids in Canada and South Africa and, following these, the sector has introduced mitigation practises. However, more could be done: particularly to understand the risk from both extreme events (for example, a major magnetic storm) and low-level risk (often a cumulative build up of minor damage from smaller storms).

## **4. ALL GPS SIGNALS ARE VULNERABLE TO SPACE WEATHER, WHICH IMPACTS ON, FOR EXAMPLE AVIATION NAVIGATION SYSTEMS**

Space weather also has a major impact on aviation, primarily because it interferes with navigation; indeed all GPS systems are vulnerable to space weather. This is a particular problem in polar regions. Airlines are developing good responses to this, especially on transpolar flights. Space weather can also increase radiation levels on board planes; particularly long-haul flights because they fly at higher altitudes. This could affect both flight crew and very frequent flyers and needs continued close surveillance by airlines.

## **5. SPACE WEATHER CAN ALSO DISRUPT PIPELINES AND RAILWAY SIGNALS**

It can cause problems such as corrosion on pipelines and incorrect signal settings on railways. Again, there are means to mitigate these effects, but they usually require keeping back-up systems, which adds to operational costs.

## **6. A VERY SEVERE OUTBREAK OF SPACE WEATHER COULD CREATE A SYSTEMIC RISK TO SOCIETY**

Because space weather affects major global systems, such as power and transport, a very severe outbreak presents a systemic risk. For example, a loss of power could lead to a cascade of operational failures that could leave society and the global economy severely disabled. Governments own only 5% to 10% of critical infrastructure, so businesses have a responsibility to ensure their systems are adequately protected.

## **7. BUSINESSES AT RISK FROM SPACE WEATHER NEED ACCESS TO RELEVANT EXPERTISE**

This may be done by expanding in-house engineering expertise or by employing specialist service providers. Whichever route is followed, it is critical to have access to measurements and forecasts that allow businesses to adapt to and mitigate the effects of space weather. This will also require better understanding of the science of space weather and its representation of that science in computer models.

## **8. FINDING DEFENCES AGAINST SPACE WEATHER MAY ALSO PROVIDE BUSINESS OPPORTUNITIES**

Specialist businesses can provide information and services to help other businesses at risk from space weather. But there is also an opportunity for those businesses at risk to use their understanding of space weather impacts to gain a competitive advantage by improving the resilience and the performance of their business systems.

# INTRODUCTION

Space weather describes disturbances that occur in near-Earth space, which can disrupt modern technologies. It is a natural hazard to which human civilisation has become vulnerable, through our use of advanced technologies. Businesses are exposed to these new risks whenever they adopt new technologies that are vulnerable to space weather. So, it is important to understand and assess these risks and weigh them against the benefits of new technologies.

The current level of awareness of these risks varies markedly from sector to sector. There is good awareness in the satellite industry, since space systems are heavily exposed to space weather. Awareness in other business sectors is patchy and is usually raised after problems have occurred, rather than through a systematic approach that anticipates problems and reduces costs through early and well-targeted mitigation measures.

The risks posed by space weather are now magnified through what some commentators have called “creeping dependency”, which means the growth of interconnected systems that business and other activities rely on. Modern businesses are rarely self-contained. They often rely on other businesses to supply both raw materials and a wide range of services; for example, energy supply and distribution services (see Figure 8). This leads to increasingly interconnected and interdependent systems. Therefore a space weather event could have wider regional and even

global impacts: by triggering cascading failures across systems. A key example of this dependency is our reliance on secure electric power. Space weather can (and has) caused significant disruption to supplies on regional scales and could affect national systems over extended periods of time.

Space weather, like ordinary weather, varies markedly in its severity. This leads to a range of business impacts. Mild disturbances are unlikely to cause major disruption but can cause minor problems as well as cumulative wear and tear on vulnerable equipment. It is valuable for business to be aware of these minor disturbances as it enables rapid diagnosis of minor problems and better estimation of equipment lifetime, both of which can help to control costs. Major disturbances are much more likely to disrupt business activities, and therefore businesses at risk from space weather need to plan how they will respond to that risk. The planning should reflect scientific knowledge of the risk levels, especially the longer-term changes that arise on timescales of decades or more. It is dangerous to base risk assessment on short-term experience as that may be during periods of mild conditions. Between 2006 and 2010 there has been the lowest level of space weather activity for nearly 100 years. There is also much historical evidence suggesting that severe space weather events have been unusually rare over the past 50 years, and there are concerns that we will see more frequent events in the coming decades.

## PART 1

# THE SCIENCE OF SPACE WEATHER

Solar flares are spectacular explosions on the Sun's surface caused by the release of magnetic energy in the solar atmosphere.



Space weather comprises a wide variety of phenomena, which cause different effects. These effects are analogous to meteorological phenomena such as rain, snow, lightning, wind and turbulence. However, the speed, size and scale of space weather effects are not matched in terrestrial weather. Because of this there is no single solution to space weather risks; instead, there are a number of solutions.

The intensity of these space weather phenomena is much influenced by an 11-year cycle of solar activity. This is traditionally measured by counting the numbers of sunspots - spots on the face of the Sun that appear dark because they are cooler than the surrounding regions. At the maximum of the solar cycle, violent events are common on the Sun. When those events eject solar

matter and energy towards the Earth they produce space weather phenomena, such as intense magnetic and radiation storms. At the minimum of the cycle the Sun is usually (but not always) much quieter, so the Earth is more exposed to the steady flows of matter and energy from the polar regions of the Sun and from outside the Solar System. These produce smaller (but still dangerous) space weather effects on Earth, including long-lasting increases in radiation and recurrent magnetic storms. The behaviour of the solar cycle since 1960 is shown in Figure 1.

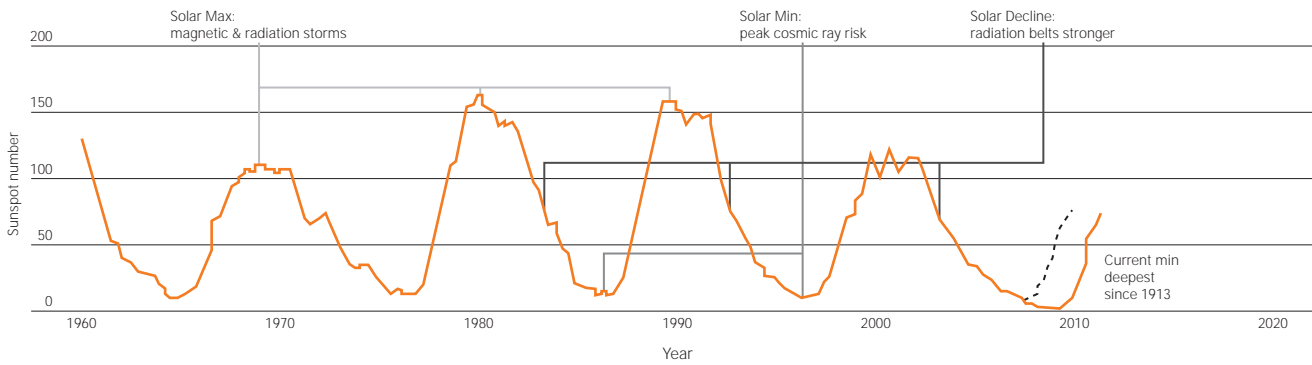


Figure 1. **Observed and predicted sunspot numbers from 1960 to 2020** - showing how space weather impacts change with the 11-year cycle. To the surprise of scientists, the start of the next solar maximum has been delayed by two years, as shown by the difference of the dashed and solid lines.

### Magnetic storms

The Sun emits a low density<sup>1</sup> wind of ionised matter (plasma) that fills the Solar System. The Earth is normally shielded from this 'solar wind' by its magnetosphere. However, the solar wind is sometimes enhanced by coronal mass ejections (CMEs): high-speed bursts of denser material ejected from the Sun when the magnetic fields in the Sun's atmosphere become unstable. They are most common near solar maximum. CMEs contain strong south-pointing magnetic fields (ie opposite to the Earth's magnetic field) and can overcome the magnetospheric shielding, allowing the CME's energy to reach the Earth. This intensifies electric currents that flow within the magnetosphere, causing rapid changes in the Earth's magnetic field (hence 'magnetic storm'). These changes can disrupt the operation of power grids, pipelines, railway signalling, magnetic surveying and drilling for oil and gas.

These electric currents also produce the aurora borealis (or northern lights). The electrons that form part of these currents interact with oxygen atoms in the upper atmosphere to produce the bright red and green glows seen in these spectacular natural phenomena.

Magnetic storms also heat the upper atmosphere, changing its density and composition and disrupting radio communications that pass through this region.

- A key example is changes in the density of the ionosphere – a layer of plasma (ionised material) in the upper atmosphere. Radio signals crossing the ionosphere are delayed, and this delay varies with the density along the signal path. This is critical for satellite navigation: satnav receivers work by measuring the time of arrival of radio signals from at least four satellites (and preferably more). Satnav receivers must apply an ionospheric correction

for positions; for example, using correction data included in the signal or using a 'dual-frequency' receiver that directly estimates the density.

- Magnetic storms also increase the amount of turbulence in the ionosphere, especially in polar and equatorial regions. This causes scintillation (or 'twinkling') of radio signals from satellites, which degrades signals. The effect is critically dependent on the quality of the receiver. Better (and usually more expensive) receivers are more likely to keep track of the strongly varying radio signal.

Severe magnetic storms, caused by large CMEs travelling at high speeds towards the Earth, are the most dangerous of the space weather phenomena because of the threat they pose to power grids and radio-based technologies such as satellite navigation. Because of this they are a major topic for scientific research. In particular, new observing techniques being developed by UK, French and US scientists working on NASA's STEREO mission are improving our ability to predict CME arrival at Earth and provide better warnings to power grid operators and many other business users.

