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Space Weather and Rail: Findings and Outlook

An event co-organised by the European Commission's Joint Research Centre,
the Swedish Civil Contingencies Agency,
the UK Department for Transport, and
the NOAA Space Weather Prediction Center

16-17 September, 2015, London, UK

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Abstract

Space weather caused by solar activity can disrupt and damage critical infrastructures in space and on the ground. Space-weather impacts to the power grid, aviation, communication, and navigation systems have already been documented. Since society relies increasingly on the services these critical infrastructures provide, awareness of the space weather threat needs to be increased and the associated risks assessed. While most research on impacts of space weather focuses on the power grid, the Global Navigation Satellite System (GNSS), and aviation, railway networks are also a potential area for concern. Anomalies in signalling systems have been observed during geomagnetic storms, and rail transport depends on power, communications, and progressively on GNSS for timing and positioning.

In order to raise awareness of this topic, and to further explore the vulnerability of rail systems to space weather, the European Commission's Joint Research Centre, the Swedish Civil Contingencies Agency, the UK Department for Transport, and the US National Oceanic and Atmospheric Administration jointly organised the "Space weather and rail" workshop in London on 16-17 September 2015. The workshop was attended by representatives from the railway sector, insurance, European and North American government agencies, academia, and the European Commission. This report presents the main findings and conclusions of this workshop.

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Executive Summary

Space weather caused by solar activity can disrupt and damage critical infrastructures in space and on the ground. Space-weather impacts to the power grid, aviation, communication, and navigation systems have already been documented. Since society relies increasingly on the services these critical infrastructures provide, awareness of the space weather threat needs to be increased and the associated risks assessed. While most research on impacts of space weather focuses on the power grid, the Global Navigation Satellite System (GNSS), and aviation, railway networks are also a potential area for concern. Anomalies in signalling systems have been observed during geomagnetic storms, and rail transport depends on power, communications, and progressively on GNSS for timing and positioning.

In order to raise awareness of this topic, and to further explore the vulnerability of rail systems to space weather, the European Commission's Joint Research Centre, the Swedish Civil Contingencies Agency, the UK Department for Transport, and the US National Oceanic and Atmospheric Administration jointly organised the "Space weather and rail" workshop in London on 16-17 September 2015. The workshop was attended by representatives from the railway sector, insurance, European and North American government agencies, academia, and the European Commission.

The main workshop conclusions are:

- Extreme space weather has a global footprint and can affect multiple infrastructures at the same time.
- Interdependencies between infrastructures need to be better understood and assessed to improve the resilience to cascading effects due to extreme space weather.
- While there is evidence of past space-weather impacts on rail, awareness in the rail sector appears to be limited.
- Documented rail-system anomalies linked to space weather are confined to high latitudes.
- Vulnerabilities in rail networks exist via direct impacts on track circuits and equipment, and indirectly via dependencies on power, communications, and GNSS.
- Due to different system architectures and approaches to operations, the vulnerability of rail to space weather varies from country to country.
- The move towards more automation in future rail traffic management will likely add vulnerabilities to space weather to the rail network.
- Timing and synchronisation are key aspects for rail networks that will be increasingly provided by GNSS. Redundancies to mitigate the risks of GNSS loss are required.
- The rail sector needs to identify its vulnerabilities and subsequently the early-warning requirements necessary to better protect its assets.
- There are US and European space-weather forecasting capabilities that provide 24/7 early warning of space-weather storms.
- Further research is needed to close knowledge gaps on consequences and probabilities of extreme space weather.
- Assessing the space-weather risk can help to create preparedness and response capabilities that can also be applied to other hazard domains.
- For extreme space weather the distribution of responsibilities should be clarified to define the obligations of each stakeholder in risk reduction, emergency response and recovery.
- International cooperation for response planning is necessary to cope with extreme events that could overwhelm national response capacities.

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1. Introduction

The Sun as the main source of energy in the solar system sustains life on Earth. However, solar activity also affects the space environment near our planet and influences the Earth's magnetosphere which helps to protect life from the effects of space radiation. This phenomenon is termed space weather. When extreme space weather batters our magnetosphere and interacts with the Earth's magnetic field, disruptions and damage to critical infrastructures in space and on the ground can be the result. Space-weather impacts to the power grid, aviation, communication, and navigation systems have already been observed and documented. Since society relies increasingly on the services these critical infrastructures provide, awareness of the space weather threat needs to be created and the risks from extreme space weather should be assessed.

While most studies on the impact of extreme space weather on infrastructures are dedicated to understanding the risks to the power grid and the Global Navigation Satellite System (GNSS), there is evidence that railway networks are also a potential area of concern. During geomagnetic storms, anomalies in signalling and train control systems have been observed, and rail transport depends on the availability of power, communications, and progressively on GNSS for timing and positioning, technologies which can be degraded or disrupted during space-weather storms.

In order to address this topic, and to further explore the vulnerability of rail systems to space weather, the Joint Research Centre (JRC) of the European Commission, the Swedish Civil Contingencies Agency (MSB), the UK Department for Transport, and the US National Oceanic and Atmospheric Administration (NOAA) jointly organised the "Space weather and rail" workshop in London on 16-17 September 2015. The event aimed to raise awareness of the space-weather risk in the rail sector, discuss the potential impacts on the rail network, in particular through interdependencies with other critical infrastructures, and to identify possible mitigation options for current and future systems. This workshop is the latest in a series of dedicated awareness-raising events which have previously addressed the potential impacts of space weather on power grids and on financial systems.

The workshop was attended by over 50 participants representing the railway sector in Europe, railway associations, insurance, European, Canadian and US government agencies, academia, and the European Commission. This report summarises the main conclusions of the event. Prior to the workshop, a survey among rail operators in Europe and North America was conducted by Natural Resources Canada to capture differences in rail system types and their associated vulnerabilities. The results of this survey are shown in Annex 1. The workshop programme and the list of participants are provided in Annexes 2 and 3.

2. Space weather and its potential impacts

Space weather is often considered an emerging risk for which awareness is limited. In the first session of the workshop, speakers from NOAA's Space Weather Prediction Centre and the Rutherford Appleton Laboratory in the UK presented an overview of space weather providing both a phenomenological and consequence perspective.

There are different mechanisms through which solar activity can affect critical infrastructures. The most important phenomena that create space weather are solar flares, solar radiation storms, and Coronal Mass Ejections or CMEs. CMEs are large quantities of magnetised solar plasma consisting of charged particles that can cause geomagnetic storms if they impact Earth. Of greatest concern are fast CMEs with speeds of up to 3,000 km/s that carry a predominantly southward magnetic field. The often cited Carrington storm of 1859, which is a canonical example of extreme space weather and, by many accounts, the largest solar storm recorded, was triggered by a fast CME that slammed into Earth's magnetosphere. Major damage to telegraph systems and auroras visible as far south as Cuba were the result. Additional past evidence of space-weather related infrastructure damage and outage

shows that space weather has a global footprint and can affect multiple infrastructures simultaneously. It is therefore believed that if a geomagnetic storm similar in severity to the Carrington event were to occur nowadays the immediate and cascading effects could cause a significant and possibly long-term disruption of critical infrastructures with potentially catastrophic economic consequences. Such an event would seriously challenge a single nation's response capacities.

