FINAL REPORT

Social and Economic Impacts of Space Weather in the United States

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Abt Associates
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1. Introduction

Space weather broadly refers to time-variable conditions in the near-Earth space environment including the sun, solar wind, magnetosphere, ionosphere, and thermosphere. It represents a natural hazard that is known to interrupt and damage technologies critical to modern society such as electric power grids, airlines, trains, pipelines, and Global Navigation Satellite Systems (GNSS) [*National Research Council*, 2008; *Baker and Lanzerotti*, 2016]. Despite such risks and our growing dependencies on these technologies for almost all aspects of daily life, there have been a limited number of studies on space weather's social and economic impacts [*National Research Council*, 2008; *Eastwood et al.*, 2017]. In order to address this significant knowledge gap, this report represents a first attempt to systematically identify, describe, and quantify the impacts of space weather events within the United States (U.S.). Since better understanding these impacts is essential for enhancing our preparedness and strategically reducing our risks, this report also establishes the comprehensive foundation and analytical framework necessary for stimulating timely discussions and advancing this frontier. We furthermore hope our initial study helps enable the proliferation of careful research that is necessary for addressing the impacts of space weather with the same rigor and attention paid to other natural hazards where our collective understanding is comparatively more mature (e.g. hurricanes, tornadoes, tsunamis, wildfires, droughts).

It is now well recognized that space weather presents significant risks to the U.S. economy and to the safety of its citizens. Space weather has been identified by the federal government as one of the grand challenges for disaster risk reduction [*National Science and Technology*, 2015], and most recently, it has been addressed in a National Space Weather Strategy [*Executive Office of the President*, 2015a] and National Space Weather Action Plan (SWAP) [*Executive Office of the President*, 2015b]. Our study was in part initiated in response to the SWAP (see Action Item 4.5.2), a much larger U.S. effort for addressing potential vulnerabilities and increasing resilience by setting detailed national goals and promoting enhanced coordination and cooperation across public and private sectors [*Executive Office of the President*, 2015b]. Furthermore, NOAA recognizes that underlying the national effort to enhance the preparedness for space weather events is the need to improve our understanding of the social and economic impacts. NOAA also understands that there is a recurring need for this type of analysis and supports the full documentation of methods, procedures, data sources, and lessons learned to encourage the consistency of future efforts. Although the growing national and international recognition of this important topic has led to a handful of other socioeconomic impact studies that were recently finished or are concurrently underway in Europe, we were unable to draw upon such efforts for this study since they differ somewhat in scope [e.g. *Oughton*, 2017], are not yet published [e.g. *Biffis and Burnett*, 2017], or are publically unavailable [e.g. *Luntama et al.*, 2017].

One of our study goals was to capture and synthesize what is known about space weather impacts across four technological sectors of prime concern: electric power, satellites, GNSS users, and aviation. Another goal involved translating our findings into quantitative estimates monetizing the potential impacts associated with different sized space weather storms including both a "moderate" and more "extreme" event. Analyzing two different sized events is an essential first step towards better understanding how impacts may change as storm size escalates. Examining "moderate" events that are lower in intensity but occur more frequently helps establish key thresholds above which notable impacts are expected based on empirical insights from sector and stakeholder experiences, including past-events where impacts were observed and impact thresholds were therefore exceeded (e.g. the March 1989 event [*Allen*, 1989] and the 2003 Halloween Storm [*Lopez et al.*, 2004]. Since impact thresholds may increase or decrease alongside changes in technologies, policies, and societal processes, studying the impacts of "moderate" events is also essential for anticipating how impacts may change in the future. The impacts of "moderate" events may also seem small when considered in isolation and/or when compared to more "extreme" event scenarios. However, since they occur more frequently, they may nonetheless add up and be significant over time. Considering more "extreme" events that are higher in intensity but occur less frequently is important for exploring more devastating and costly scenarios. To analyze a more "extreme" event, we considered both scientific and engineering expertise within each technological sector and different working definitions for "extreme" events such as the 1-in-100 year storm parameters set by the U.S. SWAP Phase I Benchmarks [*Executive Office of the President,* 2017] and "reasonable worst-case events" established by efforts in the United Kingdom (UK) [*Cannon et al.,* 2013; *Hapgood et al.,* 2016]. It is important to note that our "extreme" estimates do not necessarily reflect a Carrington-like event or the theoretical maximum level event. This topic was beyond the scope of our project since there is no scientific consensus on how large the Carrington event was or how big of an event is even possible. It is also important to note that there are inconsistencies (e.g. different event durations) with our space weather event scenarios for moderate and extreme events between sectors. This results from our approach that considers impacts on a sector by sector basis and captures stakeholder perspectives from different industries. Such inconsistences are not necessarily problematic but they should be further scrutinized and resolved with future efforts. Although we anticipate strong interest in our cost estimates, we emphasize that our numbers represent first pass estimates that should not be taken out of context or quoted without the appropriate caveats since they need to be critically reviewed and refined with future efforts. We therefore urge the reader to consider the qualitative information that we synthesize and the quantitative framework that we establish to be equally informative and perhaps the more substantive contribution of our effort.

The following sections include an overview of the study methodology and framework (Chapter 2) followed by the findings for the four technology sectors (Chapters 3 – 6). Specifically, the sector chapters are organized into impact mechanisms, stakeholder perspectives, and cost estimates. Each sector chapter begins with the impact mechanisms, which outlines the major causal pathways from solar events to physical effects and then to societal impacts. The stakeholder perspectives provide an overview of our outreach findings and also more detailed notes. The cost estimates provide a tractable description of our quantification approach, including how we used key insights and assumptions from additional stakeholder outreach to build these estimates for both moderate and more extreme storm scenarios. Finally, Chapters 7 and 8 provide a summary of key findings and recommended next steps.

The cost estimates provided in this report represent a first pass, and should not be taken out of context or quoted without appropriate caveats since they need to be critically reviewed and refined with future efforts. Readers are urged to consider the qualitative information synthesized from stakeholder outreach and peer reviewed sources and the quantitative framework established from this information as the more important contribution of this effort.

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2. Approach

> ***The impact of space weather is a formidable research problem at the intersection of science, engineering, economics, and the social sciences.***

This study began with an extensive literature review; however, similar to a concurrent and recently published study, we also found a limited number of previous studies on the social and economic impacts of space weather [*Eastwood et al.*, 2017]. We also quickly recognized that this topic represented a formidable research problem at the intersection of science, engineering, economics, and the social sciences [*Baker*, 2009]. For example, modern society's fortunate lack of direct experience of "extreme" events, and either limited or rather largely undocumented/unshared experiences of "moderate" events, pose a number of theoretical and analytical challenges that require many assumptions, simplifications, extrapolations, and inferences. In addition, there is no standard definition nor scientific agreement on what constitutes either an "extreme" [e.g. *Executive Office of the President*, 2017] or "moderate" event, and when studying impacts, will furthermore be dependent on and relative to the specific technology and impact pathway of interest [e.g. *Cannon et al.,* 2013; *Hapgood et al.,* 2016]. The response of various technologies (e.g. power grid, satellites, airplanes, GNSS) to "extreme" events is furthermore largely unknown since they fall beyond engineering standards and operational experiences. Although the response of different technologies to "moderate" events may be relatively better understood, such information is often not readily available since publically disclosing potential vulnerabilities can be devastating for businesses. Moreover, impacts are not simply directly proportional to event sizes but are also affected by a number of other important factors like geography, the time of day, or season of the year which, for example, affect the demand on the electric power grid [e.g. *Forbes and St. Cyr*, 2012]. Further complications arise from economic and social processes that are complex, interconnected, and rapidly evolving. These early study findings therefore shaped our approach, in which we aimed to develop a comprehensive and coherent framework in order to help this become a more tractable research problem that others across industries, institutions, and disciplines can build off and contribute their knowledge and expertise to.

Our review of existing information included findings of peer-reviewed literature, government reports, industry organizations, and other publically available documents. Given the lack of previous impact studies, we focused our efforts on dissecting the far more extensive scientific and engineering literature addressing the **physical effects** of space weather across our four focal sectors (electric power, satellites, GNSS users, and aviation) [see *Baker and Lanzerotti*, 2016 for a recent and comprehensive overview]. Although effects and impacts are often used interchangeably, here we consider physical effects to be fundamentally different than impacts in the sense that the former represents effects on systems or system performance caused by natural phenomenon and processes. Effects are what, if not appropriately addressed by design and engineering decisions or managed with operator actions, will ultimately cause **impacts** (in the case of space weather, negative consequences) and therefore represent different potential impact mechanisms and pathways. Focusing on physical effects furthermore helped us establish a technically sound link between space weather events and their downstream social and economic impacts on a sector by sector basis. Although not widely studied, we found that the impacts of space weather are somewhat well documented in historic accounts of notable space weather events [*Allen et al.,* 1989; *Lopez et al.,* 2004] and also often highlighted in technical work as a research motivation. To synthesize our findings for each sector, we established a discrete list that included 17 known physical effects across the four sectors (Table 1). We also constructed **impact mechanism diagrams** for each sector that outline the major causal pathways from solar events to physical effects and then impacts. These diagrams represent a first attempt to help simplify many of the complexities surrounding this interdisciplinary problem, allowing for a clear illustration of key processes and relationships. They should be refined and vetted with additional input from stakeholders and experts.

Table 1. The physical effects of space weather on different technological sectors, as identified and defined in the report, include a range of natural processes and phenomenon that are relatively well studied by scientists and engineers. If these physical effects (defined and discussed throughout the remainder of report) are not appropriately addressed by design and engineering decisions or managed with operator actions, they will ultimately cause impacts ("negative consequences") and therefore represent different potential impact mechanisms and pathways. Impacts caused by these effects can furthermore be organized into different impact categories (see Figure 1 and Table 2).

Technological Sector			
Electric Power	**Satellites**	**GNSS Users**	**Aviation**
• Reactive Power Consumption • Transformer Heating • Improper Operation of Protective Relaying Equipment • Real Power Imbalances • Generator Tripping • Loss of Precision Timing	• Loss of Altitude • Link Disruptions • Anomalies • Cumulative Dosage	• Ranging Errors • Loss of Lock	• Communication Degradation • Navigation Degradation • Avionic Upsets • Effective Dose

After noting a wide range of socioeconomic impacts from the literature, we organized our analysis by creating five broad but interrelated **impact categories** (see Figure 1 and Table 2 for more details). Our first category, *Defensive Investments*, captures expenditures that help protect technologies against potential vulnerabilities such as on engineering designs or on situational awareness. *Mitigating Actions* covers real-time decisions made by system operators to reduce the consequences of an event that is anticipated or underway. *Asset Damages* refers to any physical damage to sector equipment that may result either suddenly ("acute") or slowly over time ("chronic"). *Service Interruptions* addresses impacts seen by end users of technologies such as changes in provision, quality, and/or pricing. The final impact category is *Health Effects*, which covers any direct potential hazard to human well-being or life such as from elevated radiation. Focusing on direct health effects from events in this last category does not include any of the health effects that would result indirectly via our other impact categories (e.g. health effects from an extended power outage would be captured under Service Interruptions). In addition to showing how these different categories relate to one another, Figure 1 also shows the different types of space weather products and services, such as those provided by NOAA's Space Weather Prediction Center (SWPC), that can add value to society by lessening these impacts. Note that the first two of these impact categories capture *proactive* approaches to managing space weather impacts whereas the last three capture the impacts that could be *realized* in the advent that such *proactive* strategies are insufficient for absorbing the full magnitude of the event. Although a rigorous consideration of how the impacts categories are interrelated is beyond the scope of this current body of work, it is important to note that there are costs associated with all of these impact categories and this is apt to represent an optimization problem in which one must consider the costs, benefits, and trade-offs associated with each.

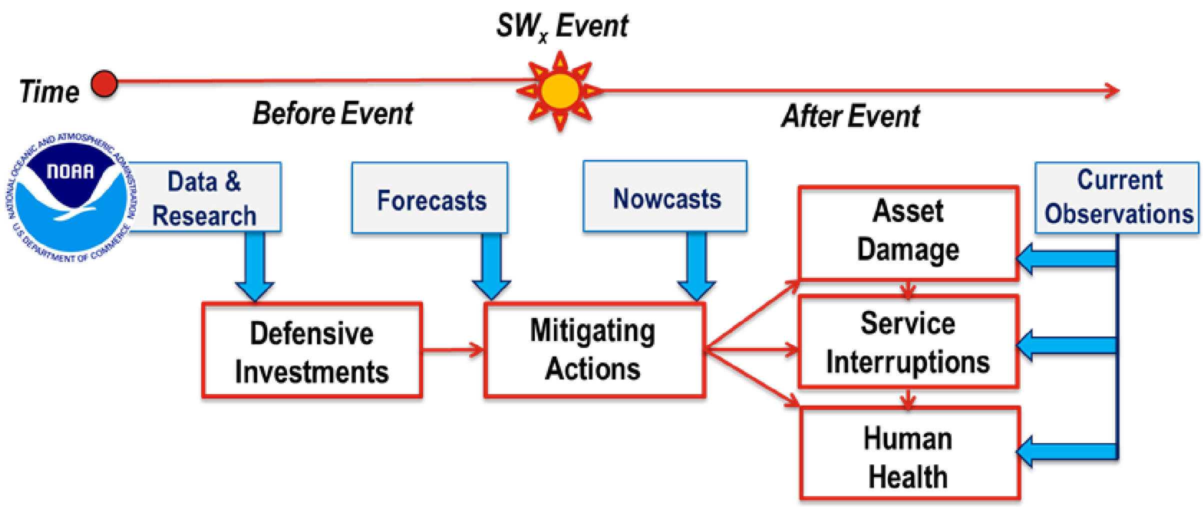

Figure 1. The range of potential economic and societal impacts of space weather to different technological sectors can be organized into five different but interrelated categories (red boxes). A range of space weather products and services, such as those offered by NOAA's SWPC (blue boxes), are valuable at different points in time and have the potential to reduce specific types of impacts.