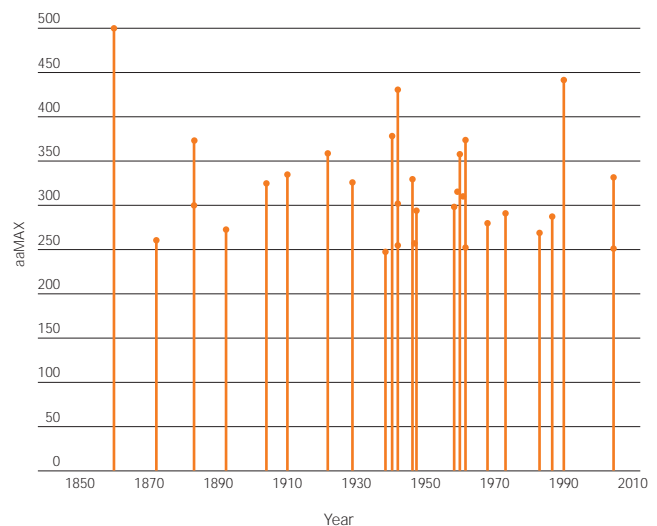


Figure 2. **Timeline of major magnetic storms from 1859 to 2010.** The vertical lines are estimates of storm strength using the AA\* index<sup>2</sup> based on magnetic data from Europe and Australia. The largest storm ever recorded known as the Carrington Event of 1859 is on the far left

## Solar radiation storms (solar energetic particle events)

The Sun occasionally produces bursts of charged particles at very high energies (see Box 1). These are a major threat to spacecraft as they can disrupt and damage electronics and power systems. Some of these particles enter the Earth's atmosphere, where they collide with oxygen and nitrogen molecules in the atmosphere to produce neutrons. During strong events these neutrons can travel to the Earth's surface and raise radiation levels above normal. This can disrupt digital systems in aircraft and on the ground and is a significant health risk for aircrew and passengers. Radiation storms can also produce an atmospheric layer that absorbs high-frequency (HF) radio waves across polar regions.

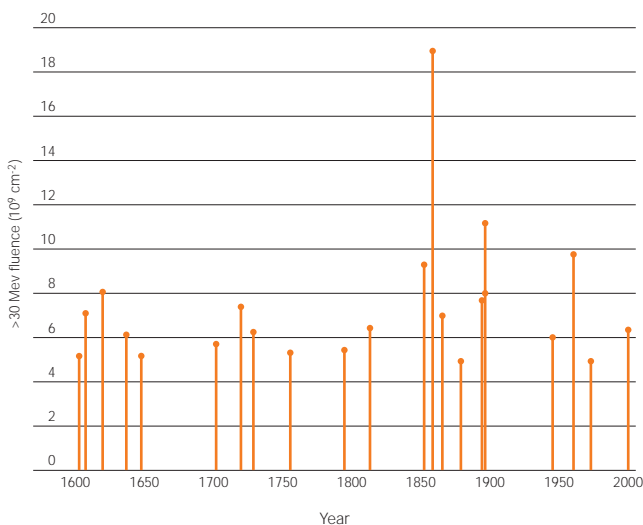


Figure 3. **Timeline of major radiation storms from 1600 to 2010.** The vertical lines are estimates of storm strength (in billions of solar particles per square centimetre) reaching Earth. Data before 1970 estimated from ice core data and recent data from space measurements. The largest peak is again due to the Carrington Event of 1859.

### Box 1. Energetic particles

Space contains much dangerous radiation in the form of electrically charged particles travelling at close to the speed of light. Scientists express this energy in electron-volts: the energy an electron would gain from crossing an electric potential of one volt. Nuclear reactions (for example, in reactors and nuclear waste) produce radiation with energies of a few million electron-volts. Space radiation is much more energetic. In solar radiation storms particles with energies of 100 million or a billion electron-volts are common.

The steady flux of cosmic rays from outside the Solar System can extend to even higher energies: a trillion electron-volts or more.

Energetic particles that reach the Earth's atmosphere produce oxides of the element nitrogen, which can be trapped in ice laid down in the Greenland ice sheet. Analysis of ice cores then allows scientists to estimate when large amounts of oxides were trapped and thereby identify pre-space age radiation events.<sup>3</sup>

### Solar radio bursts

The Sun can generate strong bursts of natural radio emissions; for example, during the launch of CMEs. These can directly interfere with radio signals on Earth. Indeed, these bursts were first discovered in 1942 when they created false signals in British defence radars.<sup>4</sup> They are now an area of growing concern because of their potential to interfere with modern wireless technologies such as satellite navigation, wireless internet, mobile telephones and short-range device controls.

### Galactic cosmic rays

The Earth is also exposed to energetic charged particles that pervade interstellar space: the regions of our galaxy between the individual stars. These particles are produced by supernovae, which are very large explosions that occur when large stars collapse or when matter is transported between two closely spaced stars. When supernovae occur within our galaxy, these particles are trapped by the magnetic fields that thread through interstellar space. Some of these particles enter the Solar System and reach Earth, where they can damage spacecraft in similar ways to the damage caused by solar radiation storms. Their very high energies allow them to penetrate Earth's atmosphere and damage systems in aircraft and on the ground. The inflow of cosmic rays is influenced by the solar wind. At solar maximum the wind is stronger, so fewer cosmic rays reach the inner Solar System and the Earth. The risk from cosmic rays therefore varies in opposition to solar cycle and is highest at solar minimum.

### High-speed solar wind streams

The solar wind emitted from regions near the poles of the Sun is much faster than the wind from its equatorial regions. This fast wind originates from regions known as 'coronal holes', where the Sun's magnetic field streams out into interplanetary space. These coronal holes are

usually located in the polar regions of the Sun, so only the slow equatorial wind reaches the Earth. However, during the declining phase of the solar cycle the coronal holes migrate towards the Sun's equator. At this time the fast solar wind from the poles often reaches the Earth. At the same time the fluxes of energetic electrons in the Earth's outer radiation belt increases. We do not yet fully understand why this happens, but the association is very clear from observations over the past 40 years. The electrons from the outer radiation belt are a threat because they penetrate deep inside spacecraft, deposit electrical charge inside insulating material and can generate electrical discharges. These can generate signals that are misinterpreted by spacecraft systems. This may cause those systems to behave oddly and, even worse, they can directly damage spacecraft systems. This is a major challenge for the many communications spacecraft in geosynchronous orbit at 36,000km altitude and for the navigation satellites (GPS and Galileo, the future European global satellite navigation system) at 20,000km altitude.

### Solar flares

Solar flares are spectacular explosions on the Sun's surface caused by the release of magnetic energy in the solar atmosphere. They are sometimes associated with CMEs, with the flare occurring as, or soon after, the CME is launched. The changes in the solar magnetic fields that trigger this launch may also release energy into the Sun's lower atmosphere, causing the flare. Despite their spectacular nature, the space weather impact of solar flares is limited to a few specific effects on radio systems. The most important of these is the X-ray flash from strong solar flares. This can produce a short-lived (10 to 20 minutes) atmospheric layer that absorbs HF radio waves: blacking out HF radio communications across the whole sunlit side of the Earth. Flares can also produce extra layers of ionised material that slow down radio signals from GPS satellites, so GPS receivers calculate positions that may be wrong by several metres.

### Box 2. Satellite damage and loss

One of the major effects of space weather is its potential to disrupt satellites through radiation damage, single event effects (SEEs) (see Box 3) and electrical charging. Disruption to satellites has the potential to disrupt businesses on the ground, which are the focus of this report. For example, communications satellites - such as those run by Intelsat<sup>5</sup> and SES<sup>6</sup> - play an important

role in many aspects of the broadcasting of television and radio programmes: direct broadcast to homes; to distributors for home delivery via cable; and the provision of links for outside broadcasts.

Satellites are well-known to be vulnerable to space weather. During the space weather events of October 2003 more than 30 satellite anomalies were reported, with one being a total loss.

A recent example of the problems that can occur is the failure of Intelsat's Galaxy-15 spacecraft in April 2010. A final conclusion has not yet been reached, but this is probably due to space weather effects.<sup>7</sup> Galaxy-15 has been nicknamed the zombie spacecraft, as it no longer responds to commands but continues to function autonomously. There has been a significant risk that Galaxy-15 will accept and re-broadcast signals sent to other spacecraft. Thus, Intelsat and other satellite operators have developed procedures to manoeuvre or shutdown other spacecraft while Galaxy-15 drifts past them. The satellite builder (Orbital Sciences Corporation) is reported to be spending around \$1m on remedial actions and is facing the loss of incentive payments (ie contractual payments dependent on in-orbit performance of the satellite) worth \$7m<sup>8</sup> (although it has purchased contingency insurance to cover against this potential loss). If the spacecraft is eventually declared a total loss, there will be a substantial capital loss: Galaxy-15 was barely four years into an operational life that is typically ten to fifteen years. Given that the typical cost of a comsat is around \$250m, this loss is likely to be over \$100m.

Truly severe space weather could devastate the existing satellite fleet. It is reported that a repeat of the Carrington Event of 1859 would cause revenue loss of around \$30 billion for satellite operators.<sup>9</sup>

Fortunately such severe spacecraft failures are rare because of careful engineering design and management,<sup>10</sup> but it highlights the need for awareness of space weather with respect to satellite design and operations. There is still considerable scope for research so that spacecraft are more robust against electrical charging and radiation. Better modelling of the space weather environment is being pursued both in the US (eg as part of the Center for Integrated Space Weather Modeling<sup>11</sup>) and in Europe (through a range of projects that have just been funded under the EU Framework 7 programme).

## PART 2

# IMPACT ON BUSINESS

Space radiation is a hazard not only to the operation of modern aircraft but also to the health of aircrew and passengers.



### A) Aviation

Space weather has significant impact on commercial airline operations, especially on transpolar routes. It can disrupt aircraft communications and navigation, as well as posing a radiation hazard to people - and digital chips - in systems on aircraft (see Box 3).

#### Communications

Communication links are essential to airline operations since aircraft must maintain continuous contact with control centres as required by international aviation rules.<sup>12</sup> When flying over oceans and polar regions these links are provided by either satellite communications or by HF radio that bounces radio waves off reflecting layers in the upper atmosphere. HF radio links are often preferred by airlines because of their lower costs (they exploit natural radio reflections), but they are degraded during severe space weather events.

In the worst cases space weather causes 'blackout'. It creates an atmosphere layer that absorbs HF radio

waves, so they cannot reach the reflecting layers and HF communications fail in the affected region. Solar flares can blackout HF links for a few hours on the sunlit side of the Earth, while solar radiation storms can blackout polar regions for several days. Blackout events are a serious issue for aviation as they prevent all HF communications in affected areas. This was the case in autumn 2003, when disruption occurred every day from 19 October to 5 November.<sup>13</sup> Aircrew must determine if such disruption is due to space weather or to equipment failure and then follow appropriate procedures.<sup>14</sup> For example, the use of alternative communications systems such as satcom and inter-aircraft VHF radio links.