Extreme space weather is rare but it can have critical impacts due to society's dependence on vulnerable technologies. Geomagnetic storms caused by CMEs have potentially significant consequences on different types of infrastructures in space and on the ground. They can affect satellite operations via both surface and internal charging and create problems with orientation and satellite tracking, while aviation can experience disruptions of communications and navigation. The power grid and other grounded infrastructures, such as rail networks or pipelines, can incur damage due to the flow of geomagnetically induced currents (GIC) which is a quasi-DC electric current generated by space-weather induced changes to the geoelectric field. The GIC in the power system can lead to a cascading failure due to the loss of reactive power and subsequent voltage collapse. The blackout of the Hydro-Québec power transmission system during a severe geomagnetic storm in 1989 is an example. The worst-case scenario usually assumed under space-weather impact are local or regional power outages of hours up to a few days. However, if GIC induction damages power-grid components, such as high-voltage transformers, sustained and extended power loss is possible. Geomagnetic storms can also affect the ionosphere, generating ionospheric storms and scintillation, which affects the signal propagation from the GNSS, causing time delays, position shifts, and in the worst case loss of lock, creating major impacts on timing and positioning.

Solar flares can trigger radio blackouts and disturb the GNSS network, radar, and communications on the ground and in space. Solar radiation storms, on the other hand, can affect the electronics in digital systems through penetration of microchips, causing single-event effects, and thereby compromise satellite operations and digital systems on Earth. For aviation there is the additional risk of exposure to increased radiation doses for crew and passengers.

The predictability of extreme space weather is still limited and there is no evidence that its occurrence depends on the solar cycle¹. In fact, on several occasions strong impacts have been observed during solar minimum. In addition, the low occurrence frequency of extreme space weather renders a quantitative risk assessment very difficult. In some infrastructure sectors there is increasing awareness of the space-weather threat and their vulnerability is fairly well understood (satellite and power-grid operations, aviation). In contrast, interdependencies between vital infrastructures require a better understanding and routine assessment to improve the resilience to possible cascading effects from this type of risk.

In the United States, reducing the country's vulnerability to space weather is a national priority. Space weather is considered one of the most challenging risks and was identified as a hazard that could potentially pose a significant threat to the US economy and security. Consequently, the US National Science and Technology Council, a White House Cabinet-level Council, was tasked with developing a National Space Weather Strategy whose aim is to define high-level strategic goals for increasing preparedness to extreme space weather. Recognising the potential for major regional and even international consequences in case of a Carrington-type storm, the Strategy also includes international cooperation as a goal to foster a coordinated global response.

The key messages from Session 1 are:

- The susceptibility of society to space weather is increasing due to its reliance on services provided by vulnerable infrastructures and interdependencies between infrastructures.

¹The solar cycle is a periodic 11-year change in the sun's activity and appearance. The peak of the solar cycle is known as solar maximum and the valley of the cycle is known as solar minimum.

- In some infrastructure sectors there is increasing awareness of the risks related to space weather and their vulnerability is fairly well understood.
- In contrast to other natural hazards, extreme space weather is a large-scale event that can lead to multiple failures in different critical infrastructures simultaneously.
- Interdependencies between critical infrastructures need to be better understood and assessed to improve the resilience to potential cascading effects caused by space weather.
- Due to the global footprint of extreme space weather, there should be multilateral and international cooperation for response planning to cope with extreme events that could overwhelm national response capacities.
- The US is developing a National Space Weather Strategy to define high-level strategic goals for increasing preparedness to extreme space weather.

3. Impacts of space weather on rail

The second part of the workshop was split into four sessions, each of which aimed to address a specific issue associated with space-weather impacts on the rail network. Three of these sessions were organised as parallel discussion groups of up to 9 persons, each of which addressed the same questions posed by the session moderator.

3.1 Direct and indirect effects of space weather on rail

In this session, four speakers from Natural Resources Canada, the Finnish Meteorological Institute, the UK consultancy Atkins, and Luleå University of Technology in Sweden presented the current state of understanding of space-weather impacts on rail technologies.

For Swedish and Russian rail operations at high latitudes there is historical evidence of a number of anomalies in signalling systems that coincided with the occurrence of geomagnetic-storm conditions. The signalling systems reported false blockages (right-side failure) in sectors where no trains were present. Statistical analyses using Russian data indicate that the occurrence and duration of these anomalies correlated well with the local geomagnetic index and showed a 5-7 times higher probability of occurrence during strong geomagnetic storms. The impacts lasted from 1 to several hours. Voltage fluctuations were observed on both feeding and relay circuits of the signalling system, and impacts concerned only electrified railway parts that made use of specific transformer types, and which had different shield wire arrangements. This suggests an increased susceptibility to space weather of certain types of design. The trigger of the signal anomalies is believed to have been induced currents and/or stray currents from the ground during strong geomagnetic storms. Under these conditions, the natural electric field is large enough to reduce the operating voltage on the relay.

Studies carried out jointly by Natural Resources Canada and the Finnish Meteorological Institute aim to understand how geomagnetic disturbances can affect track circuits. These studies are based on knowledge gained from geomagnetic induction in the power grid and pipelines, and use existing information on AC interference on railway signalling. The results suggest that in case of balanced track circuits, GIC and stray currents would create common-mode interference in which the voltages in the two tracks would cancel each other and track-circuit operations would not be affected. A different situation arises for unbalanced track circuits which are characterised by a short to the ground or between two tracks. In this case, AC studies indicate that the unbalanced track circuit would experience differential-mode interference where each track has a different voltage. This voltage difference can impact rail operations. Further studies are needed to understand this effect in more detail, in addition to determining the level of geomagnetic disturbance needed to produce an impact on track-circuit operations.

Atkins carried out a multi-disciplinary study to identify the types of rail technologies and systems in the UK that may be vulnerable to extreme space weather. The study assumed that a Carrington-type event had occurred and aimed to determine the possible impacts with respect to safety and operability. Issues were identified related to power, signalling, train traction, GNSS, radio communications and track-side staff. *Power* can be impacted via DC induction that puts transformers at a risk of failure, and loss of traction current would strand electrically powered trains. While train batteries would last 90-120 minutes in the best case, toilets, air conditioning, heating and main lighting would lose power much sooner. Stations could also be affected by a power disruption. *Signalling* may also be disrupted by a power outage. Damage to track-circuit feed transformers may lead to loss in train detection and hence to right-side failure². Currents induced or directly coupled into a rail may cause wrong-side failure. It was underlined that these conclusions were not based on detailed calculations but rather on expert judgment. Also, experience showed that the failure might mutate when the train moves. The location of a train within the network could change the probability of right- versus wrong-side failure. *Train traction* issues may be related to DC in overhead line equipment that would also flow in the rolling stock main transformer where it could lead to overheating. Sensors that detect this temperature anomaly might trigger train shut down. The quasi-DC could also be interpreted as incorrect train operations by line current monitoring equipment which would also cause the train to shut down.