We then conducted an initial round of stakeholder outreach to better understand these physical effects and the different categories of impacts associated with each. Although we use the word stakeholder generally to describe any individual with relevant knowledge from industry, government, or academics, our outreach was aimed most directly at engineers and operators working within our different focal sectors. We used a Delphi-like approach [*Helmer*, 1967] to solicit feedback on our literature review findings (e.g. physical effects and example impacts organized by impact category) from more than 30 stakeholders of diverse expertise. To facilitate these conversations, we constructed a simple matrix for each sector that connected our identified physical effects to our five different impact categories (for additional details, see sections on *Stakeholder Perspective on Impacts* within different chapters of this report). These matrices were initially populated with specific examples culled from the literature, shown to stakeholders for reactions and thoughts, and then expanded or revised based on information they provided. An updated matrix was iteratively shown to subsequent stakeholders so the next stakeholder could offer critical input on our current understanding and fill in any remaining gaps. We iterated this process until further input yielded few substantive changes but also took advantage of any additional opportunities to further discuss our matrices with other stakeholders even after they had solidified. Iterating this process allowed us to: (1) refine our list and descriptions of the physical effects; (2) gauge the relative frequency and severity of their occurrence, including information on impact thresholds; (3) identify likely future trends due to changing technologies, policies, and/or economics; (4) recognize consensus or disagreement between stakeholders; (5) contextualize space weather with other sector hazards; (6) gain insights on how the impacts may change as storm size escalates from "moderate" to "extreme"; and (7) understand how current applications of space weather information reduce sector vulnerabilities. We took detailed notes on each conversation but given that this can be a sensitive and largely private subject within various industries, our notes are organized and reported generally in tables and throughout this document without attribution to particular individuals.

Table 2. Definitions of the five impact categories created to organize the vast number and wide range of potential social and economic impacts that could potentially result from space weather events across different technological sectors. Descriptions also address how the different categories may relate to one another and where space weather products and services, such as those provided by NOAA's Space Weather Prediction Center, can add value by lessening these impacts. These impacts are presented in chronological order in relationship to a particular space weather event (see Figure 1 for additional information).

Impact Category	Definition
Defensive Investments	This impact category captures expenditures made in advance of any particular space weather event that help protect technological systems against potential impacts of an event. In general, such investments tend to be capital intensive and are therefore financially justifiable if they help make systems more robust to "all-hazards" as well (e.g. severe weather, earthquakes, floods, terrorism, etc.). Examples include the devotion of resources to engineering at both the component and system level, to enhancing real-time situational awareness, and to developing plans and operational procedures for different space weather scenarios. Space weather products and services, such as those provided by NOAA's Space Weather Prediction Center (SWPC) add value to different sectors by providing scientific information necessary to properly understand their risks and vulnerabilities.
Mitigating Actions	This refers to the undertaking of a specific action or suite of actions in preparation for an anticipated space weather event or in response to one that is underway in order to reduce or limit potential impacts. The ability to mitigate requires timely and accurate information about the space weather environment and operators must further be able to understand and act upon it. The mitigating actions enacted by operators involve different levels of resources/costs and may or may not impact the services they provide. Space weather products and services add value to different sectors by providing a range of information about the space weather environment that offer different lead times (e.g. forecasts, warnings, alerts, now casts) for different types of events (e.g. geomagnetic storms, radiation storms, and radio blackouts).
Asset Damages	This impact category refers to any degree of physical damage to sector assets that may result from space weather either suddenly ("acute") or slowly over time ("chronic"). Examples of acute damage include partial or complete destruction of an asset that may cause it to become temporarily or permanently inoperable. Acute damage may in turn lead to Service Interruptions if it is widespread or if it occurs to assets that are unique or else critically located. Chronic damage represents additional wear and tear on assets that accelerate their aging and reduce their lifespan. Chronic damage represents operational or maintenance costs to a sector as parts then have to be fixed or replaced more frequently. Space weather products and services, such as those provided by NOAA's SWPC add value to different sectors by providing the scientific information necessary to conduct post-event analysis. Better understanding what caused a specific incident of asset damage can feed into various Defensive Investments (e.g. design and engineering or situational awareness) that help reduce future losses. Asset Damages caused to any downstream industry, due to Service Interruptions of the directly impacted sector, would be covered in the following category.
Service Interruptions	This category captures the range of potential impacts seen by the end users of the services provided by a sector such as adverse changes in the quality, price, or provision. In general, Service Interruptions have direct economic consequences to service providers within each sector either by harming their reputation or due to losses in revenue during service outages. There are also economic and societal impacts on end users that vary depending on how the disturbance propagates and trickles through different businesses. It is through Service Interruptions that the sectors studied in this report are coupled to each other and to wider society. SWPC products and services add value to different sectors by allowing service providers within different sectors to better communicate with their clients about the potential and probability for Service Interruptions so they can be informed of potential threats to their businesses and have more options available to them. Also, there can be indirect impacts to upstream and downstream businesses due to Service Interruptions with the directly impacted sector.
Health Effects	This addresses direct health hazards such as radiation exposure and therefore is most applicable to humans flying at airplane altitudes at the time of a space weather event. Astronauts in space during severe space weather are also at great risk. The medical research linking aviation related exposure and adverse human health risks is tenuous but if established would imply economic impacts such as direct treatment costs (e.g., hospital bills), the costs of pain and suffering, the costs of lost life-years, and lost earnings. Space weather products and services, such as those provided by NOAA's SWPC add value through the provision of scientific information that can be used to study and explore these potential linkages and by providing information about potential exposure environment so airlines, aircrew, and astronauts can be precautionary and track their total exposure or take actions to reduce their exposure.

This initial round of stakeholder outreach allowed us to gather key insights and information that we then used to begin developing cost estimates for both our "moderate" and more "extreme" event scenarios. However, to ensure that we correctly understood and carefully interpreted these conversations and the various highly technical issues embedded within this topic, we continued to interact with these stakeholders intermittently and more informally as we proceeded with our research (e.g. quick emails, impromptu calls, in person meetings). This additional outreach helped us better understand the (1) key physical effects of concern for each sector, (2) most relevant impact category(s) and plausible impacts, (3) assumptions, nuances, and caveats surrounding these effects and their potential impacts, and (4) available information and data. Since estimating the total costs associated with both a "moderate" and more "extreme" event would involve considering impacts stemming from our 17 different physical effects across four sectors and all five social and economic impact categories, we needed to establish priorities for our quantitative effort. We decided to develop cost estimates most reflective of stakeholder concerns and for the impact categories that were also apt to reflect the largest potential impacts. Where possible (all sectors except GNSS users), we also tried to establish cost estimates for one of our *proactive* impact categories (either defensive investments or mitigation actions) and also one for our *realized* impact categories (asset damages, service interruptions, or health effects). Although tangential to our main study goals, we found it interesting and insightful to consider the different potential costs associated with these different approaches to managing space weather impacts.

Stakeholders were very vocal about the challenges associated with trying to develop potential cost estimates and cautioned us about the many complexities and large uncertainties involved. Although we began our effort wanting to model the impacts of space weather, we simply could not justify such an approach since the stakeholders we spoke to emphasized how it is intractable at this point in time to rigorously connect the magnitude of a space weather event to our list of physical effects and ultimately to the types and sizes of the impacts that may result. Recognizing the importance and need to develop a better quantitative understanding of this topic, many of our stakeholders expressed their willingness to help guide our effort as their availability allowed (which in quite a few instances involved weekend emails and phone calls). In their opinion, it was essential to capture and codify certain industry realities and nuances that are essential to this problem. We therefore opted to formulate cost estimates that capture and translate stakeholder insights on key aspects of this research problem into logical and quantitative statements. This involved, for example, initial discussions about what is reasonable to expect under "moderate" compared to more "extreme" space weather conditions. After further researching and considering such input, we put together initial equations with numbers and then shared them with our stakeholders. In addition to receiving feedback, this allowed us to obtain additional stakeholder insights including their gut reactions to assumptions we made and their best guesses to help constrain key variables even if they could only provide order of magnitudes or rough ranges. Our approach allowed us to establish a robust and novel understanding for what needs to be known in order to quantify space weather impacts and where the outstanding knowledge gaps lay. Proposing transparent, tractable cost estimates that are easy to follow and reproduce is additionally advantageous as it will allow others to readily critique, question, and improve our initial effort. It also provides flexibility, enabling our cost estimates to be updated as technologies and our societies evolve and additional knowledge is acquired. To clearly emphasize the large uncertainties surrounding the cost estimates presented herein, many of which were derived using placeholder numbers and all of which should be critically and widely reviewed, we provide lower and upper range estimates and also round all final estimates to one significant figure.

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3. Electric Power

3.1 Impact Mechanisms

A space weather event can produce Geomagnetically Induced Currents (GICs) that may be transmitted by effective conductors on the Earth's surface such as the electric-power grid. When GICs enter the power grid, they act as direct current (DC) sources that flow alongside the normal alternating currents (AC) produced at power plants and transferred along power lines to electrical substations. Basic incompatibilities between DC and AC currents may interfere with the normal functioning and performance of Extra High Voltage (EHV) transformers. The interaction of GICs with these transformers can result in a number of physical effects that, if sufficiently large and not properly managed, may adversely impact the power system [*Cannon et al.*, 2013; *Pulkkinen et al.,* 2017]. For example, GIC-transformer interactions can increase **reactive power consumption** [*Tay and Swift*, 1985; *Price,* 2002], contributing to voltage instabilities and potentially leading to power outages. They can also generate harmonics that can disconnect parts of the grid by causing the **improper operation of protective relay equipment** (e.g. static compensators) [e.g. *Bolduc,* 2002; *Pulkkinen et al.,* 2005] and/or the **tripping offline of generators** [e.g. *Rezaei-Zare and Marti,* 2013]. It is important to note that this impact pathway is the only one that has to-date been known to trigger space weather-related blackouts. Specifically, it was the underlying cause of the 1989 Hydro-Québec outage [*Bolduc,* 2002] and the Swedish outage during the 2003 Halloween storm [*Pulkkinen et al.,* 2005]. GIC-related degradations in transformer performance may also challenge electric power reliability as suggested by statistically significant empirical correlations between **real power imbalances** and GIC data [*Forbes and St. Cyr,* 2010; 2012]. And lastly, GIC-transformer interactions can cause **transformer heating** and if sustained over a sufficient period of time (e.g. tens of minutes) may become problematic (e.g. hot-spot heating). This physical effect can in turn lead to various degrees of transformer damage from incremental degradation of transformer components [*Tay and Swift*, 1985; *Gaunt and Coetzee,* 2007] to more severe physical damage, such as the melting of copper windings, that may require repairs or removal from service [e.g. *Kappenman,* 2010]. Space weather impacts on GNSS users, covered in a later chapter of this report, may also be consequential to the power grid. GNSS/GPS **precision timing** enables key components of the grid to be synchronized (e.g. generation, transmission, and distribution) and if interrupted during a space weather event, may become problematic.

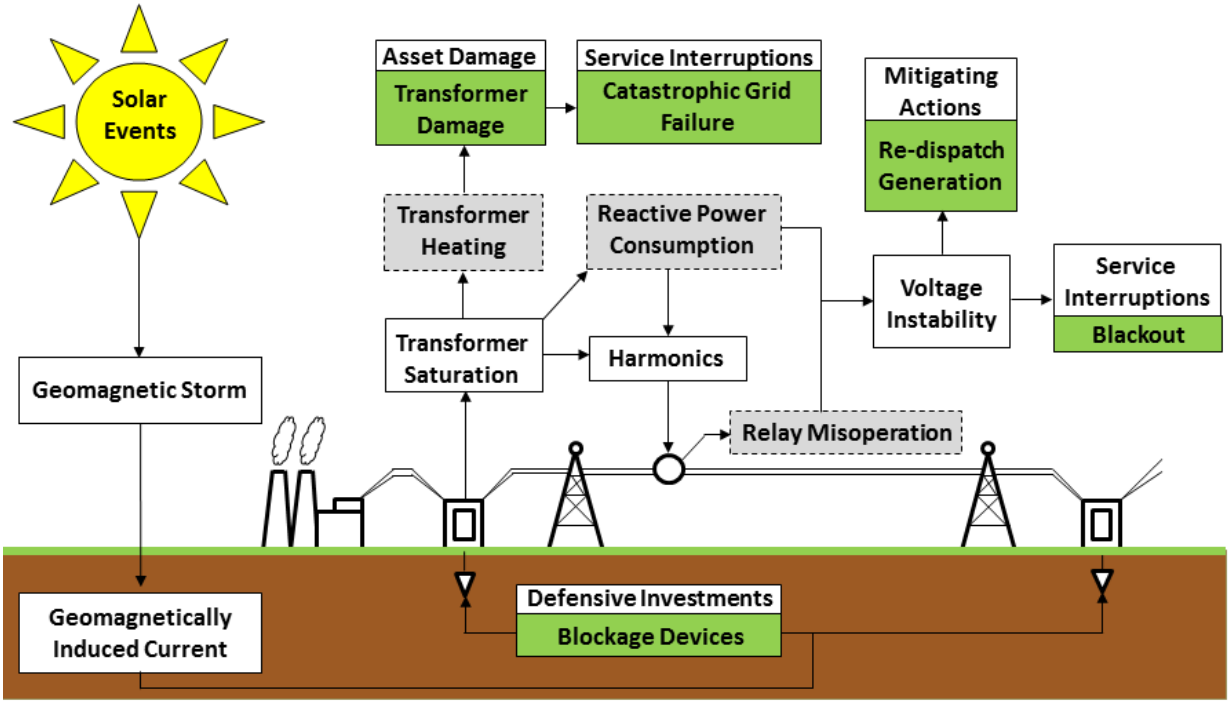

Figure 2. Impact mechanism diagram for electric power outlining the primary causal pathways from a solar event to physical effects (grey boxes) that can in turn cause a variety of social and economic impacts (green boxes). Note that our illustration depicted is not to scale, not comprehensive, and should be revised with future input from stakeholders to ensure it captures largest potential concerns.