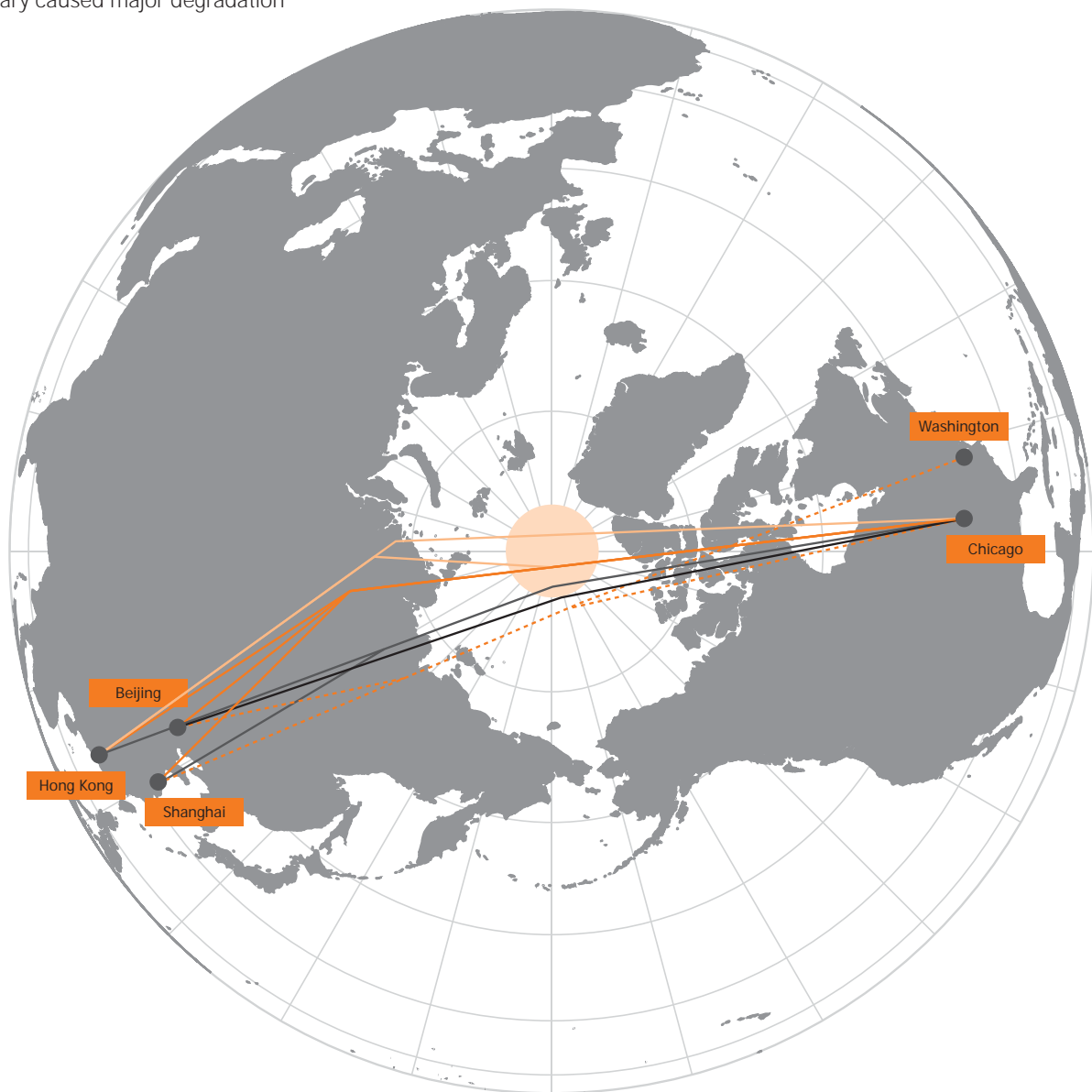
More frequently, space weather will change the frequencies and locations at which HF radio waves are reflected. During such events aircrew must alter the HF frequencies and ground stations that they use, preferably through use of modern radios that can automatically search for ground station signals. The HF Data Link - now widely used in commercial aviation - is an example of this

approach; its ability to change frequencies and ground stations enabled it to operate successfully during the October 2003 space weather event.<sup>15</sup>

Transpolar routes are particularly vulnerable to space weather effects on communications because existing communications satellites are not accessible from high latitudes (above 82 degrees). HF radio is the only option when flying over the poles. Airlines must avoid that region (see Figure 4) when HF radio links cannot maintain contact with control centres. This means that airlines have to use longer routes and therefore generate additional costs: for example, extra fuel use, extra flying hours for aircrew, and extra wear and tear on aircraft. In 2005, a series of space weather events between 15 and 19 January caused major degradation

of HF radio links in the Arctic. United Airlines had to re-route 26 transpolar flights to longer routes with better communications, but this also required more fuel and, consequently, a significant reduction in cargo capacity.<sup>16</sup>

Looking to the future, Canada is developing a satellite system, called PCW (Polar Communications and Weather), to provide satcom services in the Arctic.<sup>17</sup> Once operational (after 2016), it will provide an alternative to use of HF for aircraft communications in the high Arctic. However, the PCW orbit will also be exposed to space radiation and at risk of disruption in severe space weather conditions. It therefore remains vital, for the foreseeable future (at least on transoceanic and transpolar flights), to maintain a mix of HF and satcom.



**Key**

- Devid
- Nikin
- Aberi
- Ramel
- ..... Orvit

Official designated polar route names used in aviation

Figure 4. **Using polar routes for air traffic necessitates high-frequency radio communications at high latitudes** (circular area toward centre of figure), which can be disrupted by solar activity.

## Navigation

Reliable navigation is essential for airline operations. Satellite navigation systems offer many advantages for operators and are expected to enable more efficient use of airspace in future. But, space weather can (a) significantly degrade the accuracy of these navigation systems and (b) cause loss of the satellite signal and therefore loss of the navigation service.

In recent years, satellite navigation services in Europe and the US have been strengthened by 'augmentation systems', which generate ionospheric correction data and enable satnav receivers to measure aircraft altitudes with accuracy to approximately 10 metres. However, during the severe space weather storms in October 2003 the vertical error limit of 50 metres set by the FAA was exceeded, even with the augmentation system, and could not be used for aircraft navigation and specifically precision landings.

Loss of satellite navigation signal can occur in severe space weather conditions via:

- Strong ionospheric scintillation - where the signal varies very quickly so the receiver cannot maintain lock. This is most common in polar and equatorial regions.
- Solar radio bursts - which act as a natural jamming signal, as happened during a strong space weather event in December 2006<sup>18</sup> when the guided approach service used by airlines was lost for 15 minutes. Since then radio bursts have been rare, due to the long solar minimum, but will become more common from 2012 as solar activity increases.
- Space weather interference with spacecraft providing navigation signals (for example, GPS and Galileo). These spacecraft orbit the Earth at an altitude around 20,000km and are therefore vulnerable to radiation damage and electrical charging by the Earth's outer radiation belt.

### Box 3. Single event effects

Modern business processes and systems are increasingly controlled by software systems based on digital chips. Space radiation is a major cause of error in such devices.<sup>19, 20</sup> Neutrons produced by energetic particles from space regularly pass through them and may flip the state of digital elements. These SEEs can corrupt data and software held in chips and thereby affect the operation of systems controlled by the chip. There is a continuous low level risk of SEEs from cosmic rays and a greatly

enhanced risk during severe space radiation storms.

This risk is particularly serious for aircraft systems as the intensity of radiation from space at aircraft cruising altitudes is much higher than that on the ground. A recent example is that the effects of space radiation on avionics are being considered as a possible cause of a serious in-flight problem on an Australian aircraft in October 2008.<sup>21</sup> Nonetheless, SEEs do occur at the Earth's surface, and chip vendors will stress the need to protect critical applications of their chips; for example, by use of hardened chips.<sup>22</sup>

It is important that businesses are aware of single event risks and integrate risk mitigation into design and procurement processes. This may be done by radiation hardening of components (good chip design can significantly reduce risk), and ensuring that any control circuit affected by SEEs is outvoted by at least two correctly functioning circuits. In the UK the Defence Science and Technology Laboratory has worked with industry to raise awareness of these issues. There are also efforts to improve radiation testing; for example, a facility to simulate effects of neutrons on aircraft systems has recently been developed as part of the ISIS facility for neutron science at the STFC Rutherford Appleton Laboratory.<sup>23</sup>

However, the most intense space radiation storms can produce huge short-lived increases in radiation levels at the Earth's surface (for example, on 23 February 1956, a 50-fold increase was observed)<sup>24</sup>. Similar events could now produce such high levels of SEEs that the mitigation measures outlined above might not cope. During these rare but extreme storms it may be necessary to take additional steps to mitigate the risk. For example, reducing the height at which aircraft fly: a reduction from 40,000ft to 25,000ft would significantly reduce the occurrence of SEEs. Many short-haul flights could continue, but long-haul flights would be severely impacted, eg through increased fuel consumption. This would decrease aircraft range, thus requiring extra stops for fuel on many routes and closure of some transoceanic routes where fuel stops are not feasible.

### Radiation hazards

Space radiation is a hazard not only to the operation of modern aircraft (see Box 3) but also to the health of aircrew and passengers. Radiation from space can reach the Earth's atmosphere and create extra radiation exposure for people travelling on aircraft at typical cruise altitudes (40,000ft or 12km).

The health risk to aircrew was recognised by the International Commission on Radiological Protection in 1990 and has gradually been incorporated in recommendations by national aviation regulatory authorities. In particular, EU-based aircrew have been classified as radiation workers since 2000, and their exposure is monitored by airlines as part of the employer's duty of care.<sup>25</sup> In the US, the Federal Aviation Authority recognised the risk in 1994 and provides advice to airlines to help them manage the risk.<sup>26</sup> During the major space weather events in October 2003, the FAA issued a formal advisory bulletin indicating that all routes north and south of 35 degrees latitude were subject to excessive radiation doses.<sup>12</sup>

Aircrew are the major occupation group most exposed to radiation; no technical means exist to mitigate aircrew exposure once en-route.<sup>26</sup> In contrast, other occupation groups can be protected by heavy shielding around fixed radiation sources and good ventilation to remove airborne sources, such as radon. The mitigation measures available to airlines are to change routes or fly at lower altitudes. Cumulative radiation exposure of individual aircrew (the monitoring of which is a legal requirement in the EU) may be mitigated by moving staff from long-haul to short-haul work. This has about 50% less exposure,<sup>27</sup> as the aircraft spend less time at cruise altitudes. These mitigation measures all imply extra costs for airlines, including extra fuel and staff time when flight altitude and routes are changed and constraints on airlines' ability to deploy staff if they have to be moved to short-haul routes.

The radiation risk to passengers is usually much less than that for aircrew since most passengers spend less time in the air (the radiation dose accumulates with time in flight, especially at cruise altitudes). However, frequent flyers whose time in the air approaches that of aircrew are equally at risk. There is no legal framework for handling such risks.

