European Commission

JRC SCIENCE FOR POLICY REPORT

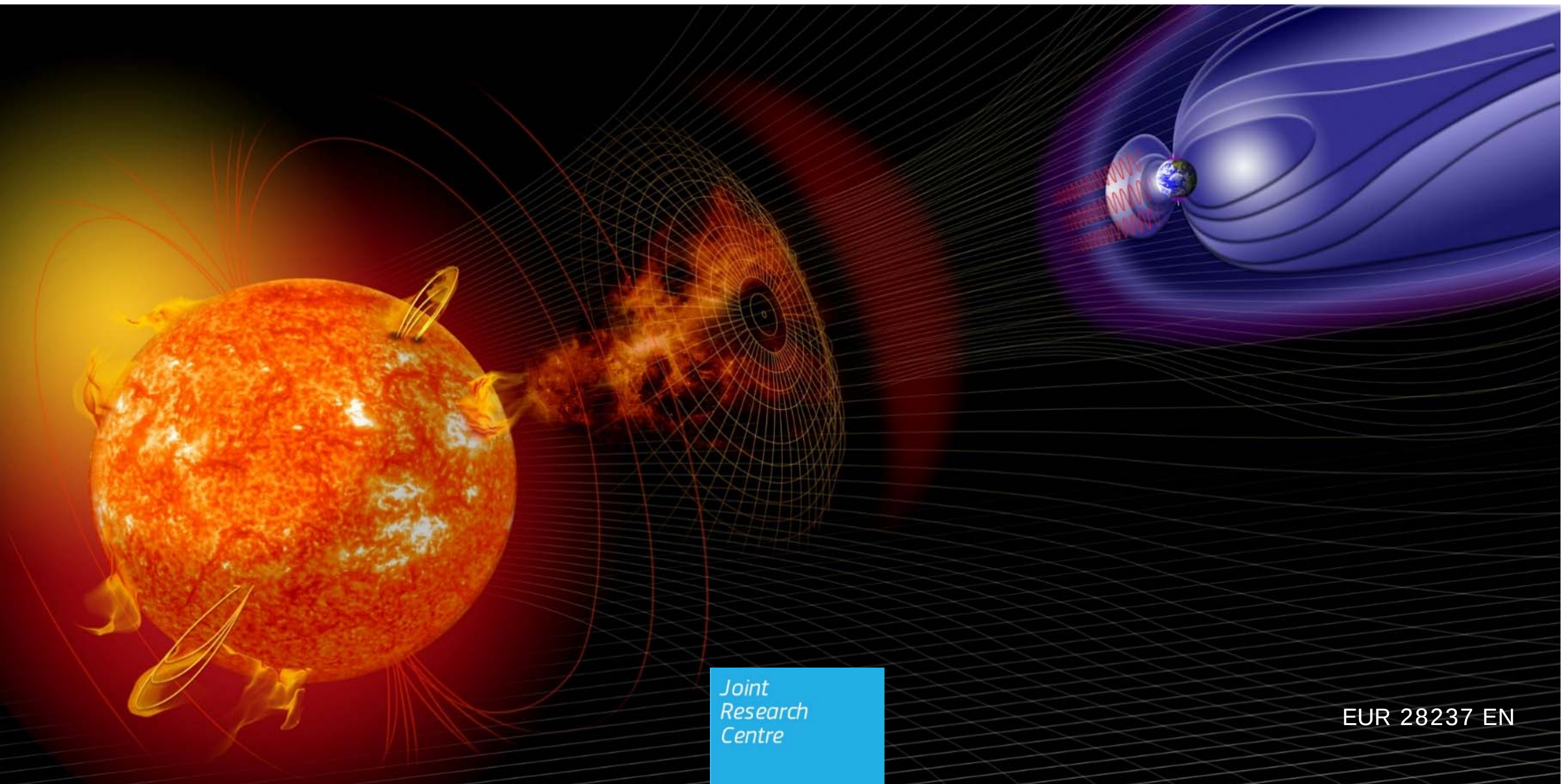
Space Weather & Critical Infrastructures: Findings and Outlook

An event co-organised by the European Commission's Joint Research Centre,
the Swedish Civil Contingencies Agency,
the UK Met Office, with the support of
the NOAA Space Weather Prediction Center

29-30 November, 2016, Ispra, Italy

Elisabeth Krausmann, Emmelie Andersson, Mark Gibbs, William Murtagh

2016



Joint Research Centre

EUR 28237 EN

Contact information
Name: Elisabeth Krausmann
Email: elisabeth.krausmann@ec.europa.eu

JRC Science Hub
https://ec.europa.eu/jrc

JRC104231

EUR 28237 EN

ISBN 978-92-79-63903-6 ISSN 1831-9424 doi:10.2788/152877

Luxembourg: Publications Office of the European Union, 2016

How to cite this report: Krausmann, E., Andersson, E., Gibbs, M., Murtagh, W., *Space Weather & Critical Infrastructures: Findings and Outlook*, EUR 28237 EN, 2016, doi:10.2788/152877

Title Space Weather & Critical Infrastructures: Findings and Outlook

Abstract
Extreme space weather has a global footprint and can affect multiple critical infrastructures at the same time. An event of such magnitude could overwhelm a single nation's response capacity. Further efforts in research, and national and international coordination in preparedness and response are required.

Space Weather and Critical Infrastructures: Findings and Outlook

An event co-organised by the European Commission's Joint Research Centre, the Swedish Civil Contingencies Agency and the UK Met Office

With the support of the NOAA Space Weather Prediction Center

29-30 November, 2016, Ispra, Italy

E. Krausmann, E. Andersson†, M. Gibbs#, W. Murtagh‡*

*European Commission, Joint Research Centre, Ispra (VA), Italy

†Swedish Defence University (formerly at MSB - Swedish Civil Contingencies Agency), Stockholm, Sweden

#Met Office, Exeter, UK

‡NOAA Space Weather Prediction Center, Boulder, Colorado, USA

Contents

Acknowledgements

The authors wish to express their gratitude to Ms. Agnes Hegedus, Ms. Maria-Giovanna Giuliani and Ms. Orsolya Sudar for their valuable assistance with the logistics of this event, and to Dr. Georgios M. Karagiannis and Dr. Joaquim Fortuny-Guasch for helpful discussions during the preparation of this report.

Executive summary

Historical evidence shows that many critical infrastructures in space and on the ground are vulnerable to the effects of space weather. Society relies increasingly on the services these infrastructures provide, and the risks from extreme space weather should be assessed to ensure adequate preparedness in industry and society.

In order to take stock of space-weather risk reduction efforts in the EU over the past five years and to identify remaining gaps, the European Commission’s Joint Research Centre, the Swedish Civil Contingencies Agency, and the UK Met Office, with the support of NOAA’s Space Weather Prediction Centre, jointly organised a 2-day Summit on the impact of extreme space weather on critical infrastructures on 29-30 November 2016 in Ispra, Italy. The objectives of the summit were to discuss the state of play in reducing the risks of extreme space-weather impacts on infrastructures, discuss transboundary effects and the associated challenges for operators and emergency response, and to provide a platform for exchange and coordination among the stakeholders.

The “Space Weather and Critical Infrastructures” Summit was attended by almost 50 representatives of European infrastructure operators, regulators, crisis-response experts, academia, the European Space Agency, NOAA, the US Department of State, the US Science and Technology Policy Institute, NASA and the European Commission.

The main workshop conclusions are:

- Extreme space weather has a global footprint and can affect multiple ground- and space-based infrastructures at the same time. An event of such magnitude could overwhelm a single nation’s response capacity.
- Some countries have recognised the threat of extreme space weather and have included it in their strategic national risk assessment.
- There is a need to develop methodologies and tools for assessing interdependencies between critical infrastructures.
- A multi-risk governance approach is needed to address cascading effects and the different stakeholders that often manage the risk in isolation from each other.
- A pan-European vulnerability assessment of the power transmission grid should be carried out to identify criticalities and the potential for transboundary effects in case of extreme space weather.
- Infrastructure operators should assess if hidden vulnerabilities to space weather are embedded in their systems, for example via dependencies on GNSS.
- Significant knowledge gaps in physical and impact modelling persist. These gaps strongly affect early-warning capabilities and preparedness in industry.
- Better communication between science and industry is needed to provide relevant, reliable and usable information to operators for decision making.
- In Europe and the USA, 24/7 space-weather forecasting capabilities are available to support the early warning of government and industry.
- There is a need for consistency in forecasting and for coordination of forecasts from different service providers.
- A strategic plan should be developed to define the roles of the key players in Europe. This can include the establishment of a centralised European strategic decision-making capability for coordinating space-weather risk mitigation and response at a pan-European level.
- The USA has issued a National Space Weather Strategy that defines high-level strategic goals and actions for increasing preparedness levels.

