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Space Weather Socioeconomic Impact Study on Canadian Infrastructure

Prepared for:
Canadian Space Agency

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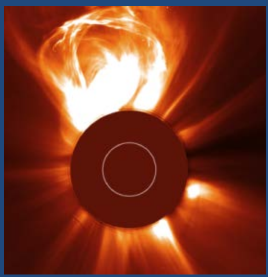

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Executive Summary

Space weather has a variety of impacts on technology, both in space and on the ground. In space, the impacts include health risks to astronauts due to radiation exposure and physical risks to satellites and their electrical components due to energetic electrons and solar flare protons. Space weather has wide-ranging impacts on Earth, due to the effects of geomagnetic storms on the electrical grid and the use of space-based services such as satellite communications and global navigation satellite systems (GNSS), and the increase in radiation exposure to passengers and crew on international flights over the polar regions. Electromagnetic radiation from the Sun can interfere with communications, either by direct radio interference or by affecting the electrical properties of the ionosphere.

The primary objectives of this study were to: assess and quantify the socioeconomic impact of various space weather scenarios; review current efforts to detect, warn and mitigate space weather events on Canada's infrastructure; and facilitate an exchange of information on the study findings with key stakeholders (Canadian government, industry and academia) and provide a preliminary assessment of the level of preparedness and knowledge of potential space weather effects and impacts amongst these stakeholders. The study relied upon a comprehensive literature review, key informant interviews, telephone surveys and a stakeholder consultation workshop as the primary research methods. A three-phase approach to analysis of the socioeconomic impacts of space weather disturbances included: development of a set of socioeconomic impact indicators; assessment of the impact of space weather for three scenarios representing different levels of space weather activity; and identification of mitigation strategies or needs for a higher resilience to space weather events in Canada. This study does not intend to measure the risk or likelihood of a space weather event, and must not be read as a vulnerability study. Separate work based on long-term measurements of space weather indicators, and accurate models of assessing their impacts on technological infrastructures, are required to assess the probability of the proposed scenarios to materialize. The study also did not quantitatively assess the broader social impacts which might arise from the effects of extreme space weather on technological infrastructure.

Initial research was conducted in two areas to provide a solid foundation for the subsequent data collection and analysis phases. A review and assessment of previous space weather socioeconomic impact studies provided insights and identified good practices that were incorporated in the design of the impact assessment methodology. Research on space weather related activities in Canada, United States, Australia and United Kingdom resulted in an inventory of space weather players (service providers and clients) in Canada, and provided information on how Canada compares with the other jurisdictions on the delivery and use of space weather information.

The space weather socioeconomic impact methodology took into account the following considerations:

- *Impact mechanisms*, including geomagnetically induced current, deep dielectric charging, surface charging, ionospheric scintillation, atmospheric heating, geomagnetic disturbances, HF radio interference, radiation and solar cell degradation.

- *Impacted infrastructure*, including electrical grid, satellites, polar aviation, polar marine transportation, magnetic surveying, directional drilling, pipelines, GNSS positioning, navigation and timing (PNT), surveying and precision farming.

- *Impact extent*, using the point of view of the economy as being of primary interest, with costs to infrastructure providers and users translated into economic GDP using an input-output model.

- *Mitigation planning*, which are dealt with by infrastructure operators by making investments in three areas: design, backup and actions (i.e. operating procedures).

- *Impact experience* that infrastructure sectors and their users have, which depends on the level of space weather that creates an impact and the significance of the effect. It is important to note that sectors must also prepare for other failure mechanisms and that the cost of mitigation of space weather impacts is spread among the response to a variety of threats.

The impacts of space weather on infrastructure systems, facilities and operations were documented for each sector. The current mitigation strategies being employed in each sector were identified and additional needs to improve mitigation measures, including improvements in space weather services and additional research activities, were determined, based primarily on the consultations with sector representatives. It is important to note that mitigation strategies have been developed in most cases without the benefit of detailed probability and impact assessments. These needs provide a strong basis for the establishment of a national Canadian Space Weather Strategy.

Economic impacts were based on three impact scenarios. These impact scenarios were defined based on the temporal extent of assumed outages. Scenario 1: Limited impacts (minutes to 2-hour electrical service denial), Scenario 2: Short-term impacts (24-hour electrical service denial) and Scenario 3: Long-term impacts (14-day electrical service denial). The table on the next page provides a summary of the economic (GDP) impacts of space weather on Canada's different infrastructure sectors and illustrates the sizeable variation between sectors. Note that no traceability to the likelihood of such scenarios in a give sector was completed since such risk (coupled likelihood and impact) studies require formal technical impact studies and these are beyond the scope of this study. Such impact studies should however be completed as a priority in the future as a follow-on the work presented here.

The study also found considerable variation in thesocial impacts of space weather on Canada's infrastructure sectors. Across all of the sectors, the impacts under Scenario 1 are either nonexistent or limited to minor inconveniences for infrastructure operators or their customers. Under Scenarios 2 and 3, important additional impacts may be experienced in some sectors (e.g. increased risk of accidents, disruptions in medical care, weather forecasting, telecommunications and emergency response services, civil unrest, increased environmental degradation). In most sectors, under Scenarios 1 and 2 the impacts will primarily be on infrastructure operators, with more limited impacts on businesses, consumers and the general public. Under Scenario 3, there would be significant impacts well beyond the infrastructure operators. By far the largest economic impact is generated in Scenarios 2 and 3 in relation to the interruption to electricity supply in the electrical grid.

An analysis was also conducted of the state of space weather awareness. In general, the level of awareness of space weather impacts is relatively high within the stakeholder community that was consulted for this study. This is not surprising, given that the participants in the consultations were specialists directly responsible for assessing the risks of environmental impacts, including space weather, to their systems and operations. It is worth noting, however, that this awareness may be from experience of very limited space weather activity in the past 10-15 years. Therefore, the perception of risk might be underestimated in the industry as a result of operational experience spanning only a relatively small range of space weather events sizes compared, for example, to ~100+ year timescales on which much larger extreme events have been observed to occur. It is important to note that awareness beyond this group of specialists is typically much lower within the broader infrastructure community.

Infrastructure Sector	Scenario 1	Scenario 2	Scenario 3
Electrical Grid	$0	$405.7 M – $1,091.8 M	$20,682.2 M - $54,945.8 M
Satellites	$1.2 M	$302.2M	$605.1 M
Polar Aviation	$1.4 M – $28.0 M	$1.4 M – $28.0 M	$1,750.0 M
Polar Marine Transportation	$0	$0	$0
Magnetic Surveying	$1.4 M – $7.0 M	$1.4 M – $7.0 M	$1.4 M – $7.0 M
Pipelines	$238.2 M	$238.2 M	$238.2 M
Surveying	$0.8 M – $1.7 M	$0.8 M – $1.7 M	$0.8 M – $1.7 M
Precision Farming	$0	$0.5 M	$0.5 M
TOTAL	**$243.0 M – $276.1 M**	**$950.2 M – $1,669.4M**	**$23,249.2 M – $ 57, 519.3 M**

In the global context, space weather awareness is growing, as indicated by a number of recent initiatives (e.g. establishment of the *Space Weather Expert Group* by the United Nations Committee on the Peaceful Uses of Outer Space, release of national space weather strategies in the US and UK, the development by the North American Electric Reliability Council (NERC) of electric grid guidelines and the approval by the International Civil Aviation Organization (ICAO) of Standards and Recommended Practices (SARPs) for space weather advisories and appointment of global space weather centres for aviation). In the Canadian context, the majority of consultation respondents felt strongly that the federal government has a role to play in further raising awareness of the risks of space weather and providing advice on how to mitigate the impacts of severe disturbances, and expressed interest in training to raise the awareness of the risk and impacts of space weather within their organizations. While there is a relatively high level of awareness and use of the Canadian government's space weather services, there were a number of suggestions for future improvements in the government's services and role (e.g. more information on the probability, duration and intensity of events and thresholds of concern for each infrastructure sector, higher levels of local/regional detail, an ongoing national forum for exchange of information and experiences in dealing with space weather, and more predictable/regular research funding to assist utilities to study risk modeling, improve simulations and identify system vulnerabilities). In order to assess such space weather risks on infrastructure such studies should be completed as a follow-on to this study.

Based on the study findings, it is **recommended that a Canada Space Weather Strategy (CSWS) be developed**. There is an increasing recognition worldwide that Space Weather Monitoring and Forecasting is required to develop actionable protocols, strategies and operating procedures to protect space assets, ground assets and ultimately human lives against risks originating in space. Space weather events can have a significant impact on Canada's critical infrastructure that is essential to national security, the economy and the health of Canadians including the electrical grid, the transportation networks and space systems (satellites and their ground facilities). Concerns have risen over the years as a result of the complexity of critical infrastructure and our increasing dependency not only on a requirement for near-continuous availability of electrical power, but also on space-based technologies such as cellular/mobile telephones, the Internet and Global Navigation Satellite Systems (GNSS)/Global Positioning Systems (GPS). When autonomous vehicles are introduced our reliance on GNSS/GPS with higher precision will increase.

Feedback from stakeholders in this study suggests a strong interest within the space weather community in the federal government taking a stronger leadership role in coordinating Canadian space weather activities. There is growing recognition in this country of the risks to an increasingly integrated critical infrastructure from severe space weather events. While many stakeholders believe that they have acceptable impact mitigation measures in place, there are fundamental knowledge gaps in assessing the technological impacts from extreme space weather events – not only in assessing the levels of disturbance, but also their occurrence frequency, and the mechanisms through which they can affect various critical infrastructures. To address this requires knowledge of realistic benchmarks of the levels of space weather disturbance which should be applied to models of the relevant infrastructure, recognizing the importance of accurate representations of how the technology is implemented. It also requires a realistic assessment of the different sizes of space weather disturbances at different geographic locations and their occurrence frequencies, including in relation to benchmark extreme events. In relation to Canada, the high latitude location of infrastructure often means the impacts can be significantly larger than those experienced, for example, by infrastructure in the United States further south. There is also strong interest in improved space weather forecasting and additional research on the specific impacts in different sectors. A coordinated effort to address this interest with a formal Canada Space Weather Strategy (CSWS) will be welcomed by the community.

The detailed recommendation proposes the following goals for the CSWS:

1. **Improve Understanding of Space Weather Impacts:** While infrastructure operators appear to be confident in their preparations to mitigate space weather impacts, there is strong interest in additional research to bolster their understanding of impacts and the frequency of occurrence of extreme events. It was noted by interviewees and survey respondents that more funding for research on space weather impacts and mitigation is needed; Canada is far behind the US & UK[1]. There is interest in understanding more about probabilities of severe events and in higher fidelity impact studies and risk assessments based on improved benchmarks.

2. **Increase Forecasting Services Tailored to Canadian Latitudes:** In order to manage the risk of space weather impacts, organizations need information upon which to base the formulation of their mitigation measures and take action in the case of significant events. It was noted by interviewees and survey respondents that forecasts on the duration, intensity and geographic area (specific to Canadian latitudes) of space weather events is needed (i.e. NOAA forecasts are not always suited for Canada). There is interest in extending the geomagnetic monitoring network.

3. **Promote Greater Awareness of the Risks and Impacts of Space Weather Events:** The majority of respondents felt strongly that the federal government has a role to play in raising awareness of the risks of space weather and providing advice on how to mitigate the impacts of severe disturbances. Many noted that Canada had fallen behind and expressed concern that other countries, particularly the U.S. and U.K., are much more proactive in both raising awareness of the risks and making investments in space weather services. It was also suggested that "space" be added to the list of Canada's critical infrastructure sectors, and included in future editions of *Canada's Emergency Management Framework* and *National Strategy and Action Plan for Critical Infrastructure*.[2]

4. **Create a Space Weather Preparedness Plan:** The creation of a Space Weather Preparedness Plan would require a coordinated approach across all government departments/agencies (possibly lead by Public Safety Canada) and commercial and academic partners to ensure a streamlined but evidence-based approach and process. Key stakeholders would include federal departments of Transport, Defence, Innovation, Science and Economic Development and Natural Resources, and the Canadian Space Agency, as well as provincial and local government and private sector infrastructure

[1] For example, the UK's new £ 8 M Data and Analytics Facility for National Infrastructure (DAFNI) is helping researchers to analyse the resilience of interdependent critical infrastructure, among other things. (https://www.dafni.ac.uk/)

[2] Note that the Government of Australia has already taken similar action, in recognition of the increasing reliance on space-based infrastructure.

operators. It would address how each government department should react in response to a space weather event (i.e. roles and responsibilities) as well as the selection of a singular entity that would play the coordination role.

5. **Continue and Enhance International Engagement:** Engagement with the international community on observation infrastructure, data sharing, numerical modeling and scientific research should be continued and enhanced where appropriate. Enhanced collaboration can also provide solutions to regional challenges associated with space weather and exchange of best practices between Canada and the international partners. Overall this will help to strengthen global capacity to respond to extreme space-weather events. Progress is being made in this area with the recent release of voluntary guidelines by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). The 21 agreed guidelines promote broader international collaboration and address the policy, regulatory, operational, safety, scientific, technical and capacity-building aspects of space activities including two specifically dedicated to space weather. The implementation of these guidelines in Canada, perhaps with oversight from the CSWS process, will support the development of practices to mitigate risks associated with the conduct of outer space activities so that present benefits can be sustained and future opportunities realized.

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1. Introduction

1.1 Background

1.1.1 Space Weather Phenomena

Space weather describes the variations in the space environment between the Sun and Earth and the phenomena that impact systems and technologies in space and on Earth. Space weather can have major impacts on Earth by disturbing our space environment. Table 1-1 summarizes notable space weather events going back to the "Carrington" event in 1859.[3]

Table 1-1: Notable Space Weather Events

Date	Comment
September 1859	The "Carrington" event is generally considered the benchmark for extreme space weather studies. The solar flare, the geomagnetic storm, and the energetic particle flux associated with this event make it one of the largest on record, with reports of telegraph lines being set on fire. Many crucial parameters were not measured directly, so its precise properties are subject to uncertainty. In particular, estimating the strength of the geomagnetic storm associated with the Carrington event has attracted some debate; with estimates of the Dst index between −850 nT[4] and −1760 nT[5]. In 2012, Riley estimated the probability of another Carrington event (based on Dst < −850 nT) occurring within the next decade to be ~12%.[6]
May 1921	This geomagnetic storm has been estimated to be comparable in size to the current best estimate of the Carrington event. Auroras were seen near the equator in Samoa, and geomagnetically induced currents (GICs) caused fires at several telegraph stations in Sweden.
May 1967	An extreme solar flare and coronal mass ejection caused very significant radio blackouts, solar radiation storms, and a major geomagnetic storm. This caused a particularly significant disruption to communications, and marked the start of a substantial U.S. investment in space weather monitoring that continues to this day.
August 1972	A historically powerful series of solar storms with intense to extreme solar flare, solar particle event, and geomagnetic storm components, which caused widespread electric- and communication-grid disturbances through large portions of North America as well as satellite disruptions. The storm also caused the accidental detonation of numerous U.S. naval mines near Haiphong, North Vietnam. While this event happened between the Apollo 16 and 17 missions, it is estimated that astronauts on the Moon surface would have faced severe acute illness and potentially a nearly universally fatal dose.

[3] J.P. Eastwood et al (2017), The Economic Impact of Space Weather: Where Do We Stand?, *Risk Analysis, 37, 2*, 206-218

[4] Siscoe, G., N. Cooker, and C. R. Clauer (2006), Dst of the Carrington storm of 1859, Adv. Space Res., 38, 173–179, doi: 10.1016/j.asr.2005.02.102.

[5] Tsurutani, B. T., W. D. Gonzalez, G. S. Lakhina, and S. Alex (2003), The extreme magnetic storm of 1–2 September 1859, J. Geophys. Res., 108, A7, 1268, doi:10.1029/2002JA009504.

[6] Riley, P. (2012). On the probability of occurrence of extreme space weather events, Space Weather 10.2 (2012), accessed on January 24, 2019 at https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2011SW000734

March 1989	The largest geomagnetic storm of the space age causing the well-known 9-hour failure of the Quebec power grid and damaging transformers in Northeastern US and the United Kingdom.
October–November 2003	A very well-observed and measured complex series of events including one of the largest observed solar flares on record. The overall technological impact is extremely well documented. A 90-minute blackout in 2003 affected 50,000 customers in Sweden. However, it is now widely recognized that this blackout would probably have been avoided if current operational warning systems had been in place.
July 2012	This CME was not Earth directed, but was measured *in situ* by the STEREO-A spacecraft. Baker et al argued in 2013 that, if this CME had been Earth directed, it may have generated a very severe geomagnetic storm larger than the Carrington event.[7] It has been argued that this event should be used to create severe space weather scenarios for planning purposes.

Source: J.P. Eastwood et al (http://onlinelibrary.wiley.com/doi/10.1111/risa.12765/full)

1.1.2 Overview of Impacts on Technology

Space weather has a variety of impacts on technology, both in space and on the ground.

Impacts in Space

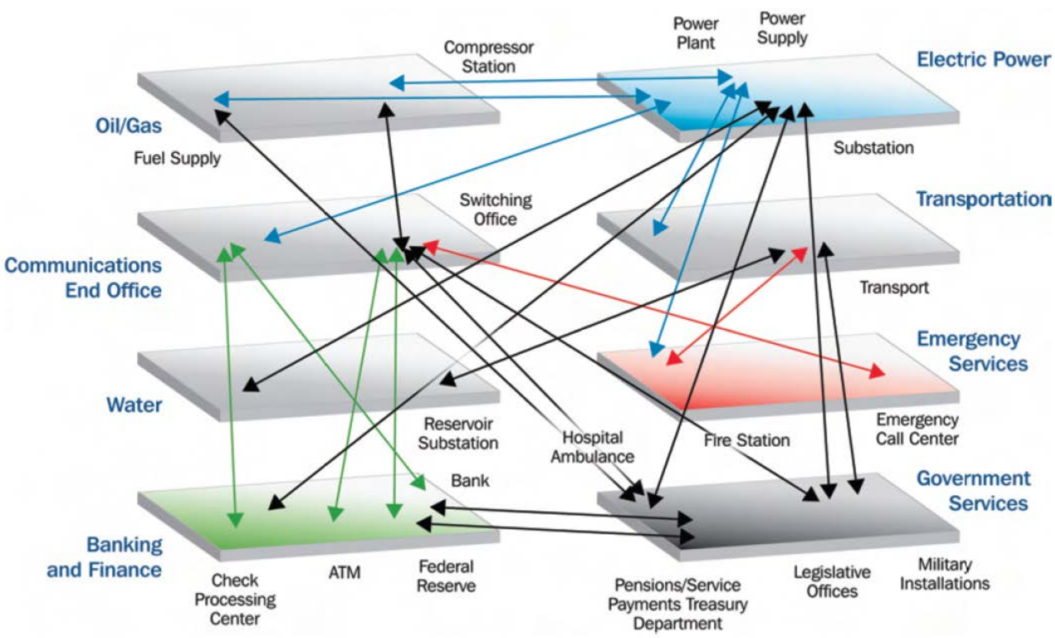
In space, the impacts of space weather include satellite and spacecraft mis-operation or equipment damage, and disruption of satellite communication and navigation systems due to radio waves being affected by variations in ionization. Astronauts on board spacecraft and in permanent space stations are also impacted by solar proton events. In addition, all satellites in low earth orbit (LEO) experience increased satellite drag as a result of space weather.

Impacts on the Ground

On the ground, space weather has even more consequences. For example, magnetic disturbances induce electric currents that can cause power system outages or pipeline corrosion and directly affect magnetic surveys, directional drilling, compass use and high frequency (HF) radio transmission. In addition, avionics operations over the polar regions may be exposed to potentially dangerous doses of radiation during severe space weather events. Because of the interdependencies between infrastructure sectors, impacts in one can have significant impact in a few or many others. Figure 1-1 illustrates the kinds of connections and interdependencies that exist across the economy.

[7] Baker, D.N., et al (2013). A major solar eruptive event in July 2012: Defining extreme space weather scenarios, Space Weather 11.10 (2013): 585-591, accessed on January 24, 2019 at https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/swe.20097

Figure 1-1: Connections and Interdependencies across the Economy



Source: Department of Homeland Security and National Aeronautics and Space Administration (https://science.nasa.gov/science-news/science-at-nasa/2009/21jan_severespaceweather)

1.2 Study Objectives

The primary objectives of the study were to:

- Assess and quantify the socioeconomic impact of various space weather threats based on scenarios of service interruptions such that CSA and its partners can identify short-term and long-term priorities;
- Evaluate the cost of space weather events as reliance on technology increases;
- Review current efforts to detect, warn and mitigate space weather events on Canada's infrastructure; and,
- Organize workshops where stakeholders (Canadian government, industry and academia) gather and exchange views on the findings.

The secondary objectives of this study were to:

- Identify priority areas for future technology roadmaps; and
- Assess the current resilience of Canadian critical infrastructure to different levels of space weather disturbances.

To support longer term planning, the study was expected to provide evidence on the socio-economic impacts of space weather events that could be used as a basis for developing the business case for a space weather strategy and/or program. Such a strategy would help to: (a) ensure that all reasonable means are in place to deal with security issues; and (b) ensure that the investment made is commensurate with the importance of the subject.

1.3 Study Approach

1.3.1 Data Collection Activities

The study relied on the following data collection methods: literature review, key informant interviews, telephone survey, and a consultation workshop. These are described below.

Literature Review of Previous Socio-Economic Studies

The literature review of previous socioeconomic studies began with a review of eight Reference Documents identified by the CSA with a focus on extracting the conclusions and consequences to Canada. The review included additional, or secondary, references identified by the CSA and HAL.

Literature Review of Canadian Organizations Involved in Space Weather

The review of Canadian service provider organizations involved in space weather included: the Canadian Space Weather Forecast Centre and the Canadian Geomagnetic Observatory Network, both operated by the Canadian Hazards Information Service of Natural Resources Canada; National Research Council of Canada’s (NRC’s) Solar Radio Monitoring Program; and CSA’s space weather mission support (e.g., CASSIOPE, GO Canada, European Space Agency’s (ESA’s) Swarm mission and National Aeronautics and Space Administration’s (NASA’s) THEMIS satellite mission). Also included was a review of Canadian client organizations (i.e., Public Safety Canada) as well as international (International Space Environment Service, World Meteorological Organization) and foreign providers (U.S. Space Weather Prediction Center, U.K. Met Office Space Weather Operations Centre, Australian Space Weather Services).

Key Informant Interviews

Interviews were conducted with key informants representing electric power, pipeline, satellite, aviation and aeromagnetic industries and Canadian researchers, as well as foreign and international service providers. The main purpose of the Canadian interviews was to inform the development of the space weather survey, and to assess the willingness of respondents to disclose information on their organization’s vulnerability to space weather disturbances, the associated costs, and to associate the name of their organization with the collected data. The main purpose of the international interviews was to identify best practices for a Canadian space weather program.

The interviews were semi-structured, allowing for effective probing of issues. Different interview guides were developed and tailored to each interview group.

Stakeholder Telephone Survey

The main purpose of the telephone survey was to collect information on the awareness of Canadian space weather stakeholders on the impacts of space weather disturbances generally and the impacts on their operations and/or critical infrastructure they rely on to be productive.

Survey questionnaires on space weather tailored to each sector were developed based on the results of the literature review and key informant interviews. The survey was administered by telephone to Canadian space weather stakeholders.

Consultation Workshop

A consultation workshop was held to allow Canadian stakeholders from government, industry and academia and international experts to exchange views on the findings from the socioeconomic impact analysis, and to recommend areas of improvement. The workshop was facilitated by Queen's University Executive Decision Centre using the Group Decision Support System (GDSS) service, which allows a group of participants to work interactively in an electronic environment.

1.3.2 Data Analysis Activities

The analysis of the socioeconomic impacts of space weather disturbances comprised three phases.

1) Phase one developed a set of indicators to assess the socioeconomic impacts of space weather on Canadian activities and a methodology for their measurement.

2) Phase two assessed the impact of space weather on Canadian activities based on information collected through the literature reviews, key informant interviews and the stakeholder survey using the model developed in phase one. The impacts were quantified in constant dollars for three scenarios representing different lengths of service level loss as a result of space weather.

3) Phase three identified mitigation strategies or needs for a higher resilience to space weather events in Canada.

1.4 Report Contents

This report is structured as follows:

Chapter 2 *Socioeconomic Impact Studies Review:* Provides the results of a review of approaches and methodologies for estimating socio-economic impacts of space weather.