## B) Power

During magnetic storms, rapid changes in the Earth's magnetic field can generate electric fields in the sub-surface of the Earth. These fields can drive electric currents into metal networks on the ground, such as power grids. The strength of these currents depends on a number of factors but, if they are strong enough, they can potentially cause loss of power. In the worst case it can permanently damage transformers. In most cases, systems protecting power grids will detect problems and switch off before serious damage occurs. However, this may lead to a cascade effect in which more and more

systems are switched off, leading to complete grid shutdown. In these situations it will take many hours to restore grid operation, causing disruption to operations and services, and potential loss of income. There will also be the additional costs of restoring grid operation. The latter may require additional skilled engineering staff.

However, protection systems will not always be fast enough to prevent serious damage to transformers, and this will reduce the capacity of the grid - and perhaps of individual power stations - to deliver electrical power. Modern high-voltage transformers are available from a limited number of manufacturers. Only a few 100 are built each year and the cost runs into hundreds of thousands of pounds. Supply is also hampered by a surge in demand from India, China, Latin America and the Middle East, where vast new grids are being constructed to cope with the increased demand for power. The supply of a replacement transformer could therefore take up to 12-16 months.

Examples of space weather impacts on grid operation have been traced back as far as 1940, when disturbances were reported on ten power systems in the US and Canada.<sup>28</sup> However, the issue only came to prominence in March 1989, when the power grid in Quebec failed in 92 seconds during a huge magnetic storm. The operators were unaware of the potential threat and were not prepared for the speed and scale of the impact. The problems triggered a cascade of protective shutdowns, so the grid went from normal operations to complete shutdown in 90 seconds. It took 9 hours to restore normal operations, during which time five million people were without electricity (in cold weather), and businesses across Quebec were disrupted. The total costs incurred have been estimated at over C\$2bn<sup>29</sup> (including C\$13m of direct damage to the Quebec grid)<sup>30</sup>. The 1989 event also caused problems in power systems elsewhere, including permanent damage to a \$12m transformer in New Jersey<sup>31</sup> and major damage to two large transformers in the UK.<sup>32</sup>

**In March 1989 the power grid in Quebec failed in 92 seconds during a huge magnetic storm. The operators were unaware of the potential threat and were not prepared for the speed and scale of the impact.**

Since 1989, the power industry has worked to improve its protection against space weather, such as adapting grid operations to reduce risk when potentially damaging space weather conditions are expected (see section 4). During a series of strong space weather events in October 2003, this work proved effective: the event did not cause the level of problems experienced in 1989. However, a true comparison cannot be made, as there is evidence that the magnetic field changes in some regions, especially the US, were a lot lower in 2003 than in 1989 (see Box 4). The 2003 events also revealed some novel aspects of the threat to power grids<sup>33,34</sup>. The loss of 14 transformers in South Africa<sup>35,36</sup> and the loss of 13% of power in the grid showed that cumulative damage due to a series of moderate space weather events - rather than a single big event, as in 1989 - can be just as harmful.

The South African experience shows that damage can also occur in countries away from the auroral regions where the majority of previous problems have been identified. This is reinforced by recent reports of space weather effects on power grids in Japan<sup>37</sup> and China.<sup>38</sup> Space weather scientists need to study all magnetospheric phenomena that can generate magnetic field changes at the Earth's surface, rather than concentrating on changes caused by the aurora alone. This enables businesses to manage the risk more efficiently by monitoring the accumulation of damage within a transformer and carrying out planned replacements before failure. Space weather awareness needs to be integrated into the procedures used to monitor and predict grid performance. Looking to the future, it is crucial to include space weather as risk factor in the development of 'super-grids' to transport electricity from remote sources; for example, solar power from the Sahara to northern Europe.<sup>39</sup> The size of these grids is a key factor determining the strength of the electric currents induced by space weather. The greater size of these grids will increase vulnerability to space weather unless resistant power grid technologies are used.

Within the UK, the Scottish power grid has been a particular focus for studies of the impact from space weather because of its proximity to the auroral zone. Scottish Power has worked with British Geological Survey (BGS) in monitoring the extra currents produced by space weather. These correlate well with the magnetic field changes measured by BGS.<sup>40</sup> More recently, the UK Engineering and Physical Sciences Research Council has funded work by BGS and Lancaster University to simulate the currents produced by space weather in power grids across the British mainland.<sup>41</sup> This is a tool that can show

where the risks from these currents are greatest and how these risks change as the grid changes.

#### **Box 4. Magnetic field changes and renewable energy**

Scientists express the strengths of magnetic fields in a unit called the Tesla. The natural magnetic fields on and around the Earth have strengths varying from 50,000 nanoteslas (ie billionths of a tesla) at the Earth's surface, to a few nanoteslas in interplanetary space. Power grids typically experience problems when the rate of change of the magnetic field exceeds a few hundred nanoteslas per minute. The Quebec failure of 1989 was triggered by magnetic field changes of around 500nT/min.<sup>42</sup> Scientists now have evidence that some historical magnetic storms (for example, in May 1921) generated changes up to 5,000nT/min.<sup>42</sup> The reoccurrence of such large changes could present a very severe challenge to grid operation. This is particularly relevant to future developments that exploit renewable sources of electricity such as wind, tides and hydro. These are often located in remote areas and therefore require long transmission lines, often over regions where the sub-surface has low conductivity. These are precisely the conditions that enhance the risk from space weather.

A recent US study analysed a range of performance data (for example: market imbalances, energy losses and congestion costs) from 12 geographically disparate power grids. These included systems in Ireland, Scotland, Czech Republic, Germany, England and Wales, New Zealand, Australia, the US and the Netherlands.<sup>43</sup> The study provides strong statistical evidence that performance of all these grids varies with space weather conditions. Variable performance can lead to variable energy prices. An interesting example of this is the behaviour of the electricity market operated by PJM<sup>44</sup> - one of the major power distribution organisations in the eastern US - during a major magnetic storm in July 2000, when space weather warnings led power companies to restrict long-distance power flows to reduce risks of grid damage. During several hours around the peak of the storm, the spot price surged from around \$20 to almost \$70 per megawatt-hour.<sup>45</sup>

Space weather threats to power grids also include the possibility of very severe events in which a large number of transformers could be damaged. In this case, full grid recovery could take many months (or even several years)

because there is limited global availability of replacements.<sup>46</sup> This would have an enormous financial impact on the wider economy, not just on power generation and distribution businesses. Current scientific knowledge suggests that such events are possible and that the relevant conditions may have occurred during historical space weather events such as those of September 1859 and May 1921. These scenarios have been the subject of major policy studies in the US<sup>47</sup> and were the subject of the first international Electrical Infrastructure Summit in London in September 2010,<sup>48</sup> and also of an associated national workshop to assess the likelihood and impact on the UK.<sup>49</sup> Such events would have a major impact on society, and governments must work with businesses to mitigate the risk. It goes far beyond the level of risk that business alone can manage. The UK National Security Strategy<sup>50</sup> published in October 2010 noted the importance of monitoring the potential impact of severe space weather on national infrastructure.

The establishment of robust estimates of the threat level for space weather was identified as an important research goal during a recent US National Research Council workshop on extreme space weather.<sup>15</sup> This is not straightforward, as we have limited statistical data and do not fully understand the physics at work in extreme events.<sup>51</sup> In the absence of robust scientific estimates, many studies have used the well-documented space weather events of September 1859 and May 1921 as exemplars of a severe space weather event. In a report by the Metatech Corporation, the latter event was modelled for the modern day US power grid system. The report found that up to 350 transformers would be at risk and more than 130 million people in the US would be left without power. The impact would also rapidly spread to other services with water distribution being affected in a few hours, perishable food being lost in 24 hours, and services as diverse as fuel supplies, sewage disposal, air-conditioning and heating also being quickly affected.<sup>52</sup>

Because globalisation means that businesses and societies are more and more interconnected, space weather damage in one sector could lead to cascade failures in other areas:

- Power - numerous systems are directly reliant on electricity, such as lighting, heating and cooking. Alternatives, such as gas, would also be affected as these require electricity to run and control their distribution systems.
- Fuel - pumping stations would shut down as these require electricity to pump the petrol up from the

underground tanks. As well as affecting domestic car use, it would have a drastic effect on the delivery of food and other essential services across the country. The loss of electricity would also shut down bulk distribution of fuel pipelines, as these also require electric pumps.

- Food - electrical refrigeration is critical in ensuring product safety in food storage and distribution.
- Water - electricity is essential to the regular supply of clean water.
- Sanitation - many sewage systems require electricity to pump sewage away from businesses and residential homes. A loss of electricity would obviously lead to potential health problems as sewage and waste water built up.
- Communications - most forms of communication rely on power. Mobile phones would eventually need connecting to a charger and email communications could only be sent via a computerised device powered by electricity.
- Medical/health - many medicines need to be kept in refrigerated locations that require electricity. Although many hospitals have back-up generators, these would not last indefinitely. Emergency response vehicles would be unable to reach destinations due to the lack of fuel and the lack of communication would make it impossible to contact anyone in the first place.
- Finance - the financial sector would be unable to conduct electronic trades, having become heavily dependent on electronic IT hardware. The retail sector is also heavily dependent on electronic transactions with a customer's bank: with credit and debit cards providing direct transfer of money at point-of-sale (whether online or in a shop), and cash points providing electronic access to cash. These retail services would be likely to shut down<sup>53</sup> during power failures, forcing customers to fall back on the use of cash or cheques. Many people have these in only limited supply, preferring to rely on modern electronic payment methods.<sup>54</sup>
- Transport - fuel based vehicles such as buses, cars and aeroplanes would soon be unable to operate after a sustained power failure. However, modern electronic trains would also grind to a halt, along with underground train networks, overground trams and even office elevators.

The longer the power supply is cut off, the more society will struggle to cope, with dense urban populations the worst hit. Sustained loss of power could mean that society reverts to 19th century practices. Severe space weather events that could cause such a major impact may be rare, but they are nonetheless a risk and cannot

be completely discounted. The critical nature of the electricity infrastructure has led to the Grid Reliability and Infrastructure Defense Act (GRID) in the US, which has now passed the House of Representatives and is awaiting discussion in the Senate. The Act requires any owner of the bulk power system in the US (the wholesale power network) to take measures to protect the systems against specified vulnerabilities, including geomagnetic storms. It also requires owners or operators of large transformers to ensure they restore reliable operation in the event of a disabling or destroying event, such as a space weather event.<sup>55</sup>

**The critical nature of the electricity infrastructure has led to the Grid Reliability and Infrastructure Defense Act (GRID) in the US.**

### **C) Transport**

Space weather has considerable potential to disrupt transport systems, especially through impacts on navigation and control systems.

#### **Road and maritime navigation**

Satellite navigation is now a standard tool for road and maritime navigation and is vulnerable to many of the same space weather problems as aviation.