1 Introduction

Many modern critical infrastructures are vulnerable to the effects of natural hazards. Of increasing concern is extreme space weather that can have serious impacts on ground-based and space-borne infrastructures. Space weather occurs across national boundaries, and crises in one country can easily spill over to neighbouring critical-infrastructure networks. Numerous 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 infrastructures provide, awareness of the space-weather threat needs to be raised and the risks from extreme space weather should be assessed to ensure adequate preparedness of infrastructure operators and society in general.

Research efforts, in particular in North America and Europe, have been launched to better understand the impact of space weather on the many different types of critical infrastructures and to identify potential risk-reduction approaches where needed. In addition, awareness-raising initiatives have engaged stakeholders related to power-grid operations, aviation, financial systems, rail transport, and crisis response to increase the resilience of critical infrastructures and society to space weather. In order to take stock of space-weather risk reduction efforts in the EU over the past five years and to identify remaining gaps, the European Commission’s Joint Research Centre (JRC), the Swedish Civil Contingencies Agency (MSB), and the UK Met Office, with the contribution of the NOAA[1] Space Weather Prediction Centre (SWPC), jointly organised a 2-day summit on the impact of extreme space weather on critical infrastructures on 29-30 November 2016 at the JRC’s Ispra site. The objectives of the summit were to discuss the state of play in reducing the risks of extreme space-weather impacts on infrastructures, address the problem of transboundary effects and the associated challenges for operators and emergency response, and to provide a platform for exchange and coordination among the stakeholders.

The “Space Weather and Critical Infrastructures” summit was attended by almost 50 representatives of European infrastructure operators, regulators, crisis-response experts, academia, ESA[2], NOAA, the US Department of State, the US Science and Technology Policy Institute, NASA[3] and the European Commission. The workshop programme and the list of participants are provided in Annexes 1 and 2, respectively.

[1] NOAA: National Oceanic and Atmospheric Administration
[2] ESA: European Space Agency
[3] NASA: National Aeronautics and Space Administration

2 Space weather today

Several countries have recognised the risks associated with extreme space weather and have launched initiatives to prevent, prepare for and respond to the threat. In the first session of the summit, six speakers from NOAA, the European Commission, Göttingen University, ESA, the US Department of State, and the Swedish Institute of Space Physics introduced the origin and characteristics of space weather and presented the status of space-weather research and policy in Europe and in the USA.

Past space-weather impacts have demonstrated the vulnerability of both ground- and space-based infrastructures to this type of hazard. In addition, space weather has a global footprint and can therefore cause global impact, as demonstrated during the October 2003 space-weather storms: several satellites were damaged or suffered anomalies, numerous polar flights had to be rerouted, and there were reports of failure of GNSS[4]-based positioning and power disruptions in Europe, widespread HF outage over the African continent, and transformer damage in South Africa, as well as SatComm and HF outages in Asia and Australia.

There are three different types of solar activity that are of concern for critical infrastructure operations: 1) solar flares, which trigger radio blackouts very quickly and affect radar, ground- and space-based communications, including high-frequency (HF) communication, and the GPS network causing loss of lock; 2) solar radiation storms, which are a threat to satellite operations, aviation and manned and robotic spaceflight; and 3) geomagnetic storms, caused by the ejection of magnetised solar plasma (so-called Coronal Mass Ejection or CME) which interacts with Earth's magnetosphere, causing impacts to satellite operations, GPS, aviation, rail transport and power-grid operations. Of particular concern is extreme space weather, such as the Carrington storm caused by a fast CME in 1859. A storm of such magnitude could result in major and possibly long-term disruptions of critical-infrastructure services with significant economic losses. It is believed that such a geomagnetic storm could overwhelm a single nation's response capacities. The probability of Carrington-type space-weather events is assumed to lie between 6 and 12% within the next decade. However, for a major geomagnetic storm to occur on Earth, the triggering CME needs to be aimed at Earth and carry a southward magnetic field to be able to interact with the magnetosphere.

The European Union (EU) disaster risk management policy covers prevention, preparedness and response for all types of disasters. In the EU there has been a shift away from disaster management towards disaster *risk* management (DRM), with risk assessment being seen as the very basis of DRM. The risk-assessment policy context is the Union Civil Protection Mechanism which requires EU Member States to prepare a National Risk Assessment (NRA) and list the priority risks the EU is facing. Six countries (Finland, Hungary, Netherlands, Sweden, UK and Norway[5]) have included space weather in their risk assessment. In addition, 20 NRAs contain critical-infrastructure loss or power outage scenarios as priority hazards. Space weather could be considered as a trigger of these scenarios. The Union Civil Protection Mechanism also requires Member States to submit a risk management capability assessment by August 2018. The purpose of this assessment is to understand the ability of Member States to address the identified priority risks. The risk-management capability should include administrative, technical and financial factors. Recently, the EU Disaster Risk Management Knowledge Centre has been set up as a tool to better exploit research results, further cooperation across the EU, and bring science and policy together. Space weather could be included in this initiative, e.g. in terms of early warning, and to provide capacity-building support.

Europe has been active in the space sector for several decades and it has actively contributed to space-weather research through involvement in milestone space missions, such as SOHO, ACE and STEREO. The EU has funded over 30 research projects related to space weather and its impacts through its 7th Framework Programme (FP7) 2007 – 2013

[4] GNSS: Global Navigation Satellite System, e.g. GPS, GLONASS, GALILEO, BeiDou

[5] Although Norway is not a member of the EU it participates in the EU Civil Protection Mechanism.

and the Horizon 2020 programme for the period 2014 – 2020. An overview of these projects is available via the European Space Weather Portal (www.spaceweather.eu). The resources associated with these programmes have led to milestone results in space-weather research, service developments and international collaboration. An example is the FP7 AFFECTS (Advanced Forecast For Ensuring Communications Through Space) project which studied impacts on the ionosphere and the effects on communication. Through its website, the project provides event awareness by offering space-weather services (e.g. Kp[6], aurora RSS feeds), space-weather reports and alerts based on solar-activity analysis, subscription services for flares, CMEs, and Solar Energetic Particles (SEP), CME databases, modelling results, etc. Further EU funding is essential for the research-to-operations path (instruments, mission development, underlying science), including ground-based infrastructures.

The European Space Agency ESA is mandated by its member countries to protect space and ground assets against adverse effects from space via its Space Situational Awareness (SSA) programme. Space weather has been identified as a threat and has recently become the largest SSA area. A cost/benefit analysis of the potential consequences of a major space-weather event highlighted that the costs can be significant. The analysis also clearly showed the economic benefits of using alert services. ESA does not have its own space weather centre but it coordinates a virtual network of expert groups in various ESA member countries that provide space-weather services. It offers 140 products in 17 different space-weather domains. Subscription services issue alerts depending on the interests of the user. These alerts provide information on what is happening in space but not how the space environment will affect, e.g., spacecraft operations. A service for power-grid operations that has become available very recently capitalises on the results of the European EURISGIC project. It provides data on the geomagnetic field and its change, the geoelectric field, and the geomagnetically induced currents (GIC) in a model power grid with a simplified grid topology. 40-min GIC forecasts are based on ground-based magnetometer data. Currently, the service covers only Scandinavia. The future objective of the SSA space-weather segment is a system of small missions with hosted payload to measure the space environment in low-Earth, medium-Earth and geostationary orbits. In addition, new applications are planned to fill gaps in current service capability. This includes benchmarking and validation of the services provided by the Expert Service Centres, and focussed developments of services and physics-based models.

The US Department of State plays a coordination and clearance role in international space cooperation. In its coordination role, it leads on government-to-government framework agreements, and in its clearance role on agency-to-agency implementing agreements. The US National Space Policy issued in 2010 includes as goals the expansion of international cooperation and the improvement of space-based Earth and solar observation capabilities needed to forecast near-Earth space weather. Multiple efforts are underway across US government agencies and internationally to increase awareness of space-weather risks. This has much increased the coordination on the topic across US agencies. For example, the FEMA[7] Federal Interagency Response Plan will include a long-term power-outage annex, and FERC[8] has issued a rule on the development of grid reliability standards for geomagnetic disturbances.