While loss of *GNSS* is not considered a safety concern for the UK rail network it could lead to disruptions as many dependencies are built into train systems. Systems that would be affected are the wireless GSM-R³ (a sub-system of the European Rail Traffic Management System ERTMS) and the telephone transmission systems as they rely on GPS for timing. In addition, Selective Door Opening (SDO) uses GPS to detect a train's location on a network and locks out sets of doors depending on where the train is. The Variable Traction Current Limiting also relies on GPS to activate the limiting in the train's propulsion software. *Radio communication* systems, such as GSM-R, that use directional antennas would only be disrupted during sunrise and sunset, but their loss could be critical during emergencies. The UK National Radio Network and Cab Secure Radio which are in the process of being phased out are more vulnerable and would also be affected in daytime due to their use of dipole antennas. Lastly, potential issues related to *track-side staff* are associated with rail system maintenance activities during geomagnetic storms due to the potentially unexpected activation of protection systems.

The Atkins study recommends further research to close knowledge gaps on single-event effects and their potential impacts, track-circuit interference, and GNSS dependency, in particular to understand if backup oscillators for timing are good enough to support vital train functions, such as communications. This includes a refinement of impact scenarios based on geographic variation and the potential for cascading effects. In addition, historical data on disruptions and failures in railway assets should be reviewed to identify potential space-weather links. The study also calls for the setting up of systems to notify track-side staff of space-weather related dangers to allow the implementation of appropriate safety measures. The UK Association of Train Operators and Network Rail has expressed interest in understanding how they would respond to space-weather alerts, e.g. issued by the UK Met Office Space Weather Operations Centre.

The Swedish railway network is exposed to space weather due to its high-latitude location. In the north of the country a lot of lines are single track with consequences on network congestion. The availability and operability of these lines is therefore critical. The objective is to achieve 24/7 availability and no rail-traffic disruptions by 2040. The rail network is becoming more and more complex with a number of dependencies on other infrastructure services that are space-weather prone. For example, geometry cars and maintenance machines cannot be used if GPS is lost. This is particularly critical because in Sweden maintenance activities are restricted to 2-3 months per year due to weather and there are questions as to how much maintenance capacity is lost every year

²A right-side failure is a failure condition in railway signaling that results in a safe state. Wrong-side failure causes an unsafe state.

³GSM-R: Global System for Mobile Communications – Railway

because of space weather. Track information or data from on-board data collection are transmitted to data repositories where the information is merged for further use. This requires cloud services and connections whose availability is uncertain during extreme space weather. Instrumented bearings can also be affected as their electronics are vulnerable to GIC loading. Space weather is, however, considered a black swan event⁴ and as such it is not included in asset integrity management considerations. Potential risks stem from the ground conductivity and the use of DC track circuits that exhibit a low resistance between joint insulations, a vulnerability that is magnified by the presence of iron powder or snow. Another risk is track degradation with material losses due to GIC. While there is as yet no proof that this is indeed due to space weather, rail tracks close to pipelines with noticeable space-weather degradation appear much more corroded.

A project has been launched to address space-weather impact on the rail network in Sweden. Expected outcomes include the dissemination of information on space-weather issues to suppliers of instrumented bearings and rail operators, collection of mitigation techniques, as well as a review of incident data tailored to identify failure mechanisms typical of space weather in Sweden's OFELIA system. While OFELIA collects data on disturbances and failures related to the rail network, space weather is not included as incident trigger. For a number of incidents the cause is unknown and there are questions as to whether they might have been triggered by geomagnetic activity.

The main conclusions of this session are:

- Historical evidence suggests that space weather has affected the rail network in the past via disturbances of the signalling system.
- Documented rail-system anomalies linked to space weather are confined to high latitudes.
- Preliminary studies on the susceptibility of track circuits to GIC or stray currents from geomagnetic activity suggest that problems can arise when GIC creates differential-mode interference in unbalanced track circuits.
- It is unknown if GIC loading in track circuits would always lead to right-side failure or wrong-side failure, thereby creating a significant safety risk.
- While awareness of the space-weather risk in rail appears to be limited in general, some countries have started to analyse the vulnerability of their infrastructures.
- A systematic study on the impacts of a Carrington-type space-weather event on the rail network in the UK has identified power, signalling, train traction, GNSS, radio communications and track-side staff as potential problem areas.
- The Swedish rail network is subject to an elevated space-weather risk due to its location, ground conductivity and the use of DC track circuits.

3.2 Vulnerability of heavy rail to GIC and loss of GNSS and communications

In this session, six parallel discussion groups tried to identify the possible vulnerabilities of heavy-rail infrastructure to GIC induction, loss of GNSS and communications and their immediate consequences during an extreme space-weather event. All groups discussed the following questions:

1. Which rail infrastructure components and systems may be affected by GIC?
2. Are there systems dependent on GNSS? If there are, how may they be affected in case of loss of GNSS both in the short and long term?

⁴ A black swan event is an event which is extremely rare and unexpected but has very significant consequences.

While the discussants agreed that rail system architecture and operations and hence also overall vulnerabilities are country specific, some universal issues related to space weather were identified. With respect to GIC loading, most groups considered transformers (both inside the rolling stock and for traction feeding) to be vulnerable. The rail sector's power-grid dependency in general was highlighted as an important vulnerability due to its direct impact on the rail network, but also indirectly as a power outage can affect ticketing machines, lighting, passenger information systems in the station, etc. From a safety criticality point of view the most important systems potentially affected by GIC are signalling and traffic control systems. This is a particular problem considering the increase in track-circuit lengths and longer trains. Issues related to the diversity in AC/DC rail systems need to be better understood. Axle counters and train detection systems were also mentioned, as well as personnel protection systems that use track circuits to activate warning sirens in case of incoming trains. Other rail equipment and components potentially vulnerable to GIC impact are wayside cables, bearings of rolling stock, telecom and lineside circuits, batteries and backup systems, CM systems, point circuits and location cabinets.

During extreme space weather, potentially prolonged loss of GNSS services is possible. GNSS is increasingly being used for timing and synchronisation of the network, positioning, rail condition monitoring and maintenance, telecommunications, power control, or supplier spares tracking. In the short term, GNSS disruption could lead to a loss of communication, timing and positioning, and loss of command and control systems. The latter is of particular importance because even a short loss of command and control could have impacts that are bigger than anticipated, and regaining command and control can be a lengthy process. The availability of a backup system could mitigate the loss of GNSS, however, the mitigation capacity of backup systems is not well understood.

In case of extreme space weather, systems in the railway network that depend on timing would be affected, although some uncertainty was expressed as to what the full range of these systems would be. Precise timing is crucial for train control and signalling, and it can be disrupted via GSM-R. Since ERTMS uses this technology, rail network management could become more vulnerable to space weather in the future. Train positioning seems to be less of a problem currently as GNSS is not the prime technology used for this purpose just yet (e.g. due to the presence of trees or tunnels). However, different location-dependent operations, such as speed control, SDO, land-slip detection and maintenance heavily rely on GPS.