In general, current road and maritime transport activities are less vulnerable to position errors (of up to tens of metres) because of normal operator awareness of the local environment, ie driver observation of the road environment and trained watch-keeping on ships. Furthermore, many countries have now established augmentation systems that reduce these errors to a few metres.

**Businesses should avoid reliance on satellite navigation as the sole source of position data.**

The major risk is the potential to lose the satellite navigation signal completely. We expect that disturbed space weather conditions will become much more common in the period from 2012 to 2015 due to increasing solar activity. Therefore it is likely users will

experience a loss of signal more often. In such cases, we may expect major position errors to arise, perhaps comparable to those caused by the transmission of competing radio signals, known as jamming. For example, a recent jamming test in the UK showed position errors of up to 20km.<sup>56</sup> Businesses should avoid reliance on satellite navigation as the sole source of position data. It is essential to have a second system that uses a different technology. A good example is the enhanced-LORAN navigation systems<sup>57</sup>, such as that now being deployed in the UK. These are based on very low frequency (VLF) radio signals from ground based systems and therefore have very different vulnerabilities compared with satellite navigation. Comparison of positions derived from satellite navigation and e-LORAN is an excellent check on the reliability of any measured position. GPS and Galileo both have similar vulnerabilities to space weather; therefore, a mix of these two systems will not provide the same protection against space weather.

#### **Rail transport**

Railways show how technological change has increased the risk from space weather. Steam trains from as little as 50 years ago were not vulnerable to space weather, but modern electric trains are. The most obvious vulnerability of rail transport is the dependence of many routes on electrical power. However, another emerging effect of space weather on railways is that it can drive additional currents in railway signalling systems (communicated via the rails). This is essentially the same phenomena as the currents that destabilise power grids and therefore occurs during major magnetic storms. There is some evidence of problems as early as 1938, when signalling apparatus on the Manchester to Sheffield line was disrupted.<sup>58</sup> There is a well-documented case, from 1982, of signals being incorrectly set in Sweden as a result of space weather.<sup>59</sup> Fortunately, engineers in Sweden were aware of the risk from space weather and had designed a safety measure. Recent studies of signalling problems in Russia provide evidence of problems caused by the great magnetic storms of 1989 and 2003, and they show how the problem is growing as more routes adopt electric signals.<sup>60</sup> It is important that operators in all countries, and not just those in the northern latitude, are aware of the increased risk of space weather and the potential effect it can have on the signal systems so that engineering staff can monitor and resolve operational problems as quickly as possible.

Looking to the future, emerging train control technologies, such as the European Train Control System,<sup>61</sup> rely on communications links based on mobile phone technology

and are therefore potentially vulnerable to interference from solar radio bursts. These links enable trains to report their speed and position to control centres and for those centres to transmit movement authorities to trains. Interference from radio bursts could break those control links and bring railway movement to a halt. This would severely disrupt railway schedules. Currently, these new control technologies are largely deployed as trials on selected lines, and most train routes still use physical signalling systems. We would therefore expect limited impact in the coming solar maximum of 2012 to 2015, but these control systems are likely to be more widespread by the following solar maximum (around 2024), so the risk could be higher. Developers and potential users of this technology will need to monitor space weather problems on the existing trial systems and look for solutions to reduce the long-term impact.

### Automotive technologies

Cars and other road vehicles contain an increasing amount of digital electronics (for example, for engine management) that may be disrupted by SEEs (see Box 3) from cosmic rays and solar radiation storms. This topic is now part of an official US study on Electronic Vehicle Controls and Unintended Acceleration;<sup>62</sup> the report is due in summer 2011 and is expected to provide a comprehensive set of recommendations on how best to ensure safety and reliability in electronic control for road vehicles. These recommendations are likely to affect future business practices across the sector. These may include; for example, improved design and testing standards to reduce the risks from SEEs.

### Summary

In summary, transport businesses are exposed to an array of space weather effects that can affect systems used to control transport activities. Businesses operating transport systems need targeted advice on these space weather risks and on the options (often quite simple) for their mitigation. (See Table one on page 22 for examples of providers of specialist advice). These options include good operational procedures and access to information on space weather conditions. Businesses supporting the transport industry can look at developing opportunities to deliver services that help operators to mitigate space weather risks.

## D) Communications

Space weather has a long history of disrupting advanced communications technologies, starting with the electric telegraph in the 19th century, extending to systems such as telephones and radio in the first half of the

20th century and now to technologies such as satellite communications, mobile phones and internet. The impact on businesses may be generalised into two groups:

1. Businesses providing communication services lose income from undelivered services and incur the costs of fixing the disruption and damage caused by space weather.
2. Businesses using communication services have a reduced ability to carry out activities that require communications; for example, operational control of business activities and communications with suppliers and customers. In all but the most severe space weather conditions, this can largely be mitigated by switching to alternative services that use more robust technologies.

The greater impact is therefore likely to be on businesses providing communication services.

### Mobile phone links are vulnerable to interference from solar radio bursts.

#### Telephones

Long distance telephone systems are historically at severe risk during strong space weather events:

- Electric currents could disrupt telephone systems based on copper wire; as in the US during a severe magnetic storm in August 1972.<sup>63</sup>
- Severe space weather effects on satellites could disrupt telephone calls routed via satellites; this happened in Canada and the US during the 1990s.<sup>30</sup>

However, the introduction of optical fibre for long distance phone lines, both over land and over transoceanic cables, has largely eliminated this risk. Only 1% of international phone traffic is now carried by satellite, with the majority being traffic to remote areas without optical fibre links.

The main space weather risks now lie elsewhere in telephone technology:

- Mobile phone links are vulnerable to interference from solar radio bursts. In June 2009 there were more than 4.3 billion global mobile phone connections.
- Mobile phone networks are often dependent on satellite navigation services for accurate timing information. This is essential to maintain synchronisation of network operation; for example, as phones move between the

cells that form the heart of every provider's network.<sup>64</sup> Therefore, network operations are at risk from space weather impacts on satellite navigation signals, as discussed in the aviation sector.

- Transoceanic cables are robust against direct interference from space weather; the cables incorporate amplifiers to boost the optical signals and ensure the delivery of adequate signals. The cables include power supply circuits that are at risk from space-weather-induced currents, in the same way as power systems and railway signals are. Voltage excursions of several hundred volts were observed on transatlantic cables during the severe space weather event in March 1989.<sup>65</sup> Fortunately, the cable power systems were robust enough to cope with these large voltages.

### Internet

The internet is relatively robust against space weather, at least in relation to links that use physical wiring (such as broadband over phone lines or standard computer cables, often called 'ethernet' cables, that are widely used in offices) rather than wireless links,<sup>66</sup> as most traffic is carried via robust optical fibre links. Internet links are rarely routed via conventional communications satellites at 36,000km altitude because this imposes signal delays that degrade internet operation.

One business, O3b Networks,<sup>67</sup> is developing satellites to provide internet services that use orbits at much lower altitudes to reduce this problem. This will allow satellite links to compete more effectively with fibre optic cables and, in particular, open up markets in areas where physical infrastructure is poorly developed. However, these spacecraft will fly in the heart of the radiation belts and therefore face a greater risk of disruption by space weather, particularly from SEEs or loss of spacecraft due to radiation damage. The developers will therefore need to use radiation-hardened spacecraft and perhaps plan for more frequent replacements of those spacecraft.

There is growing concern that the coming solar maximum will expose problems in the many wireless systems that have grown in popularity during the quiet solar conditions that have prevailed over recent years.

### Wireless communications

There has been a huge growth in the use of wireless communications over the past decade, including not

only satellite navigation and mobile phones but also wireless internet and short-range device control.<sup>68</sup> These use low-power signals in order to avoid interference with other systems, but there is evidence that they are vulnerable to interference from solar radio bursts.<sup>69</sup> There is growing concern that the coming solar maximum will expose problems in the many wireless systems that have been developed and have grown in popularity during the quiet solar conditions that have prevailed over recent years.

These wireless systems use radio signal protocols that allow radio noise to be recognised as noise, rather than as a false signal. Therefore, there is only a limited risk that the bursts will cause wireless systems to transmit false data. It is more likely that these systems will shut down for the duration of the event. Although this shutdown may be for only a few minutes, the impact on business will depend on the consequences of that shutdown. If the wireless link is part of a safety monitoring system (for example, linking smoke and fire detectors to control units), its shutdown may trigger an alarm and disrupt business activities. For example, by forcing staff evacuation. If the links are used in computerised systems that control business processes, the shutdown may halt the process and could lead to the loss of data. Many businesses rely on wireless communications to transmit data within their own organisation and also to external parties. This will be inhibited by the loss of signal, even temporarily, and could have serious consequences if the data had to be submitted according to strict deadlines, as occurs in the legal profession.

### E) Pipelines

As well as inducing currents in power grids and railway signalling, space weather can induce electric currents in long metal pipelines. The currents may interfere with 'cathodic protection systems' that reduce corrosion rates. These systems apply an electrical voltage opposite to that generated by the chemical processes that cause corrosion and thereby slow the corrosion rate. Space weather reduces the effectiveness of this protection, thus shortening the lifetime of pipelines. The effects are well known in pipelines in areas close to the auroral zone, such as Alaska and Finland, where strong electric currents (up to 1000 amps) are induced by electric currents associated with the aurora<sup>30</sup>. Some of the world's longest pipelines pass through these high latitude areas, with the world's longest pipeline running 3,800 miles from Eastern Europe to the northern Ural Mountains and the Trans-Alaska pipeline running

800 miles from the oil fields of the Arctic Ocean to the southern coast of Alaska. There is limited knowledge about space weather effects on pipelines at lower latitudes, although problems with protection systems at Grangemouth refinery in Scotland were reported during the major magnetic storm of March 1989.<sup>70</sup> A recent study of Australian pipelines shows that space weather has a significant influence on the electrical voltage of pipelines, even at mid- and low-latitudes.<sup>71</sup> The study proposes new methods for assessing the effect of space weather on pipelines and thus provides pipeline operators with better ways to integrate space weather into the monitoring of pipeline corrosion. Better knowledge can help businesses improve the management of corrosion risks, the assessment of the remaining capital value in an ageing pipeline and the planning of replacement pipelines.