The National Space Weather Strategy was released by the White House in October 2015. It defines the specific actions that US Federal agencies must undertake to prepare for and respond to space-weather storms, as well as the timelines for completion of these actions. The Strategy has six goals, including the improvement of assessment, modelling and prediction of impacts on critical infrastructure, and the enabling of increased international cooperation. This includes data sharing and research, cooperation on space-

---

[6] The planetary index K_p provides a measure of the level of geomagnetic activity over a three-hour interval based on magnetometer measurements. The index ranges from 0 to 9.

[7] FEMA: Federal Emergency Management Agency

[8] FERC: Federal Energy Regulatory Commission

weather products and services, and a collaborative approach to extreme space-weather preparedness. In October 2016 an Executive Order on preparing the nation for space weather was issued by the US President. It defines the roles and responsibilities of the various Federal government agencies in preparedness, response and recovery and their authority to direct, suspend or control critical infrastructures before, during and after a space-weather event.

The Roadmap prepared by COSPAR/ILWS, a joint undertaking of the Committee on Space Research and the International Living With a Star programme, aims to protect society's technological infrastructure sectors by laying out a path for advancing space-weather science. It focuses on high-priority challenges and prioritises those advances that can be made on short, intermediate and decadal time scales. The roadmap tries to answer fundamental questions related to processes on the Sun, the near-Earth space environment after a solar eruption, and it aims to understand how technology and society would be affected and could respond to the threat.

The roadmap's highest-priority recommendations refer to research (observational, computational, and theoretical needs), teaming (coordinated collaborative research environment) and bridging communities (collaboration between agencies and communities). Recommendations are separated into pathways which reflect a merged weighting based on assessed societal impact, scientific needs, estimated feasibility, and likelihood of near-term success. Pathways are designed to meet the differential needs of the various user groups. For example, recommendations on observational, computational and theoretical needs are divided into 3 pathways, which focus on 1) impacts of GMD[9]/GIC on electrical systems, 2) the particle environment of (aero)space assets, and 3) pre-event forecasts of flares and solar particle events. These pathways can only be achieved through interagency coordination and for each pathway there is a need for the deployment of new or additional space- or ground-based instrumentation.

The key points from the first session are:

- Extreme space weather has a global footprint and can affect multiple ground- and space-based infrastructures at the same time. An event of such magnitude could overwhelm a single nation's response capacity.
- The probability of an extreme Carrington-type geomagnetic storm is assumed to be 6-12% within the next decade.
- Some countries have recognised the threat of extreme space weather and have included it in their strategic national risk assessment for better preparedness planning.
- National and international initiatives have been launched to facilitate collaboration on research, preparedness and response planning, and multilateral coordination in response.
- Europe is actively contributing to space-weather research through involvement in space missions and the funding of research projects related to space weather and its impacts.
- The USA has issued a National Space Weather Strategy that defines high-level strategic goals and actions for increasing preparedness levels.

[9] GMD: Geomagnetic Disturbance

3 Space weather impacts and risk reduction

3.1 Known vulnerabilities to space weather and risk reduction

Many different types of critical infrastructures are known to be vulnerable to space weather. Four speakers from the UK National Grid, SolarMetrics Consulting, JRC, and Atkins presented the vulnerability of the power grid, aviation, GNSS, and rail to space weather and discussed the potentially resulting problems with respect to service disruption and cascading effects.

There is historic evidence dating back to the 1940s that power grids are vulnerable to the impact of geomagnetic storms via the generation of GICs that enter the grid. The 1989 Quebec blackout was a wake-up call for the power industry, followed by the 2003 Halloween storm with a blackout in Sweden and damage to several transformers in South Africa. Since high-voltage equipment is more susceptible to GIC, power transmission systems are particularly at risk. On the other hand, GIC cannot penetrate into the distribution network which is less vulnerable due to the higher line resistances and lower voltages. Distribution networks might, however, suffer outages through secondary impacts. Highly connected networks are also less vulnerable as the GIC would be spread over more network branches. Potential GIC-related damage paths involve high-voltage transformers (half-cycle saturation, harmonics, heating), or voltage fluctuations and line tripping that can cause power outages. Once the power grid fails there will be ripple effects to all sectors that rely on power, i.e. food and fuel distribution, water, transport, industry, etc.

An assessment of the potential space-weather risks to the UK transmission grid suggests that only Carrington-type events, assumed to have a 100-year return period, could cause disruptions. Nevertheless, widespread transformer damage and grid collapse would be rather unlikely. It is estimated that 20 transformers at most would be affected by extreme space weather. Since this constitutes only about 1% of all transformers in the UK grid, only local blackouts would be expected. National Grid relies on design (e.g. GIC-resistant transformer design, voltages lower than 400 kV, transformer spares) and on operational mitigation to handle the effects of geomagnetic storms. Operational measures include return to service of items out for maintenance and switching in of all circuits (required lead time 3-4 days), connection of all Supergrid Transformers to distribute the GIC (lead time 2-3 days), extra reactive power support, extra staff, etc.

National Grid maintains a close relationship with the Met Office who provides them with customised space-weather forecasts. Forecasting requirements are that operators should receive a warning up to five days in advance of a geomagnetic storm to take all necessary measures to protect the grid. For very fast CMEs, which take no more than 18 hours to arrive, this is currently not the case. Ideally, forecasting capabilities should be improved to allow prediction of the likelihood and expected size of a CME 3-4 days prior to its eruption, prediction of the CME's magnetic orientation once launched from the Sun, better accuracy of its arrival time at Earth, and an estimate of the geomagnetic disturbance intensity caused by the CME.

Aviation has been subject to space-weather impacts on numerous occasions with significant economic losses. For example, in 2005 the total cost of extra fuel used for rerouting flights from polar routes due to space weather amounted to $186 million (excluding costs to passengers and compensation). Space weather impacts aviation in various ways, including through satellite navigation (GPS system availability, position errors), avionics upsets/failures, communication loss, and additional human radiation exposure. Aviation does not at the moment rely exclusively on GPS for navigation. For example, in the USA the WAAS[10] is based on GPS. If it is impacted by space weather, like in October 2003, ground-based systems provide support for aircraft navigation. Since these back-up systems are expensive to maintain and there is a trend towards reducing

[10] WAAS: Wide Area Augmentation System

redundancies to be more cost effective, there is concern that the associated risks for navigation might not be fully appreciated.

The impacts on avionics are a problem that is not yet considered significant by airlines although incidents where space weather is suspected have been documented (e.g. Quantas Flight 72 in which un-commanded inputs to flight controls were reported, causing injuries to passengers and the crew). There are several backups depending on how flight-critical a system is. Nevertheless, flight electronics are becoming smaller as technology progresses which increases their susceptibility to space weather. Loss of HF communications as a primary safety-critical tool for communication is already recognised as an issue. It is the primary communication tool in remote areas (polar regions and oceans) which traffic management and airlines use to communicate. Together with navigation, loss of communications is an issue that is potentially safety-relevant and can - in the worst case - result in the closure of airspace.

It was suggested that better communication between scientists and industry is needed to provide relevant, reliable and usable information to the aviation sector for decision making. The information available today does not fulfil these criteria. This would enhance awareness and understanding of the risks in the sector, and improve global emergency response should an extreme event occur. In addition, there is a need for standardisation of space-weather information and guidance, improved education and training, as well as for risk and cost/benefit analysis.

GNSS is increasingly used for precise timing and positioning in a variety of applications (e.g. eNavigation, offshore oil and gas drilling, precision farming), making them vulnerable to space-weather impact. Recent studies recommend increased resilience of and backups for positioning, navigation and timing services used in critical infrastructures. The JRC investigates the vulnerability of GNSS to natural and anthropogenic interference sources (jamming, spoofing) and their impacts on GNSS receivers. In order to support the development of more resilient receivers, the JRC has deployed ionospheric scintillation monitoring stations in Peru, Norway and Vietnam, as well as two stations in Antarctica in collaboration with a European research consortium. Scintillation events are recorded at the monitoring stations and played back at the JRC to test standard receivers used, e.g., by aviation. This supports the development of GNSS receivers that are less vulnerable to space-weather impact but also the preparation of standards for enhanced receiver reliability. The JRC hosts a database of scintillation events (intermediate frequency data) sourced from the monitoring stations during periods of high ionospheric activity. This data is made available to the research community for free. Future work will investigate the potential of using Formosat-3/COSMIC data, as well as information from the International Ground Station (IGS) network, to monitor ionospheric scintillation.