In the long term, there is pressure to move more and more towards using GNSS services which will require a good understanding of where dependencies are embedded in the rail infrastructures, an assessment of the associated risks, and definition of the necessary redundancies to be built into the network to mitigate the risk. It was pointed out that railways can learn from the aviation sector (e.g. in terms of practices and standards) which has a good understanding of the problems created by space weather.

The key points from this session are:

- Vulnerabilities to extreme space weather exist via direct impacts on rail and through dependencies on other critical infrastructures.
- Direct impacts result, e.g., from GIC loading in transformers, overhead line equipment, and track circuits, or via damage to electronics.
- Indirect impacts are created by the rail network's dependence on the power grid, communications, and GNSS.
- Due to different system architectures and approaches to operations, the vulnerability of rail to space weather varies from country to country.
- In some countries, the disruption of GNSS services could lead to loss of communication, timing and positioning, and command and control.

- Backup systems could mitigate loss of critical-infrastructure services, but the mitigation capacity of backups is not well understood. In addition, backup systems also need to be hardened against space-weather impact.
- There is increasing pressure to use GNSS services which requires an understanding of where dependencies are embedded in the rail network, an assessment of the associated risk, and definition of the necessary redundancies to mitigate the risk.
- Rail can learn from other sectors (e.g. aviation) on how to manage the space-weather risk.

3.3 Vulnerability of other types of rail infrastructure to space weather

The discussion groups in this session analysed the vulnerabilities of rail infrastructure other than heavy rail and tried to understand how space weather might affect new technologies. The groups addressed the following questions:

1. Which space-weather impacts can be expected for a) light rail, b) diesel trains, c) underground systems, d) others?
2. How would new technology be affected?

The workshop participants agreed that other rail systems would probably face difficulties similar to heavy rail during extreme space weather. General problems would relate to loss of power and communications, disruption of signalling systems, and command and control issues. In addition, light rail is often automated and depends on GNSS in the absence of a driver. Light rail transformers might also be vulnerable. While diesel engines are probably more resilient, the disruption of signals would require driving by sight, thereby increasing the risk of collisions. This is especially problematic as communication systems may also be affected. Also, there is uncertainty as to whether trains would stop if there were no signals at all. In case of longer-term disruptions, supplying fuel for diesel engines might be a challenge.

Space-weather impacts on underground systems raise a number of issues related to emergency planning and crisis response. The risks are higher due to potentially more people getting isolated or stranded and cascading effects caused by short stock. De-training and rescue during power outages with impacts on lighting, ventilation systems, pumps, lifts and escalators would prove to be extremely challenging. Other types of rail-based systems, such as trams, would experience problems if road signals were knocked out, and unpowered trams could block roads.

Among the new technologies susceptible to space weather the one that stands out as a key vulnerability is the increasing dependence on GNSS. Risks are exacerbated when system owners are not aware of the GNSS dependence possibly embedded in their systems and the associated vulnerability. There is also a trend towards more automation in rail traffic management, and ERTMS Level 3 relies heavily on GNSS. In parallel, alternative traffic management systems that are not space-weather prone are being phased out as the ERTMS moves along. The obvious solution to tackle this problem would be the implementation of resilient backup systems, however, this is contrasted by a trend to reduce redundancies due to the high reliability of system components nowadays. Fibre optics are increasingly used to improve the resilience of communication systems but the power requirements of optical cables also render them vulnerable in a space-weather context. The use of inductive charging systems, e.g. for light rail or buses, raises the question of potential problems in terms of power-system connection.

The main messages from this session are:

- Light rail, diesel trains and underground systems would probably face the same problems during extreme space weather as heavy rail.

- While not relying on the power grid, diesel trains could be affected by signalling issues and a possible lack of fuel in case of extreme space weather.
- Underground systems pose a particular challenge to crisis response in a situation where de-training and rescue would have to be implemented during power outages with impacts on lighting, ventilation, lifts and escalators.
- The move towards more automation in future rail traffic management will likely add vulnerabilities to space weather.
- Operators should be aware of GNSS dependencies in their systems and alternative traffic management systems should be considered as a backup.
- There is a trend towards reducing redundancies due to the high reliability of system components nowadays.

3.4 Potential long-term effects of space-weather impact on rail

The last session in the second part of the workshop aimed to shed light on longer-term effects in rail operations in the aftermath of an extreme geomagnetic storm that has caused a nationwide power outage. With this boundary condition in mind, the participants discussed the following issues:

1. What will be the consequences of a power outage lasting a) 2 days, b) 1 week, c) 1 month?
2. Is there a risk of logistics problems and if yes what type?
3. How would that affect a) electricity, b) communication, c) control systems, d) fuel logistics, e) spare parts?
4. What would be the consequences on passenger rescue?
5. Are there critical businesses that depend on rail transport and what would be the potential consequences for them?

The discussants agreed that a 2-day power outage would be recoverable from a railway point of view, although several challenges would have to be faced. Command and control would be lost, communications would be down, and no information could go out to staff and passengers. The signalling system would have to be re-established, and old systems need to be reset manually. The first priority would be to localise trains on the network and start evacuating people. While there are contingency plans for evacuation, they do not consider scenarios in which several trains stop at the same time. If external evacuation takes too long and no information can be transmitted to the passengers on board the stranded trains then self-evacuation would likely start with a risk of injuries and panic. The start-up of the power grid after a major geomagnetic storm would depend on damage to grid components and most importantly to transformers as they cannot be easily replaced.

In case of a widespread power outage lasting for one week, business effects on freight customers would become important with potentially big financial impacts. Also, the lack of resources would start to be felt as people would not be able to get to work. Electric trains would shut down where they stopped and might not be able to restart with their batteries flat. Time-dependent maintenance activities might cause problems for planning. In addition, there might be issues related to the replaceability of services and the continued availability of specialist knowledge, skills and equipment. From a logistics point of view, limitations on the availability of fuel and spare parts would become evident. During a large-scale power outage that lasts several days there would be competition for scarce resources. In such a context, restoration of the rail network might be considered of low importance as national recovery priorities would probably be on road traffic due to security considerations (military use). The amount of service that could be restarted after 2 days or a week is country-specific and depends on system architecture. The interconnection between countries in the European Union implies a coordinated transboundary approach to recovery.

A power outage lasting for one month would constitute a major national disaster that could drive private train companies into bankruptcy. Recovery priorities would be on restoring power and the moving of food and fuel. Once the rail network starts up there would likely be a large demand. Freight would be prioritised under the circumstances to mitigate supply-chain impacts. It is believed that rail transport recovery times would be similar to blackout times.