3.2 Stakeholder Perspective on Impacts

Our first phase of stakeholder outreach involved hour long phone calls with six individuals working within the power industry. As previously described (Approach), we used our power sector impact matrix to guide these conversations and to systematically collect stakeholder input on the various physical effects of space weather and the types of impacts caused by each. Our final impact matrix is presented below (Table 3) along with additional and important insights from these conversations, including definitions and notes on the various physical effects (Table 4) and impacts (Table 5). The text that follows provides a high-level overview of our most important findings.

Of the various known physical effects of space weather on the power grid (Table 4), stakeholders all agreed that reactive power consumption is by far the most concerning. It is of particularly high concern because it represents a network threat that has the potential to, within less than one minute, lead to voltage collapse and system instability. Stakeholders noted that the U.S. power industry now widely and formally recognizes this threat, as evidenced by the National Energy Regulatory Commission (NERC) Emergency Preparedness and Operations (EOP) standard, EOP-010-1, which became effective in April 2015. In order to enhance electric reliability, reliability coordinators and transmission operators report that they are now required by law to have contingency procedures for mitigating the effects of geomagnetic disturbances (GMD). Stakeholders report that these contingency procedures encompass a broad range of Mitigating Actions. They were able to offer some examples of what such procedure might entail (e.g. reducing transmission flows, redispatching generation, and/or reconfiguring network topology) but stressed that actual contingency procedure that might be enacted during any particular GMD event would vary from operator-to-operator and inevitably depend on many real-time power system details. It was further noted, however, that most if not all of the Mitigating Actions that might be enacted during a space weather event are routinely enacted for other non-space weather reasons (e.g. terrestrial weather) so their costs, while potentially significant on a per event basis, may be relatively small in the context of their annualized operational costs.

Stakeholders noted that if such procedures are not enacted or are unable to boost reactive power to a sufficient level, far more costly wide-area blackouts could in theory result. Recovering the power system from such an occurrence might in turn take the industry ~6 to 9 hours, representing the time required to coordinate and synchronize the large number of individual system components. The industry stakeholders that we talked to also expressed less concern about transformer heating leading to damage (i.e. over-heating) which was the focus of early social and economic impact assessments. Although this impact pathway underpins such early scenarios envisioning catastrophic transformer damage that causes prolonged power outages (e.g. months to years) [*Kappenman,* 2010], stakeholders noted that this physical effect is only worrisome if it is substantial and sustained. It is currently thought that reactive power consumption will quickly disconnect these transformers, cutting off the heating source that could potentially cause damage. In 2016, FERC mandated (TPL-007-1) that infrastructure owners conduct rigorous analyses in order to better understand how vulnerable our nation's transformers may be to a severe, 1-in-100 years GMD benchmark event. Stakeholders report that these analyses will ultimately support decisions about what Defensive Investments (e.g. blocking capacitors, replacement transformers, etc.) the industry needs to make to increase reliability by hardening their infrastructure and assets against this benchmark event. They furthermore communicated that this mandate will likely impose one-time costs that are more substantial than the costs imposed by EOP-010-1.

Table 3. Impact matrix populated during stakeholder outreach to better understand how the well-studied physical effects of space weather on electric power can cause different types of Social and Economic Impacts. Items in matrix reflect example impacts for moderate (normal text) and extreme (italic text) storms. Question marks denote instances where the physical effect may in theory be able to cause this impact but empirical support is lacking. *Additional details pertaining to a select set of these impacts can be found in Table 5.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damage	Service Interruptions	Health Effects
Reactive Power Consumption	•Infrastructure hardening* •Situational awareness & Preparedness*	•Reduce transmission flows •Redispatch generation •Network reconfiguration •*Emergency procedures**		•Degradation in power quality* •Price fluctuations •*Blackouts?*	
Transformer Heating	•Infrastructure hardening* •Situational awareness & Preparedness* •*Spare transformers*	•Reduce transmission flows •Redispatch generation •Network reconfiguration •*Emergency procedures**	•Transformer aging •Partial damage •*Transformer Failure*	•Price fluctuations •*Blackouts?* •*Catastrophic grid failure*	
Improper Operation of Protective Relaying Equipment	•Infrastructure hardening* •Situational awareness & Preparedness*	•Reduce transmission flows •Redispatch generation •Network reconfiguration •*Emergency procedures**	•Damaged equipment	•*Blackouts**	
Real Power Imbalances		•Reduce transmission flows •Redispatch generation •Network reconfiguration •*Emergency procedures**		•Degradation in power quality •Price fluctuations •*Blackouts?*	
Generator Tripping	•Infrastructure hardening*	•Protective relay settings		•Loss of generation	
Loss of Precision Timing	•Backup technologies				

Table 4. Space weather can cause a variety of physical effects to the power grid. These physical effects, defined below, are relatively well-studied in the scientific and engineering literature. These physical effects were discussed with industry stakeholders in order to better understand their potential for causing different types of social and economic impacts.

Physical Effects	Definition	Notes from Stakeholder Outreach
Reactive Power Consumption	Reduction in amount of reactive power flowing through grid due to the increased consumption of reactive power by transformers.	• This is problematic because it depresses the system voltage and may lead to voltage collapse. It occurs at transformers but is a grid-scale threat. • Voltages are controlled within tight bands. When system gets to ~10-20% of normal voltage, this triggers a concern for blackouts. • Reactive power does not like to travel so highest vulnerability in areas farthest away from generation and highest loads. Managing reactive power issue may be most challenging in the spring and fall, where generation is modest but there are economic incentives for moving electricity long distances. • Increasing problem as we rely on higher voltage power lines (long distance transfers). Relying more heavily on local generation can help mitigate, but trend is for it to be shut down in favor of long distance transfers. Certain renewables (e.g. Solar), which tend to be local and more distributed, may be helpful for these reasons.
Transformer Heating	Substantial heating of internal transformer components that can cause accelerated asset aging and perhaps even transformer damage.	• Probability of damage depends on design, age, use history, etc. NERC's recently approved threshold based on potential transformer heating is 75 amps/phase. Transformers can take more than this but this is the trigger to pay attention. The relationship between heating and damage is transformer specific so FERC standard is conservative in order to cover potential differences across nation in transformer designs. • Certain stakeholders expressed dissatisfaction with early economic analyses and feel the potential for failure is overstated. Before failure occurs, it is likely that transformers will be disconnected. This negative feedback could cause a blackout that may also protect against catastrophic failures. Utility perspective on probability of transformer damage will be known when studies related to TPL-007-1 are complete, in ~2 to 4 years from now (2017). • Transformer overheating may have implications for real-power imbalances too.
Improper Operation of Protective Relaying Equipment	Improper functioning of relay systems that are designed to protect grid by detecting electrical aberrations (e.g. faults, surges, over/under voltages) and then isolating the impacted area from the rest of the network.	• Infrequently observed but it does happen and when it does, the cause is not clear. It will likely be attributed to space weather only if they know an event is expected or underway. • Older relays generally more susceptible to harmonics, modern relays less so. • Most often trip capacitors banks offline. This increases reactive power losses, depressing system voltage and introduces blackout threat. This is what triggered the 1989 Quebec blackout and the outage in Sweden during the Halloween 2003 storm.
Real Power Imbalances	Difference in real-time supply and demand for power that must be managed by operators to maintain grid stability.	• Caused by many things in addition to space weather such as hot weather, etc. • Industry is aware of statistical relationship but unclear about physical basis. Degradation in transformer performance may cause issue (via generation control errors and high voltage electricity flows) or may result due to operator actions.
Generator Tripping	Space weather related harmonics can also send erroneous commands to generators, tripping them offline.	• One stakeholder brought this to our attention, a more niche topic compared to other physical effects but is nonetheless an important additional issue.
Loss of Precision Timing	Loss of satellite enabled technology that provides precise timing information that is used to improve grid synchronization.	• When satellite signals are lost, substation clocks will continue to operate and remain accurate for several hours. • Not clear how space weather threat compares to spoofing threat but addressing spoofing concerns makes grid less vulnerable to space weather interruptions. The spoofing threat has been well studied by the industry and they find the threat to be small. • This could become more problematic in the future if we over rely on these systems. • Dependence on precision timing may be bigger trend in U.S. power sector than abroad. Other countries are required to maintain traditional timing devices at substations.

Table 5. Additional details on a select set of space weather impacts identified and organized in our impact matrix (Table 3).

Impact Category	Examples	Definition	Notes from Stakeholder Outreach
Defensive Investments	Infrastructure hardening	A range of engineering and design modifications that reduce grid vulnerability such as installing GIC absorbing or blocking devices (e.g. neutral ground connections, series line capacitors) or replacing aging or vulnerable transformers.	• Understanding what to do requires many analyses. Installing a blocking device, for example, can reroute current in unexpected and devastating ways. • This is the subject of the new FERC regulations. The types of investments that need to be made are understood but unclear how widely or where they will be required.
	Situational Awareness & Preparedness	Utilizing a range of data and tools to stay aware of current and anticipated future conditions. Data and products can come from the government (e.g. NOAA's Space Weather Prediction Center), GIC monitoring networks (e.g. magnetometers, internal-instruments within transformers) or transformer monitors and be fed into grid simulators and management systems. This information can then be used to inform what operational procedures should be enacted as various situations arise.	• This Defensive Investment is critical to being able to implement real-time Mitigating Actions. • Operators have training to prevent key downstream impacts but they need to be made aware of the situation, day ahead space weather warnings are most important. • Operators monitor space weather products and pay extra attention to own data when they receive alerts at the upper end of scales (K7 or greater). • Diagnostic equipment is being installed on transformers in order to optimize maintenance cycle. Although not installed for space weather events per say, it will allow any transformer heating to be rapidly assessed.
Mitigating Actions	Redispatch Generation	Deciding to utilize generators that will enhance grid stability rather than those that will maximize profits.	• Relatively low cost action. One stakeholder mentioned that one space weather event may cost ~$1s million but redispatching costs them ~$100s million per year. • This is a relatively easy action for operators and almost always impacts the price of electricity.
	Emergency Procedures	A set of operating procedures that can be enacted in extreme cases and might include, for example, generator or equipment curtailment, voltage reductions, and load shedding as a last resort.	• Different grid operators have different sets of emergency procedures and different triggers for enacting them in place.
Asset Damages	Transformer Aging	Accelerated aging of transformer caused, for example, by degradation and gas generation within insulation materials.	• Logic of argument makes sense but the empirical data is not significant enough for industry to believe that moderate events "add up" and, among all else, play a big role in transformer aging. • Data currently being compiled by industry and academics is essential for better resolving this issue.
	Transformer Failure	Any damage to a transformer that renders it permanently inoperable and cannot be repaired and so requires a replacement transformer.	• Probability and extent of damage requires long GIC durations and scale with duration of GIC. • Most likely to happen to older transformer that are near the end of their lifetime.
Service Interruptions	Blackouts	Loss of power to electricity users.	• Storms have to be particularly extreme for this to happen (K8 or K9). NOAA scales need refinement to better discriminate between large events. • More permanent loss of service that would result if a large number or certain critical transformers permanently fail, but probability of this occurring is thought to be very low. • Costs of outages depend on where and when an outage occurs, something that is almost impossible to know in advance of an event occur.

3.3 Cost Estimates

In order to translate our findings into quantitative cost estimates that capture the most concerning and potentially largest impacts, we conducted a second round of stakeholder outreach. After discussing the various possibilities and better understanding some of the challenges inherent to quantifying many of the impacts we identified (Table 3), we ultimately decided to develop power sector cost estimates for (1) Defensive Investments (~$50 million to ~$1 billion) and (2) Service Interruptions (~$400 million to ~$10 billion for a moderate event and ~$1 billion to ~$20 billion for more extreme conditions respectively). Our cost estimate for Defensive Investments focuses on the potential financial impacts of hardening the grid to comply with NERC's recently enacted, TPL-007-1 standard. Our cost estimate for Service Interruptions explores the potential impacts to the end users of electricity from potential power outages. Our quantification process involved an iterative series of discussions with particularly helpful and committed stakeholders, combined with quantitative analyses based on the Value of Lost Load [*London Economic International LLC,* 2013]. Key insights gleaned from these conversations are provided below alongside a description of how they influenced the derivation of our cost estimates.

Table 6. Simplified impact matrix with the focus of our quantitative analysis highlighted in yellow. The presence (or absence) of a circle denotes where we were able to connect a given physical effect to a particular impact category based on outreach (see Table 3 to better understand items these circles represent). Black circles denote that a physical effect is known, from direct past experience, to cause a particular category of societal impact. Open circles indicate that a given physical effect may cause a particular category of societal impact but lacks empirical support.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damages	Service Interruptions	Health Effects
Reactive Power Consumption	●	●		○	
Transformer Heating	●	●	●	○	
Improper Operation of Protective Relaying Equipment	●	●	●	●	
Real Power Imbalances		●		○	
Generator Tripping	●			●	
Loss of Precision Timing	●			○	

3.3.1 Defensive Investments

We estimate that the one-time cost of hardening the U.S. power grid against potential space weather impacts may be ~$50 million to ~$1 billion. This estimate focuses on NERC's recently approved TPL-007-1 standard requiring that our national power infrastructure be capable of withstanding a benchmark GMD event. In order to achieve this goal, TPL-007-1 (approved by FERC on September 22, 2016) requires infrastructure owners to analyze and then address the vulnerabilities of their system to NERC's established benchmark. Stakeholders report that these analyses are just beginning and it will be ~2 to 4 years until they have their results. Although they already understand the available design and engineering options for addressing potential issues such analyses uncover, they do not yet know where or how extensively they will need to implement such measures. Our cost estimate presented below therefore aims to incorporate present industry perspectives on this topic and should be revisited as more information is acquired.