Space-weather impacts on rail have been documented in Sweden and Russia, with disruptions to signalling as the primary effect. However, the rail industry lags behind the power and aviation sectors with respect to awareness of and protection against space weather. Atkins carried out an initial study to understand the vulnerability of the UK rail network to extreme space weather and its impacts on safety and operability, under the assumption that an event had already occurred. The study highlighted a strong susceptibility of rail assets to space weather due to direct impacts on the infrastructure and indirectly via its dependence on power, GNSS and radio communications. On the one hand, GICs entering rail equipment, e.g. rolling-stock transformers or track-circuit feed transformers, may result in transformer failure and train shut-down, or signalling equipment producing right-side failures[11]. Also line current monitoring equipment may interpret the quasi-DC GICs as incorrect train operation and shut the train down. There is a theoretical risk that GIC induced or directly coupled into a rail may lead to wrong-side failure which raises strong safety concerns. On the other hand, a power outage would indirectly affect train operations, with train batteries lasting no longer than 90-120

[11] Right-side failure is a condition in railway signaling that results in a safe state. Wrong-side failure causes an unsafe state.

minutes, signalling, and services at train stations, including lighting. In this context, there is concern about self-evacuation and panic behaviour with passengers stranded in trains or blocked at stations. The failure of GNSS has presently not been identified as a safety concern. However, GPS plays a key role in maintaining timing on the GSM-R[12] network, as well as in the line-side telecommunications system. GPS is also used for Selective Door Opening to determine the location of the train on the rail network, and for supporting the train's propulsion system. Radio communications that use directional antennas, such as GSM-R, would only be disrupted during sunrise and sunset. However, their loss could be critical during emergencies. Interestingly, there is also a risk to track-side staff during extreme space weather due to the unexpected activation of protection system by GICs in conductors.

The Atkins study also came up with recommendations for research, forecasting and warning, and monitoring and measuring. Most importantly, the study recommends to close existing knowledge gaps related to single-event effects, track-circuit interference, and GNSS dependency, while at the same time considering the potential for multiple and simultaneous impacts. The Rail Delivery Group and Network Rail have expressed interest in understanding how they would respond to a space-weather warning.

The main conclusions from this session are:

- Past space-weather impacts on different types of critical infrastructures (e.g. power grid, aviation, transport, GNSS) have been documented.
- Power transmission grids have been hardened in some countries based on past impacts. In the UK, it is believed that only Carrington-type geomagnetic storms would be able to cause disruptions to grid operations.
- In some countries, customised models for GIC prediction and impact assessment have been developed.
- Aviation is vulnerable to extreme space weather due to radiation exposure, loss of communications and navigation, and impacts on avionics. These aspects are considered safety-relevant.
- GNSS, and as a consequence the applications that depend on it, is vulnerable to space-weather impacts. There may be GNSS dependencies embedded in systems without infrastructure operators knowing about them.
- Space weather can affect rail either via direct impacts (e.g. GICs in transformers or rail tracks) or indirectly through dependencies on other critical infrastructures that are vulnerable (power, communications, navigation).
- Better communication between science and industry is needed to provide relevant, reliable and usable information to operators for decision making.

3.2 National space-weather risk management and forecasting

Early warning and preparedness are essential for limiting the effects of space-weather impacts. In this session four speakers from the Swedish Civil Contingencies Agency, the UK Government Office for Science, NOAA and the UK Met Office presented examples of national approaches to managing space-weather risks and gave an overview of available space-weather forecasting services in the USA and the UK.

The Swedish Civil Contingencies Agency MSB is tasked with preventing and preparing for emergencies and crises from all causes, be they natural or man-made, in collaboration with public and private stakeholders. It has published a National Risk and Capability Assessment (NRCA) with the aim to identify and analyse risks, vulnerabilities and society's capability to prevent and respond to these risks. The results of the NRCA are a strategic basis for directing and developing the Swedish civil contingency system. In the frame of the NRCA, solar storms were identified as a particularly serious threat and a

[12] GSM-R: Global System for Mobile Communications – Railway

scenario of extreme space weather affecting Sweden was developed. This scenario assumed the occurrence of a Carrington-type event with major disruptions to satellite signals and HF communications, as well as a power blackout in southern and central Sweden due to voltage collapse. It aimed to understand the potential consequences for the over 8 million people living in the affected area (Sweden's total population is close to 10 million). The major challenges identified in the immediate aftermath of the space-weather event relate to cascading effects due to the power blackout, such as shortage of drinking water, loss of communications, impacts on transportation, fuel supply, food, and healthcare. There is also a risk of civil unrest. Based on these observations it was concluded that backup power is a key factor for ensuring that critical societal functions can be maintained throughout the event. This should be supported by improved warning systems and reliable/user-friendly forecasts and warnings. Awareness, especially within the civil-protection community, was highlighted as essential for minimising risks, as well as more knowledge of the event dynamics. The space-weather scenario is included in many strategic training courses.

In the UK, the space-weather risk is owned by the Met Office while the role of the Government Office for Science is to translate science into policy. In the frame of the European Commission's call for the preparation of a National Risk Assessment, the UK also indicated space weather as one of the priority risks the country might face. Severe space weather has been included in the UK's National Risk Register with a relative likelihood of occurring over the next five years between 1 in 20 and 1 in 2 and an overall relative impact score of 3 (out of 5). There is debate if the risk is represented correctly, and a revised NRA will be published at the end of 2016 to reflect the increased understanding of impacts on other sectors. In this context, space weather might be reclassified as less likely (between 1 in 200 and 1 in 20) but with a higher impact (score 4 out of 5). In support of space-weather forecasting and alerting, the Met Office forecasting centre was developed which provides general but also tailored services to its user groups. The Cabinet Office works with local first responders, National Grid, the rail network and the aviation sector on a preparedness strategy for extreme space weather. In 2015, a Strategic Defence & Security Review recognised the important place in security of space infrastructures and their vulnerability to space weather. In the same year, the Government Office for Science carried out a space-weather table-top exercise with different industry sectors to raise awareness, understand how to best communicate space-weather risks to operators and the public, and to foster dialogue about extreme risk with high uncertainties. The next steps will follow up on the results of the table-top exercise and address the identified gaps.

In the USA, the NOAA Space Weather Prediction Center is the official source of space-weather alerts and warnings which go out to thousands of people and are used by government agencies and infrastructure operators alike. In support of the alert process, NOAA has developed space-weather scales, similar to existing hurricane or tornado scales, which the alerts are largely based on. These scales categorise solar flares (radio blackouts – R-scale), solar radiation storms (S-scale), and geomagnetic storms (G-scale). For alerts of solar flares, text and graphic products are available to the users. This includes graphics that show the areas of highest impact on HF communications on Earth as a function of time. Only probabilistic forecasts of the conditions favourable for triggering eruptive activity on the Sun are possible. When and where a sunspot cluster will emerge cannot be predicted. Similarly, forecasting of the occurrence and size of a flare is also not possible. Also for solar radiation storms, text and graphic products are available. There is some understanding of the underlying processes and hence some forecasting capability, but with significant limitations. For major radiations storms in progress, high-confidence persistence forecasts can be provided with 24 hour or more lead time. However, it is often the case that information can be given to aviation with only very little advance notice (sometimes only minutes).

Geomagnetic-storm forecasts are divided into three phases: watch, warning and alert. Forecasters observe and measure CMEs from the SOHO and STEREO spacecraft. A geomagnetic storm watch is issued upon detection of an Earth-directed CME with a lead time of typically 1-3 days. Subsequently, the WSA-Enlil model is run to determine the characteristics of solar winds and CMEs, and the likely arrival time of the CME at Earth. This is a key piece of information for power-grid operators to take protective action, e.g. delaying maintenance, switching lines back in, etc. When the CME is detected at the ACE spacecraft about 15-45 minutes before impacting Earth, a geomagnetic storm warning is released. At the current state of science, this is the moment when the CME's magnetic field orientation can be confirmed and it becomes known if a strong geomagnetic storm is to be expected. This presents a serious limitation to modelling and consequently, to mid- to long-range forecasting. An alert is issued when the storm is detected in the ground-based magnetometers of the US Geological Survey. Awareness of the risks associated with space weather is growing and there has been a steep customer increase of SWPC's products since the inception of the subscription service in 2005. Through this service, and through phone alerts for certain high-profile customers, SWPC reaches out to operators, government agencies (e.g. FEMA, FAA[13]) and the White House to ensure coordinated action for preparedness and response.