Businesses that rely on the transport of passengers and goods would be heavily impacted by rail network disruptions. This can have strong detrimental effects in entire regions where economies are largely export-based. Passenger effects would mostly involve workers that cannot commute to their work place but also emergency services that might partly rely on rail to move around. Disruption of freight transport could lead to limited availability of fuel (including coal and oil), food, medical supplies and chemicals. Interestingly, in some regions where power is produced from coal, the unavailability of rail transport to move coal could affect the power grid, which in turn impacts rail transport. Businesses might also be affected by a shortage of spare parts which are generally not stored anymore but procured when needed. Another issue that was raised concerned the transport of nuclear waste. Should a power outage occur when the waste is already on the network, safety and security concerns would quickly emerge.

The main conclusions of this session are:

- A two-day power outage is considered recoverable from a railway point of view.
- While there are contingency plans for evacuation, they do not consider scenarios in which several trains stop at the same time.
- In case of a one-week nationwide power outage, limitations on the availability of fuel and spare parts would become evident. There might also be issues related to the replaceability of services and the availability of specialist knowledge and skills.
- A one-month power outage would constitute a national disaster and recovery priorities would be on restoring power and moving food and fuel. Once the rail network starts up, freight would likely be prioritised to mitigate supply-chain effects.
- It is believed that rail transport recovery times would be similar to the duration of the power blackout.
- The interconnection between countries in the EU implies a coordinated transboundary approach to service recovery.

4. Mitigation of impacts – present and future

The third part of the workshop was dedicated to the prevention and mitigation of impacts. Two sessions discussed aspects related to space-weather forecasting and early warning, options to render current and future technologies less vulnerable, and crisis management.

4.1 Forecasting and crisis management

In this session four speakers from NOAA, National Resources Canada, the Swedish Civil Contingencies Agency, and the UK Met Office discussed the opportunities provided by forecasting and early warning, examples of crisis-response processes, and the challenges surrounding data availability and uncertainties.

NOAA's Space Weather Prediction Center (SWPC) is the US's official source of space-weather alerts and warnings. Government but also different infrastructure sectors rely on NOAA's forecasts to manage their space-weather risks. The forecasting process starts with probabilistic forecasts of

conditions favourable for triggering solar activity. Once an event occurs, e.g. a strong flare, coronal observations are used to understand if a CME has been produced, where it is headed and how fast. This is followed by a prediction of CME arrival at Earth. Once the CME hits the ACE and DSCOVR satellites, predictions can be refined before event onset on Earth. This is also the moment when the CME's magnetic field orientation can be confirmed. It was stressed that DSCOVR data are not proprietary and are made freely available to the scientific community. While forecasting is still fraught with uncertainties, both in terms of storm potential and severity, SWPC's customers are aware that there are uncertainties and they act on potential consequences to avoid the risk of major infrastructure damage or service outage. Predictive capabilities for "big and obvious" events are fairly good, but it is very difficult to distinguish very big from extreme in the forecasting process.

Space weather can manifest itself in different ways and impacts on modern technologies are complex and potentially very costly. The blackout of the Hydro-Québec power grid during a geomagnetic storm in 1989 resulted in direct costs of over \$10 million for Hydro-Québec and about \$8 million for PSE & G in New Jersey. The overall losses for the Québec economy amounted to about \$2 billion due to ripple effects to other sectors from the power outage. The direct effect of space weather on pipeline surveys is \$2-5 million per year, not counting losses due to enhanced corrosion. A risk mitigation strategy to protect critical infrastructures requires forecasts of geomagnetic disturbances and other space-weather events, robust information services to government and vulnerable infrastructure operators, hazard assessment for critical infrastructures that includes the space-weather threat, real-time simulations of system effects, and research, in collaboration with industry, on understanding system impacts. NRCan contributes to the mitigation of catastrophic power-system blackouts by providing forecasts of space-weather events and real-time alerts via specifically developed GIC simulators. For pipeline operators, NRCan has set up a customised online service that supports the assessment of space-weather hazards to their infrastructures, and it provides dedicated forecasts for planned pipeline survey times to increase their success. It also supports long-term hazard assessments for planned pipeline routes. NRCan's forecasting services are part of the Canadian Hazards Information Service.

The Swedish Civil Contingencies Agency's (MSB) remit is to prevent emergencies and crises from all causes and to be prepared to manage their consequences together with various public and private stakeholders. From a crisis-management perspective, key issues relate to understanding the potential consequences of an adverse event to enable effective prevention and mitigation actions and the assigning of resources if necessary. In this context, it is necessary to deal with the real crisis but also with people's perception of it as shaped by the media to curb speculations and rumours. Continuous information sharing with and among the stakeholders including the public will be important. When different stakeholders share responsibilities related to the protection of a critical infrastructure, it is crucial that a person in charge or a point of contact is identified for the crisis-management process to unfold smoothly and quickly. In the space-weather context, interdependencies are particularly challenging due to the high likelihood of cascading effects and the downing of lifelines (telecommunication networks, power grid) essential for effective crisis management.

The UK Met Office, which owns the space-weather risk on behalf of the UK government, has created its own 24/7 forecasting capability to support industry users and government. It has engaged in strong collaboration with UK and international partners, and produces daily space-weather forecasts with UK-centric advisories. For example, while the Met Office also uses the NOAA space-weather severity scales, it has added customised impact descriptions that reflect infrastructure architectures and vulnerabilities in the UK. The services the Met Office provides are focused on customer needs and are provided free of charge to infrastructure operators, including rail. Sector-specific pages provide space-weather related raw data but also analyses prepared by Met Office teams. Feedback from industry on their requirements with respect to the type and timing of alerts is crucial for the Met Office to better support operators. Preparedness plans for severe events contain defined escalation and management processes including protocols for communicating with government and industry stakeholders, as well as with the public and the media. These plans are exercised regularly.

The key messages of this session are:

- There are US and European space-weather forecasting capabilities that support the early warning of governments and vulnerable industries.
- The rail sector needs to identify its vulnerabilities and the early-warning requirements necessary to better protect its assets.
- Space-weather impacts on critical infrastructures can be potentially very costly due to ripple effects to other sectors.
- Targeted research efforts in collaboration with industry are necessary to close knowledge gaps with respect to the consequences and probabilities of extreme events, and to understand how standard preparedness assumptions would be challenged under these conditions.
- Scientists need infrastructure-specific data from industry for model verification and scenario development.
- Extreme space weather can be an enormous challenge for crisis management as lifelines (e.g. power, communications) needed for responding to an event may not be available.

4.2 Mitigation options for current and future vulnerabilities

In this session four speakers from Bombardier transportation, the Joint Research Centre (JRC), the Swedish Transportation Administration, and the Austrian railways ÖBB discussed which engineering solutions and risk-reduction approaches could mitigate the impacts of space weather on the current and future rail network.

The rolling stock uses equipment potentially vulnerable to damage from space weather. Impact on electronics and hardware could possibly lead to FPGA/soft errors where ionising radiation causes unintended changes to state values of memory or storage elements. Moreover, the standard rolling-stock main transformer for the rail industry is single phase and as such particularly susceptible to GIC impact, as experiences from the power grid have shown. Current safety standards require the rolling stock transformer to be protected against the thermal effects of solar radiation; however, they do not contain clear requirements on immunity, monitoring and protection for quasi-DC induction.