We base our estimate on (1) the type and number of industry assets that may be vulnerable to NERC's benchmark event and therefore may require hardening and (2) lower and upper boundaries on potential asset hardening costs. Although many specifics are lacking, such as where or how extensively hardening measures will need to be implemented, it is Extra-High Voltage (EHV) (e.g. 765-345 kV) transformers that are currently of the largest concern. Stakeholders note, however, that assets with voltages down to 220 kV are also undergoing assessment. In addition to well-established and studied vulnerabilities of these assets to space weather events, EHV transformers range in price from ~$4.5 million to ~$7.5 million (*NERC,* 2011) and therefore also represent one of the most expensive infrastructural components. At this point in time, stakeholders therefore think that EHV transformers will constitute the majority of all TPL-007-1 related hardening costs (as opposed to Corrective Action Plans (CAPs) that address operational procedures or Mitigating Actions). Although stakeholders were able to point us to various documents containing general information about the U.S.'s fleet of ~2,000 EHV transformers [*DOE,* 2014], they were quite hesitant to even venture a guess as to how many of these transformers might be vulnerable. They emphasized the complexity of the issue and why providing even rough numbers is hard in advance of them finishing their rigorous analysis. Specifically, vulnerability depends on many factors including transformer design, location, age, use history, network typology, and current system load. Most stakeholders further shared a similar hunch that the recently started studies will ultimately find a small number of vulnerable assets. A few were willing to go out on a limb and speculate that maybe ~1 to 10% of the total U.S. fleet, equating to ~20 to 200 EHV transformers, might be found vulnerable to NERC's benchmark event. Although we were unable to find readily available data on many of the important variables to further explore what stakeholders already know about variations in vulnerability (e.g. vulnerability may be largest in transformers near the system edges or nearing the end of their operational lifetimes), stakeholders were able to offer some rough numbers on transformer design: ~85% (or 1700) of all EHV transformer might be single-phase transformers with the remaining ~15% (or 300) being three-phase transformers. Noting that single-phase transformers are in general more vulnerable than three-phase transformers, we assign the lower portion of the potential vulnerability range (~1 to 10% of the total U.S. fleet) to more robust, three-phase transformers (~1 to 5%) and the higher range to more susceptible, single-phase transformers (~6 to 10%). This suggests that in total, ~102 to ~170 single-phase and ~3 to ~15 three-phase EHV transformers may require hardening in order to meet NERC's TPL-007-1 standard (Table 7).

The second part of our estimate considers the wide range of costs that could be associated with hardening these potentially vulnerable transformers. Stakeholders inform us that the least expensive option is usually to install GIC blocking devices which can cost at least ~$500,000 per EHV transformer. If this engineering measure is implemented at all vulnerable transformers, total costs would be ~$50 million to ~$100 million (Table 7). Although relatively inexpensive, stakeholders also noted that blocking devices may not be a universal solution in all locations since their installation typically pushes the GIC, and therefore the problem, elsewhere in the network. Moreover, they are generally disliked across industry because they add complexity to the system that requires additional management and maintenance. Stakeholders also discussed that the most expensive option is to replace vulnerable transformers but noted that such replacements would be warranted because of many additional, non-space weather reasons such as because they are near or have exceeded their design lifetime. If all vulnerable transformers are replaced though, costs to the industry would instead total ~$500 million to ~$1 billion (Table 7). These low and high end-member possibilities suggest a final cost estimate for Defensive Investments of ~$50 million and ~$1 billion. We emphasize that this is a rough estimate that is intended to be illustrative yet informative and should be revisited periodically as TPL-007-1 studies progress.

Table 7. Potential cost estimate of NERC TPL-007-1 standard to harden the U.S. Extra High Voltage (EHV) transmission system against space weather.

Transformer Type[1]	F.O.B Price[1]	Installed Cost[2]	Total Number in U.S.[3]	Number (%) that may require hardening[4]	Cost Estimate	
					Lowest Cost Option (Blocking)	High Cost Option (Replacement)
Single-Phase	~$4.5 m	~$5.7 m	~1700	~102-170 (6 to 10%)	~$50-90 m	~$0.5-1 b
Three-Phase	~$7.5 m	~$9.6 m	~300	~3-15 (1 to 5%)	~$2-8 m	~$30-100 m
Total			~2000	~105-185	~$50-100 m	~$0.5-1 b

[1]Information directly from p. 3 (Table 1) in *NERC*, 2011
[2]Derived from *NERC*, 2011 which notes that taxes, transportation, installation, testing, and other associated expenses which generally add an additional ~25 to 30% to F.O.B. ("Factory on Board") price. We therefore calculate the installed cost by multiplying F.O.B. prices by 1.275.
[3]The U.S. transmission system has ~2,000 EHV transformers (DOE, 2014). Estimates for the number of single- and three-phase transformers was derived based on stakeholder input that they might ~15% and ~85% of entire U.S. fleet respectively.
[4]Based on stakeholder input.
[5]Low cost option assumes that the system will be hardened by installing a blocking device (~$500,000 per transformer) at every vulnerable transformer.
[6]High cost option assumes that the system will be hardened by replaced all vulnerable transformer (e.g. Replacement costs = Installed cost).

3.3.2 Service Interruptions

If a space weather event causes a power outage, we estimate costs to U.S. electricity consumers that may be ~$400 million to ~$10 billion for a moderate event and ~$1 billion to ~$20 billion for a more extreme event. Although this potential impact has to date generated the most concern and attention, stakeholders were relentless in emphasizing the number of significant uncertainties surrounding this issue. Many stressed that there are currently so many unknowns that cost estimates should be carefully caveated. After closely reviewing the technical literature and discussing previous cost estimates with stakeholders [e.g. *Kappenman,* 2010; *Oughton et al.,* 2016; 2017], we better understood the inherent challenges but nonetheless proceeded to construct an estimate that would at the very least complement the existing work by more closely reflecting where the power industry stands on the issue. Constructing a cost estimate, for example, requires making some assertion about which of the various physical effects will cause the power outage. This is necessary in order to make appropriate and realistic statements concerning the likely spatial and temporal scales of the outage which are both first-order controls on costs. Other important assumptions fundamental to assessing the costs of potential outages include the location, time of day, season of year, and the real-time information about the grid (e.g. generation location/sources, load, etc.). Moreover, stakeholders emphasize that the U.S. has not yet directly experienced a space weather related power outage. Our moderate event estimate of ~$400 million to ~$10 billion is therefore based on a hypothetical event that causes protective relays to mis-operate and in turn leads to a power outage that is commensurate in duration and scale with the Quebec 1989 storm. Our extreme event estimate of ~$1 billion to ~$20 billion is based on a series of iterative conversations we had with stakeholders and scientists. We relied on this input to make the best possible assumptions about the most important controlling factors on the potential cost of this impact including, (1) which physical effect might cause the impact (reactive power consumption) and (2) the most likely scale (cascades across energy market) and duration (~9 hours) of the power outage. Note that ~9 hours corresponds to the length of time necessary to recover power once it is lost and assuming no equipment damage. If a space weather event causes a prolonged disturbance or causes extensive equipment damage that delays the recovery effort, the outage could be longer in duration. Note that there is no established protocol to follow when attempting to construct such estimates and the most appropriate methodology to use ultimately depends on the goal of a study. We emphasize that our estimates are intended to illustrate the power industry perspective and therefore complement the few other existing works which, for example, were instead driven by the insurance industry's desire to explore the upper-most catastrophic outages scenario in order to better understand what financial responsibilities might fall under their purview [*Oughton et al.*, 2016].

3.3.2.a. Moderate Event Scenario

We estimate that a moderate space weather event may cost U.S. consumers of electricity ~$400 million to ~$10 billion depending on where within the US it occurs. This estimate assumes a power outage that lasts ~6 hours, reflecting one similar in duration to the one occurring as a result of the Quebec 1989 storm [*Oughton et al.,* 2017]. It reflects two independent estimates that are each based on a different metric describing the scale of this historic outage: (1) The amount of power lost (~14.5 to 19 GW) and (2) the number of customers left without electricity (~6 million) [*Oughton et al.,* 2017]. We chose to develop two independent cost estimates because we were unable to find detailed studies or original references to better understand the scale of this historic outage. Our first estimate is based on the amount of lost power which yields a lower cost estimate of ~$400 million to ~$2 billion, whereas our second estimate based on the number of impacted customers yield a higher estimate of ~$4 billion to ~$10 billion.

For our first estimate, we assume that a moderate space weather event causes a power loss of ~14.5 to 19 GW for ~6 hours so the resulting energy loss totals ~87 to 114 GWh. Multiplying this energy loss by the U.S. national range for the Value of Lost Load (VOLL), $5,000 to $10,000 per MWh (*London Economic International LLC,* 2013), suggests a cost that is ~$400 million to ~$2 billion. Although using the national range for VOLL allows for a tractable and straightforward estimate, the cost of a given duration outage (e.g. 6 hours) varies dramatically with geography since different areas have different customers bases (e.g. commercial, industrial, and residential users). We nonetheless present this simple VOLL-based estimate because it represents a standard and transparent approach for quantifying how electricity customers may be impacted by a power supply interruption of a given duration [*London Economic International LLC,* 2013].

For our second estimate, we instead assume that the event causes ~6 million electricity users to lose power. To explore stakeholder concerns that cost estimates are sensitive to assumptions about where in the nation the outage occurs, we calculated costs estimates for individual states and different regions of the country (Table 8) using state-level data provided by the Energy Information Agency and the Department of Energy's Interruption Cost Estimate (ICE) Calculator (for additional details, see footnotes in Table 8). We found that an outage impacting ~6 million U.S. electricity customers could cost anywhere from ~$4 billion if it occurred in New England to ~$6 billion if it occurred in the West North Central region (Iowa, Kansas, Minnesota, Montana, Nebraska, North Dakota, and South Dakota). Since stakeholders emphasize that it is not possible to know where exactly an outage may occur, we use the full range of U.S. values for a cost estimate for the event that is ~$4 billion to ~$10 billion. At this point in time, we are unable to integrate important but not yet known information about the probability of space weather events causing outage in these different locations. Our estimate therefore only reflects the consequences of an outage (impacts) in these different locations based on the assumption that one occurs. In addition to this geographic variability, these potential Service Interruptions asymmetrically impact different types of electricity users. Across the nation, impacts to commercial and industrial users would range from ~$1 to ~$10 billion whereas impacts to residential users would only be ~$10 to ~$100 million (Figure 4). This key result emphasizes the importance of economic valuation studies that use input-output modeling to explore how these direct impacts on power users can in turn impact ("indirect impacts") upstream and downstream industries [*Oughton et al.*, 2017].

Table 8. Costs of outage that could occur during a moderate event will depend on where it occurs.

Region[1]	States[1]	Total # of Customers (in 2015)[1]	% of Customers Impacted[2]	Cost to Customers
New England	CT, ME, MA, NH, RI, VT	7,224,700	83%	~$4 b
Middle Atlantic	NJ, NY, PA	18,174,969	33%	~$4 b
East North Central	IL, IN, MI, OH, WI	22,310,236	27%	~$4 b
West North Central	IA, KS, MN, MO, NE, ND, SD	10,817,289	55%	~$6 b
South Atlantic	DE, DC, FL, GA, MD, NC, SC, VA, WV	30,532,365	20%	~$4 b
East South Central	AL, KY, MS, TN	9,580,016	63%	~$5 b
West South Central	AR, LA, OK, TX	17,811,548	34%	~$5 b
Mountain	AZ, CO, ID, MT, NV, NM, UT, WY	10,862,155	55%	~$5 b
Pacific Contiguous	CA, OR, WA	20,495,811	29%	~$5 b
Pacific Noncontiguous	AK, HI	823,933	100%	~$2s b
Total		148,633,002	4 %	~$5 b

[1]Information from the 2015 Total Electric Industry Customers, reported in Table 1 by the Energy Information Agency (Summary of data form EIA-861-schedules 4A, 4B, EIA-861S and EIA-861U), available at https://www.eia.gov/electricity/data.php#sales

[2]Percentage of region impacted is calculated by dividing the total number of people assumed to be impacted by the outage (6 million customers) by the total number of customers within the region.

[3]Cost of outage calculated by first using the U.S. Department of Energy's (DOE) Interruption Cost Estimate (ICE) Calculator (available at http://www.icecalculator.com/) to estimate the costs of a 6 hour outage to all states within each region (100% of customers) and then multiplying results by the % of customers within the region that would actually be impacted.

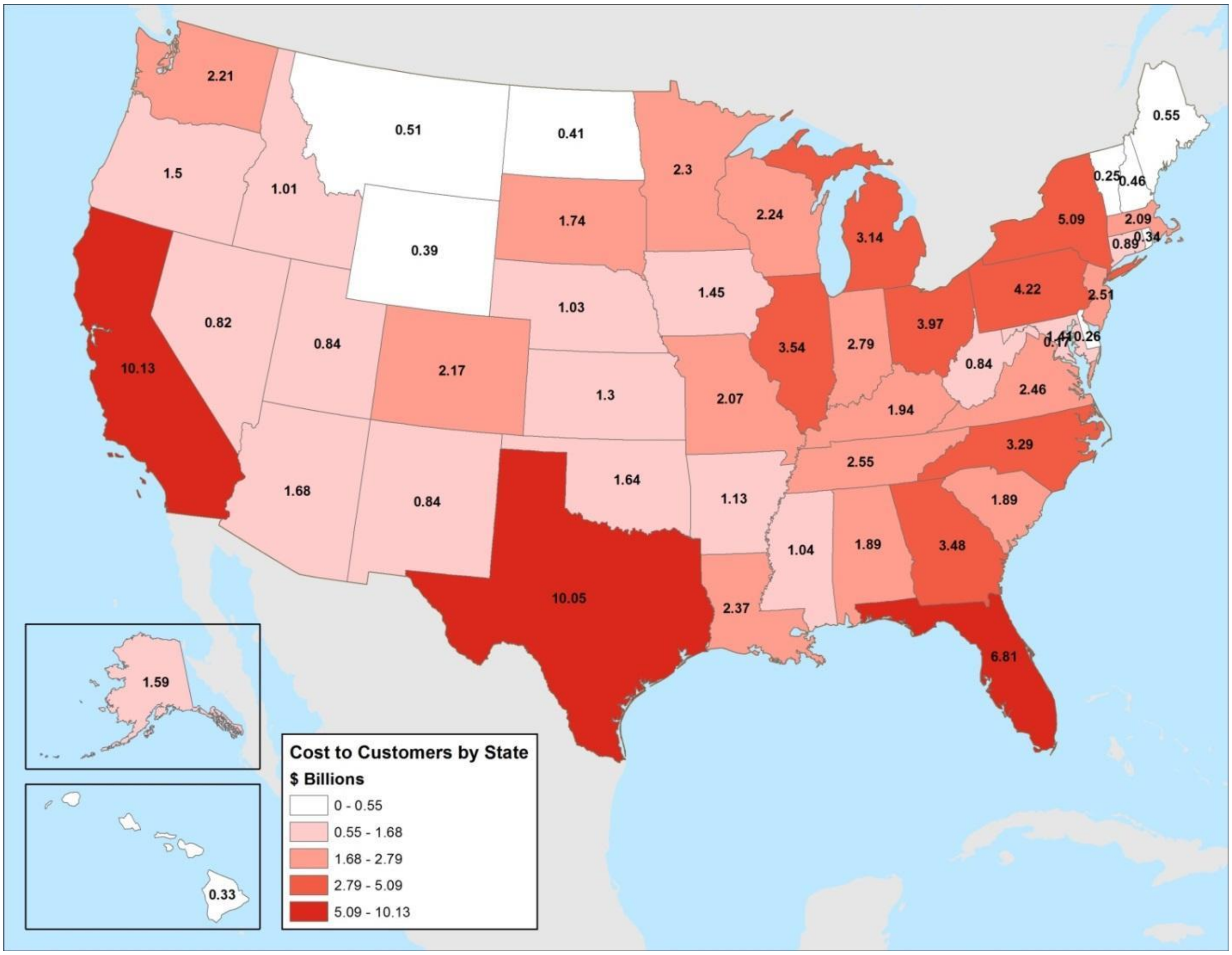

Figure 3. Cost estimates of a ~6 hour outage vary dramatically from state-to-state. Numbers in below figure derived by using state-level data provided by the Energy Information Agency and the Department of Energy's Interruption Cost Estimate (ICE) Calculator (for additional details, see footnotes in Table 8). The below results demonstrate that the costs of a ~6 hour power outage to different U.S. states depends on where the outage occurs and may ranges from ~$100s of millions to ~$10 billion**.**