The UK Met Office has created the Met Office Space Weather Operations Centre (MOSWOC) which is fully integrated within the Met Office Operations Centre. Currently, it is Europe's only operational manned 24/7 forecasting capability and it provides UK-centric advisories to support the Government, military and critical infrastructure sectors, and it coordinates with NOAA SWPC from both an operational and strategic perspective. Customised impact descriptions that reflect infrastructure architectures and vulnerabilities in the UK have been added to the NOAA space-weather scales. MOSWOC observes and provides synoptic analyses of sunspot regions, as well as space-weather related raw data and analyses prepared by Met Office teams for the different user groups. Technical forecasts and guidance are provided free of charge to infrastructure operators and consist of text and graphic products (e.g. colour-coded impact matrices). MOSWOC also offers tailored services, e.g. for terrestrial or satellite communications. These services provide customised information to address the needs of specific infrastructure sectors. Preparedness plans also include a protocol that will be activated in case of a major space-weather event after discussion with the central government and the UK Space Weather Expert Group.

The key points from this session are:

- In the frame of its national risk assessment, Sweden has identified solar storms as a priority threat and has developed a space-weather scenario for Sweden assuming a Carrington-type event.
- The UK has included extreme space weather in its risk register and the government works with local responders, National Grid, and the rail and aviation sectors on a preparedness strategy.
- In Europe and the USA, 24/7 space-weather forecasting capabilities are available to support the early warning of government and industry.
- There is a need for consistency in forecasting, and coordination of forecasts from different service providers is required.
- Significant knowledge gaps in physical and impact modelling persist. These gaps strongly affect early-warning capabilities and preparedness in industry.
- Geomagnetic-storm forecasting is hampered by the limited understanding of the CME's magnetic field orientation, reducing warning times significantly.

[13] FAA: Federal Aviation Administration

4 Interdependencies and crisis response

The potential failure of critical infrastructures during extreme space weather can lead to cascading effects to other sectors and overwhelm national response capacities. In the final session of the summit three speakers from the JRC, IIASA[14] and the UK Government Office for Science discussed interdependencies between critical infrastructures, the governance of transboundary risks, and lessons learned on crisis response from a national space-weather emergency exercise.

In the EU, the European Programme on Critical Infrastructure Protection (EPCIP) is one of the key initiatives providing a policy background for critical-infrastructure protection. In December 2008, the Directive 2008/114/EC on the "Identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection" was adopted. In 2013, the European Commission published a staff working document on a revised approach to EPCIP. In this document, the importance of resilience and interdependencies in critical infrastructures is clearly mentioned, as well as the need to develop the associated methodologies and tools. Accordingly, the JRC has launched a research activity addressing these issues for different applications and levels of granularity. Complex dynamical networks theory is applied to the modelling and criticality assessment of interdependent critical infrastructures (e.g. energy and information networks). Functional modelling methods are exploited to systematically represent causes, drivers and effects of critical events on service networks. Economic impact and disservice propagation assessment is also involved in the process, based on dynamic inoperability input/output models. In order to support these analyses, the JRC has set up a Geospatial Risk and Resilience Assessment Platform.

During extreme space weather there is a risk that critical-infrastructure disruptions will cross a nation’s borders. Recent transboundary effects of power-grid outages from other causes have already been documented. New requirements on grid architecture have increased the vulnerability of the power grid to multiple risks (e.g. diversification of electricity supply in different areas, deployment of renewable energy sources in zones far from consumption centres, grids at the limit of their capacity, etc.). In light of these findings, there is a need for multi-risk assessment but also for multi-risk governance to address issues related to the multiplicity of incident triggers, the risks of cascading effects, and the many different stakeholders that manage the risk often in isolation from each other. The latter is a problem in particular for interconnected networks within the European electricity market, where each transmission system operator is only responsible for the operation of his own network. To avoid cascading effects, regional coordination is necessary to assess risks and ensure the effectiveness of operational decisions and remedial actions taken.

Multi-risk governance is subject to many challenges, including interactions between risks, multiple hazards in interdependency, knowledge and capacity transfer, gaps between science and implementation, institutional barriers for implementation of a multi-risk approach, and different national or regional patterns for stakeholder coordination and participation. Furthermore, behavioural and cognitive biases influence decision-making in multi-hazard situations. Decision-support tools can facilitate risk governance in multi-risk situations, however, the views of users from academia and practice (civil protection) on their usefulness differ significantly and should be taken into consideration. A study on the application of decision-support tools in these user communities showed that scientists appreciate these tools for ranking and comparing risk scenarios to set risk-reduction priorities, as well as for uncertainty characterisation and sensitivity analysis. Stakeholders from civil protection, on the other hand, apply these tools for increasing transparency in decision making and breaking down complex decisions into components to support communication and training. The study further recommends the implementation of a multi-risk approach through the creation of multi-risk platforms to understand and communicate key risk components to communities, and the

[14] IIASA: International Institute for Systems Analysis

establishment of local multi-risk commissions to liaise between local communities and risk-management experts. It was pointed out that a multi-risk approach cannot be subsidiary to a single-risk approach. A recent OSCE[15] handbook on the protection of national and transnational networks from natural and man-made disasters compiles effective risk-management concepts, tools and case studies to guide practitioners in the field.

In case of national emergencies in the UK, the national emergency coordination group COBRA[16] convenes. COBRA meetings are chaired by the UK Prime Minister. The scientific consensus is brought into the meeting by the Government Chief Scientific Adviser who heads the Scientific Advisory Group on Emergencies (SAGE). Extreme space weather has been recognised as a priority threat the UK is preparing for. To test overall preparedness levels, SAGE organised a space-weather emergency exercise involving multiple stakeholders in 2015. The exercise included space-weather experts, infrastructure operators, and regulators. The scope of the exercise was limited to selected infrastructure sectors only (power grid, aviation, rail, maritime transport) and experts from some areas were absent (e.g. from avionics, communications, satellites). Communications will be tested in a separate exercise.

The exercise showed that the UK National Grid is prepared well for potential space-weather impacts and has effective emergency-management plans in place. It was noted that the exercise was artificial in the sense that no warning lead time was given to the operator. In a real event, the operator would monitor space-weather alerts as they progress and would be able to put protective measures in place before the situation became critical. The UK aviation sector was less well prepared, but it was recognised that this sector operates in a complex international system and there are currently no standard operating procedures in case of a major space-weather event or any coordination of the response. Proper command structures and communication plans would be helpful for passengers and pilots. This should include information for pilots on the radiation levels they were exposed to during the event and if they are still cleared to fly afterwards.

The UK rail sector takes note of space-weather alerts but is uncertain as to how to react and turn them into decisions. Alerts would be required that specify where exactly a problem is expected in the rail network. In addition, the rail sector is confident that signals would fail safe (right-side failure) in case of space weather, although there is no certainty in science to substantiate this belief. Maritime transport has good general emergency procedures in place but it is unclear how the sector would handle space-weather impacts, in particular if coupled with adverse weather conditions. The overall conclusion of the emergency exercise was that for rail, aviation, and communications there is no specific planning in the UK, however progress is being made to address this issue. There will be follow-up workshops to the exercise that explicitly target these sectors.

The key conclusions from this session are:

- In the EU, the European Programme on Critical Infrastructure Protection is one of the key initiatives that provides a policy background for critical infrastructure protection.
- There are important challenges associated with interdependencies between critical infrastructures, and there is a need to develop associated assessment methodologies and tools.
- New requirements on grid architecture have increased the vulnerability of the power grid to multiple risks, including space weather, and transboundary effects from recent power outages have already been documented.

[15] OSCE: Organisation for Security and Co-operation in Europe

[16] COBRA: UK government emergency-response committee set up to respond to a national or regional crisis. It is named after Cabinet Office Briefing Room A.