Engineering options to address space-weather risks in rail exist but solutions need to be adaptable, fulfil customer and market requirements and convince decision makers. Monitoring of GIC levels on-board and wayside could help mitigate the space-weather risk, with preferably local measurements considering that the GIC depends on location and system architecture. Protection levels on-board could be tuned based on vehicle design and susceptibility of power components while wayside infrastructure could be used to monitor and protect the traction power supply. For example, measures could be implemented to trip the rolling stock transformer when GIC is detected. From a prevention perspective, it is conceivable that GIC levels could be decreased by reducing the section length, both for the catenary and the rail, through isolation. This could be a temporary measure applied only during strong solar activity, although the associated design requirements are unclear. Topics that still need to be addressed in more detail are radiation damage to sensors and hardware, and reliability and availability aspects considering that more hardware and software functions would have to be monitored during geomagnetic activity. Also, it should be investigated if existing monitoring systems in rail could be utilised to increase GIC protection levels.

For railway networks, precise timing and synchronisation is a key aspect. As mentioned before, GNSS is increasingly used to provide this service, although it introduces additional vulnerability into the system. Measures to mitigate this risk in railways exist and are not too costly, considering that in addition to space weather there are other threats to GNSS service availability (e.g. multipath, jamming, tunnels, urban canyons) that need to be mitigated. Alternative timing and positioning methods and backups should be considered, e.g. eLORAN where available, more precise Inertial Navigation

System (INS) sensors (odometers, accelerometers, etc.), or the integration of new positioning and timing services from future mobile broadband network infrastructures (e.g. LTE) provided they remain functional during power outages. The quality of backup systems is essential, and benchmark exercises for GNSS timing receivers have highlighted a rapid performance degradation (time drifts) during GPS outage when low-quality holdover oscillators were used. Another method to mitigate the space-weather risk to GNSS services is the development of receivers that are more resilient, and the definition of new receiver standards in railways and time distribution networks (e.g. dual-antenna, dual-frequency, multi-constellation). Benchmarks for ionospheric scintillation events that can potentially impact rail can be established by deploying GNSS receivers or bitgrabbers at high latitudes and in the equatorial regions. Interestingly, receivers can also be used to monitor the status of the ionosphere for forecasting purposes. The JRC has deployed a monitoring station near the Polar Region in Trondheim and has plans to deploy others in Alaska in the framework of a collaborative effort with NOAA and in Antarctica. The JRC hosts a repository of intermediate frequency data sourced from these stations during periods of high ionospheric activity. This data is freely available for download to the research community.

The Swedish Transportation Administration addresses existing vulnerabilities and mitigation options in railways and defines needs for future-proofing this critical transportation infrastructure. Currently, space weather has not been identified as a high-priority risk to Swedish railways although there is not much information on its vulnerabilities and potential impacts. No detailed GIC impact assessment has been carried out so far as there is no robust data on which to base such an assessment. The current railway network uses an architecture whose space-weather proneness is believed to be minor (differential mode, opto cables). The vulnerability of power components is considered manageable as transformers are not loaded to full capacity, and the standard for electromagnetic compatibility (EMC) requirements for railway applications has been implemented. The future system foresees, e.g., audio frequency track circuits with an improved response to space-weather impact due to a higher operational frequency, and the implementation of ERTMS Level 2 which uses GPS and an alternative system for positioning, so redundancies will exist. The GSM-R dependence of ERTMS is, however, critical. In the future system architecture, the Swedish Transport Administration is interested in the implementation of an early-warning system to ensure that trains will receive timely warning in case of danger to avoid stopping in tunnels or under bridges.

In Austria the railway sector is considered safe in principle with respect to space-weather impact although questions related to service availability and shielding, e.g. against transformer damage from GIC loading, remain. Tracks and equipment follow current standards to avoid electromagnetic interference, for example in high-voltage areas. GPS is currently used to support train operations that are not safety-critical. Loss of GPS is therefore not considered significant from a safety point of view. In case a failure occurs (e.g. disruption of safety systems like control units, axle counters) the train would stop automatically. The emergency braking system is mechanical and does not contain components that could be affected by geomagnetic activity. In addition, the train driver or traffic controller would take immediate and appropriate action to ensure the safety of the passengers. Power is not needed to drive trains out from under bridges or tunnels in case they came to a stop there. Currently but also with a view to future infrastructure developments, operational guidelines on the management of disturbances and emergencies are considered adequate and staff is trained on handling them. It is believed that even if 10% of trains were damaged, operation following a nearly normal timetable would be possible. From a service-availability perspective, a potential loss of GPS, power and communications during an extreme space-weather event needs to be better understood.

The main outcomes from this session are:

- The standard rolling stock transformer is single phase and as such particularly susceptible to GIC loading.
- Engineering options to address space weather are available but solutions need to be adaptable, fulfil customer and market requirements, and convince decision makers.

- Timing and synchronisation is a key aspect for rail networks that will be increasingly provided by GNSS. Redundancies to mitigate the risks of GNSS loss are required.
- Compliance with European regulations and standards protects assets under normal operating conditions. It is inconclusive if these norms would also protect against hazards that lie outside the boundary conditions for which they were made.
- For extreme space weather the distribution of responsibilities should be clarified to define the obligations of each stakeholder in risk reduction, emergency response and recovery.

5. Discussion

During the two days of the workshop, the discussions among the multi-disciplinary group of participants raised a number of important issues with respect to the current and future vulnerability of the rail network to space weather. The main tenor of the discussions revolved around understanding if the different manifestations of space weather could affect vital functions in rail transport, both in terms of safety and availability, and how. For example, it is of the utmost importance to know a train's location, and would we lose the ability to make this determination during extreme space-weather conditions? Another important question relates to what would happen once an extreme event occurs. Could passengers be rescued easily in the general chaos following an extreme geomagnetic storm with its likely disruptions of the power supply and communications?

Significant gaps in understanding the space-weather risk to rail have been identified, the most important of which concern track-circuit issues, the potential for transformer damage, and the increasing GNSS dependency for timing and synchronisation, as well as positioning. It is as yet unclear if GIC or stray currents in track circuits could cause wrong-side failures in signalling systems. It is also unclear if GNSS dependencies might be embedded in systems unbeknownst to the operators, or what the consequences of short or long-term losses of GNSS would be.

Track-circuit technology is an on-going research area that is far from being standardised in Europe. Compliance with European safety regulations and standards provides very high protection levels, e.g. against electromagnetic interference. However, rail operates at frequencies that are higher than the quasi-DC of GICs, and it is uncertain if the protection afforded by the European norms would extend to operating conditions much beyond to what is considered routine day-to-day operations.