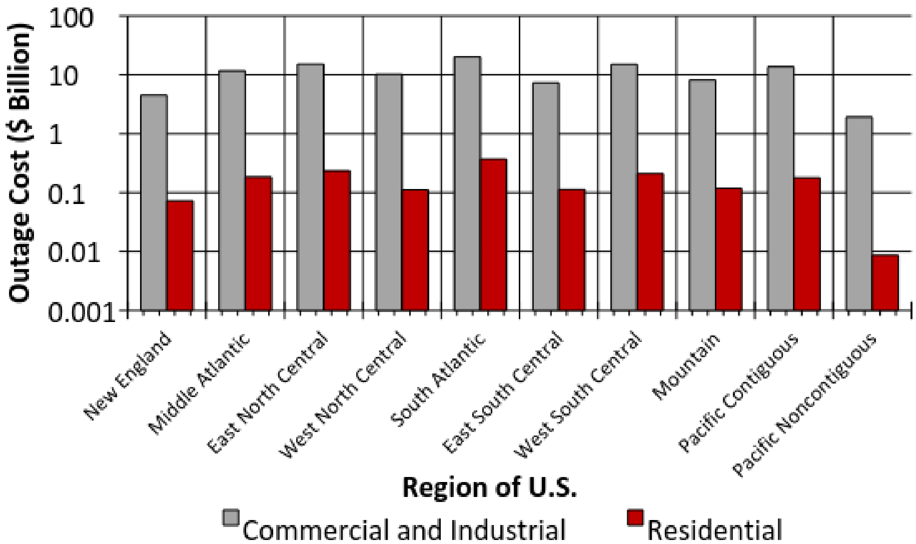

Figure 4. Costs of 6 hour outage (100% of customers) to different regions of the U.S. Note that Service Interruptions disproportionately impact different types of electricity users. Impacts to Commercial and Industrial users are $1 to $10 billion whereas impacts to Residential users are ~$10 to $100 million.

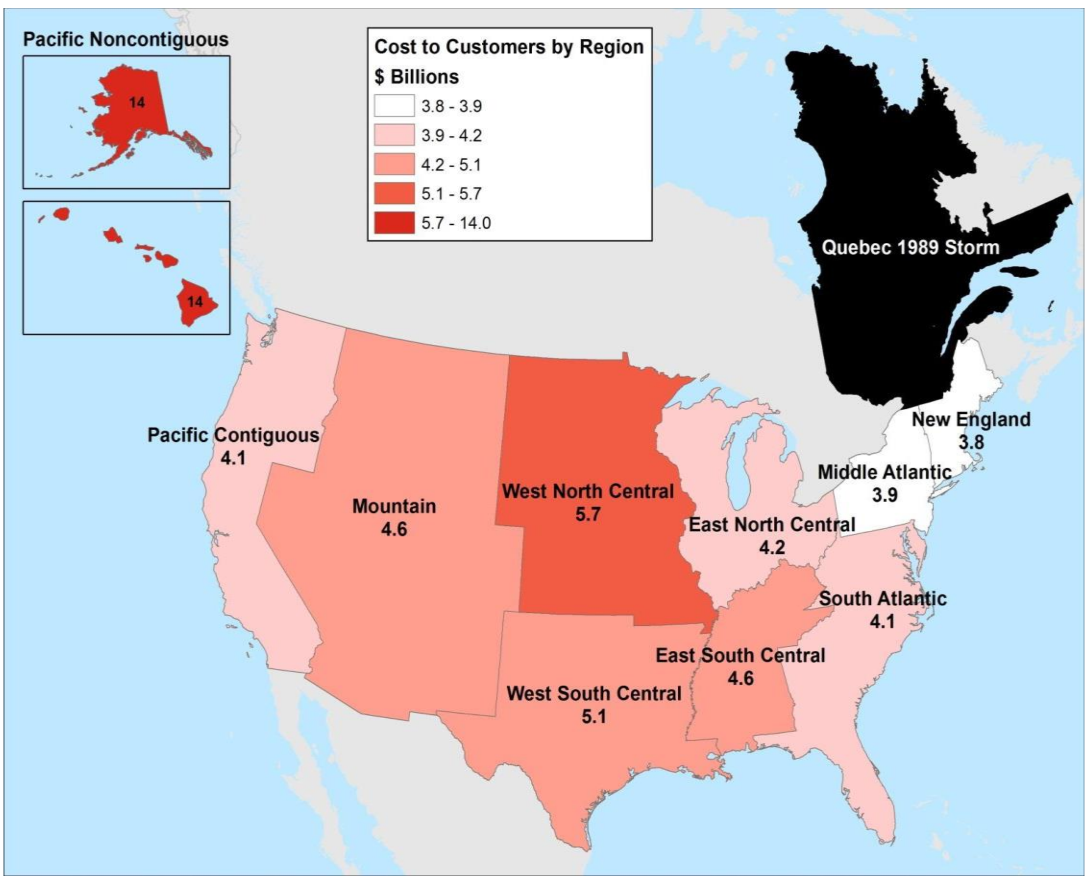

Figure 5. Cost estimate for moderate event that causes a ~6 hour outage impacting ~6 million customers in different regions of the country. Estimates derived using state-level data provided by the Energy Information Agency and the Department of Energy's Interruption Cost Estimate (ICE) Calculator (see Table 8).

3.3.2.b. More Extreme Event Scenario

We estimate that an extreme space weather event may cost U.S. consumers of electricity ~$1 billion to $20 billion. This reflects the costs of a ~9 hour blackout to an entire U.S. energy market during peak demand. Stakeholder conversations helped inform our assumptions about how long the outage might last and how large of an area it might affect. Although too early to incorporate insights from the currently ongoing U.S. SWAP extreme benchmark effort [*Love et al.,* 2016; *Executive Office of the President,* 2017], we discuss how insights from SWAP results will help bridge some of the many knowledge gaps surrounding the geography of potential power outages caused by space weather. Such information, as it becomes available, should be included in cost estimates to build a more robust understanding that includes many of the important variables (e.g. geo-electric hazards, network typology, system configuration, system load, time of day) necessary for developing more refined cost estimates.

Although more than one of the physical effects of space weather on the power grid could in theory cause an outage during an extreme event, stakeholders note that the most probable outage scenario would be one driven by reactive power consumption. This industry insight is important since different assumptions about what triggers the outage are necessary to know what statements can be made regarding two first-order controls on potential costs: (1) How long the outage might last and (2) how large of an area it may affect. Stakeholders all generally agreed that a particularly extreme space weather storm, such as one analogous in size to the Carrington event, might quickly elevate reactive power consumption to a level that, if not properly managed by grid operators, could trigger a cascading outage. Although a cascading outage could potentially impact an entire U.S. electricity market, they noted that it is very unlikely that it would be able to cross grid interconnections to impact neighboring markets. Specifically, grid interconnections in the U.S. are typically separated by a set of direct DC tie lines and therefore are not synchronously tied together with the AC transmission lines where the reactive power consumption effect would be occurring (this may not be true in certain regions of the U.S. or in other countries). Stakeholders furthermore anticipate that the envisioned outage might last at most ~9 hours. The duration of this Service Interruption is commensurate with other recent examples of cascading outages that have impacted large areas (e.g. the Hydro-Quebec outage in 1989, the Western North American outages in 1996, and the Northeast outage in 2003) but that have not involved significant infrastructural damage. Although the last two of these outages were not caused by space weather, considering them as analogous events is appropriate since they require similar recovery efforts and procedures and therefore share similar outage durations. To translate these stakeholder insights on duration and scale into monetary terms, we calculated the costs of a 9 hour outage across the different U.S. electricity markets using the national range for the VOLL (Table 9). We found cost estimates that vary by over an order of magnitude. Estimated costs are lowest if the extreme event impacts New England (~$1 billion to ~$3 billion) and highest if the event instead impacts the Southeast (~$7 billion to ~$20 billion). As for our moderate event, we were unable to integrate into our analysis important but not yet known information about the probability of space weather events causing outage in these different locations. Our estimate therefore only reflects the consequences of an outage (impacts) in these different locations based on the assumption that one occurs. Note that these numbers reflect an upper limit on our extreme scenario since we assume that the event occurs during that market's peak demand. Note that we were unable to use the ICE in this scenario because electricity markets are not organized along discrete state boundaries, the fundamental unit of analysis for this online tool (both methods are similar in that they use the VOLL methodology).

Although it is hard to predict where within the U.S. an extreme event may be most likely to cause an outage, early results of an initial effort to systematically explore this hazard at the national scale have recently been published [*Love et al.*, 2016]. It is important to note, however, that the geo-electric hazard is only loosely related to the actual GIC flow in the power system and is but one of the many other variables that needs to be known in order to rigorously assess if an outage will occur and with what level of associated costs. Therefore our initial estimate should be revisited and updated as more information is acquired.

Table 9. The upper limit on the potential cost of a nine hour power outage that cascades across all electric power markets. The worst-case estimate assumes that the event causes a power outage that coincides with peak energy demand in each of the electric power markets. Given that the highest geo-electric hazard associated with the 1-in-100 year benchmark scenario occurs within MISO, we use the cost of the outage in MISO as our worst-case extreme estimate.

Electric Power Market[1]	Peak Demand (MW)[1]	Cost of 9 hr outage[2]
California (CAISO)	50,000	~$2-5 b
Midcontinent ISO (MISO)	127,125	~$6-10 b
New England (ISO-NE)	28,130	~$1-3 b
New York (NYISO)	33,956	~$1- 3 b
Northwest	69,621	~$3-6 b
PJM	165,492	~$8-10 b
Southeast	170,000	~$8-20 b
Southwest	42,000	~$2-4 b
SPP	45,279	~$2-4 b
Texas	69,621	~$3-6 b

[1]Peak-demand for each Electric Power Market provided by FERC (https://www.ferc.gov/market-oversight/mkt-electric/overview.asp)

[2]Costs of worst case outage calculated by multiplying peak demand by 9 hours (to estimate total MWh lost) and using the national range for the VOLL of $5,000 to $10,000 per MWh).

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4. Satellites

4.1 Impact Mechanisms

Enhanced radiation resulting from space weather events can affect satellites in different ways and vary in response to many factors such as orbit, design, and age. Space weather induced increase in particulate radiation affects satellites and can cause a range of **anomalous satellite behaviors**. Anomalies may result if charges gradually accumulate and then suddenly discharge on either spacecraft surfaces ("surface charging") or in some of their interior components ("internal charging") [*Garrett,* 1981; *Baker et al.,* 1994; *Fennell et al.,* 2001; *Baker and Lanzerotti,* 2016]. Anomalies may also result when single particles deposit charge near sensitive microelectronics. Examples of anomalous satellite behaviors potentially attributable to space weather range in severity and can include software glitches such as bit flips or phantom commands to partial or complete damage of critical hardware components such as those related to power, navigation, and/or communication [*Bedingfield et al.*, 1996; *Lohmeyer et al.,* 2015; *Baker and Lanzerotti,* 2016]. In addition to satellite anomalies, which are acute in the sense that they tend to occur at the time of a space weather event, enhanced levels of particulate radiation can also represent a chronic problem by increasing the **cumulative dosage** of radiation received by a satellite. This can accelerate physical processes such as material embrittlement, displacement damage (e.g. damage to lattice structure of satellite materials), and surface erosion that may prematurely age and shorten the functional capacity and/or lifetime of satellites [*Cannon et al.*, 2013; *Baker and Lanzerotti*, 2016]. Increases in ultraviolet radiation can also affect satellites, by heating the atmosphere and increasing the ambient density of the thermosphere. This is known to increase the drag force on satellites in Low Earth Orbits (LEO) (altitudes <~800km) which may in turn accelerate **altitude losses** [*Jacchia,* 1963; *Nwankwo et al.,* 2015]. Increases in other types of electromagnetic radiation may lead to **link disruptions**, by interfering with the transmission and reception of the signals used to send information to and from satellites. Impacts from link disruptions in turn depend on many specifics including the criticality of the disrupted information and is considered in detailed in our GNSS user section.