### F) Oil and mineral industries

Magnetic measurements are widely used to search for natural resources within the Earth and also to guide drilling to locate these resources. The measurements are used to determine the orientation of the drill string and therefore to guide the direction of drilling. Magnetic storms caused by space weather can disturb the magnetic field, leading to reduced drilling direction accuracy. Many of the leading businesses involved in drilling, such as BP, Shell, Schlumberger, Statoil and ConocoPhillips, seek information on near-time geomagnetic conditions so they can schedule surveys during quiet periods. They will often avoid surveys in disturbed conditions as the results produced may be worthless. During the 1989 magnetic storm, one North Sea exploration company reported that instruments used to steer drill heads 'down well' had experienced swings of around 12 degrees.<sup>72</sup> These businesses must weigh the cost of stopping drilling operations (costing many hundreds of thousands of dollars per day) against the costs that might arise from errors in the path of the drill string, particularly the risk of intersecting other well paths, which can lead to blow-outs.

The use of magnetic sensors to measure orientation is now moving into the consumer market. Technological advances are allowing miniature magnetometers to be included in devices such as smart phones and therefore support applications that exploit orientation data (for example the compass application on iPhones). The business role of these applications is not yet clear, so it is too soon to assess the impact from space weather. However, it is a rapidly developing market, so that impact should be monitored.

**Magnetic storms caused by space weather can disturb the magnetic field, leading to reduced drilling direction accuracy.**

### E) Finance

It may seem strange to suggest that the finance sector is at risk from space weather, but there is a risk because of the increased dependence of financial activities on advanced technologies. Time-stamping of financial transactions is critical to the operation of many financial markets. In general, these timestamps are derived from satellite navigation services and sometimes via intermediary services on the internet. They are therefore vulnerable to disruption of access to those satellite services by space weather; for example, loss of signal in severe space weather conditions. Current moves towards near instant automated trading are likely to increase vulnerability to such timing errors and therefore to the effects of space weather.

As mentioned earlier, the loss of power can affect the retail sector, which relies on electronic cash transfers. However, solar radio bursts also pose a potential problem where portable credit card machines use wireless links to transmit and receive transaction data, as these links may be jammed during radio bursts.

## PART 3

# BUSINESS RESPONSES

The ideal response to space weather risks is to build robust systems that can operate through bad space weather conditions.



As we have shown in the previous section, many businesses using advanced technologies are at some risk from space weather effects. This can range from modest effects that constrain just the business performance, through to effects that permanently damage business assets or seriously disrupt performance. This requires a tailored response focused on the needs of each business. Fortunately, there are a wide range of strategies to manage the risk of space weather effects that businesses can adopt.

### **Building in protection**

The ideal response to space weather risks is to build robust assets and systems that can operate through bad space weather conditions. This approach is used widely in the space industry as this sector has a long experience of these risks and cannot easily repair damaged hardware on spacecraft. Standards in

spacecraft construction strongly emphasise the need for robustness against space weather. Spacecraft are typically designed to withstand space weather up to a high level. As a result, there is only a low probability (typically 5%) of experiencing conditions worse than that high level over the planned spacecraft lifetime. However, it is worth noting that this acceptable 5% failure rate equates to a 1 in 200 year event, which is the minimum return period that most regulators require insurers to capitalise for. Consequently, Lloyd's regularly requires its managing agents to submit data detailing the effect of a probable scenario involving an extreme solar radiation storm.

The building of robust systems will impose extra costs on business, and some measures may reduce the capacity of businesses to deliver services to customers, therefore reducing potential income.

Other examples of protection against space weather:

- Augmentation networks are used to improve accuracy of satellite navigation systems. Satellite-based augmentation networks are now used by airlines for accurate navigation in Europe<sup>73</sup> and the US.<sup>74</sup>
- Special devices are used to reduce or prevent entry into power grids of currents induced by space weather. For example, the Hydro-Québec grid in Canada installed blocking capacitors during the 1990s to reduce the risk of a repeat of its 1989 failure.<sup>30</sup> Similar work was carried out by the OKG generation company in Sweden (now part of E.ON Sverige AB) following a series of space weather problems in the 1990s.<sup>75</sup>
- Triple-redundant circuits are seen in electronics: any one circuit affected by a single event effect will be outvoted by two correctly working circuits. Chip manufacturers are increasingly offering chips with this protection built in.<sup>76</sup> The initial market is for space applications, but similar protection is needed for avionics and safety-critical electronics in ground-based systems.
- High-quality satnav receivers can be used to reduce signal loss during strong ionospheric scintillation. There are expert efforts underway to raise awareness and provide advice on how users can survive the next solar maximum.<sup>77</sup> In particular, on how to choose receivers that can accurately track satnav signals even during strong scintillation.
- High precision local clocks to enable time-sensitive services (for example, mobile phone networks) are being adopted, so these services operate robustly without frequent access to satnav or internet time services. This was described in 2008 as “the best kept secret in telecoms”.<sup>78</sup>

## Adapting operations

As mentioned throughout section three, an important response to bad space weather is to alter the normal pattern of business activities so that the impact of space weather is significantly reduced. There are many cases where such adaptations can greatly reduce the risk of disruption. Examples include:

- Re-routing of polar flights to longer routes. United Airlines have reported that they routinely use space weather data to make tactical decisions (4 to 6 hours before take-off) about routes to be used.<sup>15</sup>
- Reconfiguring power grids so that power is routed over lines at lower risk from space weather. For example, the PJM grid in the eastern US<sup>43</sup> has reported that it can greatly reduce space weather risk - given 15 minutes warning<sup>15</sup> - through measures such as switching to

nearby generators and load shedding.

- Changing the operational frequencies used on HF radio links. Services to advise on this are available in Australia<sup>79</sup> and the US.<sup>80</sup>

Similar to the first approach, adapting business operations can incur extra direct costs. For instance, the additional work needed to obtain the relevant space weather data alone will increase operational costs.

### Box 5. Space weather standards for aviation

Airlines need space weather information in forms appropriate for use by both aircrew and ground staff. Given the particular relevance of space weather to transpolar routes, the needs of these users are being assessed within the Cross Polar Working Group studying improvements to air traffic services in the Arctic.<sup>81</sup> By 2015, it is anticipated that this will lead to the deployment of international standards for provision of space weather information. This will be used in aviation and for integration with next-generation systems for aircraft traffic management such as SEASAR<sup>82</sup> in Europe and NextGen<sup>83</sup> in the US.

In addition, businesses will incur indirect costs through the need to establish operational procedures to monitor space weather conditions and initiate adaptation measures when needed. These costs may be minimised by integration with existing procedures that respond to other external conditions; including, adverse weather conditions such as heavy rainfall or cold and icy winters.

This approach relies on obtaining information on space weather conditions and converting to a useful format. There are a wide variety of sources of information, many of which are listed in Table one.

**Table 1. Examples of existing space weather services**  
 (those marked with an asterisk are members of ESA's SWENET system)

General purpose services - These provide access to data and predictions on space weather conditions. The data is usually expressed in scientific terms, so the application to business use requires some expert analysis.	
SWPC, Space Weather Prediction Centre (US)	<a href="http://www.swpc.noaa.gov">www.swpc.noaa.gov</a>
SWENET, Space Weather European Network (ESA)	<a href="http://www.esa-spaceweather.net/swenet">www.esa-spaceweather.net/swenet</a>
IPS Radio and Space Services (Australia)	<a href="http://www.ips.gov.au">www.ips.gov.au</a>
ISES, International Space Environment Service	<a href="http://www.ises-spaceweather.org">www.ises-spaceweather.org</a>
Specialist services - aviation	
SolarMetrics, Professional Space Weather Services for Aerospace	<a href="http://www.solarmetrics.com">www.solarmetrics.com</a>
QinetiQ Atmospheric Radiation Model	<a href="http://www.qarm.space.qinetiq.com">www.qarm.space.qinetiq.com</a>
Specialist services - power	
GIC Now!*	<a href="http://www.aurora.fmi.fi/gic_service/english/index.html">www.aurora.fmi.fi/gic_service/english/index.html</a>
GIC Simulator*	<a href="http://www.spaceweather.gc.ca/se-gic-eng.php">www.spaceweather.gc.ca/se-gic-eng.php</a>
Solar Wind Monitoring and Induction Modeling for GIC	<a href="http://www.geomag.bgs.ac.uk/gicpublic">www.geomag.bgs.ac.uk/gicpublic</a>
Metatech Corporation, Applied Power Solutions Division & Geomagnetic Storm Forecasting Services*	<a href="http://www.metatechcorp.com/aps/apsmain.html">www.metatechcorp.com/aps/apsmain.html</a>
Prototype GIC Forecast Service*	<a href="http://www.lund.irf.se/gicpilot/gicforecastprototype">www.lund.irf.se/gicpilot/gicforecastprototype</a>
Specialist services – oil and mineral prospecting	
BGS Geomagnetism Applications and Services	<a href="http://www.geomag.bgs.ac.uk/services.html">www.geomag.bgs.ac.uk/services.html</a>
Specialist services - pipelines	
Space Weather Service for Pipelines*	<a href="http://www.spaceweather.gc.ca/se-pip-eng.php">www.spaceweather.gc.ca/se-pip-eng.php</a>

Basic scientific information on space weather conditions can be obtained from a range of providers. Much of this is freely available via publicly funded services, in similar ways to the public provision of basic meteorological data. The critical step is to understand how this can support business decisions. This will require either the development of in-house expertise or the procurement of external expertise from specialist services such as those listed in Table 1. Access to space weather information should improve in the coming years, as Europe and the US have initiated 'space situational awareness' programmes to provide services that ensure good awareness of conditions in space, including space weather (see Box 6).

### **Box 6. Space situational awareness**

There is growing recognition that our modern civilisation is vulnerable to hazards from space, including possible collisions between objects in orbit, harmful space weather, and potential strikes by natural objects that cross Earth's orbit. To mitigate these hazards we need good awareness of conditions in space. This is the purpose of space situational awareness (SSA): the provision of timely and accurate information, data and services regarding the space environment, and particularly regarding hazards to infrastructure in orbit and on the ground. The US established its SSA programme some years ago and runs it as a cross-agency programme, including key players such as NASA, National Oceanic and Atmospheric Administration (NOAA), Department of Defense and Department of State. The European SSA programme was established in January 2009 as an optional programme within ESA,<sup>84</sup> with strong engagement by EU bodies. The ESA programme is now assessing needs of customers in both public and private sectors and studying the means to deliver them.

### **Fixing problems**

It can be difficult to eliminate all space weather impacts by building robustness in advance and/or adapting business activities. Some space weather impacts are not open to direct mitigation (for example, the blackout of HF radio communications) and other impacts may sometimes be so strong that they overwhelm prior measures (for example, a very intense radiation storm may cause simultaneous failures in parallel redundant systems). In these circumstances, businesses need to be able to fix space weather problems quickly as part of their business continuity planning.

When space weather conditions are disrupting operational processes, businesses can switch to alternative technologies that are unaffected. Examples include using landline telephone links instead of mobile phones, or using satellite communications instead of HF radio during blackouts.