Rail network architecture and operations vary from country to country and as a consequence so does the associated vulnerability. In some countries, reliance on mechanical systems versus electronic ones adds resilience. Redundancies and backups for critical systems can also increase the resilience to space weather. For example, good-quality holdover oscillators are a fairly cheap mitigation option for timing errors due to loss of GNSS. However, system analyses need to determine how much backup capacity is needed and where, and backup systems also need to be hardened against space weather to avoid common-cause failures of important system functions. This goes against a trend that has seen a reduction in backup systems due to the high reliability of systems and components industry has grown accustomed to.

In contrast to other natural hazards, the large scale of extreme space weather can lead to multiple failures in different critical infrastructures at the same time, thereby challenging standard preparedness planning assumptions. While single equipment failures or disruptions can be managed fairly easily, multiple events most likely cannot. Assessing the risk of space-weather impacts can contribute towards a better understanding of interdependencies and the creation of preparedness and response capabilities that can also be applied to other hazard domains.

There was consensus that the issue of extreme space weather and rail cannot be viewed in isolation but requires a more holistic risk-management approach that also addresses potential dependencies on other sectors. This is of particular importance for new technological developments and the move

towards more automation, e.g. with the adoption of the ERTMS in the EU and the PTC (Positive Train Control) in the US, which might add vulnerability to space weather into the rail network.

Information on the nature of extreme space-weather impact on the rail network and its probabilities is needed to map the risk in operator disruption and emergency plans. The current state of knowledge is, however, insufficient for this purpose. Targeted research efforts in collaboration with industry are necessary to shed light on this issue. In this context it is important that operators grant scientists access to infrastructure-specific data to facilitate model verification and scenario development that will eventually help industry to better protect their assets from extreme risks.

Despite limitations due to uncertainties inherent to space-weather forecasting, dedicated early-warning products are available and are integrated in various infrastructure sectors (e.g. aviation, power grid operations, navigation, and drilling). While this warning capability is in principle also available for rail, further studies with the involvement of industry actors are required to tailor the system to the needs of the rail sector. This includes the definition of the events and threshold magnitudes for which a warning should be triggered, warning contents and time lines, and appropriate operational response procedures.

Due to the potentially global impact of extreme space weather, the need for international collaboration was mentioned on several occasions during the workshop. Railway authorities have contacts to their counterparts in other nations, and Sweden, for example, exchanges daily with the competent authorities of Denmark and Germany on issues of concern. For space-weather related information to be included, protocols specifying the type of information to be communicated need to be established. Also, a common level of awareness is necessary to ensure that messages are understood across borders.

6. Conclusions

Space weather has affected aviation, the power grid and other types of critical infrastructures in the past. Historical evidence suggests that rail networks are also susceptible to space weather through direct impact on systems and components, and it is reasonable to assume indirect impacts via dependencies on other vulnerable infrastructures. In case of extreme, Carrington-type events, the consequences might not be easily foreseeable due to the multitude of affected infrastructures and the simultaneous impact.

Currently, knowledge of this type of risk appears to be limited in the rail sector, and creating awareness among operators and decision makers is the first step towards reducing the risk. Subsequently, potential vulnerabilities and the necessary redundancies can be identified to help rail operators better protect their assets and update their preparedness plans. In this regard, the rail sector can build on the experiences and lessons learned from other affected infrastructure sectors (e.g. aviation) which have started to tackle the space-weather threat with some success. It should also be acknowledged that moving towards more automation in the future might inadvertently introduce vulnerabilities into the system.

With space weather being a complex initiating event for disruption and failure, knowledge gaps need to be closed through further research on the dynamics and consequences of GIC impacts on rail, and the assessment of dependencies between systems with respect to safety and availability during extreme geomagnetic activity. This would help operators to weigh the benefits of hardening their systems to space weather against the potential costs of inaction.

ANNEX 1: Survey

As a contribution to the space weather & rail workshop, David Boteler of Natural Resources Canada carried out a survey among European and North American railway operators prior to the workshop to allow a better understanding of the differences in rail system types and their associated potential vulnerability to space weather. Austria, Denmark, Sweden, UK, USA and Canada sent replies to the survey. The results are shown in the following summary prepared by David Boteler.

Survey Questions

1. Type of rail system
2. Is your signalling based on track circuits?
 - If yes, is this DC or AC?
3. Is your signalling system based on axle counters”?
4. Do you use GNSS (for example GPS) to determine train locations?
5. Do you use GNSS for timing of railway systems?

Results

Country	Rail System	Track Circuits	Axle Counters	GNSS Location	GNSS Timing
Austria	mixed	AC	Yes	Yes	No
Denmark	mixed	DC	No	No	No
Sweden	mixed	DC	No	No	No
UK	mixed	DC, AC	Yes	Yes	Yes
USA	freight	DC, AC	No	Yes	-
Canada	freight	DC, AC	Yes	Yes	-

“mixed” = combination of freight and passenger traffic

Additional Comments

- Denmark is changing from track circuits to axle counters and GNSS in 2010.
- In Sweden, axle counters only used at entrances to tunnels and before a detector hub.
- In UK, GNSS is used but “not in any safety related function”.
- In US, half of track is “dark”, i.e. no track circuit; train control is done by other means, e.g. written orders to go from A to B.
- In US, “Positive Train Control (PTC)” is being developed to augment existing systems. Uses radio to communicate with train drivers (220 Mhz used more or less exclusively for railways).
- Canada is introducing PTC as well.

Information for Other Countries

(provided by Sam Alibrahim, Federal Railway Administration, US)

- France uses AC and DC track circuits.
- Japan uses AC and DC track circuits.
- Australia uses AC track circuits.
- China uses track circuits for freight traffic and axle counters for passenger traffic.

ANNEX 2: Agenda

Day 1 16 September 2015	
12:30-13:00	Registration
Session/time	Topic
Welcome and introductions Chair: Miles Elsdon, UK Department for Transport	
13:00-13:45	<ul style="list-style-type: none"> • Miles Elsdon, Chief Scientist, UK Department for Transport • Jean-Baptiste Simonnet, Senior Adviser, The Community of European Railway and Infrastructure Companies (CER) • Georg Peter, Head of Unit, Joint Research Centre of the European Commission (JRC)
Objective 1: To develop shared understanding of space weather and its potential impact	
Session 1 Introduction to space weather	
Session chair Elisabeth Krausmann, JRC Style Presentations followed by Q&A	Presenter <ul style="list-style-type: none"> • William Murtagh, NOAA • Mike Hapgood, RAL Space
13:45 – 14:30	<ul style="list-style-type: none"> • What is space weather? • What are the elements which might affect critical national or transnational infrastructure including the rail sector, including GICs and GNSS?
14:30-14:45	Coffee Break
Objective 2: To develop shared understanding of potential vulnerabilities of impacts on the rail network to space weather	
Session 2a: Introduction on potential direct and indirect effects of space weather on rail	
Session chair Mark Gibbs, UK Met office Style Presentations followed by Q&A	Presenters <ul style="list-style-type: none"> • Larisa Trichtchenko, Natural Resources Canada • Geoff Darch, Atkins