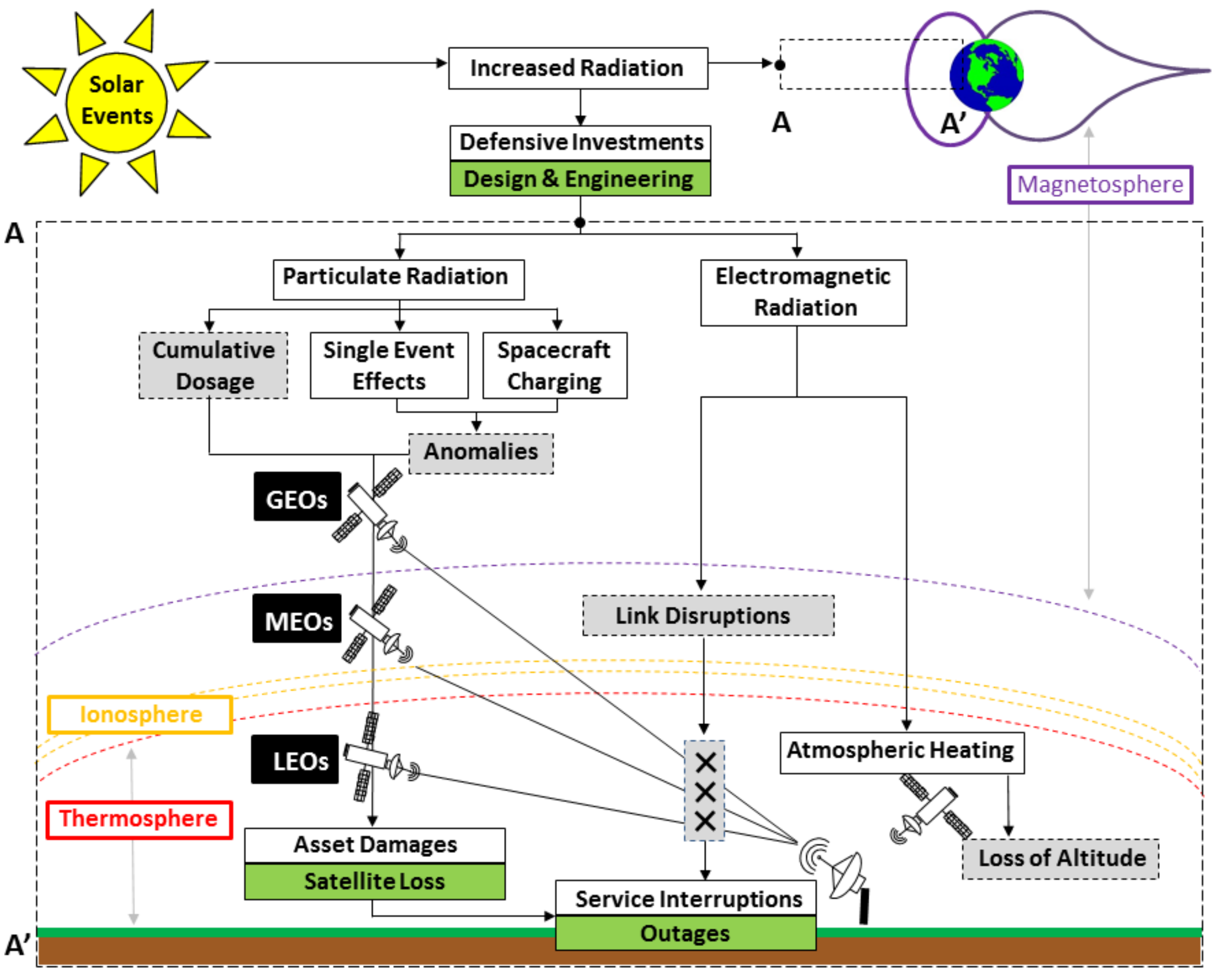

Figure 6. Impact mechanism diagram for satellites outlining the primary causal pathways from a solar event to physical effects (grey boxes) that can in turn cause a variety of social and economic impacts (green boxes). Note that our illustration depicted is not to scale, not comprehensive, and should be revised with future input from stakeholders to ensure it captures largest potential concerns.

4.2 Stakeholder Perspectives on Impacts

Our first phase of stakeholder outreach involved hour long phone calls with 8 individuals working across the satellite industry. We used our satellite sector impact matrix to guide these conversations and to systematically collect stakeholder input on the various physical effects of space weather and the types of impacts caused by each. Our final impact matrix is presented below (Table 10) along with additional and important insights from these conversations, including definitions and notes on the various physical effects (Table 11) and impacts (Table 12). This section provides a high-level overview of these discussions.

Satellite engineers and operators must overcome a range of environmental challenges in order for satellite missions in different orbits to provide various types of satellite services. Stakeholders across the industry therefore expressed different levels of concern about the different physical effects of space weather on satellites (Table 11) that tended to reflect fundamental differences between satellite orbits [e.g. Geostationary Earth Orbit (GEO) vs. Medium Earth Orbit (MEO) vs. Low Earth Orbit (LEO)] and missions [e.g. commercial communications, navigation, earth observations, military surveillance, research & development, meteorology, scientific, civil/military communications]. For example, building communication satellites to operate in GEO and Global Navigation Satellite System (GNSS) satellites to operate in MEO, where the radiation environment is relatively harsh, involves substantial Defensive Investments such as hardened components, shielding, or extra generous design margins to protect the integrity of satellites from high cumulative radiation dosages and from anomalous satellite behaviors that can be caused by surface- and deep-dielectric charging. LEO engineers and operators explained that their assets are comparatively more shielded by the atmosphere but nonetheless are concerned about radiation especially under more severe conditions when it penetrates further into the atmosphere than normal. They also expressed an additional concern about an extreme space weather event and the large number of LEO spacecraft that could potentially lose altitude from excessive atmospheric heating. Specifically, the growing orbital population is approaching a level where one accidental collision could trigger cascading collisions [e.g. "Kessler Syndrome" (*Kessler et al.,* 2010)] to potentially devastate many critical societal services such as earth observations and meteorology.

Although stakeholders emphasized that space weather impacts will be customer and mission dependent, stakeholders tended to agree that the largest impact category is Defensive Investments due to the very high costs of satellites and high value of their services. Satellite manufactures also noted that they tend to combine information from standard industry models and their own experiences when making many different decisions about design and engineering. They also noted that spare satellites add redundancy that may be inexpensive if the spare is a decommissioned satellite with some remaining capacity or costly if the spare is a new satellite. Stakeholders knowledgeable about satellite operations described different Mitigating Actions. Certain operators reported having procedures in place for space weather events, however, noted that such actions are infrequently enacted since the probability of any particular event impacting a satellite is considered low and the costs and risks of such procedures are too high (e.g. losses of revenue or potential problems recovering satellites once switched into safe mode). The preferred option at present is to instead observe what happens during an event and respond accordingly. Although not publically reported, this may involve non-routine operations and additional workload. Stakeholders noted that this represents an insignificant expense under normal conditions since companies have trained personnel on hand for such instances which can also result from other, non-space weather related issues (e.g. manufacturing glitches, terrestrial weather). Despite these concerns, most industry stakeholders emphasized that the satellite population is rather robust and that the challenges posed by space weather events are manageable, with some operational inconveniences but without any impacts to the end users of satellite services. Although the possibility of an event leading to Asset Damages and Service Interruptions is highly unlikely from their perspective, they noted that it cannot be ruled out and would furthermore be devastating if it occurred.

Table 10. Impact matrix populated during stakeholder outreach to better understand how the known physical effects of space weather on satellites can cause different types of impacts. Items in the matrix reflect example impacts and we tried to capture stakeholder thoughts on differences between impacts that might occur during moderate (normal text) compared to more extreme (italic text) space weather conditions. Question marks denote instances where the physical effect may in theory be able to cause this impact but empirical support is lacking. *Additional details pertaining to a select set of these impacts can be found in Table 12.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damage	Service Interruptions	Health Effects
Loss of Altitude (LEO only)	•Design & Engineering* •Situational awareness •Insurance •*Spares**	•Unplanned operations* •*Fire thrusters*	•*Accelerated aging** •*Asset loss?**	•Quality degradation* •Outages?*	
Link Disruptions	•Design & Engineering* •Situational awareness •*Diversification*	•Unplanned operations* •Schedule changes		•Quality degradation* •Outages?*	
Anomalies	•Insurance •Design & Engineering* •Situational awareness •Environmental testing •*Spares** •*Diversification*	•Anomaly investigations* •*Safe mode*	•*Accelerated aging** •*Asset loss**	•Quality degradation* •Outages?*	
Cumulative Dosage	•Design & Engineering* •Situation awareness •Environmental testing		•*Accelerated Aging** •*Asset loss?**	•Quality degradation* •Outages?*	

Table 11. Space weather can cause a variety of physical effects to satellites. These physical effects, defined below, are relatively well-studied in the scientific and engineering literature. These physical effects were discussed with industry stakeholders in order to better understand their potential for causing different types of impacts. These physical effects are connected to impacts in Table 10, with details on impacts provided in Table 12.

Physical Effect	Definition	Notes from Stakeholder Outreach
Cumulative Dosage	Total amount of ionizing or non-ionizing radiation that a satellite is exposed to over its lifetime.	• Very dependent on mission profile, standards are relaxed for LEOs and highest for MEOs and GEOs. • Physical effect is a natural and accepted process within the industry that causes slow and steady wear and tear. Conservatively accounted for with engineering and design. • Over engineering (x2-3 margin is typical) is costly but less costly than trying to perfectly design a satellite (lifetime ends with planned mission) or losing one early. • Experience suggests that solar minimum may be more damaging to satellites since strong solar activity shields them from really damaging heavy ions in cosmic rays. • Increasing usage of Commercial Off-the-Shelf Technologies with lower cumulative dosage specifications currently represents an unknown risk since satellites using these parts have not been tested in recent years by space weather. • Degrade all components on the satellite, including payload and bus.
Anomalies	Any malfunction in the normal, anticipated behavior of a satellite or satellite sub-system (e.g. power, attitude, stability, orientation) that is not readily explainable.	• A range of malfunctions are possible and require increased workload for operators to troubleshoot and restore nominal operations. Anomalies are rarely severe enough to impact the provision of satellite services and can be non-space weather related. • A large portion of anomalies are recurring, novel ones are more resource intensive and resolving them can carry significant expense. • Some designs are more susceptible than others and resolving anomalies requires contingency procedures that have operational costs. • Only anomalies that decrease the capability of the satellite are key concern. • Impact depends on technology satellite utilizes, its function, and how event impacts that specific technology (e.g. momentum wheels, star trackers, etc.).
Link Disruptions	Any degradation or interruption in the propagation or reception of signals used to transmit information to or from a satellite.	• Reliability of a particular satellite linkage is more often diminished due to a variety of non-space weather reasons (e.g. rain, weather). • Probability of occurring depends on what bands are being used to send/receive signals and how space whether affects these bands. Satellites use different signal frequencies for Telemetry, Tracking, and Control (TT&C) and for providing services. • Costs escalate quickly in order to attain high levels of reliability and therefore depend on value of service to end user and also their budget. • For commercial satellites that have to send and receive signals 24/7 so any interruption in the signal (even one minute) is problematic. Time is money and costs scale non-linearly with the length of time a signal problem lasts. • Of large concern to satellite operators because they can directly impact revenues.
Loss of Altitude	Lowering of satellite velocity and in turn altitude, due to increased atmospheric drag.	• Normal process that space weather can simply accelerate. • Loss of altitude due to increase in drag force relevant for LEO satellites only. Small losses (~10s-100s m) only trigger action if they introduce collision hazards but larger losses (~1-10s km) may trigger repositioning. Events where thrusters have to be fired are of special concern since it depletes fuel and fuel ends up being key constraint on mission lifetime. • Effect may become more problematic as airspace becomes more crowded: One collision initiated by space weather could trigger cascading collisions (e.g. “Kessler Syndrome”).

Table 12. Additional details on a select set of space weather impacts in our impact matrix (Table 10) identified during stakeholder outreach.

Impact Category	Examples	Definition	Notes from Stakeholder Outreach
Defensive Investments	Design and engineering	A range of engineering solutions that protect against space weather impacts such as component redundancies, physical shielding, radiation hardening, factors of safety, groundings/coatings, error detection/correction software, and end of lifetime designs.	• Many decisions that all vary with satellite mission profile (e.g. orbit, performance, lifetime) and differ between manufacturers and customer. • Engineers start at end of mission lifetime and work backwards, building in margins that are ~10-50% at the end of life. • Can include spare capacity and cold vs. hot redundant systems. Diversity also helps: dissimilar units can provide a replacement capability when the other fails (e.g. Telecommand using different frequency receivers).
	Spares	Operators may have extra satellites to replace satellites that are temporarily inoperable or permanently lost. Note that onboard spare capacity (e.g. redundant units) is part of Design & Engineering.	• Spares can be in space (“on-orbit”) and simply moved into necessary slot or stored on the ground and can be launched. • On-orbit spares can be new or old, decommissioned satellites that still function. More typical for satellites that belong to constellations (e.g. LEOs and MEOs) but GEO spares may also be invested in. • New spares, either on-orbit on the ground, are big economic investments.
Mitigating Actions	Unplanned operations	Any unplanned operational procedure that results in non-nominal operations. Example may be recalibrating orientation equipment or firing thrusters to regain lost altitude or velocity.	• Maintenance to bring sub-systems back into range. • Operators report no or rare incidences when they have had to fire thrusters but a concerning event would be one that consumes a significant % of fuel reserve. • Operations that consume fuel (e.g. fire thrusters) are biggest deal as fuel is key constraint on mission lifetime.
	Anomaly investigations	Assessment conducted after any anomalous satellite behavior is observed to understand likely cause and potential solutions. Note that most anomalies are not related to space weather but rate of anomalies is known to increase during events.	• Diagnosing the origin of an anomaly is important because the concern is that an anomaly could (but often does not) decrease capability. • Minor investigations can require couple of hours to days and be done by one person. Major investigations can require weeks to years and may require a team of people that have to consult with manufactures, troubleshoot extensively, and run many computational simulations. • Societal implications are potentially large. Need quick diagnosis if anomaly cause is from space weather or humans (e.g. terrorists).
Asset Damages	Accelerated aging	Any reduction in the capacity of satellite sub-systems (e.g. power, power storage, transponders) that is faster than anticipated and could shorten the lifetime of a satellite.	• A 4-5% reduction in capacity of satellite sub-systems is assumed and planned for. Power systems often have higher margins, ~10-20%. • Accelerated aging is only problematic if it reduces satellite lifetime or causes prime unit failures. • Ionizing vs. non-ionizing radiation causes different type of aging effects.
	Asset Loss	Permanent discontinuation of a satellite’s functionality that can occur either before or after it has exceeded its planned mission lifetime.	• If lost after planned lifetime, the loss in functionality and revenue is unfortunate but the satellite has already exceeded planned life. • If lost before planned lifetime, economic loss can be devastating since service revenue has not yet paid for invested costs. Stakeholders note that satellites are rarely lost prematurely and usually last longer than mission lifetime.
Service Interruptions	Quality degradation	Any reduction in the quality of satellite services provided including noisy data, bad images, and dropped calls.	• Impact depends on many end user specifics. • Although they would be biggest for those dependent on immediate, accurate, and continuous provision of satellite services, such users tend to have bigger budgets and invest more in quality assurance.
	Outages	Temporary or permanent loss of satellite services.	• Impact depends on many end user specifics. Impact highest for those relying on capabilities for primary rather than backup services. • When an LEO satellite malfunctions, service disruptions will be intermittent and global. When a GEO satellite malfunctions, service disruption will be continuous and localized to the satellite footprint. • Service options. End users may not be impacted because they could change service providers or service provides multiple satellites. Most likely to impact smaller businesses. • Can be triggered by false commands from space weather. Could result if a critical satellite is permanently lost. Critical satellites tend to be those in GEO that are expensive and unique.