Chapter 3 *Space Weather Related Activities in Canada:* Provides the foundation of an inventory of space weather players (service providers and clients) in Canada, and highlights the activities of selected international and foreign organizations.

Chapter 4 *Space Weather Socioeconomic Impact:* Assesses the socioeconomic impacts of space weather on critical infrastructure sectors based on three impact scenarios.

Chapter 5 *State of Awareness:* Provides an overview of the state of awareness of space weather in the global community as well as findings on awareness levels within the Canadian space weather stakeholder community.

Chapter 6 *Conclusions and Recommendations:* Presents the study conclusions and recommendations.

Appendix *Workshop Report:* Summarizes the results of a workshop held in Ottawa to discuss and validate the socioeconomic impact assessment, its assumptions and estimates.

2. Socioeconomic Impact Studies Review

2.1 Purpose

This chapter provides a summary of the *Review and Analysis of Space Weather Socioeconomic Impact Studies* Technical Note deliverable.

The purpose of this Technical Note was to:

- Conduct a literature review on previous space weather socioeconomic impact studies, extracting conclusions and consequences to Canada.
- Identify and review additional sources of material, with input from CSA, based on HAL's knowledge and familiarity with the considerable body of existing literature on space weather socioeconomic impact studies.
- Highlight relevant conclusions and take-away messages from the literature related to societal and economic impacts of space weather on both space (satellites, space flight, etc.) and Earth (air transport, pipelines, electrical grids, etc.) critical infrastructure.

2.2 Key Findings

No consensus has yet been reached by practitioners on the best approach and methodology for estimating socioeconomic impacts of space weather. Estimation of space weather socioeconomic impacts continues to be affected by the following key challenges:

- complexity of the estimation process and lack of understanding of impacts;
- lack of experience with extreme space weather during the space age, which leads to many assumptions but whose fidelity and accuracy is not well-constrained;
- opposing views on the impact of space weather between operators and analysts;
- uncertainty in the extent and nature of technical impacts on systems;
- lack of collaborative work between space physicists, engineers and economists; and
- strong reliance on qualitative assumptions.

These references provided a good basis for adaptation of current good practices to develop the study impact assessment methodology. For example, a recent evolution is the addition of input-output economics, which provides a formal framework for analyzing inter-industry transactions and modeling direct and indirect impacts of changes within the economy. Several papers provided insights into the operations of electrical power grids that helped in calculating the economic impacts of space weather on Canadian grids. The methodologies used in the recent US study for the electrical grid, aviation and satellites sectors helped to inform the approach used to estimate the sectoral economic impacts in Canada.

2.3 Primary References

The following sections highlight the results of the primary references review. Relevant estimates of economic impacts have been extracted from the references. However, it is important to note that direct comparison of those estimates with the estimates in this study is not possible because of the wide variation in methodologies used and the assumptions made in each case.

2.3.1 Quantifying the Economic Value of Space Weather Forecasting for Power Grids: An Exploratory Study[8]

This research paper describes the development of a new physics-based framework to assess the economic impact of space weather on power distribution networks and the supply of electricity. There is a focus within the framework on the phenomenon of the geomagnetic substorm, which is relatively localized in time and space, and occurs multiple times with varying severity during a geomagnetic storm, and the Auroral electrojet activity (AE) index[9] is used to characterize substorm severity.

It is proposed that the impact depends on three key factors: (i) the size of the physical driver, (ii) the resilience of the grid and (iii) the quality of the forecast. Concerning the physical driver of impacts, the researchers argue that the Kp index[10] that is normally used to characterize the severity of geomagnetic storms is not directly useful for understanding the production of GICs that may affect power grids. They believe that the AE index is more appropriate since substorm-related fluctuations have been identified as the drivers of major impacts, data are easily available and the AE index is compatible with regional forecasting, which is a goal of agencies currently tasked with forecasting space weather. Grid resilience is characterized as being dependent upon: the geographic location of the network, the structure of the network, the typical stress on the network,

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[8] Eastwood, J.P. et al (2018). *Quantifying the Economic Value of Space Weather Forecasting for Power Grids: An Exploratory Study,*

[9] The AE index is used to characterize the ground magnetic field perturbation caused by substorms through the currents generated by the aurora.

[10] The Kp index is the global geomagnetic activity index that is based on 3-hour measurements from ground-based magnetometers around the world.

any use of transformers and other equipment that is more space weather resilient and the perceived engagement from the system operator. Finally, the three forecast scenarios considered are: no forecast, current forecast and improved forecast.

The researchers used three scenarios for substorm sequences based on the 2003 (1-in-10-year event), 1989 (1-in-30-year event), and 1859 (1-in-100-year event) geomagnetic storms. Economic impact was calculated based on the duration and the geographical footprint of the power outage. Since definition of an overall global economic impact is hindered by the highly regionally inhomogeneous nature of the data currently available, only illustrative calculations were made for the European sector, for a variety of forecast and resilience scenarios. As examples, the researchers calculated that a substorm in the 1-in-10-year scenario affecting Central Europe (i.e. Denmark, Germany and parts of Austria and Italy) resulted in economic costs of €170 million and that two substorms in the 1-in-30-year scenario affecting Central and Western Europe (i.e. Portugal, Spain, United Kingdom, Ireland, Belgium, Netherlands, Denmark, Germany and parts of Poland, Czech Republic, Austria and Slovenia) resulted in economic costs of €9.3 billion.

2.3.2 Social and Economic Impacts of Space Weather in the United States[11]

This study represents the first attempt to systematically identify, describe and quantify the impacts of space weather on electric power, satellites, GNSS use and aviation in the United States (U.S.). Space weather has been identified by the U.S. federal government as one of the grand challenges for disaster risk reduction, which has been addressed in a National Space Weather Strategy and National Space Weather Action Plan (SWAP)[12,13]. This study was in part initiated in response to the SWAP, an overall U.S. effort to address potential vulnerabilities and increase resilience by setting detailed national goals and promoting enhanced coordination and cooperation across the public and private sectors.

The Abt Associates study is the most comprehensive socioeconomic impact study of space weather undertaken to date. It takes into consideration the lessons learned and good practices from previous studies and research and provides methodology details that helped inform the development of the socioeconomic impact indicators and methodology for this study. Estimates of the costs of space weather events to the U.S. economy included:

- Electric power – service interruption costs (~$400 million to ~$10 billion for a moderate event and ~$1 billion to ~$20 billion for more extreme conditions), based on the amount of power lost (~14.5 to 19 GW) and the number of customers left without electricity (~6 million)

- Satellites – asset damage costs (~$200 million to ~$2 billion for a moderate event scenario and ~$2 billion to ~$80 billion for a more extreme event scenario), based on combining

[11] Abt Associates Inc. (2017). *Social and Economic Impacts of Space Weather in the United States*
[12] Office of the President of the United States (October 2015), *National Space Weather Strategy*
[13] Office of the President of the United States (October 2015), *National Space Weather Action Plan*

insights from stakeholders with publicly available information on historic satellite loss numbers, industry financials (e.g. asset values and revenues), and a dataset containing information on the ~1,459 operational satellites that were in orbit at the end of 2016

- Aviation – service interruption costs (~$900,000 to ~$5 million for a moderate event scenario and ~$6 million to ~$200 million for a more extreme event scenario), based on the number of flights impacted by the event (40 - 6,000), the number of passengers/flight (80-240), the amount of time they are delayed (124 - 457 minutes), and the costs per unit time of their delay ($0.785/minute)

- GNSS use – service interruption costs (~$4 million to ~$8 million for a moderate event scenario and ~$100 million to ~$600 million for a more extreme event scenario), based on the duration of outages (1 hour - 3 days), the extent of the GNSS signal disruption (1% to 100% users with outages) and range of benefits to users ($37 B - $74 B/year)

2.3.3 A Risk Assessment Framework for the Socioeconomic Impacts of Electricity Transmission Infrastructure Failure Due to Space Weather: An Application to the United Kingdom[14]

This research article describes the results of research intended to overcome some of the shortcomings of previous analyses of the socioeconomic impacts of space weather on electric grids. This included properly capturing: (i) geophysical risk resulting from combined space and solid Earth physics; (ii) properties of infrastructure assets; and (iii) the network structure of the high-voltage power grid. This information was then used to quantify the potential socioeconomic impacts of space weather due to failure in electricity transmission, under different space weather forecasting scenarios (i.e. no forecast, current forecast and enhanced forecast).

Direct impacts are measured by the proportion of the population without power and local employment disruption by broad industrial group, and then the Oxford Economics Global Economic Model (OEM) was used to calculate the impact on GDP. The researchers estimated that a 1-in-100-year event would produce a gross domestic product loss to the United Kingdom of £2.9 billion based on current space weather forecasting capability, based on: (i) estimating the probability of intense magnetospheric substorms, (ii) exploring the vulnerability of electricity transmission assets to geomagnetically induced currents, and (iii) testing the socioeconomic impacts under different levels of space weather forecasting.

[14] Oughton, E.J., et al (2018). *A Risk Assessment Framework for the Socioeconomic Impacts of Electricity Transmission Infrastructure Failure Due to Space Weather: An Application to the United Kingdom*, accessed on November 19, 2018 at https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13229

2.3.4 Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure[15]

This research article explores the potential costs associated with failure in the electricity transmission infrastructure in the U.S. due to extreme space weather, focusing on daily economic loss. This provides insight into the direct and indirect economic consequences of how an extreme space weather event may affect domestic production, as well as other nations, via supply chain linkages.

Two opposing views have emerged on the impact of space weather that has affected the assessment, modeling, and prediction of the impact of this threat on the electric power sector. The first group believes that the potential damage would not be that large and the worst-case scenario is an electrical collapse of the transmission grid. The grid connections could then be re-established, leading to a disruption only lasting hours or a few days. The second group believes that damage might be initiated before a system loses stability or might occur outside the region of the electrical collapse and that there could be extensive damage to equipment and a scenario where blackouts last weeks, even months, until exposed assets (with many supply issues) are replaced. Future research is still needed to determine which of these scenarios best represents the likely risks and should be the focus of future impact assessments.

The authors contend that, if indirect supply chain costs are not considered when undertaking cost-benefit analysis of space weather forecasting and mitigation investment, the total potential macroeconomic cost is not correctly represented. The research results indicated total daily economic losses to the U.S. economy from different blackout zones ranging from $6.2 billion to $41.5 billion, based on: (1) determining blackout zone by scenario; (2) estimating state-level direct economic impact from production disruptions (lost economic activity proportional to the state GDP under business-as-usual conditions); (3) aggregating state-level direct economic impact to national-level sector-specific impact (using a balanced Multi-Regional Input-Output table that characterizes interdependencies between 40 countries and 35 economic sectors); and (4) estimating indirect domestic and global economic impact using an IO approach.

2.3.5 Helios Solar Storm Technology Catastrophe Stress Test Scenario[16]

This study provides various catastrophe scenarios for a U.S.-wide power system collapse that is caused by an extreme space weather event affecting Earth, that being a Helios Solar Storm scenario, and the economic impacts of such an event. The study purposefully explored the sensitivity of economic loss due to different temporal restoration periods, in order to provide a tool for stressing the portfolio exposure of global insurance companies. It is not a prediction but a hypothetical range of scenarios to enable mitigation of space weather risks in the insurance

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[15] Oughton, E.J., et al (2017). *Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure*

[16] Centre for Risk Studies (2016). *Helios Solar Storm Technology Catastrophe Stress Test Scenario*

industry. The study results indicate a range of potential U.S. insurance industry losses resulting from blackouts due to three variants of an extreme space weather scenario that explore different damage distributions and restoration periods, culminating in losses between $55.0 and $333.7 billion.

2.3.6 Solar Storm Risk to the North American Electric Grid[17]

This report discusses the likelihood of extreme geomagnetic storms, specific vulnerabilities of the North American power grid, the regions at highest risk from this complex natural hazard and the implications for the insurance industry and society generally. The contents include: a description of space weather phenomena and their frequency; the relative risk factors associated with space weather; dynamic risk assessment; awareness and preparation for space weather impacts; and implications for the insurance industry. The total estimated cost of a power outage lasting from 16 days to two years caused by an extreme (1-in-150-year) geomagnetic storm event was $0.6 – $2.6 trillion, based on calculating the percentage of residential, commercial, and industrial customers without power by state and using the average amount of electricity consumed by each segment in each state per hour.

2.3.7 How severe space weather can disrupt global supply chains[18]

In this paper the authors employ a new high-resolution model of the global economy to simulate the economic impact of strong Coronal Mass Ejections (CMEs) for three different planetary orientations. They account for the economic impacts within the countries directly affected as well as the post-disaster economic shock in partner economies linked by international trade. Key contributions of this study were the use of a physical model that represented likely footprints and the economic analysis technique. The researchers estimated that for a 1989 Quebec-like event (i.e. 1-in30-year), the global economic impacts would range from $2.4 to $3.4 trillion over a year, based on simulating the economic impact of strong CMEs for three different planetary orientations (S1: over the Americas, S2: Europe and the southern ocean, and S3: East Asia and Australia), accounting for the economic impacts within the countries directly affected as well as the post-disaster economic shock in partner economies linked by international trade though IO modelling.

2.3.8 The Economic Impact of Critical National Infrastructure Failure Due to Space Weather[19]

This paper tracks the origin and development of the socioeconomic evaluation of space weather, from 1989 to 2017, and articulates future research directions for the field. The paper traces the evolution of the socioeconomic impact of space weather and proposes a model for assessing the economic impacts. The author contends that efforts on this subject have historically been relatively

[17] Lloyd's of London. (2013). *Solar Storm Risk to the North American Electric Grid*
[18] Schulte in den Bäumen, H., et al (2014). *How severe Space Weather can disrupt global supply chains*
[19] Oughton, E.J. (2018). *The Economic Impact of Critical National Infrastructure Failure Due to Space Weather*

piecemeal, which has led to little exploration of model sensitivities, particularly in relation to different assumption sets about infrastructure failure and restoration. It is suggested that improvements could be expedited in this research area by open-sourcing model code, increasing the existing level of data sharing, and improving multi-disciplinary research collaborations between scientists, engineers and economists. The paper does not include any economic impact estimates.

2.3.9 The Economic Impact of Space Weather: Where Do We Stand?[20]

This paper provides an initial literature review to gather and assess the quality of published assessments of space weather impacts and socioeconomic studies. The literature on the economic impacts of space weather is rather sparse, probably due to the somewhat limited data that are available from end-users. The authors contend that major risk is attached to electricity transmission systems and there is disagreement as to the severity of the technological footprint, which strongly controls the economic impact. Consequently, urgent work is required to better quantify the risk of future space weather events. The paper does not include any economic impact estimates.

[20] Eastwood, J.P. et al (2017). *The Economic Impact of Space Weather: Where Do We Stand?*

3. Space Weather Related Activities in Canada Review

3.1 Purpose

This chapter provides a summary of the *Space Weather Related Activities in Canada Review* Technical Note deliverable.

The purpose of this Technical Note was to:

- Review/document the roles and responsibilities of the various Canadian organizations in space weather (as a service provider or client);
- Develop an inventory of space weather players in Canada for the purpose of establishing a formal system to coordinate and manage space weather issues; and,
- Begin addressing one of the primary objectives to review current efforts to detect, warn and mitigate space weather events on Canada's infrastructure.

3.2 Key Findings

Key findings include:

- Start of an inventory of space weather players (service providers and clients) in Canada, and basis for the survey list.
- Canada's *An Emergency Management Framework for Canada* (Third Edition, May 2017) only mentions terrestrial weather as a hazard.
- By comparison, UK included space weather as a risk to its National Risk Register in 2012.
- Australia obtains external revenue from products tailored to specific customer needs (e.g. Defence), and is considering adding a small fee on other products (e.g. modelled GICs flowing through power network transformers and transmission lines for near real-time and forecast applications; pipe-to-soil potentials at user-defined test points along pipeline assets).

3.3 Canadian Space Weather Service Providers

The following sections profile Canada's current space weather service providers: Natural Resources Canada; the Canadian Space Agency; and National Research Council of Canada.

3.3.1 Natural Resources Canada

Overview

Natural Resources Canada (NRCan) "monitors potential natural hazards, helps Canadians prepare to respond to disasters, and shares information about the risks of natural processes or phenomena, including space weather, that may be a damaging event with Canadians".

NRCan's Canadian Space Weather Forecast Centre (also known as Space Weather Canada) monitors, analyzes, and forecasts space weather and dispatches warnings and alerts across Canada. This includes tracking solar disturbances from the Sun to the Earth and monitoring the Earth's magnetic field on the ground using a network of magnetometers distributed throughout Canada. The goal of the Centre "is to reduce the risk of interruptions to the safe operation of critical infrastructure, such as power grids, pipelines, satellites, communication, and navigation." This includes developing forecasts, providing alerts of hazardous space weather storms, and modeling and monitoring effects on power systems, pipelines, satellites, HF communication, and GPS navigation. The Centre collaborates with other government departments, universities and industrial partners on measures to reduce the vulnerability of critical technology to space weather hazards.[21]

- The Centre, which is housed in NRCan's **Geomagnetic Laboratory**, is a Regional Warning Centre (RWC) of the International Space Environment Service (ISES) and it provides geomagnetic data and space weather forecasts to the World Meteorological Organization (WMO).[22]

- The **Canadian Geomagnetic Observatory Network,** operated by the Geomagnetic Laboratory, provides forecasts and reports of geomagnetic activity, as well as calibration of professional and military grade magnetic compasses, and calibration of magnetometers for field strengths of the order of the Earth's magnetic field and smaller.[23]

- ICAO has appointed NRCan as one of the global space weather centres to provide space weather advisories for aviation, in a consortium with France, Australia and Japan.

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[21] NRCan, Canadian Space Weather Forecast Centre accessed December 4, 2018 at http://www.spaceweather.gc.ca/info-gen/abt-en.php
[22] *Ibid.*
[23] NRCan, Geomagnetic Laboratory accessed December 4, 2018 at http://geomag.nrcan.gc.ca/lab/default-en.php

Space Weather Canada provides Space Weather Forecasts; Magnetic Plots; Magnetic Data; Solar Radio Flux; Satellite Services; Pipeline Services; and Effects on Technology research.

Space Weather Forecasts

Space weather forecasts are provided by seven regions (current status, and over the next 3 and 6 hours), over the short term (next 6, 24 and 48 hours) by three regions, the long term (over the next 27 days) by three regions, and by energetic electron fluence.[24]

- *Regional Conditions:* Reports showing the status (last hour) and forecast (0-3 hours and 3-6 hours) are provided for seven geographic regions (Eastern North America, Southern Prairies, South Western Canada, Northern Prairies, Eastern Auroral, Central Auroral and Western Auroral). Magnetic conditions are displayed using the Kr index, ranging from green (Kr activity level 0 to 2, or quiet) through yellow (Kr 3, or unsettled), amber (Kr 4, or active), orange (Kr 5 to 6, or stormy), to red (Kr 7 to 9, or major storm). Regional reports are updated every fifteen minutes.[25]

- *Short Term Forecast:* Levels of geomagnetic field activity, or disturbance, are shown over the last 24 and 6 hours, current conditions, and over the next 6, 24 and 48 hours. Status and short term forecasts are provided for three major zones (subauroral, auroral and polar cap), with the range of activity typically experienced in the zone subdivided into five classifications: quiet, unsettled, active, stormy and major storm.[26] Intensities are based on measurements derived from representative magnetic observatories in each zone (units are nanoteslas, nT) as shown in Table 3-1.[27]

Table 3-1: : Short Term Hourly Range Activity Levels (nT)

Zone	Quiet	Unsettled	Active	Stormy	Major Storm
Polar Cap	0 – 50	50 - 100	100 - 180	180 - 600	600+
Auroral Zone	0 – 90	90 - 170	170 - 300	300 - 1000	1000+
Sub-Auroral Zone	0 – 30	30 - 50	50 – 90	90 - 300	300+

[24] Forecasts show the fluence (flux accumulation over 24 hours) of highly energetic (relativistic) electrons with energies > 2 MeV at an altitude of 6.6 Earth radii in geosynchronous orbit.

[25] Regional Magnetic Conditions and Forecasts accessed January 2, 2019 at http://www.spaceweather.gc.ca/forecast-prevision/regional/sr-en.php

[26] For users who need to relate to the Kp index, the following equivalences apply to all three of the zones used in Space Weather Canada's forecasts: quiet is equivalent to Kp values from 0 to 3 minus; unsettled from 3 to 4 minus; active from 4 to 5 minus; stormy from 5 to 7; and, major storm from 7 plus to 9.

[27] Short Term Magnetic Review and Forecast accessed January 2, 2019 at http://www.spaceweather.gc.ca/forecast-prevision/short-court/sfst-en.php

- *Long Term Forecast:* Long term forecasts are provided by the three major zones (subauroral, auroral and polar cap), with the range of activity divided into four classifications: quiet, unsettled, active and storm.[28]

- *Energetic Electron Fluence Forecast:* This forecast is a 3-day forecast of the > 2MeV electron fluence (flux accumulation over 24 hours). It consists of a range of forecast values for the current day and next 2 days. Fluence values greater than 5.0E+07 electrons/cm2-sr-day are indicative of adverse space weather conditions hazardous to geosynchronous satellites. Under such conditions, there is a high likelihood of internal charging of satellite components by energetic electrons, with possible electric discharges that could result in malfunction or even complete failure of the satellite.[29]

Magnetic Plots

Plots, or magnetograms, of the one-minute variations of the geomagnetic field are available for all Canadian magnetic observatories. These magnetograms can display the data in XYZF, HDZF, or DIF. Data is available from July 20, 1972 to the present less one day. Following is a brief summary of the components and a description of each of the magnetogram types[30]:

- X component is the northward magnetic field.
- Y component is the eastward magnetic field.
- Z component is the vertical downward magnetic field.
- Intensity (F) component is the scalar magnetic field.
- Horizontal (H) component is the horizontal magnetic field.
- Declination (D) component is the angle between true North and the horizontal component of the magnetic field.
- Inclination (I) component is the angle measured from the horizontal plane to the magnetic field vector.

The following types of magnetograms are available[31]:

- XYZF magnetogram plots show the Bx (northward), By (eastward), and Bz (vertical downward) components of the magnetic field in Universal Time (UT);
- HDZF magnetogram plots show the horizontal (H), declination (D, the angle between true North and the horizontal component of the magnetic field), and the vertical downward (Z) components of the magnetic field in Universal Time;
- DIF magnetogram plots show the declination (D, the angle between true North and the horizontal component of the magnetic field), the inclination (I, angle measured from the

[28] Long Term Magnetic Review and Forecast accessed January 2, 2019 at http://www.spaceweather.gc.ca/forecast-prevision/long/sflt-en.php
[29] Review and Forecast of Energetic Electron Fluence accessed January 2, 2019 at http://www.spaceweather.gc.ca/forecast-prevision/fluence/sffl-en.php
[30] Magnetic Plotting Service Information accessed January 2, 2019 at http://www.spaceweather.gc.ca/plot-tracee/mp-i-en.php
[31] *Ibid.*

horizontal plane to the magnetic field vector) and the intensity of the magnetic field. Universal Time (UT); and,

- Rate of change plots (dB/dt) show the minute rate of change of the northward (dX/dt), eastward (dY/dt) and vertical downward (dZ/dt) components of the geomagnetic field in Universal Time (UT).

Magnetic Indices

Canadian K Indices and Canadian Hourly Ranges are the two types of magnetic indices provided by Space Weather Canada. The k-indices are computed for three Canadian observatories; Ottawa, Meanook and Victoria. These indices are also used in the production of the Kp index and other planetary indices.[32, 33] The K-index quantifies disturbances in the horizontal component of earth's magnetic field with an integer in the range 0-9, with 1 being calm and 5 or more indicating a geomagnetic storm. It is derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval. Provisional hourly ranges, hourly means, and maximum rate-of-change values are produced for all Canadian Magnetic Observatory System (CANMOS) observatories. They are available 15 minutes after the data hour.

Solar Radio Flux

Solar radio flux data are provided by the Solar Radio Monitoring program, which is operated by the National Research Council of Canada (NRC). A description of the program is provided below in Section 3.3.3 (National Research Council of Canada).