Some of these solutions may incur extra costs so should only be maintained for the duration of bad conditions. In general, businesses should consider the availability of such back-up systems as part of their overall business continuity plans. If company business continuity processes exist, the switch to a back-up may occur automatically. Nonetheless, it is important that operations staff are aware of the switch-over - and why it has occurred - so they can verify that business operations continue as required and can return operations to normal once the space weather conditions have passed. For example, companies operating HF radio stations need the capability to distinguish space weather problems from technical problems with their equipment (see Box 7).

### **Box 7. Radio communications for transatlantic flights**

Radio communications to aircraft crossing the Atlantic regions to the west of the British Isles have long been provided by Shannon Aer Radio. In the 1980s, they recognised a need to be able to check if problems with their HF radio links were due to space weather events or other technical problems. At that time, information on space weather was not readily available outside the specialist scientific community, so they established contact with ionospheric scientists based at the Rutherford Appleton Laboratory in the UK. This allowed them to seek advice by telephone whenever needed. This service is now generally provided by the internet.

In some cases, the technologies affected by space weather will resume normal operation of their own accord when the bad conditions pass. This applies when space weather disrupts operational environments rather than equipment; for example, disturbances of the upper atmosphere that interfere with HF radio and satellite navigation and also magnetic disturbances that disrupt directional drilling. Drilling companies subscribe to real-time geomagnetism services, such as that provided by British Geological Survey,<sup>85</sup> so they know when to resume drilling as well as when to stop. In other cases space weather directly disrupts equipment; for example,

power and satellite operations. In these cases it is vital to identify the affected equipment and take appropriate remedial measures. If one is lucky this may just be a straightforward restart. The Quebec power failure of 1989 is an example of this: most equipment was protected by the automatic switch-off, so the restoration of electric power required only a restart of the grid.<sup>86</sup> But in less fortunate cases, it may be necessary to isolate the equipment so that it cannot cause further harm and then take time to fix the problem.

Just as in the adaptation approach, businesses need to be able to access information on space weather conditions. Awareness of space weather conditions will allow businesses to ensure teams are ready to recognise and address problems as they occur, to strengthen operations teams if a spate of problems is expected, and to have highly experienced staff available to provide advice on difficult problems. Businesses that already have continuity procedures for dealing with problems caused by normal weather conditions may find it helpful to approach space weather in a similar way. This may be especially important in transport businesses and in sectors that employ just-in-time models for the delivery of products.

### Assessment of impact

When business activities are impacted by space weather it is useful to assess what went wrong and to see what lessons can be learned.

There are many examples of this approach, where damaging space weather exposed unsuspected weaknesses in technological systems. One example of this is the transformer failures in South Africa in 2003. The sharing of knowledge from this has expanded everyone's understanding of the threat to power grids, indicating that all countries are at risk and that even modest space weather poses a potential threat if sustained for several days. It has also stimulated debate over further measures and contributed to the development of the GRID Act in the US.<sup>87</sup>

Another important example of lessons learned is the follow-up to the major loss of GPS position accuracy over the US during a severe magnetic storm in October 2003. The sharing of this knowledge has stimulated efforts to improve the reliability of position measurements. In this case, a major focus has been to improve scientific understanding of the Earth's ionosphere so that better computer models can generate more reliable ionospheric corrections needed by users of satellite navigation systems. Improving knowledge about the impacts of

space weather will be greatly facilitated by a willingness to exchange information on space weather problems. Unfortunately, this exchange is sometimes hampered by issues of commercial confidentiality, so it is important to find ways to exchange information while respecting that confidentiality. This is a particular problem in the space industry, as information on anomalies may influence market decisions about procurement of satellite services. This has particularly hampered the ability of the insurance industry to analyse the true risk of space weather to the satellites. However, the space industry has begun to address the need to share knowledge by releasing information in anonymous forms so that it cannot be used to assess the performance of a specific spacecraft. This is now being organised through the Space Data Association,<sup>88</sup> a not-for-profit body established in October 2009 by satellite companies Inmarsat, Intelsat and SES. This builds on previous ad-hoc exchanges by providing a formal structure (and governance) for information exchange. Governance is important as a means of ensuring that commercial sensitivities are respected.

There is a need to increase awareness among businesses that assessing the impact of space weather is a useful activity; especially in areas such as pipelines, railways, wireless systems and automotive technology, which would not normally consider this risk. Businesses can benefit in these ways:

- Assessment can improve understanding of the impact on technological systems used by business.
- Reduce costs by limiting interruptions and improving maintenance procedures.
- Businesses can also mutually benefit at a sector level by sharing knowledge.

Assessing the cause of a particular problem will require quick access to data on the actual space weather conditions at the time of the fault. If the business already has in-house engineering expertise to maintain core systems, it may extend that expertise to include space weather. Otherwise it may be better to employ a specialist service external to the business.

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## Opportunities

The risks posed by space weather also present a range of business opportunities. The most obvious is the provision of specialist services to help businesses mitigate their exposure to space weather risks. There are also potential opportunities for businesses that can improve their effectiveness by incorporating awareness of space weather into their processes.

The market demand for specialist services has been the subject of several studies funded by the European Space Agency. A market survey carried out in 2000 and 2001<sup>89</sup> found a strong need for services focused on customer needs:

- Potential customers were willing to pay for space weather services that convert scientific data into forms that are meaningful to operations staff with a minimum of additional training. For example, a simple index indicating the level of threat.
- It also found that potential customers were not willing to pay for scientific data. They saw that as a raw product that should be generated by public sector activities.

It seems not much has changed in the last ten years. Many existing services remain science-led and fail to provide this focus on customer needs.

This market survey was supplemented by a cost-benefit analysis carried out in 2006.<sup>90</sup> This suggested that there is considerable potential to develop a European market in specialist space weather services, especially for businesses subject to ground effects (such as induced currents) and ionospheric effects (such as HF communications in aircraft).

As our understanding of space weather impacts on business expands, so do the opportunities to provide risk management solutions, including insurance against the risks posed by those impacts. The insurance industry in particular has considerable experience of insuring space assets and includes the risk from space weather when pricing these assets. There could be a business opportunity to extend insurance to cover space weather threats to assets and services based on Earth. The immediate focus should probably be on the more moderate but frequent threats which can impose significant costs on individual customers. The severe threats that attract most media attention are fortunately relatively rare and could create such widespread disruption that government would need to play a key role in managing these risks. There may well be opportunities

for insurance, but these probably need to operate within a wider strategy set by government.

Businesses in sectors affected by space weather also have the opportunity to turn this risk to their advantage. As we have seen, space weather does not just cause disruptions, it can also cause wear and tear of equipment and influence the performance of business systems. Such impacts have been demonstrated in the power industry and there is growing evidence of impacts in other sectors, such as the oil and gas industry and transportation. Inclusion of space weather into models used by affected businesses should improve:

- Planning for the use and replacement of assets. This may lead to financial benefits, either by allowing longer use of equipment or by scheduling replacements more effectively.
- Understanding of how space weather affects system performance and therefore results in a potential competitive advantage.
- Decisions around the location of activities in terms of magnetic latitude.

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# CONCLUSIONS

There are a wide range of space weather phenomena that can impact on business activities. Reliance on more advanced technologies has made businesses more vulnerable to the effects of space weather.

The electric power sector has already done much work to respond to space weather. However, recent scientific advances show that we need a better understanding of the maximum likely risk and also a better understanding of lower-level effects that modulate the performance, and hence profitability, of power grids.

Pipelines and railway signalling experience space weather effects similar to those in the power sector. It is timely to raise awareness of space weather in both sectors before we reach the next solar maximum, especially of the lower-level effects that may have significant cost implications.

Space weather can disrupt several technologies vital to modern aviation; including, communications, navigation and digital control systems. It can also generate a significant radiation hazard for aircrew and passengers. Airlines need good knowledge of space weather to mitigate these risks in a cost-effective manner.

The US has recently launched a high-level study on the reliability and safety of digital control systems in road vehicles. That study will include the space weather risk and its report (due summer 2011) may provide valuable insights to businesses that provide and service road vehicles.

The transport sector is vulnerable to space weather disruption of technologies such as navigation and radio communications. It is important to have back-up solutions that have different vulnerabilities to space weather: for example, use of e-LORAN as well as GPS for navigation.

The vulnerability of the communications sector has declined markedly over the past 30 years with the introduction of optical fibre for long-distance communications on land and more recently across

the oceans. However, wireless communications systems such as mobile phones, wireless internet and short-range device controls are vulnerable to interference from strong solar radio bursts. These bursts will simultaneously disrupt many systems and could be very disruptive for business activities.

The finance sector is vulnerable to space weather disruption of technologies used to time-stamp financial transactions and to provide electronic access to money (credit and debit cards).

Businesses have a wide range of options for mitigation of space weather risks. These should be tailored to the needs of each business but may use one or more of the following approaches:

- Building protection into the systems at risk so they can withstand the extremes of space weather.
- Adjusting the systems at risk in advance to reduce the space weather impact during the event. This may involve temporary reconfiguration of the system.
- Being ready to respond to space weather problems, as they arise, during the event.
- Analysing what went wrong during a space weather event and applying the lessons-learned to improve the response to future events.

Most of the above options require good access to specialist space weather services that are targeted on business needs and not just the provision of science-level data.

Space weather offers opportunities for new business activities:

- The provision of services to help other businesses mitigate space weather.
- The use of space weather knowledge to improve the return from systems affected by space weather.