- A multi-risk governance approach is needed to address issues related to the risks of cascading effects and the many different stakeholders that manage the risk often in isolation from each other.
- A space-weather exercise in the UK showed that National Grid is prepared well for such an extreme event, but other infrastructure sectors may not be.

5 Table-top exercise

5.1 Early warning and preparedness

The first part of the exercise focused on understanding space-weather warning possibilities, including how they translate into stakeholder preparedness, and the limitations of current forecasting capabilities. The participants worked in breakout groups on the first part of the scenario which included alerts for radio blackouts and radiation storms on 9-11 January. They were then asked to discuss the following questions:

1. How would you expect to be alerted of a potential extreme space-weather event?
2. Which contingency plans would you expect to be in place at national level to deal with such an event?
3. Should action to an event of this severity be coordinated across Europe or can it be managed at national or organisation level?

In response to the first question, the groups indicated that they would expect email and phone alerts should an extreme space-weather event occur, with follow-up phone calls. Information could “piggy-back” also on other existing routes for information sharing, e.g. broadcasting. Messages should be targeted to those stakeholders who can act upon the alert, and a clear protocol is needed to define the actors responsible for providing information, and for coordinating and initiating action. For alerts to be effective, information on the potential consequences of an impact needs to have been communicated to the stakeholders already prior to an event to educate them on the effects and on how to react. This information should include an articulation of the uncertainties associated with the issue.

The UK and the USA have contingency plans for extreme space weather (Question 2). In particular, there are well-defined processes in place for the protection of the power transmission grid. It was mentioned that in other countries contingency plans for general power blackouts exist. Although they are not specific to space-weather impacts, they could still help to mitigate the impacts of an extreme event. However, most emergency plans for power blackouts assume that other critical infrastructures, e.g. transportation and communications, are operational. This assumption is likely not valid during/after an extreme geomagnetic storms. There is also a need to develop national contingency plans for wide-range loss of communications and GNSS.

Extreme space weather could potentially impact large parts of Europe. In response to the third question, the groups indicated that pan-European guidelines on how to address the threat would be helpful considering that many critical infrastructures (e.g. power grid, transportation) are interconnected across borders. However, it was pointed out that crisis-response decisions would be taken nationally, and coordination across Europe would not necessarily be considered a priority. It was suggested to define the areas for which coordination at European level would provide added value and those that should be managed on a national scale. For example, there was consensus that emergency plans for securing water and food supplies need to held nationally.

The exercise continued with a situation update of a fast CME launched towards Earth on 13 January and arriving one day after the warning. An alert for an extreme geomagnetic storm is issued which is classified as a Carrington-type storm. With this information, the breakout groups were asked to discuss the following two questions:

1. Are additional observational and modelling capabilities needed to provide the stakeholders with the information they require at this point in the scenario? If not, what are the key gaps and priorities?
2. Which information could and should be shared with the public at this stage? Should information be restricted to general space-weather forecasts or already include predictions of potential impacts?

Replying to the first question, all participant groups agreed that there are still significant gaps in the modelling of physical phenomena and impacts that affect preparedness levels. There was consensus that one priority need is to determine the orientation of the magnetic field of an Earth-directed CME before it reaches L1[17] to extend warning lead times for infrastructure operators. Other identified gaps relate to ionospheric forecasting and the lack of an end-to-end Sun-Earth interaction model. On the impact side, capabilities need to be created or improved with respect to predicting CME arrival times, the probability and size of an impact, and the granularity of the forecasts. Customised warning messages should be available for each country, as not all countries will be equally affected. Since infrastructure operators require local or regional information to prepare in the best possible way, impact maps per space-weather effect would be highly desirable (e.g. power-grid impacts vs. geomagnetic storm magnitude across Europe). It was pointed out that authorities would have to know when conditions have stabilised to commence remedial action.

At this stage of the scenario, all infrastructure owners should have been made aware of the situation (Question 2). In the UK, the government would not yet issue a warning. Rather, the Met Office would publish awareness notices. With respect to information to the public it was highlighted that it needs to come from the responsible authorities and be understandable and consistent. This information should explain what is happening, how it will impact the public, what is being done about it, how long the situation is expected to last, and what the public should or should not do. The question was raised what the private sector's (e.g. aviation) responsibilities towards the public are when government issues a space-weather warning.

5.2 Response and recovery

The second part of the table top exercise addressed the response and recovery phases. It aimed to highlight the common challenges EU Member States might have to address in this case (situational awareness, communication to sectors, the public, and across borders), identify major capacity gaps at national and EU level, and discuss how industry and government can reduce the risk of infrastructure disruptions and prepare for mitigating their consequences.

5.2.1 Response

In a situation update, the breakout groups were informed that on 15 January, the day after the CME impact, the resulting extreme geomagnetic storm has led to infrastructure disruptions and cascading effects throughout Europe. The power grid is down in 45% of the affected area, and many basic societal functions, such as water supply, heating, and ATM services, have been disrupted. The fuel supply is limited. Mobile phones and landlines are expected to be unusable due to capacity overloads. In the two days that follow (16-17 January), power outages persist and several nuclear power plants run on back-up power. Police and other emergency responders are affected by communication and navigation disruptions. GPS positioning is unavailable across much of the globe. As a consequence, hundreds of thousands of people in the affected area are stuck in trains. First responders are overloaded and there is a risk of civil unrest. Against this background the breakout groups were asked to address the following questions:

1. What are operator requirements for continued operability and constraints to respond to such an event?
2. Which problems may appear when satellite-based services are temporarily disrupted?
3. How should the public be informed about the current situation and which information should they be given at this stage in the scenario?

[17] L1: Lagrange Point L1 is located between Earth and the Sun at a distance of about 1.5 million km from Earth. The solar wind reaches satellites positioned at L1 about an hour before reaching Earth.

In response to the first question, the breakout groups agreed that extreme space weather is expected to disrupt many different types of critical infrastructures more or less at the same time (e.g. power grid, communications, transport, etc.) with ripple effects to nearly every industry sector and in society. One of the main challenges during response are the widespread impacts which are not focused on a particular community and which can extend across national boundaries. The groups indicated that the main driver for response and recovery is to restore the power grid as the backbone of society. However, in case of multi-country impacts, pan-European plans for re-establishing power in a coordinated way would be required. This includes a transformer spare strategy across Europe that has addressed potential interoperability problems.

The size and cost of Large Power Transformers (LPTs) makes it impossible for all power grid operators to hold a reserve stock of more than a few units. In addition, LPTs are usually back-ordered and are custom-built to each operator's specifications. It is unclear whether LPTs of two networks may be interchangeable, enabling Member States to assist each other in the framework of the solidarity clause. Furthermore, there are only a few manufacturers of LPTs in the world, and the lead time to have a LPT delivered may be up to a year. Therefore, the pressure on LPT manufacturers in the event of a Carrington-type storm may be considerable, especially if power systems in production facilities are themselves inoperable.

The availability of the workforce is another important limiting factor for operability and it needs to be understood how the problem of missing trained manpower can be alleviated to keep essential infrastructures running during the response phase. The groups agreed that emergency-response plans, including national and possibly transnational protocols, need to be in place before an event to be effective. Access to these plans should not require internet or computer availability. Prior to the event, government should also prioritise the critical utilities that require power to define where resources are routed during response and recovery.

The main problem related to the temporary disruption of satellite-based services (Question 2) is uncertainty about where GNSS dependency is embedded in other infrastructure sectors, e.g. via the use of timing signals for synchronisation. This dependency may be unknown to the operators. All transportation would be affected to some degree (road, rail, maritime, aviation) due to a loss of navigation and communications. In addition to potentially causing problems for just-in-time delivery of products or essential supplies, this would also impact emergency-response services, warranting an assessment of their vulnerability under extreme-event conditions. The finance sector would also feel the effects of loss of GNSS as it uses GPS-based timing in many applications; weather forecasting would also be hampered. Protocols should be established to define priority access to the limited communication possibilities that will remain.

For communicating with the public during the response phase (Question 3), radio would be the most likely option, if still operative, because other communications system may not be operational immediately at this stage. Emergency-service announcements from vehicles or public gatherings, with the participation of local government which speaks with a position of authority, might be needed. In Germany, some areas have developed information hubs, so-called "lighthouses" which have built-in resilience and can communicate with other lighthouses, thereby enabling communication between cities. The government is responsible for providing the public with information during response. This information should give some level of reassurance but be realistic, provide an estimate of the timeframe of the emergency situation, as well as instructions on where to get water, food, etc. Interestingly, it was noted that the basic infrastructure in the past was much more resilient than today. The many (inter)dependencies of modern infrastructures have created inherent vulnerabilities with the accompanying risks.