Satellite Service

Space Weather Canada's Electron Flux Satellite Service is intended to provide a quick view of space environment conditions at the time and prior to an anomaly in spacecraft operation. It consists of plots comparing magnetic conditions on the ground and particle conditions at geosynchronous orbit. Hourly ranges in the X component of the geomagnetic field (HRX) are computed from NRCan's magnetic observatories, and particle fluxes are observed by both primary and secondary GOES satellites (courtesy of NOAA/Space Weather Prediction Center in Boulder).[34] Forecasts of Energetic Electron Fluence (described earlier) are also available for users to analyze geomagnetic effects on satellites.

[32] Magnetic Indices accessed January 2, 2019 at http://www.spaceweather.gc.ca/data-donnee/indices/si-en.php

[33] The Kp-index is derived by calculating a weighted average of K-indices from a network of geomagnetic observatories. Since these observatories do not report their data in real-time, various operations centers around the globe estimate the index based on data available from their local network of observatories.

[34] Electron Flux - Satellite Service accessed January 2, 2019 at http://www.spaceweather.gc.ca/service-satellite/mpf-en.php

Pipeline Service

The Pipeline Service is intended to provide pipeline operators with a quick simulation of the pipe-to-soil potential (PSP) variations that would occur at different locations on a pipeline. It provides plots of the PSP variations along a sample or custom pipeline using geomagnetic field data from the observatory closest to the selected pipeline. Plots are provided by twelve observatories: Baker Lake, Brandon, Cambridge Bay, Fort Churchill, Iqaluit, Meanook, Ottawa, Resolute, Sanikiluaq, St. John's, Victoria and Yellowknife.[35]

Research on the Effects on Technology

Research is conducted on the effects of space weather phenomenon on critical infrastructure such as power systems, satellites, GNSS services, pipelines, communication services, etc. Space Weather Canada's website provides information on the effects of space weather on power systems, satellites, GPS positioning, pipelines, communication cables, and HF radio. Also provided is a chronology of space weather effects on technology from 1847 to the present.[36]

3.3.2 Canadian Space Agency

The Canadian Space Agency's (CSA's) Space Data, Information and Services program provides space-based solutions (data, information and services). The program also supports ground infrastructure that processes the data and operates satellites.[37]

CSA supports the following space weather initiatives:

- CSA has funded the **CASSIOPE** (Cascade Smallsat and Ionospheric Polar Explorer) science mission called ePOP (Enhanced Polar Outflow Probe). ePOP is collecting data about the effects of solar storms and, more specifically, their harmful impact on radio communications, satellite navigation and other space and ground-based technologies.
- Leads the **Geospace Observatory (GO) Canada** instrument arrays deployed across Canada, including magnetometers, radars, visual and radio observations of space weather effects. The initiative consists of two streams: instruments and data acquisition, and science and applications.
- Contributes to **ESA's Swarm mission**, under the Canada-ESA Cooperation Agreement. The Swarm mission's 3-satellites constellation measures the Earth's electric and magnetic fields.

[35] Pipeline Service accessed January 2, 2019 at http://www.spaceweather.gc.ca/service-pipeline/se-pip-o-en.php
[36] NRCan (2012), *Space Weather - Effects on Technology*; and Space Weather Effects on Technology accessed January 2, 2019 at http://www.spaceweather.gc.ca/tech/se-en.php
[37] CSA (2017). *2017-18 Departmental Plan.*

- Participates in international working groups of **UN-COPUOS** (United Nations Committee on the Peaceful Uses of Outer Space) on best practices and guidelines supporting international collaboration on the peaceful and sustainable use of space.[38]
- Supports scientists from the University of Calgary and the University of Alberta to operate ground instruments for **NASA's THEMIS mission** ("time history of events and macroscale interactions during substorms"). NASA launched a constellation of small satellites on February 17, 2007, all carrying identical suites of electric, magnetic, and particle detectors to study the mechanisms that drive the aurora.

3.3.3 National Research Council of Canada

The **Solar Radio Monitoring Program**, operated by the National Research Council of Canada (NRC) provides current and previous values of the 10.7cm Solar Flux solar activity index[39] to users. The data are obtained using two Solar Flux Monitors, operating at a wavelength of 10.7 cm. A new instrument, the Next Generation Solar Flux Monitor, provides data at five additional wavelengths, as part of developing data products meeting a wider range of user needs.[40]

3.4 Key Canadian Clients/Users of Space Weather Information

The following sections profile key clients/users of space weather information: Public Safety Canada; and the Electrical Grid; Satellites; Polar Aviation; Polar Marine Transportation; Pipelines; Magnetic Surveying; Directional Drilling; Surveying; Precision Farming; and GNSS Positioning, Navigation and Timing user sectors.

3.4.1 Public Safety Canada

Public Safety Canada is identified as the organization that would be the main federal government client for the "general/non-infrastructure-specific" impacts of space weather. Its mandate is to "keep Canadians safe from a range of risks such as natural disasters, crime and terrorism". The department works with other levels of government, first responders, community groups, the private sector and other nations, on national security, border strategies, countering crime and emergency management issues.[41]

The 2017 (or third edition) of the *Emergency Management Framework for Canada* recognizes that "emergency management is a shared responsibility across all sectors of society" with the ultimate purpose "to save lives, preserve the environment and protect property and the economy". The

[38] *Ibid.*
[39] The 10.7cm solar radio flux, or $F_{10.7}$, is one of the most widely used indices of solar activity.
[40] NRC (2017). Solar weather monitoring, accessed January 2, 2018 at https://www.nrc-cnrc.gc.ca/eng/solutions/advisory/solar_weather_monitoring.html
[41] About Public Safety Canada accessed December 14, 2017 at https://www.publicsafety.gc.ca/cnt/bt/index-en.aspx

Framework, developed by the federal and all provincial and territorial (FPT) Ministers Responsible for Emergency Management, is comprised of four interdependent components:

- *Prevention and Mitigation* – to adapt to, eliminate, or reduce the risks of disasters in order to protect lives, property, the environment, and reduce economic disruption. Prevention/mitigation includes structural mitigative measures (e.g. construction of floodways and dykes), and non-structural mitigative measures (e.g. building codes, land-use planning, and insurance incentives).
- *Preparedness* – to be ready to respond to a disaster and manage its consequences through measures taken prior to an event, for example emergency response plans, mutual assistance agreements, resource inventories and training, public awareness activities, equipment and exercise programs.
- *Response* – to act during, immediately before or after a disaster to manage its consequences through, for example, emergency public communication, search and rescue, emergency medical assistance and evacuation to minimize suffering and losses associated with disasters.
- *Recovery* – to repair or restore conditions to an acceptable level through measures taken after a disaster, for example return of evacuees, trauma counseling, reconstruction, economic impact studies and financial assistance. There is a strong relationship between long-term sustainable recovery and prevention and mitigation of future disasters.

3.4.2 Electrical Grid

Electric grid operators that are impacted by space weather include:

- Alberta Electric System Operator (AESO)
- AltaLink
- BC Hydro
- Bruce Power
- Capital Power Corporation
- ENMAX
- EPCOR
- Gentec
- Hydro One
- Hydro Ottawa
- Hydro-Québec
- Independent Electricity System Operator (IESO)
- Manitoba Hydro
- Maritime Electric
- NB Power
- Newfoundland and Labrador Hydro
- Newfoundland Power (Fortis Inc.)
- Northwest Territories Power Corporation
- Nova Scotia Power
- Ontario Power Generation
- Qulliq Energy Corporation
- SaskPower
- TransAlta
- Yukon Energy Corporation

3.4.3 Satellites

Satellite operators that are impacted by space weather include:

- Advantech Wireless Inc.
- Ciel Satellite Group
- exactEarth Ltd.
- Honeywell/COM DEV
- Maxar Technologies / MDA / Neptec
- Planet / BlackBridge
- SED Systems
- Telesat Canada
- Urthecast Corp.
- Canadian Space Agency

3.4.4 Polar Aviation

International Civil Aviation Organization (ICAO)

The International Civil Aviation Organization (ICAO) is a specialized agency of the United Nations that works with Member States and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. As noted below, Canada will be part of an ICAO global center for space weather advisories for aviation.

NAV CANADA

NAV CANADA is a privately run, not-for-profit corporation that owns and operates Canada's civil air navigation system (ANS). Its mission is to provide safe, efficient and cost-effective air navigation services on a sustainable basis. In support of its mission, NAV CANADA provides the following services: (1) air traffic control; (2) airport advisory and flight information; and, (3) aeronautical information.

Aviation Operators

Aviation operators that are impacted by space weather include:

- Air Canada
- Air Transat
- Cargojet Airways
- FedEx Express
- UPS Airlines
- WestJet Flight Operations

3.4.5 Polar Marine Transportation

Transport Canada

Transport Canada is responsible for the Government of Canada’s transportation policies and programs. The Department develops legislative and regulatory frameworks, and conducts transportation oversight through legislative, regulatory, surveillance and enforcement activities. While not directly responsible for all aspects or modes of transportation, the Department plays a leadership role to ensure that all parts of the transportation system across Canada work together effectively.

Canadian Coast Guard

The Canadian Coast Guard (CCG) owns and operates the federal government's civilian fleet and the Differential Global Positioning System (DGPS) service, and provides key maritime services to Canadians. As a Special Operating Agency of Fisheries and Oceans Canada (DFO), the CCG helps DFO meet its responsibility to ensure safe, secure and accessible waterways for Canadians. The CCG also plays a key role in ensuring the sustainable use and development of Canada's oceans and waterways.

Marine Transportation Operators

Marine transportation operators that are impacted by space weather include:

- Adventure Canada
- Algoma Central Corporation
- Fednav Limited
- G-Adventures
- Maersk Canada Inc.
- NEAS
- One Ocean Expeditions
- Canadian Coast Guard

3.4.6 Pipelines

Transmission pipeline operators that are impacted by space weather include:

- Access Pipeline Inc.
- Alliance Pipeline Ltd.
- ATCO Pipelines
- Corrosion Service Company Limited
- Emera Brunswick Pipeline
- Enbridge Pipelines Inc.
- FortisBC Inc.
- Inter Pipeline Ltd.
- Kinder Morgan Canada
- Maritimes & Northeast Pipeline
- Pembina Pipeline Corporation
- Plains Midstream Canada ULC
- TransCanada Pipelines Limited
- TransGas Limited
- Trans-Northern Pipelines Inc.

3.4.7 Magnetic Surveying

Magnetic surveying operators that are impacted by space weather include:

- EON Geosciences Inc.
- Firefly Aviation Ltd.
- Novatem Inc.
- Precision Geosurveys Inc.

- Fugro Airborne Surveys
- Geodata Solutions Inc.
- Geophysics GPR International Inc.
- Geotech Ltd.
- Goldak Airborne Surveys
- MPX Geophysics Ltd.
- New-Sense Geophysics Ltd.
- Sander Geophysics Ltd.
- Scott Hogg & Assoc. Ltd.
- SkyTEM Canada Inc.
- Sumac Geomatics
- Terraquest Ltd.
- Tundra Airborne Surveys Ltd.

3.4.8 Directional Drilling

Directional drilling operators that are impacted by space weather include:

- Canadian Horizontal Drilling
- Canadian Hydrovac & Directional Drilling
- CCD Energy Services
- Choice Directional Services Ltd
- Compass Directional Services Ltd
- D & R Directional Services Inc
- Drill on Target Drilling Solutions
- Dynamic Directional Drilling
- Michels Canada
- Millennium Directional Service Ltd.
- Newsco Directional & Horizontal Drilling Services Inc
- Pacesetter Directional Service Facility
- Standard Directional
- The Crossing Company
- True Directional Services Ltd.

3.4.9 Surveying

Surveying companies and related real-time kinematic (RTK)[42] correction service companies that are particularly impacted by space weather in the auroral zone include:

- Canadian Surveyors
- Can-Am Geomatics
- Challenger Geomatics
- Edwards Land Surveys
- Leica Geosystems
- Ollerhead & Associates
- Rx Networks Inc.
- Sub-Arctic Surveys
- Underhill Geomatics

[42] RTK is a satellite navigation technique used to enhance the precision of position data derived from satellite-based positioning systems. It uses measurements of the phase of the signal's carrier wave in addition to the information content of the signal and relies on a single reference station or interpolated virtual station to provide real-time corrections.

3.4.10 Precision Farming

While farmers and agricultural contractors that provide services to farmers (e.g. cultivation, seeding, fertilizing, harvesting, etc.), which use GNSS technologies, are impacted by space weather, there is no comprehensive source of these users. Other impacted companies, the providers of the RTK correction services on which precision farming technologies rely, include[43]:

- Brandt – Brandtnet
- Cansel – Can-Net
- GeoShack - TopNEXT
- John Deere – RTK Mobile
- Leica – SmartNet
- Northern Plains Drainage Systems – Ag-RTK

3.4.11 GNSS Positioning, Navigation and Timing

The users of GNSS for positioning, navigation and timing are diverse and span across all sectors of the Canadian economy. Many of the user sectors have been dealt with above (e.g. positioning/navigation: aviation and marine transportation, magnetic surveying, directional drilling, surveying, precision farming; and timing: electrical grid). Additional timing users include the finance and information and communications technologies sectors.

Although ground transportation is not included in the sectors that are particularly vulnerable to space weather described above, it is important to note that this sector is an important user of GNSS navigation services and that this use will become even more critical in the future once autonomous vehicles and autonomous rail locomotives become more widely adopted.

3.5 Selected International and Foreign Organizations

3.5.1 International Space Environment Service

The International Space Environment Service[44] (ISES) is a collaborative network of space weather service-providing organizations around the globe. Its mission is to improve, to coordinate, and to deliver operational space weather services. ISES is organized and operated for the benefit of the international space weather user community.

At present, there are fifteen Members distributed around the globe. These centres are located in China (Beijing), USA (Boulder), Russia (Moscow), India (New Delhi), **Canada (Ottawa),** Czech Republic (Prague), Japan (Tokyo), Australia (Sydney), Sweden (Lund), Belgium (Brussels),

[43] Note that the RTK services provided by most of these companies are also used by the surveying sector.
[44] International Space Environment Service accessed January 2, 2018 at http://www.spaceweather.org/

Poland (Warsaw), South Africa (Hermanus), South Korea (Jeju), Brazil (São José dos Campos), Austria (Treffen) and UK (Exeter).

ISES currently includes 16 Regional Warning Centres (RWC), four Associate Warning Centres, and one Collaborative Expert Centre. The Canadian centre is an ISES RWC.

3.5.2 World Meteorological Organization

The World Meteorological Organization (WMO) provides the framework for international cooperation and coordination on the state and behaviour of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate it produces, and the resulting distribution of water resources. Through its Technical Commission, Programmes and Regional Offices as well as by synergistic partnerships, WMO facilitates the maintenance and expansion of its Members' atmospheric, oceanographic and land-based observational networks; the free unrestricted exchange of the resulting data and information; and related capacity development and research in order to optimize the production weather, climate and water-related services worldwide.[45]

In May 2010, WMO established the Inter-programme Coordination Team on Space Weather (ICTSW, now known as IPT-SWeISS (Inter-Programme Team on Space Weather Information Systems and Services)) with a mandate to support Space Weather observation, data exchange, product and services delivery, and operational applications. As of May 2016, IPT-SWeISS involved experts from 26 different countries and 7 international organizations.[46]

3.5.3 U.S. National Space Weather Strategy and Program

This section identifies the organizations involved in the development of the national space weather strategy and action plan, and implementation of the space weather program in the U.S.

Space Weather Strategy and Action Plan

The U.S. *National Space Weather Strategy* (Strategy) and *National Space Weather Action Plan* (Action Plan) were approved by the Executive Office of the President of the United States' Office of Science and Technology Policy (OSTP) in October 2015. OSTP's responsibilities include advising the President in policy formulation and budget development on questions in which science and technology are important elements; articulating the President's science and technology policy and programs; and fostering strong partnerships among federal, state, and local governments, and the scientific communities in industry and academia. The Director of OSTP also serves as Assistant to the President for Science and Technology and manages the National Science and Technology Council (NSTC).

[45] World Meteorological Organization, Our Mandate accessed January 8, 2018 at https://public.wmo.int/en/our-mandate
[46] World Meteorological Organization, Space Weather Impacts accessed January 8, 2018 at http://www.wmo.int/pages/prog/sat/spaceweather-intro_en.php

Space Weather Program

The National Space Weather Program (NSWP) is an "interagency initiative to speed improvement in space weather services and prepare the country to deal with technological vulnerabilities associated with the space environment." The mission of the NWSP is to serve "as the focal point for the Federal government's national space weather enterprise and partnerships. By providing an active, synergistic, interagency forum for collaboration, the NSWP facilitates mutually beneficial interactions among the Nation's research and operational communities." The National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC) is the service delivery centre within the NSWP.[47]

SWORM

The Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee is a Federal interagency coordinating body of the Committee on Environment, Natural Resources, and Sustainability (CENRS). The CENRS advises and assists the National Science and Technology Council. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and the activities defined in the Space Weather Action Plan.[48] Each of the STORM's Working Group supports one of the six goals for the National Space Weather Strategy, which are to:

- establish benchmarks for space-weather events;
- enhance response and recovery capabilities;
- improve protection and mitigation efforts;
- improve assessment, modeling, and prediction of impacts on critical infrastructure;
- improve space-weather services through advancing understanding and forecasting; and
- increase international cooperation.

In June 2018, the STORM published *Space Weather Phase 1 Benchmarks*[49], which identifies initial benchmarks for two different scales (i.e. those that are likely to occur once in 100 years and those associated with the theoretical maximum) for five phenomena associated with space weather events: 1. induced geo-electric fields, 2. ionizing radiation, 3. ionospheric disturbances, 4. solar radio bursts and 5. upper atmospheric expansion. For the majority of the phenomena, theoretical maximum benchmarks could not be computed, due primarily to inadequate understanding or limitations on observatory data.

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[47] Bonadonna, Michael F. (Office of the Federal Coordinator for Meteorology, National Oceanic and Atmospheric Administration (2017). *The National Space Weather Program: Two Decades of Interagency Partnership and Accomplishments*, presented at the United Nations/United States of America Workshop on the International Space Weather Initiative, Boston College, Chestnut Hill, Massachusetts, USA, 31 July – 4 August 2017

[48] SWORM (2019). Accessed on January 24, 2019 at https://www.sworm.gov/about.htm

[49] SWORM (2018). SPACE WEATHER PHASE 1 BENCHMARKS, accessed on January 24, 2019 at https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf

Related Initiatives

Several recent initiatives in the U.S. suggest that the concern for the protection of the nation's critical infrastructure, and especially the electric grid, is on the rise. For example, in January 2018, the Department of Energy issued the *Grid Security Emergency Orders: Procedures for Issuance* rule, establishing procedural regulations concerning the Secretary of Energy's ability to order emergency measures to protect or restore the reliability of critical electric infrastructure. Such an emergency may result from a range of causes, including "a physical attack, a cyber-attack using electronic communication, an electromagnetic pulse (EMP), or a geomagnetic storm event".[50]

In October 2018, the Department of Homeland Security published *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances*. The Strategy and the forthcoming companion Implementation Plan are intended to improve the Department's understanding of electromagnetic threats and hazards and inform efforts to increase national preparedness for any electromagnetic incident.[51] The goals of the strategy are to:

- Improve risk awareness of electromagnetic threats and hazards;
- Enhance capabilities to protect critical infrastructure from the impact of an electromagnetic incident; and
- Promote effective electromagnetic-incident response and recovery efforts.

The President's National Infrastructure Advisory Council (NIAC) was tasked to examine the respond to this problem in two overarching ways: 1) design a national approach to prepare for, respond to, and recover from catastrophic power outages that provides the federal guidance, resources, and incentives needed to take action across all levels of government and industry and down to communities and individuals; and 2) improve our understanding of how cascading failures across critical infrastructure will affect restoration and survival ability of the U.S. to respond to and recover from a catastrophic power outage of a magnitude beyond modern experience, exceeding prior events in severity, scale, duration, and consequence. The Council's report, *Surviving a Catastrophic Power Outage: How to Strengthen the Capabilities of the Nation,* was released in December 2018.[52] NIAC found that existing national plans, response resources, and coordination strategies would be outmatched by a such a catastrophic outage. The Council makes recommendations on how to respond to this problem through strong public-private collaboration:

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[50] Department of Energy (2018). *Grid Security Emergency Orders: Procedures for Issuance*, Federal Register/Vol. 83, No. 7/Wednesday, January 10, 2018/Rules and Regulations, accessed February 4, 2019 at https://www.govinfo.gov/content/pkg/FR-2018-01-10/pdf/2018-00259.pdf

[51] Department of Homeland Security (2018). *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances*, accessed February 4, 2019 at https://www.dhs.gov/sites/default/files/publications/18_1009_EMP_GMD_Strategy-Non-Embargoed.pdf

[52] NIAC (2018). *Surviving a Catastrophic Power Outage: How to Strengthen the Capabilities of the Nation*, accessed February 4, 2019 at https://www.dhs.gov/sites/default/files/publications/NIAC%20Catastrophic%20Power%20Outage%20Study_FINAL.pdf

1) design a national approach to prepare for, respond to, and recover from catastrophic power outages that provides the federal guidance, resources, and incentives needed to take action across all levels of government and industry and down to communities and individuals; and 2) improve understanding of how cascading failures across critical infrastructure will affect restoration and survival. It is important to note that space weather is only one of many hazards that could cause catastrophic power outages and has a lower probability than other causes.

3.5.4 FERC and NERC Standards and Guidelines

The Federal Energy Regulatory Commission (FERC) is an independent agency of the U.S. government that regulates the interstate transmission of electricity, natural gas, and oil. One of its responsibilities is to protect the reliability of the high voltage interstate transmission system through mandatory reliability standards. In June 2014, FERC adopted a new reliability standard to mitigate the impacts of geomagnetic disturbances (GMDs) that can have potentially severe, widespread effects on reliable operation of the nation's Bulk-Power System.[53] This action approved a reliability standard developed by the North American Electric Reliability Corporation (NERC) to address implementation of operating plans, procedures and processes to mitigate effects of GMD.

NERC is an international, not-for-profit regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid over an area of responsibility spanning the continental United States, Canada, and the northern portion of Baja California, Mexico.[54] One of NERC's responsibilities is to develop reliability standards, which are adopted by FERC. Of particular importance are two new NERC standards: TPL-007-2 (establishing requirements for transmission system planned performance during GMD events); and EOP-010-1 (mitigating the effects of GMD events by implementing operating plans, processes, and procedures)[55], which are currently being examined by Canadian electricity utilities.

3.5.5 U.K. Space Weather Preparedness Strategy

This section identifies the organizations involved in the development and implementation of the U.K. *Space Weather Preparedness Strategy* (Strategy).

Development of the Strategy

The development of the Strategy was coordinated by the Cabinet Office (Civil Contingencies Secretariat), in collaboration with the Met Office, Severe Space Weather Project. The Project

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[53] FERC (2014). FERC Adopts Reliability Standard on Geomagnetic Disturbances, accessed on January 24, 2019 at https://www.ferc.gov/media/news-releases/2014/2014-2/06-19-14-E-17.asp#.XEoNIHdFzD4

[54] NERC (2014). About NERC, accessed on January 24, 2019 at https://www.nerc.com/AboutNERC/Pages/default.aspx

[55] NERC (2018). Reliability Standards for the Bulk Electric Systems of North America, accessed on November 8, 2018 at https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

benefited from: (a) the advice of the Space Environment Impacts Expert Group (SEIEG), formed in November 2010 and chaired by Professor Mike Hapgood; and (b) the Met Office's 'own' assessment of the risk. In 2012, space weather was included as a risk to the National Risk Register.[56]

Implementation of the Strategy

In 2015, responsibility for managing the risk of space weather events passed from the Cabinet Office to the Department for Business, Innovation and Skills (BIS). BIS is responsible for managing the risk of severe space weather on behalf of the U.K. and co-ordinates efforts to improve resilience. Other agencies involved in planning for severe space weather events include:

- The Met Office Space Weather Operations Centre (which is embedded in the Met Office Hazard Centre) assesses the risk for the National Risk Assessment[57] (NRA) and operates the UK's forecasting center for space weather.
- The British Geological Survey (BGS), which operates the geomagnetic observatory network in the UK, conducts research on geomagnetic effects on ground infrastructure. The Department of Energy & Climate Change, Department for Transport, the Ministry of Defence, and other departments, also play a role in preparing for space weather risks, with a particular focus on building resilience of the UK's national infrastructure to mitigate any impacts.
- The National Grid to increase the resilience of its Transmission Network and to develop operational plans for severe events.
- The aviation sector, which deals with the effects of space weather as an ongoing issue, to plan for extreme events.