## REFERENCES

- <sup>1</sup> Under normal conditions the solar wind passing the Earth contains only a few particles in each cubic centimetre.
- <sup>2</sup> <http://www.ngdc.noaa.gov/stp/geomag/aastar.html>
- <sup>3</sup> Some scientists have suggested that these ice core signatures could arise from other natural sources, but this would require the other possible sources to have occurred at the same time as those well-documented space weather events, eg in 1859 and 1946.
- <sup>4</sup> Hey, J.S. Solar radiations in the 4–6 metre radio wavelength band, *Nature* 157, 47-48, 1946.
- <sup>5</sup> <http://www.intelsat.com/>
- <sup>6</sup> <http://www.ses.com/>
- <sup>7</sup> For discussion of the possible space weather effects on Galaxy-15 see the US Naval Research Laboratory report on <http://www.nrl.navy.mil/media/news-releases/75-10r/>
- <sup>8</sup> [http://www.spacenews.com/satellite\\_telecom/100722-orbitals-revenue-rises-earnings-fall.html](http://www.spacenews.com/satellite_telecom/100722-orbitals-revenue-rises-earnings-fall.html)
- <sup>9</sup> <http://dx.doi.org/10.1029/2006SW000262>
- <sup>10</sup> <http://www.intelsat.com/resources/tech-talk/solar-weather.asp>
- <sup>11</sup> <http://www.bu.edu/cism/>
- <sup>12</sup> The Rules of the Air as established by the International Civil Aviation Organisation.
- <sup>13</sup> Service Assessment: Intense Space Weather Storms October 19 – November 07, 2003, [http://www.swpc.noaa.gov/Services/SWstorms\\_assessment.pdf](http://www.swpc.noaa.gov/Services/SWstorms_assessment.pdf)
- <sup>14</sup> For example, North Atlantic MNPS Airspace Operations Manual, European and North Atlantic Office of ICAO
- <sup>15</sup> It is reported that 97% of HF Data Link messages were delivered, see <http://dx.doi.org/10.1029/2005RS003404>
- <sup>16</sup> Severe Space Weather Events—Understanding Societal and Economic Impacts, Report of NRC Workshop, ISBN: 0-309-12770-X, <http://www.nap.edu/catalog/12507.html>
- <sup>17</sup> <http://www.asc-csa.gc.ca/eng/satellites/pcw/overview.asp>
- <sup>18</sup> <http://dx.doi.org/10.1029/2008RS004039>
- <sup>19</sup> <http://www.newscientist.com/blog/technology/2008/03/do-we-need-cosmic-ray-alerts-for.html>
- <sup>20</sup> <http://news.bbc.co.uk/1/hi/7335322.stm>

- <sup>21</sup> ATSB Transport Safety Report, Aviation Occurrence Investigation AO-2008-070 Interim Factual No 2, [http://www.atsb.gov.au/media/1363394/ao2008070\\_ifr\\_2.pdf](http://www.atsb.gov.au/media/1363394/ao2008070_ifr_2.pdf)
- <sup>22</sup> For example, see <http://www.actel.com/documents/FirmErrorPIB.pdf>
- <sup>23</sup> <http://www.isis.stfc.ac.uk/instruments/Chipir/>
- <sup>24</sup> [http://dx.doi.org/10.1016/0021-9169\(56\)90135-0](http://dx.doi.org/10.1016/0021-9169(56)90135-0)
- <sup>25</sup> EU Directive 96/29/EURATOM
- <sup>26</sup> [http://www.faa.gov/data\\_research/research/med\\_humanfacs/aeromedical/radiobiology/solarradiation/](http://www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation/)
- <sup>27</sup> Henning Lubbe, Recommendations to minimize Aircrew Radiation Exposure, <http://tinyurl.com/2vawc3s>
- <sup>28</sup> Space Weather Canada - 150 Years of Geomagnetic Effects: <http://www.spaceweather.gc.ca/se-chr1-eng.php>
- <sup>29</sup> <http://www.zurich.com/NR/rdonlyres/E7A8BC6C-86D9-4C1A-ABFC-F6213EB23D73/0/SolarStorms.pdf>
- <sup>30</sup> [http://dx.doi.org/10.1016/S1364-6826\(02\)00128-1](http://dx.doi.org/10.1016/S1364-6826(02)00128-1)
- <sup>31</sup> <http://www.solarstorms.org/>
- <sup>32</sup> [http://dx.doi.org/10.1016/S1364-6826\(02\)00036-6](http://dx.doi.org/10.1016/S1364-6826(02)00036-6)
- <sup>33</sup> <http://dx.doi.org/10.1016/j.asr.2009.11.023>
- <sup>34</sup> <http://dx.doi.org/10.1111/j.1468-4004.2010.51523.x>
- <sup>35</sup> [http://www.nytimes.com/2010/08/16/opinion/16joseph.html?\\_r=2&ref=todayspaper](http://www.nytimes.com/2010/08/16/opinion/16joseph.html?_r=2&ref=todayspaper)
- <sup>36</sup> Gaunt, C. T., and G. Coetzee, Transformer failure in regions incorrectly considered to have low GIC-risk, paper presented at Power Tech 2007, Inst. of Electr. and Electron. Eng., Lausanne, July 2007.
- <sup>37</sup> <http://dx.doi.org/10.1029/2008SW000417>
- <sup>38</sup> <http://dx.doi.org/10.1029/2008SW000439>
- <sup>39</sup> For example <http://www.desertec.org/>
- <sup>40</sup> <http://dx.doi.org/10.1029/2005SW000156>
- <sup>41</sup> <http://dx.doi.org/10.1111/j.1468-4004.2010.51525.x>
- <sup>42</sup> <http://dx.doi.org/10.1016/j.asr.2005.08.055>
- <sup>43</sup> <http://dx.doi.org/10.1029/2007SW000350>
- <sup>44</sup> <http://www.pjm.com/about-pjm.aspx>

- <sup>45</sup> <http://dx.doi.org/10.1029/2003SW000005>
- <sup>46</sup> Transformers a risk to keeping the power on, see <http://tinyurl.com/2vlxmax>
- <sup>47</sup> For example, see <http://www.nerc.com/files/HILF.pdf>
- <sup>48</sup> <http://www.eissummit.com>
- <sup>49</sup> <http://www.publications.parliament.uk/pa/ld201011/ldhansrd/text/101011w0001.htm#10101110000395>
- <sup>50</sup> <http://tinyurl.com/28sdh9c>
- <sup>51</sup> <http://dx.doi.org/10.1016/j.asr.2010.02.007>
- <sup>52</sup> [http://science.nasa.gov/science-news/science-at-nasa/2009/21jan\\_severespaceweather/](http://science.nasa.gov/science-news/science-at-nasa/2009/21jan_severespaceweather/)
- <sup>53</sup> Unless those retail outlets have back-up power systems, like those that protect the central servers operated by banks and other financial institutions.
- <sup>54</sup> When Will God Destroy Our Money? [http://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=1591768](http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1591768)
- <sup>55</sup> [http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=111\\_cong\\_bills&docid=f:h5026ih.txt.pdf](http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=111_cong_bills&docid=f:h5026ih.txt.pdf)
- <sup>56</sup> Executive summary of RPT-26-AJG-08, [www.gla-rrnav.org/pdfs/gps\\_jamming\\_executive\\_summary.pdf](http://www.gla-rrnav.org/pdfs/gps_jamming_executive_summary.pdf)
- <sup>57</sup> <http://www.loran.org/about.html>
- <sup>58</sup> <http://www.solarstorms.org/SRefStorms.html>
- <sup>59</sup> <http://www.ann-geophys.net/27/1775/2009/>
- <sup>60</sup> <http://dx.doi.org/10.1016/j.asr.2010.05.017>
- <sup>61</sup> ETCS development is led by the European Rail Agency <http://www.era.europa.eu/>. ETCS use extends beyond Europe, notably to China.
- <sup>62</sup> <http://www8.nationalacademies.org/cp/projectview.aspx?key=49236>
- <sup>63</sup> <http://dx.doi.org/10.1029/1999GL900035>
- <sup>64</sup> Mobile phone technology divides the geographic coverage of every network into 'cells'. Each cell is operated by one base station. Calls must continue smoothly as phones move between cells.
- <sup>65</sup> <http://dx.doi.org/10.1029/GL016i010p01145>
- <sup>66</sup> It is sometimes stated in popular works on space weather that the internet needs accurate time-stamping to operate correctly. However, there is no evidence to support this view.

<sup>67</sup> For example, see <http://www.o3bnetworks.com/>

<sup>68</sup> Radio links to control electrically operated systems; for example, linking sensors such as thermostats and smoke detectors to system controls without the need for installing control cables (thereby reducing installation costs).

<sup>69</sup> <http://dx.doi.org/10.1029/2001RS002481>

<sup>70</sup> M. Hapgood, private communication

<sup>71</sup> <http://dx.doi.org/10.1029/2009SW000553>

<sup>72</sup> <http://catless.ncl.ac.uk/Risks/8.72.htmlsubj2#subj2>

<sup>73</sup> European Geostationary Navigation Overlay Service (EGNOS), <http://www.esa.int/esaNA/egnos.html>

<sup>74</sup> Wide Area Augmentation System, <http://gps.faa.gov/>

<sup>75</sup> [http://www.esa-spaceweather.net/spweather/workshops/proceedings\\_w2/doc/gic.pdf](http://www.esa-spaceweather.net/spweather/workshops/proceedings_w2/doc/gic.pdf)

<sup>76</sup> <http://www.electronicweekly.com/Articles/2010/08/24/49316/rad-hard-chips-the-next-generation.htm>

<sup>77</sup> GNSS and Ionospheric Scintillation, How to Survive the Next Solar Maximum <http://www.insidegnss.com/auto/julyaug09-kintner.pdf>

<sup>78</sup> <http://www.optisynx.com/OptiSynxArticleForWirelessBusinessReviewV3.pdf>

<sup>79</sup> [http://www.ips.gov.au/Products\\_and\\_Services/1/1](http://www.ips.gov.au/Products_and_Services/1/1)

<sup>80</sup> <http://www.jmg-associates-ltd.com/>

<sup>81</sup> [http://www.faa.gov/about/office\\_org/headquarters\\_offices/ato/service\\_units/enroute/oceanic/cross\\_polar/](http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/enroute/oceanic/cross_polar/)

<sup>82</sup> Single European Sky ATM Research

<sup>83</sup> Next Generation Air Transportation System

<sup>84</sup> <http://www.esa.int/esaMI/SSA/index.html>

<sup>85</sup> <http://www.geomag.bgs.ac.uk/services.html>

<sup>86</sup> The term "blackstart" is widely used to describe restart of a complete power grid

<sup>87</sup> <http://www.opencongress.org/bill/111-h5026/show>

<sup>88</sup> <http://www.space-data.org/sda/>

<sup>89</sup> <http://tinyurl.com/34ndlac>

<sup>90</sup> <http://esamultimedia.esa.int/docs/gsp/completed/C18459ExS.pdf>

## USEFUL CONTACTS

**Rutherford Appleton Laboratory**

[www.stfc.ac.uk/RALSpace](http://www.stfc.ac.uk/RALSpace)

**Lloyd's**

[www.lloyds.com/360](http://www.lloyds.com/360)

**NASA**

[www.nasa.gov](http://www.nasa.gov)

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**NOAA/Space Weather Prediction Center**

[www.swpc.noaa.gov](http://www.swpc.noaa.gov)

**UK Space Agency**

[www.ukspaceagency.bis.gov.uk](http://www.ukspaceagency.bis.gov.uk)

**British Geological Society**

[www.bgs.ac.uk](http://www.bgs.ac.uk)

**Spaceweather.com**

[www.spaceweather.com](http://www.spaceweather.com)

**Electrical Infrastructure Security Council**

[www.empcoalition.org](http://www.empcoalition.org)

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