5.2.2 Recovery

Situation update: On 18 January the power supply is slowly being restored although some locations are still without electricity due to transformer damage. Telephone communications and broadcasting have returned to service. However, the geomagnetic storm has left the society at large without food, water, heating, personnel and life-sustaining equipment for days. The impacts of the storm on electricity distribution will be felt for the coming 6-12 months. The overall economic consequences are substantial and correspond to approximately 1-2% of GNP. With this scenario in mind, the breakout groups addressed the following questions:

1. What are the major lessons learned in European infrastructure sectors related to emergency preparedness for this type of event?
2. What are the major challenges for the communication of warnings, risks, and mitigation measures taken at national and at EU level?
3. Which are the common challenges the EU Member States and the EU will have to address in such an event?

Replying to the first question, one of the main lessons identified by the groups is that stakeholders need to be convinced that the space-weather threat to critical infrastructures is real. National response and recovery plans are essential and should be exercised. There is a question as to whether general-purpose plans are sufficient or whether they have to be space-weather (multi-disruption) specific. National protocols have to be supplemented by pan-European protocols and decision-making in case of an emergency. It was indicated that there is currently no European strategic decision-making capability that could quickly respond to a European crisis. Opportunities offered by the European Response Coordination Centre (ERCC) could be explored in this context. With respect to the power grid, the different owners in Europe need to collaborate to restore power in a controlled manner. This requires pan-European modelling to understand how the grids will be impacted by an extreme event and how recovery could be achieved in the fastest way. With power restored, food and other goods may, however, take longer to recover, a fact the public needs to be aware of. It was highlighted that the concept of resilience should be considered more explicitly (e.g. via a cost/benefit analysis) when changing technological systems to capture potential vulnerabilities introduced in the system when making the change.

The major communication challenges according to the groups (Question 2) are related to the unavailability of the usual mass communication options (e.g. broadcasting) and the necessity to provide clear and useful information while at the same time trying to avoid panic and civil unrest. Protocols at authority level are needed to ensure that the appropriate information is shared. With the existence of different forecasting centres there is a risk of inconsistent space-weather forecasts. Coordination (e.g. at EU level) should guarantee that disseminated alerts contain consistent information.

The challenges associated with addressing an extreme event differ between countries as they depend on national priorities. However, some common challenges were identified when discussing the third question. In the short term, power, food, water, heating, etc. and public order and safety will have to be ensured. This involves the implementation of measures that will allow people to return to their workplace and the restoration of production lines. There will have to be a re-prioritisation of scarce resources, e.g. spare parts in limited supply, nationally and possibly even at European level. It is unclear how and by whom these resources should be distributed. In the longer term, economic recovery from an extreme event will not be without difficulty. Another challenge is the rebuilding of trust into utilities and government which will have suffered during the emergency, as well as public reaction to the relative performance in neighbouring countries and the potential for international tensions.

6 The way forward: discussion and recommendations

The final session of the summit aimed to capture participants' impressions on the two days of the event, discuss strategic and policy issues related to the identified gaps, and to provide a basis for the prioritisation of actions for future incident prevention and consequence mitigation.

There was agreement that extreme space weather poses a real threat to a multitude of critical infrastructure sectors at the same time, and that the potential impacts may be so significant that standard preparedness planning assumptions should be revisited. Preparedness plans are mostly based on single infrastructure disruptions whose management is rather straightforward, but they would likely not be able to address the complex challenges associated with multiple events. Furthermore, the assessment of space-weather impacts requires a multi-disciplinary approach by all stakeholders (science, engineering, industry, policy) that is not necessarily common for other types of risks. A change in mindset may be required to adequately address multi-hazard risks in general, and extreme space weather in particular.

Knowledge gaps related to space-weather modelling and infrastructure vulnerabilities persist. For example, it is still not possible to predict the orientation of a CME's magnetic field before it has almost reached Earth, thereby losing valuable time that operators would need to implement the most appropriate actions to protect infrastructures. Extending predictions on lead time by one day would be an important step towards improving preparedness, and science is confident that with a better understanding of solar processes this can be accomplished. On the impact side, there is a need for the prediction of the probability and size of an impact, and for local or regional forecasts, all of which are beyond current scientific capabilities. The importance of having a credible worst-case scenario as a baseline for impact assessment was also emphasised.

Another concern are infrastructure vulnerabilities that operators may not be aware of. For example, GNSS dependencies may be embedded in systems without operators realising it and consequently there would be no preparedness for loss of GNSS. Further work is required to better understand these hidden vulnerabilities as we can only manage challenges if we know what they are. Care should be taken to not introduce additional vulnerabilities into systems in the frame of technological modernisation processes. For existing vulnerabilities, redundancies to mitigate space-weather risks may be required.

The discussions showed that awareness of space-weather risks is highest among power transmission grid operators in some countries and in the aviation sector (for loss of communications only). Overall, the power grid appears to be the best prepared infrastructure sector, partly because it has experienced space-weather related incidents in the past that led to design improvements and accompanying operational mitigation measures. Nevertheless, almost nothing is known about the risks of extreme space weather to power grids in continental Europe. There was a call for a comprehensive vulnerability assessment of the European power grid (including transboundary effects) to have a full picture of what could happen Europe-wide in case an extreme geomagnetic storm hits.

From a strategic and policy perspective, the lack of clearly defined roles in Europe was highlighted. Suggestions were made for appointing an entity that takes the lead in all matters related to space-weather risk mitigation in Europe. This would facilitate pan-European preparedness planning and coordination in case of a European crisis, as well as provide consistency in forecasting and alerting. Currently, there are several support tools at EU level in case of a major disaster, neither of which includes, however, strategic decision-making power. The solidarity clause will be invoked when a major event overwhelms the capacity of a single country to respond. Extreme space weather could be an example. The ERCC, a 24/7 emergency operations centre, is becoming the European Commission's hub for response to all crises. It reacts upon receiving a request for support from a country. The difficulty of acting at EU level without a mandate from the Member States was emphasised. The European Commission is willing to offer all its tools (including risk assessment and scenario building) but there needs to be political support due to the sensitivities involved in critical infrastructure protection.

As a first practical step at EU level, it was suggested to organise an emergency exercise testing a scenario in which infrastructures needed for emergency response are unavailable. This or other space-weather exercises could be organised as a multi-national exercise under the Union Civil Protection Mechanism. The USA are interested in exploring the opportunity for collaborating on such a joint European exercise. International collaboration is crucial considering the potentially global impact of extreme space weather.

Based on the conclusions of the Summit, the following recommendations for action targeting stakeholders in science, industry and policy are proposed:

Recommendations for science:

1. Physical models should be improved or - where necessary - new models developed to allow a better prediction of CME arrival times, an earlier determination of the interplanetary magnetic field orientation, and an estimate of the probability and size of the likely impacts.
2. Forecasting capabilities should be enhanced to provide regional or local forecasts on the severity and duration of extreme space weather to ensure the most appropriate operator response.
3. Extreme space-weather scenarios should be defined against which operators can benchmark the performance of their infrastructures and develop risk mitigation strategies. This should be accompanied by a reference document for all stakeholders which includes a clarification of terminology.
4. Impact models for different types of critical infrastructures and their components should be developed to facilitate risk assessment. Cooperation with industry should be sought to obtain access to infrastructure-specific data for model verification and scenario building.
5. Methodologies for multi-hazard risk assessment and the modelling of infrastructure interdependencies should be developed for a realistic estimate of extreme space-weather impacts on industry and the ripple effects in society.

Recommendations for operators:

1. Operators should be aware that a satisfactory performance of infrastructures during moderate space weather does not guarantee continued operability and lack of damage during Carrington-type geomagnetic storms.
2. Also, operators should be aware that during extreme space-weather conditions, areas normally unaffected by geomagnetic storms are likely to be hit. Response plans should be ready in case of an alert.
3. A comprehensive vulnerability assessment of the European power transmission grid to extreme space weather should be carried out to identify criticalities and the possibility of transboundary effects.
4. Operators should assess if hidden vulnerabilities to space weather are embedded in their systems, for example via dependencies on GNSS.
5. Care should be exercised when modernising technology to ascertain that new vulnerabilities to space weather are not inadvertently introduced into systems.