3.5.6 Australia's Space Weather Services

Australia's Space Weather Services or SWS, is a specialized service of the Australian Government Bureau of Meteorology. SWS monitors and forecasts space weather conditions, which includes solar activity, and geophysical and ionospheric conditions.[58] SWS provides real-time and long-term planning services to customers, liaises with national and international agencies in space

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[56] The National Risk Register provides the government's assessment of the likelihood and potential impact of a range of different civil emergency risks (including naturally and accidentally occurring hazards and malicious threats) that may directly affect the UK over the next 5 years. In addition to providing information on how the UK government and local responders manage these emergencies, the National Risk Register also signposts advice and guidance on what members of the public can do to prepare for these events. *National Risk Register of Civil Emergencies – 2017 Edition* accessed January 2, 2018 at https://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies-2017

[57] NRA is the classified Government version of the National Risk Register (NRR). A number of risks in the NRA have been grouped together into more generic categories for the purposes of producing the NRR. This is partly to bring thematic risks together and also due to the sensitivity of the NRA. Cabinet Office (2017), *National Risk Register of Civil Emergencies - 2017 Edition.*

[58] Space Weather Services accessed January 29, 2018 at http://www.sws.bom.gov.au/

weather and affected technology stakeholders, and hosts a national archive of space weather observations. SWS products and services are aimed at mitigating the adverse effects of space weather activities on infrastructure.

In 2014, a *Review of the Bureau of Meteorology's Space Weather Service* was conducted by Professor Paul Cannon and Dr Terry Onsager. Some of their 42 recommendations of interest to Canada include:

- Reinforcing the positioning of the SWS as a core function delivered through the Bureau's Hazards, Warning and Forecasts Division, and ensuring that space weather is incorporated in the Critical Infrastructure Resilience Strategy.
- Ensuring improved awareness and preparedness by government in relation to the hazard potential and risks posed by space weather events and steps to assist in mitigating their impact.
- Conducting a market research study to ensure, where appropriate, SWS is realizing the full commercial value of their space weather services. Some of the cost-recovery options suggested by the Review include: recovering the cost of space weather services provided to other government departments; charging a fee for tailored forecasting services requested by commercial customers; positioning SWS as either a regional or a global income generating International Civil Aviation Organisation (ICAO) Space Weather Centre.[59]

[59] Cannon, Paul S. and Terry Onsager (2014). R*eview of the Bureau of Meteorology's Space Weather Service*; and Marshall, Richard (2016), *Recent Space Weather Activities in Australia.*

4. Space Weather Socioeconomic Impact

4.1 Impact Considerations

Estimation of the socioeconomic impact of space weather has a number of considerations:

1. Impact mechanisms – the various components of space weather which can adversely interact with Canadian infrastructure.

2. Impacted infrastructure – the various types of Canadian infrastructure that can be adversely impacted by space weather mechanisms.

3. Impact result – the different social and economic results of space weather impacts on Canadian economic sectors.

4. Impact extent – the severity of the direct impact and the possible ways that can propagate to secondary impacts in other parts of the economy.

5. Mitigation planning – the means by which the impact extent can be reduced by actions before, during, or after a space weather event.

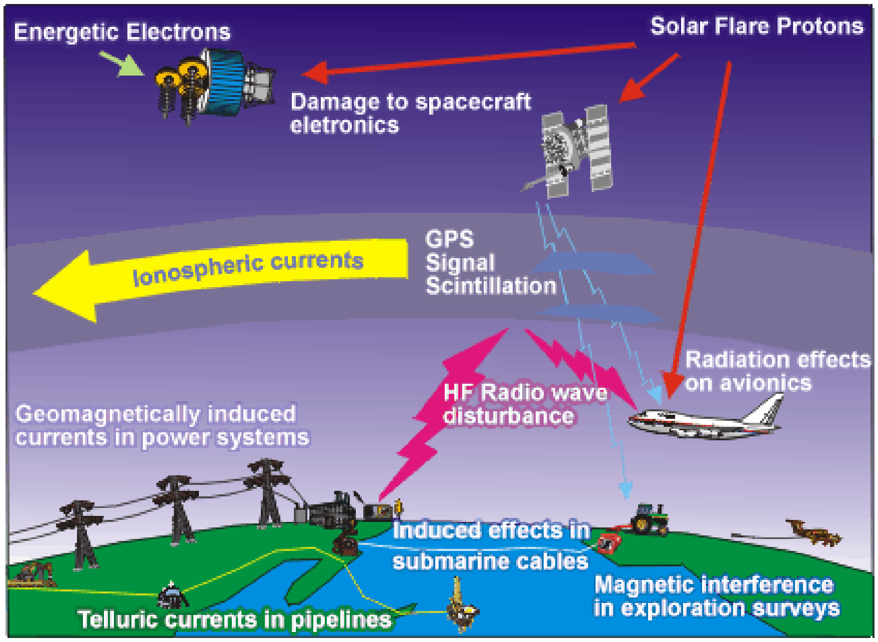
6. Impact experience – the degree to which infrastructure sectors and their users have experience with the impact mechanisms that will provide guidance and incentive to prepare for space weather events. Also, other mechanisms that have impacts similar to those of space weather, such as terrestrial weather, can provide additional incentives to prepare.

These considerations are discussed in the following sections.

4.1.1 Impact Mechanisms

Space weather describes the variations in the environment between the Sun and Earth and the phenomena that impact systems and technologies in space and on Earth. The situation is summarized in Figure 4-1.

Figure 4-1: Space Weather Effects on Infrastructure



Source: Natural Resources Canada (http://www.spaceweather.gc.ca/tech/se-en.php)

The sun emits energy during eruptions known as solar flares in the form of electromagnetic radiation (radio waves, infra-red, light, ultraviolet, X-rays). Energetic electrically charged particles may also be emitted as a result of the flaring process. In addition, clouds of magnetized plasma are sometimes ejected into space usually in association with the flaring process[60] (referred to as Coronal Mass Ejections). The CMEs and electromagnetic and particle radiation may interact with the Earth's outer atmosphere and (geo)magnetic field in complex ways, causing concentrations of energetic particles to collect and electric currents to flow in regions of the outer atmosphere (magnetosphere and ionosphere). While the Sun is the main driver of space weather impacts, other effects (e.g., radiation belt dynamics) play a less significant but still important role. In addition, coronal holes that release high-speed streams of plasma into the solar wind may also be geo-effective. CMEs and coronal holes can trigger geomagnetic storms in our magnetosphere (the region surrounding a planet where its magnetic field dominates charged particle motion).

The chain from solar activity, to effect, to impact mechanism is shown in Table 4-1.

[60] It is noted that each solar phenomenon can occur interdependently.

Table 4-1: Solar Activity, Effects and Impact Mechanisms[61]

<table>
<tr><th>Solar Activity</th><th>Effect</th><th>Impact Mechanism</th></tr>
<tr><td rowspan="5">Coronal Mass Ejection</td><td rowspan="6">Magnetic Activity</td><td>Geomagnetically Induced Current</td></tr>
<tr><td>Deep Dielectric Charging</td></tr>
<tr><td>Surface Charging</td></tr>
<tr><td>Ionospheric Scintillation/Gradients</td></tr>
<tr><td>Atmospheric Heating</td></tr>
<tr><td rowspan="2">Coronal Holes</td><td>Magnetic Disturbance</td></tr>
<tr><td>Auroral Absorption</td><td rowspan="3">HF Radio Interference</td></tr>
<tr><td>Solar Flares</td><td>Short Wave Fadeout</td></tr>
<tr><td rowspan="3">Solar Radiation Storms</td><td>Polar Cap Absorption</td></tr>
<tr><td rowspan="2">Solar Energetic Particles</td><td>Radiation</td></tr>
<tr><td>Solar Cell Degradation</td></tr>
</table>

Coronal Mass Ejections

Coronal mass ejections (CMEs) are “clouds” of magnetized plasma ejected from the Sun’s corona during eruptive processes when magnetic fields in the Sun’s atmosphere become unstable. CMEs travel outward from the Sun typically at speeds greater than 300 kilometers per second, but can be as slow as 100 kilometers per second or faster than 3,000 kilometers per second. The fastest CMEs can reach Earth in as little as 11-17 hours, while slower CMEs take several days to traverse the distance from the sun to Earth[62]. Due to their immense size, slower CMEs can take as long as 36 hours to pass over the Earth, once the leading edge has arrived. When CMEs impact the Earth’s magnetosphere, they have a high likelihood of producing geomagnetic storms.

In order to predict the strength of the resulting geomagnetic storm, estimates of the CME magnetic field strength and direction are important. At the present time, the magnetic field can only be determined when it is measured as the CME passes over a monitoring satellite. If the magnetic field direction of the CME has a strong southward component, there is a high likelihood of geoeffectiveness. Some CMEs show predominately one direction of magnetic field in their passage past the Earth, but most exhibit changing field directions as the large magnetic cloud passes over the Earth’s relatively tiny magnetosphere. Most CMEs will at some point have magnetic field conditions that favor the generation of geomagnetic storms, with associated geomagnetically induced currents (GICs) at the ground, and subsequent ionospheric storms that result in spatial and temporal variations of electron density of the upper atmosphere.

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[61] Note that DD Charging is usually considered to be more associated with energization processes associated with coronal holes, whereas surface charging is generally associated with CME disturbances. Also, auroral absorption is more associated with CMEs than coronal holes.

[62] Note that fast CMEs are usually associated with the energetic processes of solar flares whereas slow moving CMEs are usually associated with disappearing solar filaments.

Coronal Holes

Coronal holes appear as dark areas in the solar corona because they are cooler, less dense regions than the surrounding plasma and are regions of open, unipolar magnetic fields. This open magnetic field line structure allows the solar wind to escape more readily into space, resulting in streams of relatively fast solar wind. Coronal holes are more common and persistent during the declining years of the solar cycle. Persistent coronal holes are long-lasting sources for high speed solar wind streams.

Solar winds from coronal holes can cause periods of geomagnetic storming at minor to moderate levels, although rarer cases of stronger storming may also occur. The larger and more expansive coronal holes can often be a source for high solar wind speeds that buffet Earth for many days.

Solar Flares

Solar flares are relatively intense emissions of electromagnetic radiation from the Sun lasting from minutes to hours. The sudden outburst of electromagnetic energy travels at the speed of light; therefore, any effect upon the sunlit side of Earth's exposed outer atmosphere occurs at the same time the event is observed on Earth. Solar flares usually take place in high gradient magnetic field regions within sunspot groups. As sunspot magnetic fields evolve, they can reach a point of instability and release energy in a variety of forms. These include electromagnetic radiation at X-ray wavelengths, which are observed as solar flares. The increased level of X-ray and extreme ultraviolet (EUV) radiation results in ionization in the lower layers of the ionosphere on the sunlit side of Earth.

The space weather impact of solar flares is generally limited to effects on radio systems, but the radio emissions (up to GHz) associated with solar flares can and have caused interference with radar systems and even GNSS. The X-ray flash from strong solar flares can produce an atmospheric layer that absorbs HF radio waves, blacking out HF radio communications across areas of the sunlit side of the Earth from minutes to several hours. Flares can also produce extra layers of ionised material that slow down radio signals from GNSS satellites, so GNSS receivers calculate positions that may be wrong by several meters.

Solar Radiation Storms

The Sun occasionally produces bursts of charged particles at very high energies referred to as Solar Energetic Particles (or SEPs). The most important particles are protons, which can be accelerated to around 100,000 km/sec and traverse from Sun to Earth in just 10's of minutes[63]. When they reach Earth, the fast-moving protons penetrate the magnetosphere that shields Earth from lower energy charged particles. Once inside the magnetosphere, the particles are guided by the magnetic field lines such that they penetrate into the atmosphere near the poles more readily than at lower

[63] http://www.swpc.noaa.gov/phenomena/solar-radiation-storm

latitudes. When they enter the Earth's atmosphere, they collide with oxygen and nitrogen molecules in the atmosphere to produce neutrons. During strongly energetic events these neutrons can cascade to aviation altitude and even the Earth's surface and raise radiation levels above background levels. Additionally, these particles can easily pass through or stop in satellite systems, sometimes depositing enough energy to result in errors or damage in spacecraft electronics and systems.

Geomagnetic Storms

A geomagnetic storm is a major disturbance of the Earth's magnetosphere, which results from variations in the solar wind that produce major changes in the currents, plasmas, and fields in Earth's magnetosphere. The solar wind conditions that are effective for creating geomagnetic storms (for several to many hours) are sustained periods of high-speed solar wind, and most importantly, a southward directed interplanetary magnetic field (opposite to the direction of Earth's field) at the dayside of the magnetosphere. These conditions are effective for transferring energy from the solar wind into Earth's magnetosphere. The largest storms that result from these conditions are generally associated with CMEs. Another solar wind disturbance that creates less intense geomagnetic storms is a coronal hole high-speed solar wind stream (HSS).

During storms, the currents in the ionosphere and the energetic particles that precipitate into that region add energy in the form of heat, causing expansion of the atmosphere and an increase in density of the upper atmosphere, creating extra drag on satellites in low-earth orbit. The local heating also creates strong thermospheric winds, varying the ionospheric electron density that can modify the path of radio signals, degrading GNSS and HF radio systems.

4.1.2 Impacted Infrastructure

The impact mechanisms outlined in the previous section can affect different infrastructure as summarized in Table 4-2.

Table 4-2: Impact Mechanisms and Impacted Infrastructure

<table>
<tr><th>Impact Mechanism</th><th>Impacted Infrastructure</th></tr>
<tr><td rowspan="2">Geomagnetically Induced Current</td><td>Electrical Grid</td></tr>
<tr><td>Pipeline</td></tr>
<tr><td>Deep Dielectric Charging</td><td rowspan="5">Satellites</td></tr>
<tr><td>Surface Charging</td></tr>
<tr><td>Solar Cell Degradation</td></tr>
<tr><td>Atmospheric Heating</td></tr>
<tr><td rowspan="6">Ionospheric Scintillation/Gradients</td></tr>
<tr><td>Surveying</td></tr>
<tr><td>Precision Farming</td></tr>
<tr><td>Polar Marine Transportation</td></tr>
<tr><td>GNSS Positioning, Navigation and Timing</td></tr>
<tr><td rowspan="3">Polar Aviation</td></tr>
<tr><td>Radiation</td></tr>
<tr><td rowspan="2">HF Radio Interference</td></tr>
<tr><td>Polar Marine Transportation</td></tr>
<tr><td rowspan="2">Magnetic Disturbance</td><td>Magnetic Surveying</td></tr>
<tr><td>Directional Drilling</td></tr>
</table>

The form of that impact is summarized as follows:

- Electrical grid – Geomagnetically Induced Currents (GICs) can lead to transformer half-cycle saturation resulting in failure, voltage instability, increased reactive power consumption and/or unwanted relay operations, which can threaten system stability and potentially result in blackouts.

- Satellites – Deep dielectric charging and surface charging can result in temporary anomalies in system function or system failure. The loss of solar cell efficiency due to degradation over the life of the satellite means that larger solar cell arrays are required, increasing capital costs and launch costs. Atmospheric heating increases the drag on satellites in low earth orbit (LEO), requiring them to expend propellant to raise their orbit and thus reducing their lifespan. The weight of extra propellant increases launch costs. Ionospheric scintillation can interfere with satellite communications.

- Polar Aviation – Ionospheric scintillation and gradients can interfere with reception and integrity of GNSS position signals, resulting in the need to use less accurate alternative navigation techniques. HF radio interference can restrict communications or require the use of more expensive satellite communications.

- Polar Marine Transportation – Ionospheric scintillation and gradients can interfere with reception and integrity of GNSS position signals, resulting in the need to use less accurate traditional navigation techniques. HF radio interference can restrict communications or require the use of more expensive satellite communications.

- Magnetic Surveying – Magnetic disturbances can interfere with magnetic survey data, resulting in the delay of operations or the need to resurvey.
- Directional Drilling – Magnetic disturbances can interfere with drill positioning, resulting in the delay of operations or the need to re-drill.
- Pipelines – GICs interfere with pipeline surveying, resulting in delays or the need to resurvey, and in the long term may accelerate corrosion of buried pipelines.
- GNSS Positioning, Navigation and Timing – Disturbances in the ionosphere can disrupt reception and integrity of GNSS position and timing signals.
- Surveying – Ionospheric scintillation and gradients can interfere with reception and integrity of GNSS position signals, resulting in the delay of operations or the need to use less efficient methods.
- Precision Farming – Ionospheric scintillation and gradients can interfere with reception and integrity of GNSS position signals, resulting in the delay of operations or the need to use less efficient methods.

Some of these sectors can then have cascading impacts on the rest of the economy. In particular, large portions of the economy depend on the electrical grid, satellite communications, and GNSS timing. Loss of any of these systems would have far-ranging social and economic consequences.

4.1.3 Event Probability

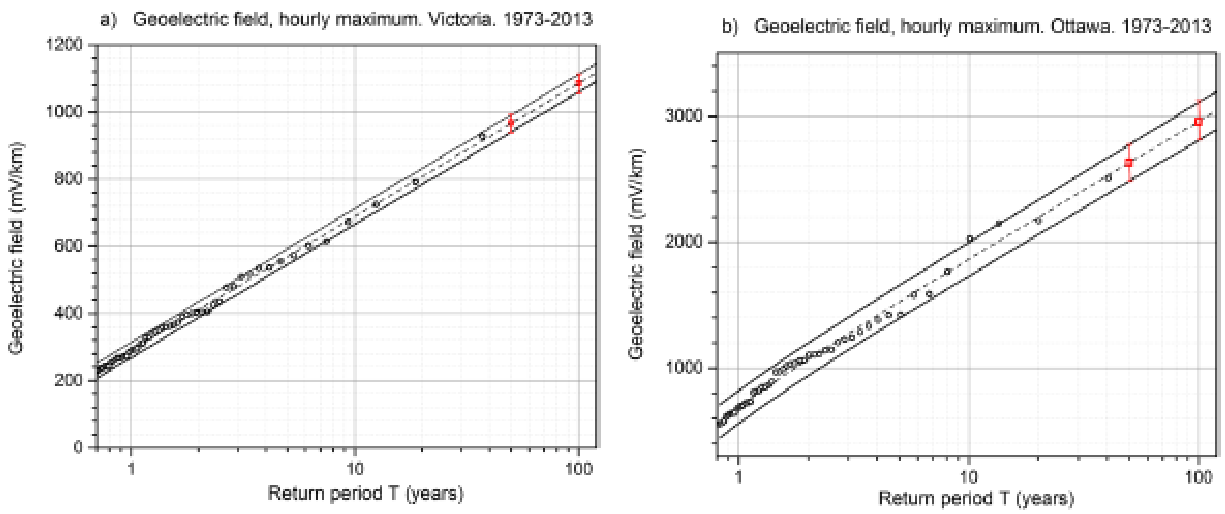
The probability of an impact is directly tied to the probability of a space weather event of a sufficient magnitude to cause problems in the infrastructure. Statistics on 'normal' events (i.e. the range of events experienced during the period of modern solar weather measurements over the last four decades) are good. Unfortunately, estimating the probability of 'extreme' events is problematic. Such extreme events cannot be directly extrapolated from the occurrence of more frequent events. For example, it has been shown that the probability of extreme events is not tied to the 11-year solar cycle of normal events.

Figure 4-2 shows the results of an analysis of extreme events by Nikitina et al, which are extrapolating the geoelectric field values.[64] A similar analysis could be performed for other storm metrics, such as the magnetic field deviation or GNSS scintillation. Normal solar events in the

[64] Nikitina, L., L. Trichtchenko, and D. H. Boteler (2016), Assessment of extreme values in geomagnetic and geoelectric field variations for Canada, SpaceWeather, 14, doi:10.1002/2016SW001386.

period from 1973 to 2013 have been extrapolated to 100-year events for Ottawa and Victoria using a generalized extreme value distribution with a 99% confidence interval. In both cases, the extrapolated 100-year event is about 20% greater than the worst event experienced in the previous 40-year period. Extrapolating further, to a 1,000-year event, results in about a 65% greater event[65].

Figure 4-2: Extreme Space Weather Events for Victoria and Ottawa



While this does not preclude a significantly worse event, it does provide guidance on the size of event that should be planned for. More of this type of analysis of extreme events is required to understand the geographical variations across Canada, and identify the infrastructure most at risk.

4.1.4 Impact Result

There is a variety of points of view in assessing the economic impact of space weather events:

- Service Providers – impacts from investment in prevention, loss of revenue if the investment in prevention is not considered, is not entirely successful or is not possible, and damage remediation.
- Industrial Service Users – impacts from investment in backups, and loss of revenue as a result of losing access to the infrastructure.
- Consumer Service Users – impacts from loss of consumer surplus[66] as a result of losing access to the infrastructure. It is important to note that such loses do not factor into traditional economic statistics.

[65] It is noted that these estimates are based on data from past events, which may not be a good predicter of the future.
[66] Consumer surplus is an economic measure of consumer benefit. It is calculated by analyzing the difference between what consumers are willing and able to pay for a good or service relative to its market price, or what they actually do spend on the good or service. (Wikipedia)

- Economy – the net economic value taken out of the economy by space weather events. The usual metric of this is the change in GDP.

Note that a loss to one sector of the economy can result in a gain to another sector, which means that individual economic actors cannot be considered in isolation when determining economy-wide impacts[67]. For this reason, care must be taken when trying to add impacts from different points of view, since in most cases the impacts are not simply additive.

For this study, it is the point of view that the economy is of primary interest – however, other perspectives will be considered in determining the impact on the economy. From the economy's point of view, many of the alternative perspectives may net to close to zero. Take, for example, the loss of revenue to the electric utility as a result of a blackout. From the economy's point of view that loss of revenue is offset by cost savings to consumers of the electricity they do not purchase that can then be used to purchase other things (although, given a positive consumer surplus, they presumably would prefer to have the electricity over the cost savings).

In this study, costs to infrastructure providers and users have been translated into economic GDP using an input-output model.

In addition to economic impacts, there are other important impacts that cannot be easily translated into economic terms, such as health, safety, environment, quality of life, etc.

4.1.5 Impact Extent

The extent of space weather impacts depends on a number of factors, such as:

- The geographic region of the event (refer to Figure 4-2a and b).
- The duration and timing of the event (e.g. day vs night, summer vs winter).
- Whether the impact will extend to the users of the service provided by the infrastructure. This depends on the previous two factors, and whether alternatives are available.

4.1.6 Mitigation Possibilities

In order to mitigate the impacts of space weather, infrastructure operators make investments in three areas:

- *Design* – operators invest in pre-event design modifications of infrastructure components (e.g. "hardening" and shielding of satellite electronics, placement of GIC monitoring equipment on electrical power lines, cathodic protection of pipelines, etc.)

[67] Other studies have taken other points of view; for example, that of insurance providers.

- *Backup* – operators establish backup technologies and commercial arrangements that are implemented as necessary during space weather events (e.g. offloading arrangements for satellite communication services, atomic clocks for precise timing, satellite telecommunications for polar aviation and marine transportation, etc.)

- *Actions* – during or following space weather events, operators take specific mitigation actions as necessary (e.g. re-configure the power system to remove vulnerable components from service or de-rate transformers, delay critical satellite maneuvers, hibernate satellites into "safe-mode", reduce altitudes in aviation, use backup systems, etc.)

Design and backup mitigation costs have proven to be difficult to determine. In most cases, the design and backup measures are put in place to respond to other risks in addition to space weather. For example, backups may be there anyway as a result of the possibility of terrestrial weather or other modes of system failure. In these cases, attribution becomes an issue – how much of the cost of the backup should be attributed to the other risks, and how much to the specific risk of space weather. Another issue is depreciation – design and backup costs, once incurred, typically provide value over an extended period making their value at any point in time challenging to determine. Finally, in most cases the infrastructure providers were unwilling or unable to provide estimates of how much they had spent on design and backup measures.

For these reasons, design and backup mitigation costs have not been included in the economic impact calculations of Section 4.3.

4.1.7 Impact Experience

The space weather experience that infrastructure sectors and their users have depends on i) the level of space weather that creates an impact, ii) the significance of the effect. Sectors that commonly experience significant effects are more likely to track and prepare for space weather events.