	<ul style="list-style-type: none"> • Risto Pirjola, Finnish Meteorological Institute
14:45-15:45	<ul style="list-style-type: none"> • What is the current state of our understanding of the risk for the rail sector? • What sort of systems might be affected by severe space weather and why? • Differences in how general impacts might be experienced between Europe, North America and other parts of the world? • Q & A
Session 2b: What are the possible vulnerabilities for rail as a result of Geomagnetically Induced Currents and loss of GNSS and communications systems in the initial stage?	
Session moderator Chris Felton Style Table discussions and feedback to plenary	Discussion leads⁵ Geoff Darch, Atkins Janet Benini, US Department of Transportation Mark Gibbs, UK Met office William Murtagh, NOAA Mike Hapgood, RAL Space Seth Jonas, Science and Technology Policy Institute
15:45–17:30	<ul style="list-style-type: none"> • What equipment/systems may be affected by geomagnetically induced currents? • Are there systems that are dependent on GNSS? If so, how may they be affected if there is a GNSS disruption (short term and long term)?
Day 2 17 September 2015	
Recap of day 1 Moderator Elisabeth Krausmann, JRC	
09:00-09:05	<ul style="list-style-type: none"> • Summary of day 1 discussion and main themes for day 2 • Add any new comments related to yesterday's session if necessary • Dr Diego Galar, Swedish Luleå University of Technology
09:05-09:25	
Session 2c: Are there any vulnerabilities of other types of railway infrastructure and vehicles?	
Session moderator Terry Russell, UK Department for Transport Style Table discussions and feedback to plenary.	Discussion leads Mark Gibbs, UK Met office Robert Rutledge, NOAA Barbara Barr, US Department of Transportation Claudia Lally, UK Government Office for Science Pär Söderström, SJ

⁵ Discussion leads are those with particular expertise which will be distributed amongst tables or called on by moderator during the discussion.

09:25–10:15	<ul style="list-style-type: none"> • What type of effects can be expected on for example <ul style="list-style-type: none"> a. Light rail b. Diesel driven trains c. Underground systems d. other? • How may new technology be affected?
Session 2d: What are the possible long-term effects on rail of wider impacts of space weather?	
Session moderator Emmelie Andersson, MSB Style Table discussions and feedback to plenary.	Discussion leads William Murtagh, NOAA Mike Hapgood, RAL Space Janet Benini, US Department of Transportation Georg Peter, JRC Robert Rutledge, NOAA Geoff Darch, Atkins
10:15–11:35	<ul style="list-style-type: none"> • What will be the consequences of a long-lasting power outage lasting: a. 2 days b. A week c. A month? d. Potential problems during system start up? • Is there a risk of logistic problems? What type? • And how will that affect for example: a. trains dependent on electricity b. Communications c. Control systems d. Fuel logistics? • May there be difficulties getting hold of spare parts? • Rescue of passengers? • Are there critical businesses that are depending on rail traffic? What are the potential consequences for them?
11:35-11:50	Coffee Break
Objective 3: How can we mitigate the potential impacts?	
Session 3a: Forecasting & crisis management	
Session moderator William Murtagh, NOAA Style Panel presentations and discussion	Panel members Robert Rutledge, NOAA Larisa Trichtchenko, NRCan Emmelie Andersson, MSB Catherine Burnett, UK Met office
11:50-12:45	<ul style="list-style-type: none"> • Can we establish benchmarks for space weather events? • What are the consequences of action and inaction for a severe event? • What planning could be put in place to manage an event? • How can forecasting and alerting help? • What operational mitigations exist?

12:45-13:30	Lunch
Session 3b: What are the potential mitigations to existing vulnerabilities or scope for future proofing infrastructure and railway vehicles?	
Session moderator Chris Felton, UK Home office Style Panel presentations and discussion	Panel members <ul style="list-style-type: none"> • Surajit Midya, Bombardier transportation • Joaquim Fortuny-Guasch, JRC • Stefan Niska, Swedish Transport Administration • Robert Weber, Austrian railways
13:30-14:30	<ul style="list-style-type: none"> • What engineering solutions exist? • How might future technological developments be made less vulnerable to the effects of space weather? • How much would mitigation cost?
Objective 4: Agree next steps	
Session 4: Round up, conclusions and next steps Chair: Söderström Pär, SJ & Emmelie Andersson, MSB	
14:30-15:00	<ul style="list-style-type: none"> • Recap discussion and agree next steps <p style="text-align: center;">The end</p>

ANNEX 3: Participants

Name	Affiliation
Andersson Emmelie	Swedish Civil Contingencies Agency (MSB)
Backman Anders	Swedish Transport Administration
Benini Janet	US Department of Transportation
Bisi Mario	RAL Space, UK
Bjorkqvist Stefan	Swedish Transport Administration
Bock Hans-Hermann	Deutsche Bahn AG (DB), Germany
Burnett Catherine	UK Met Office
Christensen Ole	Banedanmark, Denmark
Cid Consuelo	University of Alcala, Spain
Cook Adam	UK Civil Contingencies Secretariat
Darch Geoff	Atkins, UK
Dixon Richard	DB Schenker Rail UK
Donnelly Bryan	ATOC, UK
Durand Eric	Swiss Re
Elsden Miles	UK Department for Transport
Fairbank Jeremy	Network Rail, UK
Felton Chris	UK Home Office
Fortuny Guasch Joaquim	European Commission Joint Research Centre
Galar Diego	Luleå University of Technology, Sweden
Gibbs Mark	UK Met Office
Guo Jianguang	China Meteorological Administration (CMA)
Hapgood Mike	RAL Space, UK
Hayes Darren	Atkins, UK
Hoad Richard	QinetiQ
Huckle Guy	Network Rail, UK
Jin Jianhong	RSSB, UK
Jonas Seth	US Science and Technology Policy Institute
Jones Lewys	Network Rail, UK
Knights David	RSSB, UK
Krausmann Elisabeth	European Commission Joint Research Centre
Lally Claudia	UK Government Office for Science
Lampen Daniel	UK Department for Business, Innovation and Skills
Lobo Leon	National Physical Laboratory, UK
Lovegrove Peter	ATOC, UK
Midya Surajit	Bombardier Transportation, Sweden
Mitchison Neil	Formerly European Commission Joint Research Centre
Murtagh William	NOAA, USA
Niska Stefan	Swedish Transport Administration
Peter Georg	European Commission Joint Research Centre

Pirjola Risto	Natural Resources Canada
Proctor Andy	Innovate UK
Rameder Stefan	Austrian Railways (ÖBB)
Russell Terry	UK Department for Transport
Rutledge Robert	NOAA, USA
Sawh Tony	UK Department for Transport
Siapkidou Elli	RSSB, UK
Simmonet Jean Baptiste	CER
Söderström Pär	SJ AB, Sweden
Thaduri Adithya	Luleå University of Technology, Sweden
Trichtchenko Larisa	Natural Resources Canada
Velji Shamil	RSSB, UK
Weber Robert	Austrian Railways (ÖBB)
Wright Anthony	UK Department for Transport

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