Recommendations for policy:

1. A strategic plan should be developed to define the roles of the key players in Europe. This can include the establishment of a centralised European strategic decision-making capability tasked with coordinating space-weather risk mitigation (including alerting) and response at a pan-European level.

2. Consistency in forecasting needs to be ensured. Protocols are needed to coordinate forecasts of different space-weather service providers.
3. Protocols should be developed that define responsibilities and ensure good coordination between the stakeholders before, during and after an extreme event. This includes communication of the risks and potential impacts to the public.
4. Emergency plans for extreme space weather should consider the full range of critical infrastructures possibly affected. Once drawn up, these plans need to be tested.
5. The opportunity for organising a joint space-weather exercise at EU level should be explored to test existing response capabilities and identify critical gaps.
6. It should be determined if further measures may be necessary to guarantee the integrity of critical infrastructures and their continued operability in case of a major event.
7. Coordinated strategic investments into developing scientific capability and know-how in the EU should be explored.

Annexes

Annex 1. Participant list

Name	Affiliation
Allen, John	NASA
Andersson, Anders	Luftfartsverket, Sweden
Boniface, Karen	Joint Research Centre, European Commission
Bothmer, Volker	Goettingen University, Germany
Cannizzaro, Chris	U.S. Department of State
Chondrogiannis, Stamatios	Joint Research Centre, European Commission
Cid, Consuelo	University of Alcala, Spain
Clark, Ian	Joint Research Centre, European Commission
De Gier, Martijn	Ministry of Security and Justice, The Netherlands
Dovis, Fabio	Turin Politecnico, Italy
Durand, Eric	Swiss Re
Eichner, Jan	Munich Re
Elsbacher, Hansi	Swedish Civil Contingencies Agency MSB
Fortuny Guasch, Joaquim	Joint Research Centre, European Commission
Fulli, Gianluca	Joint Research Centre, European Commission
Galbusera, Luca	Joint Research Centre, European Commission
Gibbs, Mark	UK Met Office
Gibson, Andrew	Department for Business, Energy and Industrial Strategy, UK
Goede, Christina	Swedish Civil Contingencies Agency MSB
Haggarty, Ewan	Airbus Defence and Space
Jonas, Seth	Science and Technology Policy Institute, USA
Jones, Bryn	SolarMetrics Consulting
Karagiannis, Georgios	Joint Research Centre, European Commission
Karlsson, Annette	Swedish Civil Contingencies Agency MSB
Komendantova, Nadejda	IIASA
Kopustinskas, Vytis	Joint Research Centre, European Commission
Krausmann, Elisabeth	Joint Research Centre, European Commission
Laitinen, Tiera	Finnish Meteorological Institute
Lally, Claudia	Government Office for Science, UK
Luntama, Juha-Pekka	ESA
McCormack, Leslie	Atkins
Murtagh, William	NOAA
Oberger, Par	LFV, Air Navigation Services of Sweden
Oexl, Bettina	Airbus DS GmbH
Opgenoorth, Hermann	Swedish Institute of Space Physics
Pescaroli, Gianluca	University College London, UK
Praks, Pavel	Joint Research Centre, European Commission
Prouse, Mark	Department for Business, Energy and Industrial Strategy, UK
Richards, Andrew	UK National Grid
Ruffenach, Alexis	EDF, France
Schimmer, Muriel	Haut Commissariat à la Protection Nationale, Luxemburg
Anja, Stromme	Norwegian Space Centre
Svennesen, Thomas	Energinet, Denmark
Thorn, Peter	UK Met Office
Voigt, Philipp	Airbus DS GmbH
Von Stapelmohr, Anne	Swedish Civil Contingencies Agency MSB
Wick, Robert	University College London, UK

Annex 2. Agenda

Space Weather and Critical Infrastructures Summit

29-30 November, Ispra, Italy

Room 3, Building 36b

DAY 1

08:45 – 09:00 Opening and welcome (*D. Chirondojan, JRC*)

09:00 – 11:00 Session 1: Space weather today and progress made

Chair: M. Gibbs, UK Met Office

09:00 – 09:20 Introduction to space weather (*B. Murtagh, NOAA*)
09:20 – 09:40 Space weather and disaster risk reduction (*DG ECHO, represented by I. Clark, JRC*)
Awareness, policy action and international cooperation for space weather: progress over the past 5 years:
09:40 – 10:00 Developments in the EU – FP7 and H2020 (*V. Bothmer, Göttingen University*)
10:00 – 10:20 Space Situational Awareness programme (*J.-P. Luntama, ESA*)
10:20 – 10:40 US National Space Weather Strategy (*C. Cannizzaro, US Dept. of State*)
10:40 – 11:00 COSPAR Space Weather Roadmap (*H. Opgenoorth, Swedish Institute of Space Physics*)

11:00 – 11:15 Coffee break

11:15 – 12:35 Session 2: Space-weather impacts on critical infrastructures and risk reduction: Part I

Chair: W. Murtagh, NOAA

Known vulnerabilities of critical infrastructures to space weather and risk reduction:
11:15 – 11:35 Power grid (*A. Richards, UK National Grid*)
11:35 – 11:55 Aviation (*B. Jones, SolarMetrics Consulting*)
11:55 – 12:15 GNSS (*J. Fortuny-Guasch, JRC*)
12:15 – 12:35 Rail *(L. McCormack, Atkins*)

12:35 – 13:30 Lunch

13:30 – 14:50 Session 3: Space-weather impacts on critical infrastructures and risk reduction: Part II

Chair: S. Jonas, U.S. Science and Technology Policy Institute

13:30 – 13:50 National approaches to space weather risk management: Sweden (*C. Goede, MSB*)
13:50 – 14:10 National approaches to space weather risk management: UK (*C. Lally, UK Government Office for Science)*
14:10 – 14:30 US forecasting and alert capabilities (*B. Murtagh, NOAA*)
14:30 – 14:50 UK forecasting and alert capabilities (*M. Gibbs, UK Met Office*)

14:50 – 15:15 Coffee break

15:15 – 18:00 Table top exercise Part I – Gap analysis

Moderator: H. Opgenoorth, Swedish Institute of Space Physics
Scenario presentation: M. Gibbs, UK Met Office

Experts have spotted an Earth directed CME. What additional measures and capabilities are required to protect infrastructures?

- Which additional structural and organisational measures for risk reduction in industry are required?
- Which additional observational and modelling capabilities are needed to improve forecasting?
- In case of an alert, how is information shared with the stakeholders?

19:30 Social dinner

DAY 2

9:00 – 10:15 Session 4: Interdependencies and crisis response

Chair: N. Kourti, JRC

09:00 – 09:25 CIP initiatives in Europe, interdependencies and cascading effects (*L. Galbusera, JRC*)
09:25 – 09:50 Transboundary effects (*N. Komendantova*, *IIASA*)
09:50 – 10:15 Lessons learned from UK space-weather emergency exercise (*C. Lally, UK Government Office for Science*)

10:15 – 10:30 Coffee break

10:30 – 13:10 Table top exercise Part II – Impact analysis and crisis response

Moderator: I. Clark, JRC
Scenario presentation: M. Gibbs, UK Met Office

The extreme space weather event caused a number of power outages across Europe and has resulted in loss of GNSS services across much of Europe. The impact is spreading across sectors. Identify potential deficiencies in the crisis management and the measures required to create robust infrastructure and redundancy in society.

- What are operator requirements for continued operability and constraints to respond to such an event?
- Which are the common challenges the Member States and the EU will have to address in such an event?
- Are additional emergency planning and response capabilities needed?
- Which information can and should be shared with the public?

13:10 – 14:15 Lunch

14:15 – 15:15 Session 5: The way forward

Chair: W. Murtagh, NOAA

*Panel members: I. Clark (JRC), M. Gibbs (UK Met Office), C. Canizzaro (U.S. Department of State),
H. Opgenoorth (Swedish Inst. of Space Physics)*

- Summary of recommendations to close gaps (feedback from Table Top exercise)
- Mechanisms for collaboration between countries (bilateral and multilateral)
- Identification of common capabilities that need to be developed
- Discussion of next steps

15:15 – 15:30 Closing of the event (*N. Kourti, JRC*)

LB-NA-28237-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi: 10.2788/152877

ISBN 978-92-79-63903-6