However, it is not only space weather than can provide the incentive for preparation. Other failure mechanisms that create circumstances similar to those caused by space weather are common in many sectors. For example, terrestrial weather is a frequent disruption in aviation, marine transportation, magnetic surveying, surveying, and farming. In these sectors, space weather is one more irritant that is considered part of the cost of doing business. Even for electrical grids, the probability of blackouts from causes other than space weather means that all sectors of the economy should have backup plans in place commensurate with the criticality of electricity to their operations – for example, UPS power for computer systems and backup generators for hospitals.

The result of these other, but similar, failure modes means that economic sectors have relevant experience with the type of impacts that space weather can create, and that the cost of mitigation of space weather impacts is spread among the response to a variety of threats.

4.2 Infrastructure Impacts and Mitigation Strategies

The following sections discuss space weather effects and the mitigation measures employed in each of the critical infrastructure sectors to deal with those effects.

4.2.1 Electrical Grid

Space Weather Effects

The impacts of space weather phenomena are perhaps best known and documented with respect to electric power grids. During major geomagnetic disturbances, geomagnetically induced currents (GICs) are produced by the magnetic field variations that occur. GICs flow to/from ground through substation transformers, which can lead to transformer half-cycle saturation that can result in transformer overheating or failure, increased reactive power consumption, voltage instability, and unwanted relay operations, suddenly tripping out power lines. As compensators switch out of service, entire system stability can be affected.[68]

The economic impacts of space weather on electric power systems can be considerable. The effects of the March 1989 space weather storm cost two large utilities, Hydro Quebec in Canada and Public Service Electric and Gas (PSE&G) in New Jersey, an estimated total of US $30 million in direct costs[69]. Since 1989, the power industry has improved its protection against space weather, such as adapting grid operations to reduce risk when potentially damaging space weather conditions are expected.[70] This work seemed to have a positive impact during a series of strong space weather events in October 2003, which did not cause the level of problems experienced in 1989[71].

It is important to note that, in Canada, Quebec and Ontario experience the most significant impacts of space weather because many of their power lines cross the Canadian shield[72], which increases resistance – the higher the Earth resistance, the larger the electric fields produced and the larger the GIC in the power system. Hydro Quebec has spent considerable resources on upgrading capacitors and other equipment that they believe will prevent the recurrence of the 1989 blackout. In Ontario, Hydro One's primary mitigation action is to bring up as much transmission capacity as possible, to cancel outages during a storm in accordance with guidelines from the North American Electric Reliability Council (NERC).[73]

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[68] Office of Critical Infrastructure Protection and Emergency Preparedness (2002). *Geomagnetic Storms – Reducing the Threat to Critical Infrastructure in Canada*, accessed January 7, 2019 at http://www.solarstorms.org/CanadaPipelines.html

[69] Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), (2006). Report of the Assessment Committee for the National Space Weather Program

[70] Lloyd's (2010), *op. cit.*

[71] Note that we have not had storms of the magnitude of March 1989 since then.

[72] The Canadian Shield, also called the Laurentian Plateau, is a large area of exposed Precambrian igneous and high-grade metamorphic rocks (geological shield) that forms the ancient geological core of the North American continent.

[73] HAL (2008), *op. cit.*

Current Mitigation Measures

This sector is arguably the most knowledgeable about space weather and its impacts, primarily resulting from geomagnetic disturbance (GMD) events. Based on experience with significant blackouts caused by space weather and other sources, electrical utilities have adopted a number of measures to mitigate the impacts of space weather, as identified in Table 4-3.

Table 4-3: Mitigation Measures for Electrical Grids

Design	Backup	Actions
▪ Improved network design ▪ Improved operational procedures ▪ Installation of GIC monitors	▪ Operators – backup transformers ▪ Customers – backup generators	▪ Activate emergency procedures ▪ Replace damaged transformers ▪ Activate backup generators

Additional Mitigation Needs

The study has identified the following additional mitigation needs:

- Higher standards of electrical grid protection that will be required under two new NERC standards: TPL-007-2 (establishing requirements for Transmission system planned performance during GMD events); and EOP-010-1 (mitigating the effects of GMD events by implementing Operating Plans, Processes, and Procedures)[74]
- Additional research to improve modeling of real-time GIC simulations that are used to examine the impact of space weather on the electrical grid[75]
- More field work to determine and take into account the role of local geology in different geographical areas on space weather impacts [76]
- Space Weather Canada provision of geomagnetic readings converted to geoelectric readings and displayed on a map that shows how the intensity is changing with different colours[77]
- Improved geomagnetic data resolution with additional geomagnetic monitoring sites in Canada[78]

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[74] NERC (2018). *supra*
[75] Information provided by interviewee
[76] Information provided by interviewee
[77] Information provided by interviewee
[78] Information provided by interviewee

- Published data relating the effect of GMDs on transformer voltage, current and MVARS of various variables including soil type, strength of storm/duration, etc.[79]

- Improved prediction of the timing, the shape in time, the location, the intensity and duration of space weather events; there are large gaps in magnetosphere-ionospheric science and not enough strong validated models[80]

4.2.2 Satellites

Space Weather Effects

In space, the impacts of space weather include satellite and spacecraft mis-operation or equipment damage, and disruption of satellite communication and navigation systems due to radio waves being affected by the increased ionization. Table 4-4 provides a summary of the space weather mechanisms and their effects on satellites.

Table 4-4: Space Weather Mechanisms and Their Effects on Satellites

Mechanism	Effect
Total Ionizing Dose (TID)	Degradation of microelectronics
Displacement Damage Dose (DDD)	Degradation of optical components and some electronics Degradation of solar cells
Single-Event Effects (SEE)	Data corruption Noise in images System shutdowns Electronic component damage
Surface Erosion	Degradation of thermal, electrical and optical properties Degradation of structural integrity
Geomagnetic Field Outer Boundary Compression	Magnetometer altitude control issues
Surface Charging	Biasing of instrument readings Power drains Electrical discharges causing physical damage
Deep Dielectric Charging	Biasing of instrument readings Electrical discharges causing physical damage
Satellite Drag	Torques Orbital decay

Source: Zheng, Y. (2017). Space Weather impacts on satellites (https://ccmc.gsfc.nasa.gov/RoR_WWW/SWREDI/2017/zheng_REDI2017_SWX_sat_impacts.pdf)

79 Information provided by interviewee
80 Information provided by interviewee

The impact of space weather on satellite operations is dependent upon the orbits being used. For example, most communications satellites are in geosynchronous (GEO) orbits, with the exception of Iridium and Globalstar, which are in low earth orbit (LEO). GNSS satellites are in mid earth orbit (MEO) and the orbits of scientific satellites can vary between LEO, MEO and elliptical.

An impact of space weather that affects all satellites in low earth orbit (LEO) is satellite drag. Although the air density in those layers of the atmosphere where satellites in LEO travel is much lower than near the Earth's surface, the air resistance is still strong enough to produce drag and pull them closer to the Earth. When the Sun is quiet, satellites in LEO have to boost their orbits about four times per year to make up for atmospheric drag. When solar activity is at its greatest over the 11-year solar cycle, satellites may have to be maneuvered every 2-3 weeks to maintain their orbit.[81]

Communications Satellites

The satellite communications industry is the largest commercial user of space and therefore is the sector most significantly impacted by space weather. Solar-initiated geomagnetic storms can create serious problems. Particles with higher energy can permanently degrade solar cells, and penetrate the circuitry and cause either damage or false signals that lead to unintended responses by the satellite.[82] Major storms in 1994 and 1997 appear to have been the cause of the damage to three communications satellites: U.S. Telstar 401 and Canada's Anik-E1 and Anik-E2 satellites. Total replacement and repair costs for these satellites were estimated to be US $600 million[83].

In addition to the costs to communications companies, space weather damage to satellites impacts communications service users. For example, satellite communication services[84]:

- provide remote populations with news, education, and entertainment (e.g. global cell phones, satellite-to-home TV and radio, and distance learning);
- provide telemedicine service to remote communities;
- interconnect geographically distributed business offices;
- connect businesses with their customers (e.g., facilitate point-of-sale retail purchases made with credit or debit cards at retail outlets); and

[81] http://www.swpc.noaa.gov/impacts/satellite-drag
[82] Stern, D.P. (2010). Educational Websites on Astronomy, Physics, Spaceflight and the Earth's Magnetism – #31. Space Weather, accessed November 2, 2018 at http://www.phy6.org/Education/weather.html
[83] Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), 2006: Report of the Assessment Committee for the National Space Weather Program, accessed January 7, 2019 at https://www.ofcm.gov/publications/spacewx/nswpr24.pdf
[84] National Academies Press, 2008, Severe Space Weather Events – Understanding Societal and Economic Impacts: A Workshop Report

- provide critical backup when catastrophic events (e.g. earthquakes, hurricanes) damage ground-based communications systems.

Communications satellite operators continuously monitor for anomalies, or malfunctions, in the operation of their satellites. The three most common anomaly producing mechanisms in space systems are electrostatic surface discharges, electron-caused electromagnetic pulses, and single event upsets.[85] Space radiation impacts on satellites are a function of the particle environment, satellite location and solar cycle phase. During solar maximum, solar protons are the main cause of geostationary satellite anomalies, whereas during the growth, and especially decline of solar activity, the magnetospheric relativistic electrons are the main cause.[86] While anomalies occur every day within the global satellite fleet, occasionally severe anomalies result in a total or partial inability for the satellite to perform its mission. Investigation showed that the failure of Intelsat-804 in January 2005, after more than seven years in orbit, was triggered by spacecraft charging. High-fidelity models have been developed to reconstruct "the way it was" and are essential to anomaly assessment and corrective engineering.[87]

One method of mitigating the potential impacts of space weather is to "harden" satellite components against radiation. While communications satellite operators could theoretically take such mitigation actions as turning the satellite off or manoeuvring it to avoid the consequences of severe events, in practice such actions are seldom taken.[88] The common practice is to put operations staff in standby mode in the face of severe or extreme storms being forecast, so that traffic can be rerouted to another communications satellite company's service if their satellites become inoperable.[89]

Global Navigation Satellite Systems Satellites

Because Global Navigation Satellite Systems (GNSS) satellites are in more vulnerable orbits than communications satellites, they are at even higher risk of suffering the impacts of space weather (i.e. degraded solar cells and damaged circuitry), although for this reason they are well hardened. Similar mitigation actions can be taken and the costs of not mitigating the risks of damages from space weather are also similar. Changes in the electron density due to space weather activity can also change the speed at which the radio waves travel, introducing a "propagation delay" in the GNSS signal.

[85] http://stinet.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA246880
[86] Romanova, N, Pilipenko, V, Crosby, N, and Chizenkov, V. (2006). The Relationship of Satellite Anomalies and Launch Failures to the Space Weather
[87] Chenette, David (2007). Space Environment Knowledge Needs: A Perspective from Lockheed Martin, Space Weather Workshop presentation
[88] HAL (2008), *op. cit.*
[89] Information provided by interviewee

Current Mitigation Measures

Satellite operators are also very knowledgeable about the impacts of space weather on their assets and services and have adopted effective mitigation measures, as identified in Table 4-5.

Table 4-5: Mitigation Measures for Satellites

Design	Backup	Actions
▪ Hardening of spacecraft ▪ Hardening of electronics ▪ Increased solar panel size ▪ Addition of extra fuel ▪ Improved operational procedures	▪ Backup satellites ▪ Offloading arrangements	▪ Activate emergency procedures ▪ Delay critical maneuvers ▪ Burn more fuel to correct orbit ▪ Repair damages

Additional Mitigation Needs

- More customization of the space weather information made available by Space Weather Canada[90]
- Additional research on the effects of space weather on solar panel degradation and surface charging through experiments on operational satellites.

4.2.3 Polar Aviation

Space Weather Effects

Commercial aircraft using polar flight routes are impacted in three ways by space weather events. Solar proton events (SPEs) increase radiation exposure levels for passengers and crew on high-altitude flights and produce large increases in ionospheric attenuation (i.e. polar cap absorption) that can lead to complete blackouts of HF radio communications over the polar regions lasting for several days[91]. In addition, aircraft navigation using GNSS can be impacted by ionospheric scintillation and gradients caused by space weather.

Position, navigation and communication services are essential to airline operations, with satellite communications representing the primary source of voice and data communication in the polar regions and GNSS the primary source of navigation for most commercial airlines. Space weather has impact on commercial airline operations, especially on transpolar routes. Space weather can

[90] Information provided by interviewee

[91] Neal, J. J., Rodger, C. J., & Green, J. C. (2013). Empirical determination of solar proton access to the atmosphere: Impact on polar flight paths. *Space Weather*, *11*(7), 420–433. https://doi.org/10.1002/swe.20066

degrade the accuracy of satellite navigation systems and cause loss of the GNSS signal and therefore loss of the navigation service in the non-precision enroute portion of the journey.

HF radio links, which are also used for communications over the poles, are also degraded during severe space weather events. Solar flares can blackout HF links for a few hours on the sunlit side of the Earth, and auroral absorption also interferes with HF radio communication. Blackout events can prevent all HF communications in affected areas. Space weather will more frequently change the frequencies and locations at which HF radio waves are reflected. During such events and if satellite communications were lost, aircrew would have to alter the HF frequencies and ground stations that they use, preferably through use of modern radios that can automatically search for ground station signals.

Current Mitigation Measures

Space weather events produce both economic and non-economic (primarily human health) consequences for the aviation industry. Table 4-6 identifies mitigation measures adopted in the aviation sector to reduce or eliminate these impacts.

Table 4-6: Mitigation Measures for Polar Aviation

Design	Backup	Actions
Radiation		
▪ No	▪ No	▪ Re-route flights to lower latitudes or altitudes ▪ Delay flights ▪ Control the amount of exposure to aircrew flying over the poles
HF Radio		
▪ No	▪ Satellite communications (SatCom)	▪ Switch communications to SatCom
GNSS		
▪ Improved receiver designs ▪ Augmentation systems	▪ Other navigation means (ground aids, inertial)	▪ Switch to backup means

Additional Mitigation Needs

The study has identified the following additional mitigation needs:

- Needs identified in the ICAO Concept of Operations (ConOps) for Space Weather Information in Support of International Air Navigation as a basis for new Standards and Recommended Practices (SARPs)[92]:
    - Refined probabilities, both from a user and an air traffic management (ATM) standpoint and improved forecast accuracy and reliability as heliospheric space physics models evolve
    - Improved forecasts that identify and predict the time, duration and intensity of space weather events for aviation users
    - Ability to forecast solar eruptive activity prior to initial event, and duration of events
    - Improved identification of affected area for HF outage impacts
    - Probability output disseminated in gridded format
    - Standard space weather forecasts by all space weather provider centres
    - New or adopted standards for ionospheric HF radio support (e.g. the ionospheric T-index) for monitoring and forecasting ionospheric support for HF radio during geomagnetic storms
    - Investigate use of neutron monitors for GCR monitoring, Ground Level Events (GLEs), and modeling the radiation hazard for aviation

4.2.4 Polar Marine Transportation

Space Weather Effects

The major impacts of space weather in the marine transportation sector is related to navigation and communications systems. Satellite navigation is now a standard tool for navigation on water and is vulnerable to similar space weather problems as aviation (i.e. loss or degradation of the satellite signal). Extended loss or degradation of GNSS service due to space weather can result in inconvenience and costs to marine shipping companies. For extended outages, navigation may have to be suspended in restricted waterways (e.g. the St. Lawrence Seaway), where narrow channels and low bottom clearances make navigation by other means unsafe. However, such restrictions are uncommon in the polar region. In addition, environmental damage could occur if a heavily loaded cargo vessel or tanker went aground while attempting to navigate to a safe harbor, resulting in ecological and human health impacts. As with aviation, loss of HF radio communications can also affect mariners' ability to communicate with other vessels and with shore-based facilities.

[92] ICAO (2013). *Concept of Operations (ConOps) for Space Weather Information in Support of International Air Navigation*, accessed on November 8, 2018 at https://www.google.ca/search?q=Concept+of+Operations+(ConOps)+for+Space+Weather+Information+in+Support+of+International+Air+Navigation&rlz=1C1GCEU_enCA821CA821&oq=Concept+of+Operations+(ConOps)+for+Space+Weather+Information+in+Support+of+International+Air+Navigation&aqs=chrome..69i57.1484j0j4&sourceid=chrome&ie=UTF-8

Current Mitigation Measures

Similar to polar aviation, Table 4-7 identifies mitigation measures adopted in the marine transportation sector to reduce or eliminate these impacts.

Table 4-7: Mitigation Measures for Polar Marine Transportation

Design	Backup	Actions
HF Radio		
▪ Improve polar SatCom coverage	▪ Satellite communications (SatCom)	▪ Switch communications to SatCom
GNSS		
▪ Improved receiver designs	▪ Other navigation means (nav aids, inertial)	▪ Switch to backup means

Additional Mitigation Needs

The study identified the following additional mitigation needs for polar marine transportation[93]:

- Improved forecasts that identify and predict the time, duration and intensity of space weather events for maritime users
- Ability to forecast solar eruptive activity prior to initial event, and duration of events
- Improved identification of affected area for HF outage impacts

4.2.5 Magnetic Surveying

Space Weather Effects

Magnetic measurements are widely used to survey for mineral and energy resources within the Earth. Geomagnetic storms have a significant impact on aeromagnetic surveys, both within and outside the auroral region. These storms can cause rapid magnetic field variations, which create magnetic survey data interpretation problems. Minor disturbances happen regularly and have little impact on operations, but major disturbances can ground aircraft and crews for several days at a time, anywhere in the world.

Current Mitigation Measures

Mitigation measures adopted by this sector are identified in Table 4-8.

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[93] Information provided by interviewee

Table 4-8: Mitigation Measures for Magnetic Surveying

Design	Backup	Actions
▪ Magnetometer placement in survey area	▪ No	▪ Delay surveys

Additional Mitigation Needs

The study has not identified any additional mitigation needs for magnetic surveying.

4.2.6 Directional Drilling

Space Weather Effects

In the directional drilling industry, continuous monitoring of the azimuth and inclination of the well path is accomplished with measurements while drilling (MWD), which are made along the well by magnetometers housed in a tool within the drill string[94]. These MWD magnetic surveys require estimates of the Earth's magnetic field at the drilling location to correct the downhole magnetometer readings. These estimates are impacted by the rapid magnetic field variations caused by space weather, which can reduce drilling accuracy. During the 1989 magnetic storm, one North Sea exploration company reported that instruments used to steer drill heads had experienced swings of around 12 degrees.[95] Developed by the British Geological Survey (BGS) and Sperry-Sun Drilling Services to give one-minute magnetic values at oil well locations, the interpolated in-field referencing (IIFR) model enables the MWD technique to achieve the accuracy required. IIFR can be characterized primarily as a near real-time monitoring service. Forecasting is not likely to play a significant role because no decisions are made affecting drilling operations based on space weather forecasts. IFFR has been applied in offshore oilfields around the U.K. and in other high latitude offshore locations in Canada and the U.S.[96]

If no mitigation action is taken and directional drilling continues during severe space weather, drill shafts may miss target areas resulting in expensive faulty findings and or the requirement for repeat drilling operations. An additional risk factor in Canada, where new wells are being drilled in mature fields, is that if the drill goes too far off course it could run into an existing well.

Current Mitigation Measures

Mitigation measures adopted by the directional drilling sector are identified in Table 4-9.

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[94] Reay, S. J. et al (2005). Space weather effects on drilling accuracy in the North Sea. Accessed on November 5, 2018 at https://www.ann-geophys.net/23/3081/2005/

[95] Lloyd's (2010), *op. cit.*

[96] Clark, Toby D.G. and Clarke, Ellen (2001). Space Weather Services for the Offshore Drilling Industry, Proceedings of the Workshop on Space Weather, ESTEC, December 2001

Table 4-9: Mitigation Measures for Directional Drilling

Design	Backup	Actions
▪ Use of Interpolation In-Field Referencing (IIFR) model ▪ Use of Disturbance Function method ▪ Magnetometer placement in drilling area ▪ Operational procedures for regular correction of drill head direction	▪ No	▪ Delay drilling

Additional Mitigation Needs

The study has identified the following additional mitigation needs:

- Additional research on ways to correct for magnetic distortions (i.e. correction for an inaccurate azimuth reading based on the severity of a geomagnetic storm)[97]

4.2.7 Pipelines

Space Weather Effects

Variations of the Earth's magnetic field induce electric currents in long conducting pipelines and the surrounding soil. These time-varying currents create voltage swings in the cathodic protection rectifier systems installed on pipelines and make it difficult to maintain pipe-to-soil potential in the safe region. During magnetic storms, these variations can be large enough to keep a pipeline in the unprotected region for some time[98]. These storms can also affect surveys that are undertaken to monitor and test the pipeline protection.

This creates several problems for pipeline engineers. Modern pipelines are protected from long-term current flows by a weak counter current of a few amperes which is applied so that the pipeline has a net, negative potential relative to ground. During geomagnetic storms, ground-induced currents change polarity in minutes, measurement systems in the pipeline can transmit erroneous information, and the corrosion rate of the pipeline is increased. If engineers unwittingly attempt to

[97] Information provided by interviewee

[98] Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), (2006). *Report of the Assessment Committee for the National Space Weather Program*

balance the current during a geomagnetic storm based on erroneous readings or space weather information, corrosion rates may increase even more[99].

Current Mitigation Measures

Pipeline operators have adopted the measures shown in Table 4-10 to mitigate these space weather impacts[100].

Table 4-10: Mitigation Measures for Pipelines

Design	Backup	Actions
▪ Installation of cathodic protection systems ▪ Installation of GMD monitoring devices ▪ Test station facilities incorporating corrosion protection (CP) coupons[101]	▪ No	▪ Delay testing surveys

Additional Mitigation Needs

The study has identified the following additional mitigation needs:

- Space Weather Canada provision of an E-mail subscription option, for customized space weather forecasts, rather than having to go to the NRCan space weather website to find information[102]
- Improved geomagnetic data resolution with additional geomagnetic monitoring sites in Canada[103]
- Additional research on means of quantifying pipeline corrosion during periods of geomagnetic activity and on the impacts of underlying geology on the pipe-to-soil potentials (PSPs)[104]

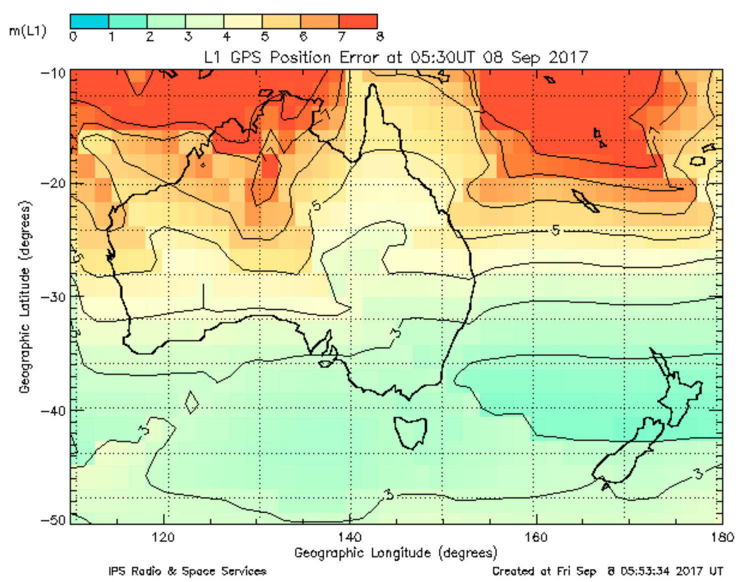
[99] http://www.swpc.noaa.gov/primer/Primer3.htm
[100] Gummow, R.A. (2002). *GIC effects on pipeline corrosion and corrosion control systems*
[101] CP coupons simulate an uncoated part of the structure to which they are electrically bonded. Measurements are made by momentarily disconnecting the coupon and recording the "instant disconnect" potential (http://www.edi-cp.com/products_uc_intro.php).
[102] Information provided by interviewee
[103] Information provided by interviewee
[104] Information provided by interviewee

4.2.8 GNSS Positioning and Navigation

Space Weather Effects

Many elements of commerce and society have become very dependent on satellite-based global positioning and navigation systems, known as Global Navigation Satellite Systems (GNSS). GNSS radio signals travel from the satellite to the receiver on the ground, passing through the Earth's ionosphere. The plasma of the ionosphere slows the path of the signal and, in the absence of space weather, GNSS systems compensate for the "average" or "quiet" ionosphere, using a model to correct its effect on the accuracy of the positioning information. Changes in the electron density due to space weather activity can change the speed at which the radio waves travel, introducing a "propagation delay" in the GNSS signal. The propagation delay can vary from minute to minute, and such intervals of rapid change can last for several hours, especially in the polar and auroral regions, causing positioning errors.[105] When the ionosphere is disturbed by a space weather event, departures of the ionosphere from the average conditions can lead to range errors of up to tens of meters in single frequency GNSS applications. For example, Figure 4-3 shows the estimated range error over the Australian region for a single frequency end-user system during the September 2017 space weather event[106]. Range errors may be mitigated by proper ionospheric models.[107] In addition, use of dual-frequency solutions and GNSS augmentation systems are helping to reduce the impact of large-scale electron density variations, although time-to-first-fix to resolve ambiguities will remain a space weather effect.