4.3 Cost Estimates

In order to translate our findings into quantitative cost estimates that capture the most concerning and potentially largest impacts, we conducted a second round of stakeholder outreach. After discussing the various possibilities and better understanding some of the challenges inherent to quantifying many of the impacts we identified (Table 10), we ultimately decided to develop satellite sector cost estimates for Defensive Investments (~$400 to ~$700 million in 2016) and Asset Damages (~$200 million to ~$2 billion for our moderate event scenario and ~$2 billion to ~$80 billion for our more extreme event scenario). Our cost estimate for Defensive Investments focuses on the potential financial impacts of designing and engineering satellites to withstand the physical effects caused by space weather. Our cost estimate for Asset Damages examines the possible costs associated with asset losses, including satellite replacement costs and losses in revenue. Almost all of our stakeholders agreed that Defensive Investments may represent the largest costs of space weather to the industry. They also emphasized that potential Asset Damages represents a worst-case scenario. In particular, stakeholders consider the possibility of this happening during an event to be highly unlikely, due to substantial Defensive Investments, but noted that it would nonetheless be very costly and is not entirely without precedent. Key insights gleaned from these conversations are provided below alongside a description of how they influenced the derivation of our cost estimates.

Table 13. Simplified impact matrix with the focus of our quantitative analysis highlighted in yellow. The presence (or absence) of a circle denotes where we were able to connect a given physical effect to a particular impact category based on outreach, see Table 10). Black circles denote that a physical effect is known, from direct past experience, to cause a particular category of societal impact. Open circles indicate that a given physical effect may cause a particular category of societal impact, but stakeholders emphasize that this impact lacks empirical support.

Physical Effects	Impact Categories				
	Defensive Investments	Mitigating Actions	Asset Damages	Service Interruptions	Health Effects
Cumulative Dose	●		○	○	
Anomalies	●	●	●	●	
Link Disruptions	●	●		●	
Loss of Altitude[1]	●	○	○	○	

[1]Only applicable to LEO satellites

4.3.1 Defensive Investments

We estimate that building satellites capable of withstanding space weather may have cost U.S. manufactures ~$400 to ~$700 million in 2016 (Table 14). This estimate aims to capture what we heard from many of the engaged stakeholders during this study. The impacts of space weather events on satellites to date are relatively low because the industry carefully addresses the well-recognized hazard with appropriate design and engineering measures. Although many stakeholders thought that the largest costs to the industry would be associated with this impact category, they noted that substantial Defensive Investments are warranted and justified because losing a satellite or the services it provides would be far more economically devastating.

We derived our estimate for Defensive Investments by combining manufacturing revenue data provided by the

Satellite Industry Association [*SIA*, 2017] with stakeholder best judgement on the proportion of satellite manufacturing costs that may be attributable to defense from space weather. Although many specific satellite details on both topics represent well-kept trade secrets, stakeholders were able to offer general but important insights on the manufacturing process and its related costs. They discussed, for example, the complexity of various design and engineering decisions and the considerable variation between mission types (e.g. orbital regime and planned lifetime), manufacturers (e.g. experience and business strategy), and customers (e.g. service requirements, budget and risk aversion). For the best financial data, they pointed us to publically available information that is collected, aggregated, and reported annually by the Satellite Industry Association (SIA). According to the most recent SIA report [*SIA*, 2017], manufacturing revenues from satellites launched in 2016 totaled ~$13.9 billion globally. Global revenue is further broken down in the report by mission type, allowing us to calculate how much was spent on different types of satellite missions in 2016 (Table 14).

Since stakeholders were unable to discuss specific design and engineering details, we instead probed for estimates of how much space weather might add to the manufacturing costs of a satellite. Stakeholders had a hard time answering this question despite finding it relatively easy to list many examples of Defensive Investments and knowing that each involved significant expenses (for details, see Table 12). One stakeholder, for example, noted that a radiation hardened component may cost orders of magnitude more than an analogous, non-radiation hardened component. However another noted that the physical parts of a satellite represent a very small percentage of a satellite's total cost: The majority of a satellite's costs is instead attributable to the painstaking design, engineering, and testing efforts (e.g. environmental simulations, space qualifying, performance testing and reviews etc.) that goes into ensuring that it will reliably operate and provide the planned services in the harsh space environment throughout its planned mission lifetime. Although hard to quantify what percentage of this total effort might be attributable specifically to space weather, a few stakeholders independently provided similar estimates that it might represent somewhere between ~1% and ~10% of a satellite's manufacturing costs. These individuals further noted that the lower end of this range (~1-5%) would apply to satellites with recurring engineering (RE) while the higher end (~6-10%) to those with non-recurring engineering (NRE) due to one-time production costs (e.g. research, development, design, and testing)[1]. To estimate how much might have been spent across the global satellite industry in 2016, we multiplied our previously derived manufacturing revenues [*SIA*, 2017] by these percentages based on whether a mission type typically involves RE or NRE (Table 14). Global revenues associated with the manufacturing of satellites for military surveillance, for example, were $6.1 billion in 2016. Since these satellites typically entail NRE, Defensive Investments were estimated to be 6 percent to 10 percent of total revenues, or ~$400 million to ~$600 million. Similar computations were performed for each mission type, yielding an estimated Defensive Investment cost of ~$600 million to ~$1 billion globally in 2016. U.S. firms account for 64 percent of the market globally (for all mission types), so the Defensive Investment cost for the U.S. was estimated to range from ~$400 million to ~$700 million in 2016 (64 percent of the global cost) (Table 14). Note that the aggregated data provided by the *SIA* [2017] does not allow us to provide a more granular cost estimate (broken down by mission type) of U.S. Defensive Investments.

[1] Recurring Engineering (RE) refers to an engineering effort that has been previously researched, tested, and successfully implemented. Non-Recurring Engineering (NRE) refers to the novel engineering effort required to bring a new product or innovation to market and therefore tends to be more costly.

Table 14. Cost estimate of Defensive Investments made by the global satellite industry in 2016.

Mission Type[1]	Global Manufacturing Revenue[2]	Recurring Engineering (RE)[3]	Non-Recurring Engineering (NRE)[3]	Cost Estimate of 2016 Defensive Investments	
				Globally[4]	U.S.[5]
Military Surveillance	~$6.1 b		●	~$400-600 m	
Commercial Communications	~$2.2 b	●		~$20-100 m	
Civil/Military Communications	~$0.83 b		●	~$50-80 m	
Earth Observations	~$1.7 b	●		~$20-80 m	
Navigation (GNSS)	~$1.7 b	●		~$20-80 m	
Scientific	~$0.70 b		●	~$40-70 m	
Meteorology	~$0.56 b		●	~$30-60 m	
Research & Development	~$0.14 b		●	~$8-14 m	
Total	$13.9 b			~$0.6-1 b[6]	~$400-700 m

[1]Mission Type categories from SIA 2017 which does not report on government or university manufactured satellites.
[2]Manufacturing revenue by Mission Type is derived from p. 17 of SIA 2017 by multiplying the total industry manufacturing revenue in 2016 ($13.9 billion) by percentage of total revenue attributable to different Mission Types.
[3]Stakeholders were able to identify which Mission Types tend to utilize Recurring Engineering (RE) versus those that tend to involve Non-Recurring Engineering (NRE).
[4]Cost of Defensive Investments in 2016 calculated by simply multiply total manufacturing revenues by Mission Type by ~1 to 5% or ~6 to 10% for missions involving RE or NRE respectively.
[5]Derived from SIA 2017 data that U.S. firms earned ~64% of total manufacturing revenues in 2016.
[6]The final estimate represents ~5% of total manufacturing revenues in 2016 of ~$13.9 b (p. 17 of SIA 2017).

4.3.2. Asset Damages

Our moderate and extreme space weather event scenarios both assume the loss of satellite assets, with costs to the U.S. satellite industry estimated at ~$200 million to ~$2 billion and ~$2 billion to ~$80 billion, respectively. Both of these estimates assume that space weather causes complete and permanent satellite damage and therefore they account for the costs of lost satellite asset values and satellite service revenues. Stakeholders stressed that this potential impact represents a worst-case scenario. They consider the possibility of this happening to be highly unlikely, due to substantial Defensive Investments discussed above, but noted that it would nonetheless be very costly and is not without precedent. Stakeholders therefore encouraged us to base our cost estimates on the industry's collective experience of this impact and noted that it was intractable at this point in time to defensibly connect the magnitude of a space weather event to our list of physical effects (Table 11) and ultimately to the number of satellites that may be lost as a result. The cost estimates below are therefore based on combining insights from iterative stakeholder discussions with publically 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 (Union of Concerned Scientists Satellite Database).

4.3.2.a. Moderate Event Scenario

We estimate that a moderate space weather event may cost the U.S. satellite industry ~$200 million to ~$2 billion, including ~$20 million to ~$500 million of lost asset value and ~$200 million to ~$1 billion in lost revenues (as discussed in our approach, all numbers are rounded to one significant figure). In order to construct this estimate, stakeholders encouraged us to start by reviewing the industry's collective experience of this impact (Table 15). In the last ~20 years, there have been a handful of complete and permanent satellite losses from space weather with only one loss observed during any specific event (Table 15) [*Cannon et al.*, 2013]. Our moderate event scenario therefore begins by assuming the loss of one satellite. Although this reflects industry's experience to date, one stakeholder further emphasized that this historic loss record is actually quite ambiguous since attributing an observed satellite loss to space weather is not straightforward. In certain cases, for example, subsequent investigations have concluded that at least one of these losses was not from space weather (e.g. *Bodeau,* 2007). A different stakeholder also noted that insurance companies typically cover space weather related losses in their standard packages, further supporting the low-probability nature of this impact.

Table 15. Historic examples of complete and permanent Asset Damages caused by space weather.

Event Date[1] (Event Name)	Satellite[1]	Orbit[1]	Cause[1]	Satellite Type	Launch date[2]	Age at Loss (yr)[3]
01/11/97	Telstar 401	GEO	Anomaly	Commercial Communications	12/16/93	4
05/19/98	Galaxy IV	GEO	Anomaly[4]	Commercial Communications	06/24/93	5
07/15/00 (Bastille Day)	Astro-D (ASCA)	LEO	Loss of Altitude	Scientific	02/20/93	8
10/24/03 (Halloween Storm)	MIDORI 2 (ADEOS)	LEO	Anomaly	Scientific	12/14/02	7
01/14/05	Intelsat 804	GEO	Anomaly	Commercial Communications	12/22/97	8

[1]Information reported by Cannon et al. 2013
[2]Information from http://space.skyrocket.de/
[3]Derived by comparing event/loss date with launch date.
[4]Note that further investigations by Bodeau 2007 suggests that this loss was not attributable to space weather.

In order to quantify the total financial impact of this lost satellite, we assume the loss of one U.S. satellite and examine the potential loss of its value. As discussed previously, satellite financial data is proprietary information. Our stakeholders could only generally discuss satellite asset values by explaining, for example, that costs vary widely depending on the mission profile, manufacturer, and customer. To solicit more specific information, we asked stakeholder if they could at least provide their best guess on the asset values for different satellite missions. A few were willing to offer rough estimates but expressed many hesitations given the wide ranges and large uncertainties (Table 16). Therefore we also derived an independent estimate for typical asset values of different satellite missions by combining aggregated financial data on satellite manufacturing with satellite launch numbers (both provided in *SIA* [2017] with methodology details provided in Table 16 footnotes). Consistent with stakeholder sentiments, we derived a wide range of asset values. Research and Development missions are on the lower end of the spectrum, with costs that may be ~$20 million per satellite, and Military Surveillance missions are on the upper end with costs that may be ~$500 million per satellite. Although we use these derived values in our analysis, future efforts may want to focus on clarifying these uncertainties. Since it is not possible to know in advance of the event which satellite type will be the one that will be lost, we simply assume this lost satellite might cost anywhere between ~$20 million and $500 million. Note that individual satellites lost in historical, moderate space weather events have been either a commercial communication satellite (estimated here at ~$100 million per satellite) or a scientific satellite (estimated here at ~$200 million per satellite) (Table 16).