Figure 4-3: Estimated Range Error over the Australian Region for a Single Frequency End-User System During the September 2017 Space Weather Event



[105] *Ibid.*
[106] No comparable GNSS range error estimation has been found for Canada.
[107] Schrijver, C. J. et al (2015), *op. cit.*

Extended GNSS signal loss would have important impacts on road transportation today, particularly in the goods shipping sector. Although truckers could revert to the use of paper maps, research on the impacts of space weather in Europe found that they don't carry maps anymore and would have difficulty using them to locate weigh stations and truck stops, resulting in significant impacts[108]. With the impending introduction of autonomous vehicles, the reliance on GNSS will increase dramatically and the loss of service will have significantly higher economic impacts and, in the early stages of GNSS outages, potentially result in loss of life or injury impacts.

Current Mitigation Measures

GNSS positioning and navigation applications span a broad range of sectors, so mitigation measures are a very important means of minimizing or eliminating the impacts of space weather, as identified in Table 4-11.

Table 4-11: Mitigation Measures for GNSS Positioning and Navigation

Design	Backup	Actions
▪ Improved receiver designs ▪ Multiple satellite constellations ▪ Improved augmentation systems	▪ Other positioning and navigation methods	▪ Switch to backup methods

Additional Mitigation Needs

The study has not identified any additional mitigation needs for GNSS positioning and navigation.

4.2.9 GNSS Timing

Space Weather Effects

GNSS provides an inexpensive, globally-available, highly reliable, and extremely accurate reference time and frequency source. GNSS timing services have been in use for more than 30 years by a number of communities for setting and synchronizing clocks. For example, applications can be found in communications (e.g. CDMA cellular phone networks use GNSS timing to coordinate time between base stations), finance (e.g. time stamping of financial transactions), electric power transmission (e.g. balancing and synchronizing power loads and locating faults), and aviation (e.g. synchronizing radar sweeps). Of these applications, the electric power and telecommunications sectors are the most critical; loss of these services will undoubtedly produce cascading effects across other sectors.

[108] http://esamultimedia.esa.int/docs/business_with_esa/Space_Weather_Cost_Benefit_Analysis_ESA_2016.pdf

In the energy sector, for example, GNSS timing is used in Phasor Measuring Units (PMUs) for high-speed power grid monitoring and grid coordination, sequence of events and digital fault recorders, and travelling wave fault location.[109] Requirements to analyze frequent power blackouts have led to the installation of GNSS-based time synchronization devices in power plants and substations. The exact location of a power line break can be determined by the precise timing of an electrical anomaly as it travels through the grid.[110] Loss of GNSS can cause disruptions in these timing and synchronization procedures and resort to less efficient procedures.

The impacts of space weather on the communications infrastructure vary with the type of communications medium. In wireless networks, for example, GNSS is used to synchronize mobile phones to the cellular network, to synchronize cellular network elements to one another, and to precisely synchronize radio carrier frequencies. In wireline networks, a diverse range of telecommunications network equipment, including switching offices, SONET and Synchronous Digital Hierarchy nodes, digital cross connects, customer premise equipment and mobile switching centers, all use GNSS as a primary reference timing source. In satellite networks, GNSS signals provide a timing reference and synchronization across satellite constellations and satellite network elements, and support telemetry, tracking, and control, time tracking and ranging operations and frequency referencing for many applications. Many devices and applications on the Internet of Things (IoT) will require one or more of three synchronizations – frequency, phase and time – which will all need to cross layers, boundaries and networks from their sources of accurate time. To facilitate the massive growth of IoT, data processing and networking will converge with timing, creating seamless cyber and physical integration[111].

There is growing concern that the next solar cycle will expose problems in the proliferation of integrated Internet and wireless systems that have been developed during the quiet solar conditions that have prevailed over recent years. Loss of GNSS timing can create major service disruptions resulting in inconveniences to both businesses and the public that have become so dependent upon this infrastructure and integrated applications.

Current Mitigation Measures

GNSS timing is integrated in many different energy and information and communication devices in time stamping and synchronization applications. Table 4-12 identifies mitigation measures adopted for GNSS timing.

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[109] North American Synchrophasor Initiative (2017). Time Synchronization in the Electric Power System, (see https://www.naspi.org/sites/default/files/reference_documents/tstf_electric_power_system_report_pnnl_26331_march_2017_0.pdf)

[110] GPS.gov (2014). Official US government information about GPS and related topics: Timing, (see http://www.gps.gov/applications/timing)

[111] Weiss, M. et al (2015). Time-Aware Applications, Computers and Communication Systems (TAACCS), NIST Technical Note 1867, (see https://www.nist.gov/publications/time-aware-applications-computers-and-communication-systems-taaccs)

Table 4-12: Mitigation Measures for GNSS Timing

Design	Backup	Actions
▪ Improved receiver designs ▪ Multiple satellite constellations	▪ Other precise timing methods (e.g. atomic clocks)	▪ Switch to backup methods

Additional Mitigation Needs

The study has not identified any additional mitigation needs for GNSS timing.

4.2.10 Surveying

Space Weather Effects

Modern survey practices and procedures are heavily reliant on GNSS for precise positioning. GNSS services are impacted by changes in the electron density due to space weather activity that can change the speed at which the GNSS radio waves travel, introducing a "propagation delay" in the GNSS signal and producing errors in position (see Section 4.2.8 for more details). Loss of GNSS requires reversion to surveying with less efficient technologies such as total stations.

Current Mitigation Measures

In order to reduce the impacts of GNSS service disruptions, surveyors have adopted the mitigation measures identified in Table 4-13.

Table 4-13: Mitigation Measures for Surveying

Design	Backup	Actions
▪ Improved receiver designs	▪ Other surveying methods (total stations, electronic theodolites)	▪ Delay surveys ▪ Switch to backup methods

Additional Mitigation Needs

The study has not identified any additional mitigation needs for surveying.

4.2.11 Precision Farming

Space Weather Effects

Even more so than modern surveying, precision agriculture technologies are dependent upon GNSS navigation and positioning to achieve the efficiencies provided by these technologies. To meet precision farming navigation requirements, use of RTK correction services are employed to achieve the best possible accuracies. Without GNSS services, the RTK service providers cannot supply these corrections to their customers.

Current Mitigation Measures

To deal with GNSS disruptions, farmers have adopted the mitigation measures identified in Table 4-14.

Table 4-14: Mitigation Measures for Precision Farming

Design	Backup	Actions
▪ Improved receiver designs	▪ Other farming methods	▪ Delay farming operations ▪ Switch to backup methods

Additional Mitigation Needs

The study has not identified any additional mitigation needs for precision farming.

4.3 Socioeconomic Impacts

In this section, quantified estimates are made of the economic impact of space weather on each of the sectors that could be affected. Costs experienced within sectors have been translated into GDP impacts using an input-output model of the Canadian economy. The GDP impact figures quoted below are the total of the direct, indirect, and induced impacts.[112] It is important to note that the growing interconnectedness of key infrastructure, such as the electrical grid, information and communications and GNSS, increases the likelihood of greater socioeconomic impacts of space weather in the future.

4.3.1 Scenario Definition

There are a few impediments to the goal of developing a complete model that describes the economic impact of space weather. First, as discussed previously, modeling of extreme event

[112] Direct Effects – The industrial change that occurs resulting from the initial shock. The initial shock is broken down between the region's production, international imports, taxes, and inter-regional imports.
Indirect Effects – The resulting industrial change from the increase in inputs required to produce the commodities of the directly affected industries. This is an iterative calculation since each supplying industry will also require inputs, and so on. At each iteration, 'leakages' are removed from the region in the form of taxes and international and inter-regional imports.
Induced Effects – Direct and indirect effects generate labour income for households (i.e. wages and salaries), which can either be saved or used to purchase consumer products. Saving is a leakage to the flow of income in the economy. Spending this income will create more demand for both domestic and international commodities, which in turn will generate more industrial production and labour income. This cycle continues until the leakages erode the flow of income to zero.
The direct, indirect and induced effects can be translated using fixed ratios into other economic indicators, including: employment, GDP, labour income, and taxes:

probability is problematic. Second, and more importantly, there are insufficient data relating event magnitude to economic impact magnitude to allow the relationship to be modeled. This is because economic actors, for the most part, do not track the costs associated with normal space weather, and do not have experience with extreme space weather. Therefore, a scenario-based approach has been used, without trying to assess the likelihood of those scenarios. Separate work based on long-term measurements of space weather indicators is required to assess the probability of the proposed scenarios to materialize. For this reason, this study must not be mistaken for a vulnerability study.

The following assessment of socioeconomic impacts was based on three impact scenarios:

- Scenario 1: Normal space weather events at levels to be expected in a typical space weather cycle.
    - Limited impacts (minutes to 2-hour service denial for infrastructure affected by normal space weather events)
    - Local disruptions
- Scenario 2: A significant event.
    - Short-term impacts (24-hour service denial for infrastructure affected by significant space weather events)
    - Regional disruptions
- Scenario 3: A catastrophic event.
    - Long-term impacts (14-day service denial for electrical grid infrastructure, 1-year loss of WAAS)
    - Significant infrastructure damage (loss of communication and WAAS satellites)

It is important to recognize that some sectors are affected routinely by space weather and others are not until space weather reaches a high threshold. Those low threshold sectors typically do not suffer any additional financial impacts at high thresholds as they are already impacted. Therefore, for many sectors, there is no incremental impact from a Scenario 1 to a Scenario 2 event because the maximum impact (for example denial of service) occurs at levels below Scenario 2 – increasing the magnitude of the event therefore has no additional impact.

Space weather events have varied effects. Therefore, the impact on different sectors is not necessarily correlated (i.e. an event that is strong enough to impact the electrical grid will not necessarily impact satellites and vice versa).

The Socioeconomic Impacts component includes the following sub-components: (1) economic impacts; and (2) social impacts.

4.3.2 Economic Impacts

Electrical Grid

The general consensus in the industry in Canada is that, given the improvements that have been made since 1989, electrical grids are not in danger from normal space weather events (Scenario 1).

It is possible that a significant space weather event (Scenario 2) could force a temporary shutdown of a portion of the electrical grid (considered here to be a province for a period of up to 24 hours). Such a shutdown would have two impacts:

1. The utility would lose the revenue for the amount of electricity that would otherwise be sold. This revenue loss can be translated into an impact on GDP using the input-output model (see Table 4-15 and Figures 4-4 and 4-5).

2. The industrial users of electricity would not be able to operate. Since essentially all economic actors are dependent on electricity, this would essentially shut down the economy for the period of the blackout. However, since much activity could be rescheduled for a later time, the impact on the economy is not equal to 100% of the activity that would otherwise occur. Rather, studies have shown that the potential impact could be reduced to only 20% of normal GDP activity if all mitigation is capable of being implemented, including electricity substitution (from backup generation), production input factor substation, use of inventories, power conservation, production rescheduling, etc..[113] This assumes that there is no permanent damage to the grid, and that the grid can be effectively restarted at full capacity following the outage. As discussed in section 2.3.4, due primarily to the lack of fidelity in current benchmarks and infrastructure impact models, there is no consensus on whether this assumption is valid.

It is important to note that, in the opinion of the electricity industry professionals consulted during this study, it is highly unlikely that space weather events in Scenarios 2 and 3 would result in loss of electrical service across the whole country. Consequently, under this assumption, the GDP impact for Scenario 2 would be somewhere in the range of from $405.7 M (i.e. the largest regional impact, in Ontario) and $1,091.8 M (i.e. the total possible impact for all of Canada). For Scenario 3, the GDP impact would range from $20,682.2 M to $54,945.8 M.

[113] For example, Rose et al arrive at a number of 16%. See: Adam Rose, Gbadebo Oladosu, and Shu-Yi Liao (2007) Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout; Risk Analysis, Vol. 27, No. 3.

Table 4-15: Electrical Grid Economic Impacts[114]

GDP Impact:	Provider	User	Total
Scenario 1	None	None	
Scenario 2			
Newfoundland	$3.2 M	$14.6 M	$17.8 M
Maritimes	$11.0 M	$36.0 M	$47.0 M
Quebec	$37.2 M	$180.0 M	$217.2 M
Ontario	$48.5 M	$357.2 M	$405.7 M
Manitoba	$5.0 M	$31.4 M	$36.4 M
Saskatchewan	$7.7 M	$33.2 M	$40.9 M
Alberta	$17.8 M	$166.9 M	$184.7 M
BC	$17.1 M	$125.0 M	$142.1 M
All of Canada	$147.5 M	$944.3 M	$1,091.8 M
Scenario 3			
Newfoundland	$44.8 M	$817.6 M	$862.4 M
Maritimes	$154.0 M	$2,016.0 M	$2,170.0 M
Quebec	$520.8 M	$10,080.0 M	$10,600.8 M
Ontario	$679.0 M	$20,003.2 M	$20,682.2 M
Manitoba	$70.0 M	$1,758.4 M	$1,828.4 M
Saskatchewan	$107.8 M	$1,859.2 M	$1,967.0 M
Alberta	$249.2 M	$9,346.4 M	$9,595.6 M
BC	$239.4 M	$7,000.0 M	$7,239.4 M
All of Canada	$2,065.0 M	$52,880.8 M	$54,945.8 M

[114] Design and mitigation costs excluded (see Section 4.1.6 for explanation)

Figure 4-4: GDP Impacts by Province/Region ($ millions) – Scenario 2

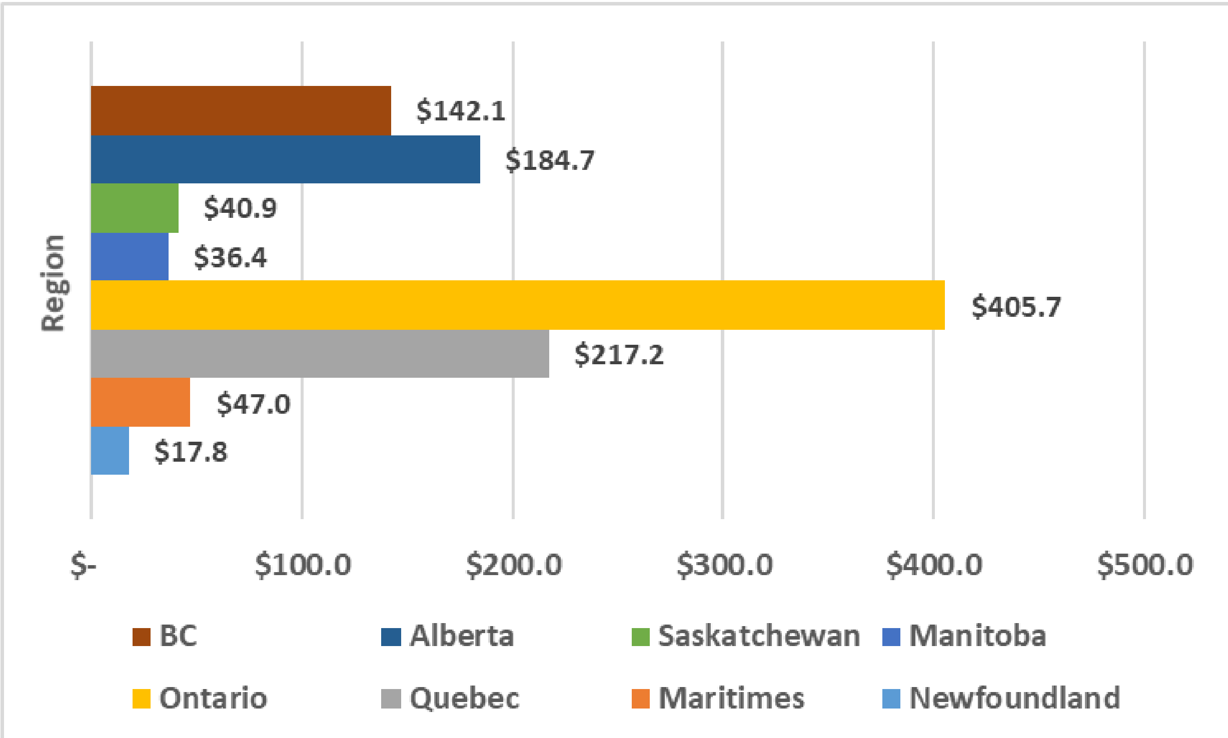
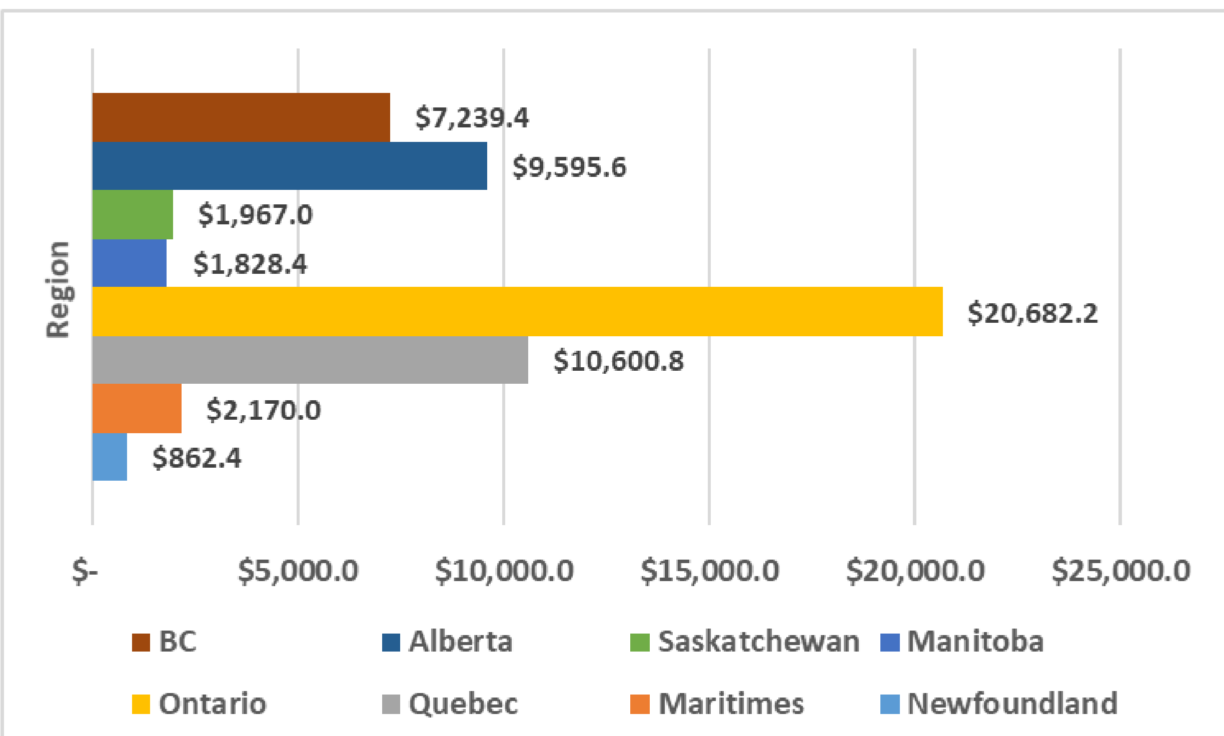


Figure 4-5: GDP Impacts by Province/Region ($ millions) – Scenario 3



Some previous studies have considered scenarios where space weather has resulted in damage to many large transformers that would require more than a year to replace. Based on consultations with Canadian electrical grid experts from industry, such scenarios are not considered plausible for a number of reasons:

- The electrical grid would collapse before any widespread transformer damage
- Utilities have taken measures to protect networks from damage
- Modern transformers may not be as susceptible to GIC damage
- Transformer replacement times should be much shorter under emergency conditions
- Other measures could be taken to bypass damaged transformers

As many experts have never experienced the impacts of large Space Weather Events, they are easily dismissed. A careful study of historical data is required to estimate the probability of an event large enough to cause catastrophic impacts such as scenarios 2 and 3. Such statistical analysis is beyond the scope of this socioeconomic impact study, which deals with the consequences of such an event, if it manifests. Given the potential impacts of under-estimating the resilience of the grid, detailed technical assessment and validation of such assertions should be addressed in future studies.

Satellites

Satellites are at risk from a number of space weather effects (e.g. atmospheric heating for LEO satellites, solar panel degradation, and anomalies and failures) that can be substantially mitigated by design choices (e.g. additional fuel, larger solar panels, and hardening) that come at an increased cost for construction and launch. Satellite designers are experienced at making these trade-offs, but the result is that satellites are, by design, not impervious to space weather effects.

Given that solar panel degradation and atmospheric heating effects are factored into the design choices, it is really only the possibility of anomalies and failures that results in economic impacts. However, anomalies persist in all space weather conditions, and there are difficulties differentiating from other types of anomalies (e.g. there is always a background event rate).[115] Satellite users can be insulated from anomalies and failures on communication satellites by re-routing traffic, although usually at minimal additional cost to the satellite operator since re-routing is normally to other satellites in the operator's fleet[116].

[115] Green, J. C., Likar, J., Shprits, Y. (2017): Impact of space weather on the satellite industry. *Space Weather, 15*, 6, pp. 804—818. Accessed January 2, 2018 at http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:2679913:5/component/escidoc:2679924/2679913.pdf

[116] Information provided by interviewee

Under Scenario 1, the costs to satellite operators are assessed to be from short-term anomalies that result in off-loading costs. Assuming six days of off-loading per year and an increase in operational costs, this would be worth $0.5 M[117], with a $0.6 M impact on GDP (see Table 4-16).

Under Scenario 2, the costs are increased as a result of satellite failures. The depreciated value of Canadian satellites is $2.2 B. Assuming 10% of satellites are permanently disabled[118], the cost to the industry of asset losses would be $223.3 M, with a $258.7 M impact on GDP with off-loading costs of $37.5 M, with a $43.5 M impacts on GDP. The combined GDP impact for Scenario 2 would be $302.2 M (see Table 4-16).

Under Scenario 3, assuming 20% of satellites are permanently disabled[119], the cost to the industry of asset losses would be $446.6 M, with a $518.1 M impact on GDP and the off-loading costs would be $75.0 M, with a $87.0 M impacts on GDP. The combined GDP impact for Scenario 3 would be $605.1 M (see Table 4-16).

It is important to note that these estimates do not include costs to foreign satellite operators supplying services in Canada, which do not impact Canadian GDP.

Table 4-16: Satellite Economic Impacts[120]

GDP Impact:	Provider	User
Scenario 1	$0.6 M	Consumer inconvenience
Scenario 2	$302.2 M	No incremental impact
Scenario 3	$605.1 M	No incremental impact

Polar Aviation and Other Aviation

Space weather can create delays and changes in routes for polar aviation due to losses of GNSS and HF radio services and increased radiation exposure to flight personnel. The extra costs for airlines are in the order of $10 K to $100 K per flight[121]. Under Scenario 1 between 4% and 8% of Canada's 3,600 annual polar flights are affected by space weather. This would result in $1.4 M to $28.0 M in costs, which translates to about the same amounts in GDP (see Table 4-17). There are no incremental costs associated with Scenario 2 for polar aviation.

If a Scenario 3 extreme space weather event caused the failure of all three satellites providing Wide Area Augmentation System (WAAS) services that are used for precision landings, there would be

[117] Information provided by interviewee
[118] Information provided by interviewee, and taking into consideration the history of satellite failures due to space weather
[119] Information provided by interviewee
[120] Design and mitigation costs excluded (see Section 4.1.6 for explanation)
[121] Information provided by interviewee

an economic impact to all aviation in Canada (not just polar aviation).[122]This would increase delays in the air traffic control system by 30% and would, through a resulting combination of increases in airline costs and decreases in labour productivity, decrease national GDP by 0.092%, which is equivalent to $1,750 M.[123] It is important to note that these estimates do not include costs to foreign airlines transiting through Canada, which do not impact Canadian GDP.

It should be kept in mind that the costs to both operators and passengers of delays caused by space weather are trivial compared to the costs of delays caused by terrestrial weather and other causes.

Table 4-17: Polar Aviation Economic Impacts[124]

GDP Impact:	Provider	User
Scenario 1	$1.4 M to $28.0 M	Consumer inconvenience
Scenario 2	No incremental impact	No incremental impact
Scenario 3	$1,750.0 M (all Canadian aviation)	

Polar Marine Transportation

Given the backups in place for both navigation and communication, consultations with the sector indicated that polar marine transportation are not affected by Scenario 1, and there is no incremental impact from Scenarios 2 and 3.

Table 4-18: Polar Marine Transportation Economic Impacts[123]

GDP Impact:	Provider	User
Scenario 1	None	None
Scenario 2	None	None
Scenario 3	None	None

Magnetic Surveying

Space weather can create delays for magnetic surveying and possibly result in the need to resurvey. There are about 17 geomagnetic surveying companies in Canada. Assuming that each experiences 15 to 30 resurveying days per year at a cost of $3 K to $10 K per day[125], the loss to the companies is between about $1.0 M and $5.0 M. That translates to between $ 1.4 M and $ 7.0 M in GDP (see Table 4-19).

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[122] Given the existence of three (soon to be four) independent and interoperable GNSS constellations, the loss of all GNSS functionality for an extended period is highly improbable.
[123] See: The Economic Cost of Airline Flight Delay; Author(s): Everett B. Peterson, Kevin Neels, Nathan Barczi and Thea Graham; Source: Journal of Transport Economics and Policy, Vol. 47, No. 1 (January 2013), pp. 107-121
[124] Design and mitigation costs excluded (see Section 4.1.6 for explanation)
[125] Information provided by interviewee

There is no incremental impact under Scenarios 2 and 3 since threshold values are present in Scenario 1. Since the impact is dependent on the number of resurveying days, the length of the outage does not affect this estimate.

Table 4-19: Magnetic Surveying Economic Impacts[126]

GDP Impact:	Provider	User
Scenario 1	$1.4 M to $7.0 M	None
Scenario 2	No incremental impact	No incremental impact
Scenario 3	No incremental impact	No incremental impact

Directional Drilling

Space weather could create delays; however, the very limited response from the sector indicated that this has had no significant cost impact on drilling companies.

There is no incremental impact under Scenarios 2 and 3 since threshold values are present in Scenario 1.

Table 4-20: Directional Drilling Economic Impacts[126]

GDP Impact:	Provider	User
Scenario 1	None	None
Scenario 2	No incremental impact	No incremental impact
Scenario 3	No incremental impact	No incremental impact

Pipelines

Space weather can result in accelerated corrosion for pipelines and possibly delays in pipeline testing. Canada has about 117,000 km of transmission pipelines with an estimated cost on average of $3.7 M / km to construct[127]. If about 1% are replaced per year due to corrosion and space weather conservatively accounts for 5% of that corrosion[128], the costs are $216.5 M per year, which would have a $238.2 M impact on GDP (see Table 4-21).

There is no incremental impact under Scenarios 2 and 3 since threshold values are present in Scenario 1.

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[126] Design and mitigation costs excluded (see Section 4.1.6 for explanation)
[127] Based on 2016 US data (converted to CAN $) from Oil & Gas Journal, accessed December 4, 2018 at https://www.ogj.com/articles/print/volume-114/issue-9/special-report-pipeline-economics/natural-gas-pipeline-profits-construction-both-up.html
[128] Information provided by interviewee

Table 4-21: Pipelines Economic Impacts[129]

GDP Impact:	Provider	User
Scenario 1	$238.2 M	None
Scenario 2	No incremental impact	No incremental impact
Scenario 3	No incremental impact	No incremental impact

Surveying

Space weather can create delays for surveying and possibly the need to use less efficient methods. There are between 30 and 60 surveying companies in the auroral zone of Canada. Assuming that each experiences 2 resurveying days per year at a cost of $10 K per day[130], the loss to the companies is between about $0.6 M and $1.2 M. That translates to between $0.8 M and $1.7 M in GDP (see Table 4-22).

There is no incremental impact under Scenarios 2 and 3 since threshold values are present in Scenario 1. Since the impact is dependent on the number of resurveying days, the length of the outage does not affect this estimate.

Table 4-22: Surveying Economic Impacts[129]

GDP Impact:	Provider	User
Scenario 1	$0.8 M to $1.7 M	None
Scenario 2	No incremental impact	No incremental impact
Scenario 3	No incremental impact	No incremental impact

Precision Farming

Under Scenario 2, space weather can create delays for precision farming and possibly the need to use less efficient methods. Precision farming is used by about 50% of farms and is about 3% more efficient than traditional techniques. Given the $11.8 B contribution of farming to Canadian GDP, the loss of the technique for 24 hours would result in a $ 0.5 M in GDP (see Table 4-23).

There is no incremental impact under Scenario 3 since threshold values are present in Scenario 2.

[129] Design and mitigation costs excluded (see Section 4.1.6 for explanation)
[130] Information provided by interviewee

Table 4-23: Precision Farming Economic Impacts[131]

GDP Impact:	Provider	User
Scenario 1	None	None
Scenario 2	$0.5 M	No incremental impact
Scenario 3	No incremental impact	No incremental impact

4.3.3 Social Impacts

The social impacts of space weather are the substantial non-quantifiable effects on the direct users of infrastructure and on the general public. The following sections discuss the social impacts of space weather on each of the infrastructure sectors.

Electrical Grid

Space weather effects on the electrical grid have the highest socioeconomic impacts because of the high levels of dependency of the other critical infrastructure sectors on electric power. The extent and severity of the social impacts is influenced by a number of factors (e.g. the geographical extent and levels of GICs, electrical grid resilience, population density in affected areas, backup power generation capacity, etc.). When blackouts occur, technologies without backup power will fail immediately (e.g. cable television, phone, internet service, water and gasoline pumps, heating and cooling systems, refrigeration, etc.). Most devices that rely on batteries will fail within two to 24 hours (e.g. smartphones, communications towers, fixed broadband cabinets, medical devices, etc.). Generator backup power will generally last for two to seven days without refueling[132].

A Scenario 1 space weather event will have no significant social impacts. One- to two-hour power losses due to terrestrial weather events or accidents are very common, and aside from minor inconveniences to businesses and the public, have very little impact. In the case of significant space weather events causing 24-hour blackouts (i.e. Scenario 2), the inconvenience will be more substantial but still largely manageable. Under a 14-day blackout caused by an extreme space weather event (Scenario 3), businesses will experience major inconveniences (e.g. the need to switch from electronic and credit card to cash transactions, employee absenteeism, etc.). As discussed for example by the U.K. Royal Academy of Engineering[133], the socio-economic impacts of extended intervals of electrical power outages beyond around 24 hours in duration are very difficult to accurately assess. The general public wouldface challenges with internet, telecommunications, weather forecasting, transportation and financial service disruptions, loss of water and sewage services, limited access to fuel, etc. Important health and safety impacts may include increased risk of accidents, disruptions in medical care services, delays in response to

[131] Design and mitigation costs excluded (see Section 4.1.6 for explanation)
[132] MacAlester, M. H. and W. Murtagh (2014). Extreme Space Weather Impact: An Emergency Management Perspective, Space Weather, 12, 530–537, doi:10.1002/2014SW001095
[133] Counting the cost: the economic and social costs of electricity shortfalls in the UK, U.K. Royal Academy of Engineering, 2014.

emergency situations, civil unrest that may lead to property , etc. Finally, environmental degradation may occur with the increased risk of dangerous goods spills and sewage treatment malfunctions.

Satellites

Since satellites operate in the space environment, they are vulnerable to the impacts of space weather on the space craft exterior, solar panels and interior electronics. Satellite communications are used directly or indirectly in a broad and growing range of applications (e.g. Internet Access, Broadband Data Communications, Rural Telephony, Public Switched Telephone Network Infrastructure Extension, News Distribution, Distance Learning, Telemedicine, Disaster Recovery, etc.) and it is not unusual for Canadians to use this technology every day[134]. For all three scenarios, the social impacts are limited by backup arrangements that commercial satellite operators typically have with other service suppliers.[135] Because of telecommunications infrastructure interconnectedness, SatCom service outages may result in short-term disruptions in long distance and cellular services on the ground as well as internet and broadband data services, especially in rural and remote regions of the country. Health and safety impacts may include disruptions in the telemedicine services that are critically important in remote areas. If weather satellites are lost, forecasting services will be impacted, causing disruption of services across the economy. Loss of scientific satellites would disrupt research programs and affect research results.

Polar Aviation

Commercial aircraft using polar flight routes are impacted in three ways by space weather events – increased radiation exposure levels for passengers and crew on high-altitude flights and HF radio and GNSS and augmentation system navigation disruptions. Each of these impacts may create the need to either re-route or delay polar flights. The main social impact for individual passengers will be the inconvenience resulting from flight delays and the possible missing of flight connections. For businesses, the primary impact will be the inconvenience resulting from delays in the receipt of goods transported by polar flights. Re-routing of flights to lower latitudes or altitudes will typically increase fuel consumption with the resulting environmental impacts of additional greenhouse gas emissions.

Polar Marine Transportation

While marine transportation in the polar regions can also be impacted by HF radio and GNSS navigation disruptions, these will have negligible social impacts on operators and customers under all three scenarios since the deployment of backup systems minimizes any voyage delays. Loss of

[134] Dell (2011). Role of Communication Satellites in Socio-Economic Development, accessed October 30, 2018 at http://www.suparco.gov.pk/downloadables/11-Role-of-Satellites-in-Socio-Economic-Development.pdf
[135] Information provided by interviewee

GNSS under Scenarios 2 and 3 could have environmental impacts if vessels run aground due to less precise navigation methods.

Magnetic Surveying

The rapid magnetic field variations that can result from space weather events can interfere with magnetic survey operations, resulting in either survey delays or requirements for resurveys. The primary social impacts of such delays are the resulting inconveniences to operators (e.g. the need to postpone or reschedule subsequent surveys). Space weather effects on magnetic surveying do not have any social impacts on the general public.

Directional Drilling

Magnetic field variations resulting from space weather events can also interfere with the accuracy of directional drilling operations. While drilling direction is regularly being corrected for a variety of reasons, including space weather-induced magnetic field variations, this typically does not result in operational delays. Consequently, there will be no social impacts of space weather under all three scenarios on customers or the general public.

Pipelines

The primary social impact of space weather on the pipelines sector is the inconvenience produced by the delays in testing surveys during significant GMD events. Space weather effects on pipelines do not have any social impacts on pipeline customers or the general public.

GNSS Positioning and Navigation

Beyond the uses of GNSS positioning and navigation in the other infrastructure sectors (e.g. aviation, marine transportation, surveying, precision farming, etc.), this technology has applications across the economy. Other uses include road and rail transportation, location-based consumer services, disaster mitigation, response and recovery, and national defence, among many others. Short-term GNSS positioning and navigation disruptions caused by Scenario 1 and 2 space weather impacts may produce service delays and inconvenience for businesses and the general public and may have health and safety impacts as, for example, policing and ambulance service responses are delayed.

GNSS Timing

GNSS is used as the primary source of precise timing for time-stamping and synchronization applications by a range of sectors (e.g. electric power, finance, information and communications technologies). The disruption of GNSS timing services under all three scenarios will have no significant social impacts on businesses and the general public since backup systems are in place to deal with these short-term outages.

Surveying

The short-term loss of GNSS positioning under Scenarios 1 and 2 will have limited social impact, causing minor inconvenience to surveyors, who need to revert to other technologies (e.g. total stations[136] and electronic theodolites[137]) to complete their work or suffer short delays due to the requirement to conduct resurveys. Space weather effects on surveying do not have any social impacts on the general public.

Precision Farming

Precision farming applications rely on GNSS with real-time kinematic corrections for farm planning, field mapping, precise navigation of farm vehicles and variable rate application of seeds, fertilizers and pest control products. For Scenarios 1 and 2, short-term GNSS outages will cause minor farmer inconvenience as traditional, less efficient farming practices are used or certain activities are delayed. Space weather effects on precision farming do not have any social impacts on farm product purchasers or the general public.

[136] A total station is an electronic/optical instrument used in modern surveying and building construction for angle, distance and coordinate measurements.

[137] An electronic theodolite is a precision optical instrument for measuring angles between designated visible points in the horizontal and vertical planes, where the readout of the horizontal and vertical circles is usually done with a rotary encoder.

5. State of Awareness

5.1 Purpose

This chapter provides an overview of the state of awareness of space weather in the global community as well as findings on awareness levels within the Canadian space weather stakeholder community. More specifically, this chapter discusses stakeholders' use of space weather forecasting services (including future requirements), the role government should play in raising awareness and potential means of closing knowledge gaps. It also presents a brief summary of space weather related training needs.

5.2 Global Context

Awareness of space weather has been growing, as indicated by the "exponential growth of the number of web pages on space weather and in the number of customers subscribing to alert and forecast services"[138], based on the importance given this issue by the U.S., U.K. and other countries. Both the U.K. and U.S. released National Space Weather Strategies in 2015[139] [140] that define high-level strategic goals and actions for increased preparedness levels. In addition to this, the U.S. passed the Space Weather Research and Forecasting Act in 2017, which builds on its national space weather strategy and provides further direction and funding for research and responsive actions. In addition, the U.K. has added space weather to its National Risk Registry of Civil Emergencies[141] to ensure it receives a higher profile and that threats are well understood.

Internationally, a *Space Weather Expert Group* was established by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) in 2015 with the mandate to promote awareness, provide guidance, and enable cooperation in space weather-related activities among member states and other related organizations. This expert group recently recommended that an international workshop on space weather be held in 2019 to continue to raise awareness among member states of the importance of the impact of space weather.[142] In addition, the *European Union's Space Weather and Critical Infrastructures Summit* that took place in November 2016 was attended by almost 50 representatives from European infrastructure operators, regulators, crisis-

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138 Schrijver, C. J. et al (June 15, 2015), "Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS", *Advances in Space Research 55, 12*: 2745-2807.
139 National Science and Technology Council, (October 2015), *US National Space Weather Action Plan.*
140 Department for Business, Innovation & Skills, Cabinet Office, V2.1 (July 2015) *UK Space Weather Preparedness Strategy*
141 UK Cabinet Office (2015), *UK Risk Registry of Civil Emergencies*.
142 UN General Assembly, Committee on the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee, Draft report, VIII. Space weather, February 2018.

response experts, academia and government agencies.[143] Discussion focused on risks of extreme space-weather impacts on infrastructures, and the associated challenges for operators and emergency response organizations. This forum provided a platform for exchange and coordination among key stakeholders.

These initiatives are building awareness of space weather and continue to highlight the need to address knowledge gaps and improve international communication and collaboration between government, science and industry to provide reliable and usable information to operators for decision-making. As such, understanding the risks and impacts of space weather is becoming increasingly important as our technologically dependent world advances.

5.3 Awareness Levels and Role of Government in Canada

As part of this study, Canadian researchers and operational experts in all critical infrastructure sectors (i.e. electrical grid, aviation, satellites, pipelines, etc.) were surveyed to: (i) assess their level of awareness of space weather (ii) gather views on what role government should play in raising awareness/mitigating risk and (iii) gauge their interest in training and receiving guidance about what they could do to mitigate risk.

All respondents indicated some level of awareness of space weather risks, as applicable to their particular infrastructure area, and the majority utilized both NRCan's and NOAA's space weather prediction services. Some respondents monitored these services on an irregular basis (e.g. pipelines, magnetic surveying, directional drilling and surveying) while others monitored them daily (e.g. electrical grid and aviation). One satellite operator noted that for their US customers they utilized NOAA supplied data exclusively for uniformity but indicated if the Canada-supplied data offered something unique they would be willing to take advantage of it.

Several respondents provided suggestions for future improvements to space weather forecasting services. A customized and automated forecast service (i.e. email push notifications and alerts when risk is high) would be helpful to ensure users are getting the right information at the right time. Others indicated that forecasts could be improved to provide more information on the probability, duration and intensity of an event as well as local/regional detail but were unaware if current scientific capabilities could address this. Some emphasized the importance of providing information on the thresholds of concern for each infrastructure sector and credible worst-case scenarios as a baseline for impact assessment. However, several felt that NRCan space weather forecasting services were acceptable as currently provided and noted that the government should continue to provide those services free of charge.

[143] European Commission's Joint Research Centre, Swedish Civil Contingencies Agency, the UK Met Office, with the support of NOAA Space Weather Prediction Center (November 2016), *Space Weather and Critical Infrastructure: Findings and Outlook.*

The majority of respondents felt strongly that the federal government has a role to play in raising awareness of the risks of space weather and providing advice on how to mitigate the impacts of severe disturbances. It was noted by some that the situational awareness of the economic impacts of space weather are perhaps being under-estimated in some cases due to the very low levels of solar activity during the present solar cycle. Many noted that Canada had fallen behind and expressed concern that other countries, particularly the U.S. and U.K, are much more proactive in both raising awareness of the risks and making investments in space weather services. Many felt there is a need for a stronger Canadian presence in the international community, particularly given our vulnerabilities to space weather variations and our level of expertise, experience and research capacity. The need for a comprehensive national action plan to support sustained research/partnerships and new equipment/tools and applications to mitigate risk was also noted.

Specific comments and suggestions in regards to government's role to fill **knowledge gaps** included:

- More proactive outreach to affected infrastructure sectors is necessary (e.g. targeted/niche publications indicating the impacts of space weather on different systems). The subtle impacts of space weather are often hard for industry to identify. Researchers, in particular, noted that it is important for the government to provide science-based evidence on potential/credible risk areas to help industry fully understand threats, correlate them with actual consequences/costs and subsequently raise risk profile to senior managers that are not directly involved in operations.

- Initiate an ongoing national forum for exchange of information and experiences in dealing with space weather. Several stakeholders indicated they would be interested in participating in a space weather conference in Canada to learn about mitigation strategies across critical infrastructure areas; "*it is very important to have an open sharing of information and exchange of views on the impacts of space weather so that there is a better understanding of the risks and consequences and users can share their current knowledge*".

- Provide more predictable/regular research funding to assist utilities to study risk modeling, improve simulations and identify system vulnerabilities as well as fund broader studies to look at the wider impacts of space weather that have not yet been identified. Canada is lacking support in this area; "*doing complex modelling is too expensive for the utilities, need the government to defer some of the costs. Need the government to fund actionable research; address what the utilities don't know*".

- Consolidate space weather forecasting, science, engineering and research in one Space Weather Centre to create a knowledge hub and more effective collaboration. This would address the need for better coordination of space weather activities in Canada, within government and between government, academia and industry; "*we need strategic discussion on highest priority needs for industries' operational services that can guide future research and this can be achieved with a more collaborative approach*."

5.4 Need for Training

The majority of stakeholders indicated they would be interested in exploring training options to raise the awareness of the risk and impacts of space weather within their organization, with senior management and the respondents themselves. It was noted that training which combined information on the risks and impacts of space weather, along with possible measures which could be taken to mitigate these risks, would be the most useful and of the most interest. Stakeholders that were not interested felt that, since space weather had limited impact on their operations on a regular basis (e.g. directional drilling, regional aviation), it would be difficult to garner any interest in or approval for such training. Others noted that they themselves were "experts on space weather and mitigation strategies" in the context of their organization, thus training would not necessarily provide any value-add, but they would be interested in exchanging experience/ knowledge.

5.5 Other Knowledge Gaps

In addition to the knowledge gaps noted above in Section 5.3, and the underlying uncertainty as to intensity and probability of the next space weather event, a review of international activities and related space weather strategy documents suggest there are additional important knowledge gaps that need to be addressed in the Canadian context. These include:

- Limited public understanding and clarity about what space weather is, how it might affect them and what remediation is already in place. It is important to gauge public awareness to determine how far members of the public think the government and companies should go to mitigate space weather impacts as well as to inform policy and spending in regards to resilience strategies.

- Lack of space weather emergency preparedness planning. This is particularly necessary in the event of an extended power outage. Most communities can be reasonably self-sufficient during a power outage for a few days up to a week, but the situation can become difficult quickly without the ability to refuel generators after an extended period of time. There is a requirement for all levels of government to think beyond the normal challenges of a traditional space weather event and plan to manage impacts.

- Limited understanding of user needs for space weather forecasting in order to establish lead-time and accuracy goals. More can be done to ensure space weather products are intelligible, applicable to sector needs and actionable to inform decision-making.

- Research limitations in the understanding of the complex interactions between the sun and earth, and in how disturbances in space weather impact technological infrastructure. This understanding largely drives the ability to accurately develop space weather forecasts. More could be done to prioritize and identify opportunities for R&D in modelling (i.e. geospace dynamics and GICs, solar wind propagation and evolution, probabilistic solar flare and CME forecasts, ionospheric scintillation forecasts, etc) and to quantify the short- and long-term variability of space weather, as well as improved and high fidelity models of the levels of disturbance imposed on technological infrastructure and their impact.

6. Conclusions and Recommendations

6.1 Conclusions

6.1.1 Current Supply and Use of Space Weather Information

Within Canada's infrastructure sectors there is a varying level of knowledge and understanding of space weather and its impacts on systems and operations. Based on the research and consultations for this study, this level is relatively high in those sectors that are most impacted (e.g. electrical grid, aviation, satellites) and relatively low in those that have historically been least impacted (e.g. GNSS timing, marine transportation, precision farming). What is often lacking in organizations is a detailed understanding of specific space weather impacts relative to other impacts (e.g. the amount of pipeline corrosion attributable to telluric currents due to space weather).

The primary supplier of space weather information in Canada, Natural Resources Canada, has a solid clientele within the user community, which relies upon them for quality space weather forecasts. Other sources of information used by the infrastructure sectors include the US Space Weather Prediction Centre and online services such as spaceweather.com. The study identified some 240 organizations in Canada that are prospective users of space weather forecasts, which can serve as a foundation for development of a complete inventory of organizations affected by space weather.

6.1.2 Economic Impacts of Space Weather

The analysis of economic impacts was based on three impact scenarios: Scenario 1: Limited impacts (minutes to 2-hour service denial), Scenario 2: Short-term impacts (24-hour service denial) and Scenario 3: Long-term impacts (14-day service denial for electrical grid infrastructure, 1-year loss of WAAS). Table 6-1 provides a summary of the economic impacts of space weather on Canada's infrastructure sectors.

Table 6-1: GDP Impacts of Space Weather on Canada's Infrastructure Sectors

Infrastructure Sector	Scenario 1	Scenario 2	Scenario 3
Electrical Grid	$0	$405.7 M – $1,091.8 M	$20,682.2 M – $54,945.8 M
Satellites	$0.6 M	$287.7 M	$576.1 M
Polar Aviation	$1.4 M – $28.0 M	$1.4 M – $28.0 M	$1,750.0 M (all aviation)
Polar Marine Transportation	$0	$0	$0
Magnetic Surveying	$1.4 M – $7.0 M	$1.4 M – $7.0 M	$1.4 M – $7.0 M
Pipelines	$238.2 M	$238.2 M	$238.2 M
Surveying	$0.8 M – $1.7 M	$0.8 M – $1.7 M	$0.8 M – $1.7 M
Precision Farming	$0	$0.5 M	$0.5 M
TOTAL	**$243.0 M – $276.1 M**	**$950.2 M – $1,669.4 M**	**$23,249.2 M – $57,519.3 M**

The table above clearly demonstrates the wide variation in economic impacts of space weather, with Scenario 1 impacts ranging from $0 (electrical grid, polar marine transportation and precision farming) to $238.2 million (pipelines sector), Scenario 2 impacts ranging from $0 (polar marine transportation) to $1,091.8 million (electrical grid) and Scenario 3 ranging from $0 (polar marine transportation) to $54,945.8 (electrical grid).

6.1.3 Social Impacts of Space Weather

As with the economic impacts, there is considerable variation in the social impacts of space weather on Canada's infrastructure sectors. Across all of the sectors, the impacts under Scenario 1 are either nonexistent or limited to minor inconveniences for infrastructure operators or their customers. Under Scenarios 2 and 3, additional impacts may be experienced in some sectors (e.g. increased risk of accidents, disruptions in telecommunications, weather forecasting, medical care and emergency response services, increased environmental degradation). In most sectors, the impacts will primarily be on infrastructure operators, with more limited impacts on businesses, consumers and the general public.

However, the broader social impacts of extended intervals of electrical power outages beyond around 48 hours in duration are difficult to accurately assess but can be extensive.

6.1.4 Mitigation of Space Weather Impacts

The study research and consultations suggest that effective measures have been adopted by most infrastructure sectors to mitigate the impacts of space weather. Infrastructure operators are making investments in three mitigation areas: i) *design* – pre-event design modifications of infrastructure components; ii) *backup* – alternative technologies and commercial arrangements that are implemented as necessary during space weather events; and iii) *actions* – mitigation actions taken during or following space weather events as necessary. While those consulted indicated a strong awareness of space weather impacts and generally express confidence in their mitigation measures, there is strong interest in additional research to bolster their understanding of impacts. It is worth noting, however, that this awareness may be based upon experience of very limited space weather activity in the past 10-15 years. Therefore, the perception of risk might be underestimated in the industry as a result of operational experience spanning only a relatively small range of space weather events sizes compared, for example, to ~100+ year timescales on which much larger extreme events have been observed to occur. Much of the technology affected by space weather did not exist 50 years ago, providing little historical records of the impact of a very large event. It is important to note that awareness beyond the group of specialists that were consulted for the study is typically much lower within the broader infrastructure community.

6.1.5 Value of Space Weather Services Improvement

There is growing awareness of the impacts of space weather internationally and within Canada, and several nations have included this risk in their national risk registers or emergency response strategies. In order to manage this risk, organizations need information upon which to base the formulation of their mitigation measures and take action in the case of significant events. Space weather services such as the Canadian Space Weather Forecast Centre (CSWFC) operated by Natural Resources Canada provide this information to users in Canada. The following paragraphs discuss the value of improving such services to each of the infrastructure sectors against the backdrop of the socioeconomic impacts of space weather events. Specifically, they address the question, "How much would improvements in space weather services and additional research benefit this infrastructure sector?"

Electrical Grid

Canada's electrical grid is arguably the infrastructure sector that is most impacted by space weather. As indicated in Section 4.3, major space weather events have severe economic impacts and widespread social impacts, given the dependency of other infrastructure sectors on electric power. Electric utilities make use of the space weather forecasts provided by the CSWFC, but they are not dependent upon this information (e.g. they use GIC monitors as well). However, as discussed in Section 4.2.1, there is strong interest in improvement of the government's services, including more precise forecasting, additional geomagnetic monitoring sites and more research to address critical knowledge gaps. While those consulted in this sector believe that their mitigation measures are adequate, there is a strong likelihood that the resilience of the electrical grid to space weather impacts would be increased if these improvements were realized. In summary, the electrical grid sector's needs for improvements in space weather services and for additional research are both rated as *very high*.

Satellites

Satellites are also significantly impacted by space weather. Given that the primary mitigation strategy is design, the use of space weather forecasts is primarily limited to supporting decision-making related to the timing of critical satellite maneuvers. While consultations with industry representatives revealed limited interest in additional research and improved forecasting, the literature review identified ongoing concerns in the satellite industry about the difficulty of identifying whether or not an anomaly is the result of space weather[144]. In summary, the satellites sector's needs for improvements in space weather services is rated as *low* and for additional research is rated as *medium*.

Polar Aviation

The aviation sector employs space weather forecasts to help identify when re-routing of polar flights is necessary because of space weather impacts on aircraft avionics and crew (i.e. risk of radiation exposure). While no interest in forecasting improvements or additional research was indicated in consultations, ICAO has identified needs in both areas, and Canada will be part of an ICAO global center for space weather advisories for aviation. In summary, the aviation sector's needs for improvements in space weather services and for additional research are both rated as *high*.

Polar Marine Transportation

No evidence has been found of space weather services use within this sector, with some interest in forecasting improvements. As a consequence, the marine transportation sector's needs for improvements in space weather services is rated as medium and for additional research is rated as *low*.

Magnetic Surveying

This sector's use of space weather forecasts is primarily limited to supporting decision-making related to potential delays in surveys due to significant space weather events. Consultations with industry representatives revealed some interest in improved forecasting and additional research. In summary, the magnetic surveying sector's needs for improvements in space weather services and for additional research are both rated as *medium*.

Directional Drilling

The primary use of space weather services within this sector is for awareness of significant events that may impact drilling operations. Some interest was expressed during consultations in additional

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[144] Green, J. C., Likar, J., Shprits, Y. (2017), *op. cit.*

research. In summary, the directional drilling sector's needs for improvements in space weather services are rated as *low* and for additional research are rated as *medium*.

Pipelines

The pipeline sector's use of space weather information assists with planning, and potential postponement, of corrosion testing surveys. During consultations, interest was expressed in both space weather services improvements and additional research. In summary, the pipelines sector's needs for improvements in space weather services and for additional research are both rated as *high*.

GNSS Positioning, Navigation and Timing

No evidence has been found of the use of space weather forecasting services within the broad GNSS user community. As a consequence, this sector's needs for improvements in space weather services and for additional research are both rated as *low*. However, it is important to note that use of forecasting services may increase in the future as reliance on GNSS becomes even greater and expectations of higher precision continue to grow.

Surveying

The surveying sector's use of space weather information assists with planning, and potential postponement, of surveys. During consultations, no interest was expressed in space weather services improvements and additional research. As a consequence, this sector's needs for improvements in space weather services and for additional research are both rated as *low*.

Precision Farming

Similar to the broader GNSS user community, there is no use of space weather forecasting services within the precision farming sector. As a consequence, this sector's needs for improvements in space weather services and for additional research are both rated as *low*.

Summary

Figure 6-1 illustrates the overall interest in improved space weather services and additional research activities within the Canadian infrastructure sectors.

Figure 6-1: Needs for Improved Space Weather Services and Additional Research

Infrastructure Sector	Space Weather Services	Space Weather Research
Electrical Grid	Red	Red
Satellites	Green	Yellow
Polar Aviation	Orange	Orange
Polar Marine Transportation	Yellow	Green
Magnetic Surveying	Yellow	Yellow
Directional Drilling	Green	Yellow
Pipelines	Orange	Orange
GNSS Positioning, Navigation and Timing	Green	Green
Surveying	Green	Green
Precision Farming	Green	Green

Legend:

Very High	Red
High	Orange
Medium	Yellow
Low	Green

6.2 Recommendation

This section outlines the rationale for developing a Canada Space Weather Strategy (CSWS) and proposes the following goals: improve understanding of space weather impacts; increase forecasting services tailored to Canadian latitudes; promote greater awareness of the risks and impacts of space weather events; create a space weather preparedness plan; and continue and enhance international engagement.

6.2.1 Rationale for a Canada Space Weather Strategy

Canada's Sovereignty and Security is an element of Canada's Space Policy Framework. There is an increasing recognition worldwide that Space Weather Monitoring and Forecasting is required to protect space assets, ground assets and ultimately human lives against risks originating in space.

Space weather events can have a significant impact on Canada's critical infrastructure essential to national security, economy and the health of Canadians including the electrical grid, the transportation networks and space systems (satellites and their ground facilities). Concerns have risen over the years as a result of the complexity of critical infrastructure and our increasing dependency on space-based technologies such as cellular/mobile telephones, the Internet and Global Navigation Satellite Systems (GNSS)/Global Positioning Systems (GPS). When autonomous vehicles are introduced and become more common in Canada, our reliance on GNSS with higher precision will increase.

For this reason, national governments are developing strategies and programs to mitigate the effects of severe space weather events. For example, in 2013, the United Kingdom generated an exhaustive study concluding that their infrastructure is at risk and underlining the importance of maintaining current mitigation strategies and developing new approaches. The same year, the United States followed through with a more focused study which identified the risk of losing critical space weather observing and forecasting capabilities and the necessity to maintain their space-based and ground-based observing systems. Both the U.S. National Space Weather Strategy and the U.K. Space Weather Preparedness Strategy recognize that severe space weather is an inter-disciplinary risk, with the potential to impact myriad technologies and activities in space and on Earth, and requires a coordinated response from multiple organizations.

Feedback from stakeholders in this study suggests a strong interest within the space weather community in the Federal government taking a stronger leadership role in coordinating Canadian space weather activities. There is growing recognition in this country of the risks to an increasingly integrated critical infrastructure of severe space weather events. While many stakeholders believe that they have acceptable impact mitigation measures in place, there is also strong interest in improved space weather forecasting and additional research on the specific impacts in different sectors. A coordinated effort to address this interest with a formal Canada Space Weather Strategy (CSWS) will be welcomed by the community.

6.2.2 Improve Understanding of Space Weather Impacts

As noted earlier, while infrastructure operators are confident in their preparations to mitigate space weather impacts, there are fundamental knowledge gaps in assessing the technological impacts from extreme space weather events. To address this requires knowledge of realistic benchmarks of the levels of space weather disturbance which should be applied to models of the relevant infrastructure, recognizing the importance of accurate representations of how the technology is implemented, as well as a realistic assessment of the different sizes of space weather disturbances at different geographic locations. There is strong interest in additional research to bolster understanding of impacts. It was noted by interviewees and survey respondents that more funding for research on space weather impacts and mitigation is needed; Canada is far behind the U.S. and

U.K.[145]. There is also interest in understanding more about probabilities of severe events and in higher fidelity impact studies and risk assessments based on improved benchmarks. In addition to targeted funding for space weather research and related technical impact assessments, some suggestions for improving understanding include:

- Initiate a ***Canadian Space Weather Symposium*** to bring together key stakeholders (policy makers, scientists/researchers, industry, meteorologists) from across Canada to share best practices, and discuss next steps in research/forecasting as well as future concerns and challenges.

- Develop ***online training modules*** customized to key infrastructure sectors that would present: (i) the range/types of risks of concern for their sector; (ii) mitigation procedures and advice; and (iii) strategies for raising the risk profile within their organization. They could also include industry guidelines for how best to use space weather data/information effectively to inform decision making.

6.2.3 Increase Forecasting Services Tailored to Canadian Latitudes

- As noted earlier, in order to manage the risk of space weather impacts, organizations need information upon which to base the formulation of their mitigation measures and take action in the case of significant events. It was noted by interviewees and survey respondents that forecasts on the duration, intensity and geographic area (specific to Canadian latitudes) of space weather events is needed (i.e. NOAA forecasts are not always suited for Canada). There is also interest in extending the geomagnetic monitoring network. Some suggestions to tailor forecasting services to Canadian latitudes include: Conduct a ***comprehensive survey of space-weather data and product requirements*** for the user community in each sector to help improve and customize space weather forecasting services. The survey could involve questions related to satisfaction levels with existing forecasting services, future information needs (i.e. frequency, accuracy, format preferences) and suggestions for value-added services that could be provided.

- Develop ***enhanced warnings and alerts*** that utilize the best data, research and information to deliver space weather forecasts. Initiate actions to improve forecasting lead-time and accuracy as well as an online platform where stakeholders can sign up for specific alerts and warnings. This platform could also provide additional information and data, in a more user-friendly format, for the public through the use of Apps.

- Develop a plan that will ensure the ***improvement, testing, and maintenance of operational forecasting models*** driven by research findings**.** This action will leverage existing

[145] For example, the UK's new £ 8 M Data and Analytics Facility for National Infrastructure (DAFNI) is helping researchers to analyse the resilience of interdependent critical infrastructure, among other things. (https://www.dafni.ac.uk/)

capabilities in academia and the private sector and enable feedback from operations to research to improve operational space-weather forecasting.

6.2.4 Promote Greater Awareness of the Risks and Impacts of Space Weather Events

As noted earlier, the majority of respondents felt strongly that the federal government has a role to play in raising awareness of the risks of space weather and providing advice on how to mitigate the impacts of severe disturbances. Many noted that Canada had fallen behind and expressed concern that other countries, particularly the U.S. and U.K, are much more proactive in both raising awareness of the risks and making investments in space weather services. Some suggestions to promote greater awareness of the risks and impacts of space weather events include:

- Develop ***Mechanisms for Wider Awareness Raising*** so that general information relating to space weather could be made available in the public domain, in order to familiarize people with the concepts and terminology of space weather in the context of other risks that exist in the realm of public safety and security. Additional resources and links to research could also be provided to allow individuals to undertake further investigation to expand their understanding if they desired. This would help to provide clarity to key questions such as: (i) What is space weather? (ii) How long could a severe space weather event last, what would the likely impacts be as a result and what can we do about it? (iii) How vulnerable is Canada?

- Champion the addition of "space" to the list of Canada's critical infrastructure sectors, and its inclusion in future editions of *Canada's Emergency Management Framework* and *National Strategy and Action Plan for Critical Infrastructure*.[146]

6.2.5 Create a Space Weather Preparedness Plan

The creation of a ***Space Weather Preparedness Plan*** would require a coordinated approach across all government departments/agencies (possibly lead by Public Safety Canada) and commercial partners to ensure a streamlined process. Key stakeholders would include federal departments of Transport, Defence, Innovation, Science and Innovation and Natural Resources, and the Canadian Space Agency, as well as provincial and local government and private sector infrastructure operators. We also note the importance of space to across the federal government. As such space weather impacts, as well as space in general, would benefit from a more coordinated whole-of-government approach reflecting also the acknowledgement in the recently released Canadian Space Strategy[147] that "*The Government of Canada recognizes the importance of space as a strategic national asset*". It would address how each government department should react in

[146] Note that the Government of Australia has already taken similar action, in recognition of the increasing reliance on space-based infrastructure.

[147] Exploration, Imagination, Innovation: A New Space Strategy for Canada, http://www.asc-csa.gc.ca/pdf/eng/publications/space-strategy-for-canada.pdf

response to a space weather event (i.e. roles and responsibilities) as well as the selection of a singular entity that would play the coordination role. It could also provide guidance on contingency planning for the effects of space weather on essential services, power restoration priorities as well as response and recovery plans. It could include consideration of specific planning requirements in different sectors (e.g. for the electrical grid sector, potential establishment of a spare parts register and selection of routes for transportation of transformer replacements to avoid obstacles such as bridges and tunnels). Initiatives that such a Plan would need to take into account include:

- *Canada's Emergency Management Framework*: The Framework "adopts a comprehensive all-hazards approach to coordinate and integrate **prevention and mitigation, preparedness, response** and **recovery** functions[148] to maximize the safety of Canadians." The third (2017) edition of the Framework focuses on putting greater attention/investment on **prevention** and **mitigation.**

- *National Strategy and Action Plan for Critical Infrastructure*: The Strategy defines critical infrastructure as comprising the following ten sectors: (1) energy and utilities; (2) information and communication technology; (3) finance; (4) health; (5) food; (6) water; (7) transportation; (8) safety; (9) government; and (10) manufacturing.[149] There are a number of action items in the 2018-2020 Action Plan concerning the resiliency of critical infrastructure sectors, such as: the work of the Federal/Provincial/Territorial (FPT) Critical Infrastructure Working Group; expanding regional outreach of critical infrastructure programs; the Critical Infrastructure Information Gateway; identifying ways to support the critical infrastructure community in taking action to address risks; and conducting cross-sector exercises to strengthen preparedness and response.[150]

- PNT Office (formerly GNSS Coordination Office): The main purpose of the PNT Office is to coordinate federal PNT/GNSS initiatives by: (a) formally bringing together departments and agencies with PNT/GNSS interests and ensure a collective effort; (b) collaborating, sharing information and expertise and providing advice; and (c) providing an ongoing central point of contact for federal PNT/GNSS issues.

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[148] As noted earlier, the four interdependent components of the Emergency Management Framework are: (1) Prevention and Mitigation – to adapt to, eliminate, or reduce the risks of disasters in order to protect lives, property, the environment, and reduce economic disruption. Prevention/mitigation includes structural mitigative measures (e.g. construction of floodways and dykes), and non-structural mitigative measures (e.g. building codes, land-use planning, and insurance incentives); (2) Preparedness – to be ready to respond to a disaster and manage its consequences through measures taken prior to an event, for example emergency response plans, mutual assistance agreements, resource inventories and training, public awareness activities, equipment and exercise programs; (3) Response – to act during, immediately before or after a disaster to manage its consequences through, for example, emergency public communication, search and rescue, emergency medical assistance and evacuation to minimize suffering and losses associated with disasters; and (4) Recovery – to repair or restore conditions to an acceptable level through measures taken after a disaster, for example return of evacuees, trauma counseling, reconstruction, economic impact studies and financial assistance. There is a strong relationship between long-term sustainable recovery and prevention and mitigation of future disasters.

[149] Ministers Responsible for Emergency Management (2009), *National Strategy for Critical Infrastructure*

[150] Public Safety Canada (2018), *National Cross Sector Forum 2018-2020 Action Plan for Critical Infrastructure*

6.2.6 Continue and Enhance International Engagement

- ***Engagement with the international community*** on observation infrastructure, data sharing, numerical modeling and scientific research should be continued and enhanced where appropriate. Enhanced collaboration can also provide solutions to regional challenges associated with space weather and exchange of best practices between Canada and the international partners. Overall this will help to strengthen global capacity to respond to extreme space-weather events. Progress is being made in this area with the recent release of voluntary guidelines by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). The 21 agreed guidelines promote broader international collaboration and address the policy, regulatory, operational, safety, scientific, technical and capacity-building aspects of space activities including space weather, and include two dedicated to space weather. The implementation of the guidelines will support the development of practices to mitigate risks associated with the conduct of outer space activities so that present benefits can be sustained and future opportunities realized.

  Additional international initiatives that will need to be taken into account include:

  - Space weather advisory services for international aviation: The International Civil Aviation Organization (ICAO) is in the process of approving regulations (Standard and Recommended Practices or SARPs) related to the introduction of space weather advisory information services for international air navigation. Designated space weather providers will be required to produce near real-time and forecast information regarding the potential impacts of space weather (i.e. coronal mass ejections and high-speed streams, geomagnetic storms, solar radiation storms, solar flares, solar radio bursts and ionospheric activity) in order to avoid the risks posed to flight safety regarding communications, satellite-based navigation surveillance, and avionics, as well the risk to the health of aircraft occupants (i.e. flight crew and passengers) due to radiation exposure. Final Concept of Operations (ConOps) and SARPs for the provision of space weather information were scheduled to come into effect in November 2018[151,152], and NRCan is to become part of an ICAO global space weather center.

  - Electric Infrastructure Security (EIS) Council: The EIS Council facilitates national and international collaboration and planning to protect critical utilities against uniquely severe Black Sky Hazards. Black Sky Hazards are defined as catastrophic events that severely disrupt the normal functioning of critical infrastructures in multiple regions for long durations. It includes both **manmade** (i.e. high-altitude electromagnetic pulses, intentional electromagnetic interference, cyber terrorism

[151] ICAO (Raul Romero) (2018), "Establishment of Space Weather Information Service for International Air Navigation", *Inter-Programme Team on Space Weather Information, System and Services, Second Session*, Tokyo, Japan, 21-23 May 2018

[152] At the time of this report, final ConOps and SARPs had not been released.

and coordinated physical assaults) and **natural** (i.e. seismic event/high magnitude earthquake, **Geomagnetic Disturbance/space weather** and hurricanes and other severe weather events) **hazards**. Some of the protection initiatives include coordinated global simulation exercises for Black Sky Hazards, of which space weather is one. The EIS Summit Series (annual conference) is the primary international framework for senior government, industry and NGO officials to collaborate on resilience assessment and planning, addressing severe national-scale hazards to lifeline utilities. The last summit was held in London, UK, June 25-26, 2018.[153]

- *Canada-U.S. Action Plan for Critical Infrastructure*: The purpose of the Action Plan is to strengthen the safety, security and resiliency of Canada and the United States by establishing a comprehensive cross-border approach to critical infrastructure resilience.[154]

- Critical 5: Critical 5 is an international forum, established in 2012, comprising members from government agencies responsible for critical infrastructure protection and resilience in Australia, Canada, New Zealand, the United Kingdom and the United States, to develop a common understanding of critical infrastructure and its role in society. [155]

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[153] Electric Infrastructure Security (EIS) Council accessed November 12, 2018 at https://www.eiscouncil.org/

[154] Public Safety Canada (2018). *Canada-U.S. Action Plan for Critical Infrastructure*, accessed January 11, 2019 at https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/cnd-ntdstts-ctnpln/index-en.aspx

[155] Public Safety Canada (2014). *Forging a Common Understanding for Critical Infrastructure: Shared Narrative*, accessed January 11, 2019 at https://www.dhs.gov/sites/default/files/publications/critical-five-shared-narrative-critical-infrastructure-2014-508.pdf

Appendix 1: Workshop Report

Purpose

On October 25, 2018, a workshop was held in Ottawa to present initial findings from the study and provide a forum to discuss and validate the socioeconomic impact assessment model, its assumptions and estimates. The participants were leading experts in space weather and representatives of the major sectors that are impacted by space weather. The workshop reviewed and discussed the following topics:

- Background study highlights
- Socioeconomic indicators and methodology
- Impact scenarios
- Impact summaries
- Next steps

The following sections provide in bullet form the key highlights of the discussions by the workshop participants.

Impact Scenarios

- Scenarios should be defined by space weather intensity, location and duration and have “immediate” effects (duration of the storm) and “long-term” effects (time to recover damaged facilities).
- The likelihood of space weather events and likelihood of damage to infrastructure should be indicated in scenarios.
- The likelihood of significant electric power blackouts is reduced due to compliance with standards developed by the North American Electric Reliability Corporation (NERC). In Eastern Canada, the Northeast Power Coordinating Council, Inc. (NPCC) also has a role to play, under a delegation agreement with NERC. Regulation of electric power operators is a provincial jurisdiction, but the provincial energy boards typically adopt NERC standards.
- In practice, for the entire electric grid Scenario 3 is unlikely because the grid will either shut down automatically or collapse, preventing significant transformer damage. In a catastrophic event, since relays are now digital, there will be a controlled shutdown or load shedding, so once the SW event is over, it is likely that most of the grid will be back up in a few hours. However, the overall impact of such an event is very unpredictable, since certain nodes may be impacted to the extent that power may be out in some local areas for several weeks.

- It is important to note in the report that impacts will be more significant in the future due to interdependencies between infrastructures (e.g. loss of GNSS navigation and positioning impact due to increased use of autonomous vehicles, loss of GNSS timing impact due to increased dependencies in the electrical grid, etc.).

Impact Summaries

Electrical Grid

- Scenario 3 is unrealistic because when you get to a certain level, the grid collapses and, if utilities adhere to the new NERC guidelines, then even scenario 2 is unlikely
- Series compensation should not be indicated as a mitigation method, since it redirects GIC, which can have adverse effects in other parts of the grid.
- There are operating and capital costs that need to be considered related to improving design to NERC standards.
- Timing could be more of an issue in future as many systems will not have atomic clock backup. Special protection schemes such as load shedding need precise time (= 0.0167 sec) in terms of cycle duration.
- Economic impact calculation should take different provincial grid circumstances into consideration (e.g. adherence to NERC standards EOP-010 and TPL-007, use of phasor measurement units (PMUs), differences in heating sources, etc.)
- If possible, quantification of social impacts is desirable (e.g. impact of loss of access to water or refrigerated food due to extended power blackouts).

Satellites

- LEO satellite drag impacts include not only fuel costs but costs of extra work for operators on the ground.
- LEO satellites rely on GNSS; loss of GNSS will mean degradation in performance due to reversion to ground tracking.
- Loss of power also impacts LEO ground stations; backup generators are a significant cost as well.
- Economic impact of 1-5% of manufacturing costs for design seems low.

Polar Aviation

- Lack of specialized space weather forecasts for aviation means that it is not possible to correlate flight delays with space weather events, which makes it very difficult to estimate the impacts of space weather on polar aviation.
- Flight rerouting due to loss of HF radio or GNSS is very rare because backup systems are available but inefficiencies created due to increased aircraft spacing in flight; rerouting due to radiation is common.

- WAAS navigation is more vulnerable because only one satellite will cover Atlantic Canada in the future; no safety danger since ground-based backups in place.
- Scenario 1 economic impact is too high; probably close to zero.

Directional Drilling

- Limited operator knowledge of space weather impacts; regular direction corrections due to multiple impacts are common and difficult to isolate space weather impacts.

Magnetic Surveying

- Magnetic base stations in survey area can mitigate space weather impacts; but not commonly used because the cost is higher than the cost of occasional lost data because of storms.

Pipelines

- More frequent Scenario 2 events are of most concern because of cumulative impacts on corrosion. No way to measure the impacts of space weather on corrosion compared to other causes.

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