In addition to the costs of this lost asset, additional impacts may result from the loss of this satellite's services. Many types of satellite missions provide valuable societal services that are not straightforward to quantify (e.g. military surveillance, meteorology, navigation). We therefore assume that the lost satellite was generating revenue (e.g. commercial satellites). In order to estimate how much revenue the satellite may have been generating, we combined aggregated industry data on satellite service revenues with information from the Union of Concern Science's (UCS) database on operational satellites. At the end of 2016, there were 1,459 operating satellites in orbit (UCS database) that globally generated a total of $260.5 billion in satellite services revenue [*SIA*, 2017]. This suggests that the average service revenue generated by an average satellite in 2016 was ~$200 million/satellite per year (=$260.5 billion/1,459 satellites). We derived a similar value of ~$200 million/satellite per year by noting that 594 of these 1,459 operational satellite were U.S. assets (UCS database) that collectively generated ~$110.3 billion in revenue in 2016 [*SIA*, 2017] (=$110.3 billion/594 satellites). Note that this reflects a conservative value for the services provided by each satellite since it does not account for any non-market, societal benefits generated by satellites. In order to assess how many years of revenue may be lost as a result of the event, we returned to the historical loss record (Table 15). Stakeholders noted that Scientific Satellites do not generate "revenue" for their owners and have large ranges in planned lifetimes whereas Commercial Communication satellites do generate revenue and typically have planned mission lifetimes that are ~10 years. Based on publically available information (for details, see footnotes in Table 15), we were able to estimate that the two Commercial Communication satellites that may have been lost due to space weather, Telstar 401 in 1997 and Intelsat 804 in 2005, were ~4 and ~8 years old when lost (Table 15). These historic events therefore resulted in ~6 and ~2 years of lost revenue for each satellite owner respectively. Combining ~2 to 6 years of lost revenue with our previous estimate of the amount of revenue the satellite may have been generating (~$200 million/year) suggests a financial impact that may be ~$200 million to ~$1 billion. Note that this loss only applies if the lost asset in this scenario fails prior to the end of its planned life. Loss of revenue from any satellites that have already exceeded their planned lifetimes would be unfortunate but not devastating.

Table 16. Typical costs of different types of satellite assets vary my mission type.

Mission Type[1]	Typical Asset Values (per satellite)			
		Derived Estimate[3]		
	Stakeholder Estimate[2]	Manufacturing Revenue[4]	2016 Launches (% of total)[5]	Final Derived Estimate[3]
Earth Observations	$300,000	~$1.7 b	64 (51%)	$30 m
Commercial Communications	$200-250 m	~$2.2 b	20 (16%)	$100 m
Navigation (GNSS)	$200 m	~$1.7 b	13 (10%)	$100 m
Military Surveillance	$1-2 b	~$6.1 b	13 (10%)	$500 m
Research & Development	$10-20 m	~$0.14 b	8 (6%)	$20 m
Meteorology	$150 m	~$0.56 b	4 (3%)	$100 m
Scientific	$500-750 m	~$0.70 b	4 (3%)	$200 m
Civil/Military Communications	$200-250 m	~$0.83 b	2 (2%)	$400 m
Total		$13.9 b	126 (100%)	~$20-500 m

[1]Mission Type list consistent with SIA annual reports (e.g. SIA 2017).
[2]Stakeholders were able to provide rough estimates of typical asset values for different Mission Types but noted wide ranges and large uncertainties.
[3]Given uncertainties surrounding stakeholder estimates, we derived an independent estimate of typical asset values using industry data provided in SIA 2017.
[4]For additional details, see Table 14
[5]Lauch numbers derived from p. 7 of SIA 2017, by multiplying percentages by 126 total launches.
[6]Derived estimate divides reported manufacturing revenues by number of satellites launched for all Mission Types in 2016.

4.3.2.b. More Extreme Event Scenario

We estimate that a more extreme event may cost the U.S. satellite industry ~$2 billion to ~$80 billion, accounting for both lost asset values and potential losses in satellite revenue. Our extreme scenario follows the methodology outlined for our moderate scenario and the only difference is in the assumed number of satellite losses. In discussing with industry stakeholders the potential number of satellites that could be lost in an extreme event, for which we have no historical experience, most noted that this is very uncertain but nonetheless expect the total number to be small. Our extreme scenario therefore assumes the loss of 10 to 100 satellites globally, representing one to two orders of magnitude more asset losses than assumed in our moderate event scenario. Note that this level of loss is unprecedented to date and would represent ~0.7-7% of all currently operational satellites (1,459 satellites as of the end of 2016). We calculate the value of these lost satellite assets at ~$200 million to ~$50 billion (= 10-100 satellites x ~$20-500 million per satellite) and the value of their lost service revenues at ~$4 billion to ~$120 billion (= 10-100 satellites x ~$200 million per satellite per year x 2-6 years). Summing together these estimates suggests a total, global economic impact of ~$4 billion to ~$200 billion. As previously discussed, 594 of the 1,459 satellites (~40%) globally are currently owned/operated by the U.S. so we assume this portion of our global costs impacts the U.S. for a final estimate of ~$2 billion to ~$80 billion.

4.4 Satellite References

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5. Global Navigation Satellite Systems (GNSS) Users

5.1 Impact Mechanisms

A space weather event can potentially impact GNSS users by either directly affecting GNSS satellites and/or by interfering with the transmission of the broadcasted GNSS signal. This section focuses on potential impacts resulting from how space weather is known to physically affect the transmission of GNSS signals (For more information about potential impacts to satellites, please see previous section (Satellites) of this report). GNSS signals are sent from GNSS satellites via low power radio waves to different GNSS receivers and end users around the globe. These radio waves must transit the ionosphere, a region of our Earth's upper atmosphere (extending from ~70 to 1000 km above sea level) comprised of enough ionized molecules and free electrons to significantly alter their propagation [*Hernández-Pajares et al.,* 2011]. The nature and extent of this alteration depends largely on the number of electrons encountered by these radio waves. This varies dramatically under background or non-space weather conditions, since electron density in the ionosphere varies spatially (e.g. vertically and horizontally, small- and large-scale variations) and temporally (e.g. solar cycle variations (~11 years), seasonal changes, dawn/dusk instabilities, rolling disturbances) [for an overview, see *Hernández-Pajares et al.,* 2011 and references therein]. Space weather events can cause additional variations to the electron density of the ionosphere and therefore alterations to the propagation of GNSS signals, introducing additional complexities that are not yet fully understood but are known to affect GNSS users in at least two ways [e.g. *Kintner et al.,* 2007; *Tsurutani et al.,* 2009; *Cannon et al.,* 2013; *Baker and Lanzerotti*, 2016]. First, when space weather events sufficiently disturb the ionosphere from background (modeled) conditions, unaccounted for changes in the propagation speed of the GNSS signal can lead to **ranging errors**. Second, they can modify signal-to-noise ratios, preventing GNSS users from tracking or "locking" onto GNSS satellites. This can degrade or even prevent GNSS signal reception (e.g. **Loss of lock**). For example, small-scale variations in electron densities (ionospheric scintillations) are known to cause significant variations in both the phase and amplitude of GNSS signals [e.g. *Kintner et. al.*, 2007]. Enhanced levels of solar radio noise emitted by solar flares can also overwhelm the GNSS signal, by increasing the total amount of noise in the system to also result in loss of lock [*Cerruti et al.*, 2006; *Cerruti et al.*, 2008; *Tsurutani et al.*, 2009]. The physical effects can impact different GNSS users in different ways, depending on their utilization and reliance on the Positioning, Navigation, and Timing (PNT) information provided by GNSS satellites.

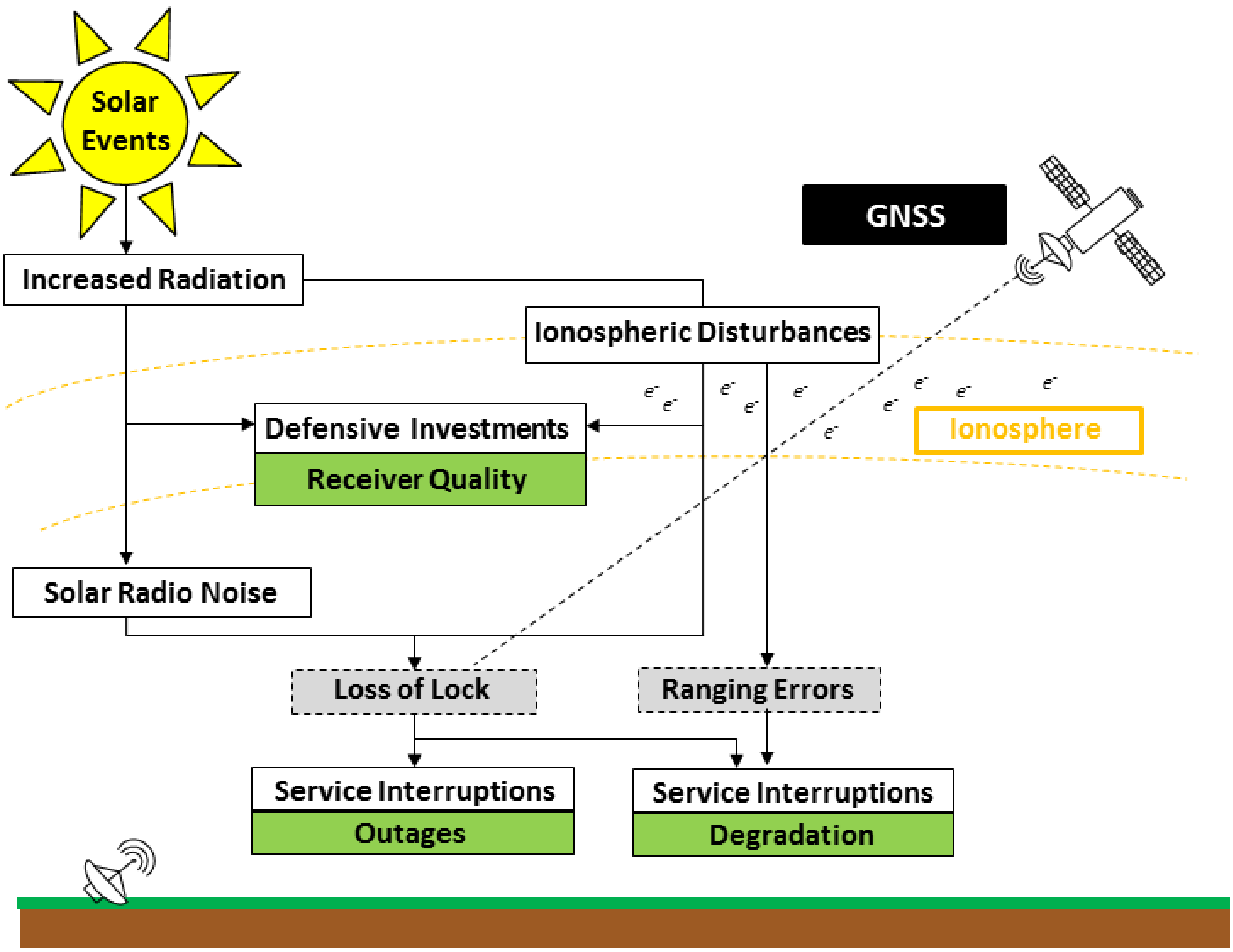

Figure 7. Impact mechanism diagram for GNSS users outlining the primary causal pathways from a solar event to physical effects (grey boxes) that can in turn cause a variety of social and economic impacts (green boxes). Note that our illustration depicted is not to scale, not comprehensive, and should be revised with future input from stakeholders to ensure it captures largest potential concerns.

5.2 Stakeholder Perspectives on Impacts

Our first phase of stakeholder outreach involved hour long phone calls with four individuals with expertise on space weather and GNSS. We used our impact matrix to guide these conversations and to systematically collect input on the known physical effects of space weather on the GNSS signal and the types of end user impacts that each may cause. Our final impact matrix is presented below (Table 17) along with additional and important insights from these conversations, including definitions and notes on the various physical effects (Table 18) and impacts (Table 19). The remainder of this section provides a high-level overview of what we learned from these stakeholder discussions.

Of the two known physical effects (Table 18), the stakeholders we spoke to all agreed that loss of lock is more concerning than ranging errors. “Lock” means that a GNSS receiver has an established connection with a GNSS satellite and can therefore acquire its Position Navigation, and Timing (PNT) information. Loss of lock therefore describes a situation where the GNSS user is not receiving a usable GNSS signal from a GNSS satellite. Stakeholders emphasized that the likelihood of this physical effect occurring varies dramatically from receiver-to-receiver, depending on many internal (e.g. design) and external (e.g. geography, time of day) specifics. The possibility that it will ultimately lead to an actual GNSS outage for the user also depends on which PNT service the end user needs. A GNSS receiver needs to be locked onto at least four satellites for positioning and/or navigation information but only one for timing. Stakeholders also noted that overall susceptibilities to this effect may or may not be in process of decreasing due to the increasing number of operational (e.g. the U.S.'s Global Positioning System and Russia's GLONASS) and planned (e.g. the E.U.'s Galileo and China's BeiDou) GNSS constellations. Stakeholders explained that ranging errors are less concerning because they can be largely eliminated with dual-frequency receivers. One stakeholder, however, noted that a fairly large portion of GNSS users remain reliant on single-frequency receivers. There may therefore be a subset of GNSS applications in which ranging errors remain a potentially large issue.

Stakeholders offered a number of general insights about our social and economic impact categories and emphasized the large number of important, user specific details that need to be considered when trying to understand potential space weather impacts. They were able to readily discuss different Defensive Investments, Service Interruptions (Table 17 and Table 19), and the direct relationship between these impact categories. Specifically, there is an extraordinarily wide variety of GNSS receivers on the market, which range in price (and therefore quality of GNSS service) from ~$10 to upwards of $100,000 each. In addition to end user decisions about what type of GNSS receiver to purchase, which involves individual cost-benefit considerations, stakeholders discussed how entities and/or industries using GNSS for safety-critical applications typically build external systems to enhance the overall performance of the standard GNSS service. These augmentation systems can be either space- or ground-based and tend to be quite costly since they require additional hardware and software that needs to be bought, deployed, and maintained. In addition to decreasing the potential for impacts during a space weather event, these expensive systems are justified because they increase the overall performance of GNSS across a broad spectrum of potential issues (e.g. terrestrial weather, intentional/non-intentional interference, multipath problems). Stakeholders also noted that these safety-critical applications (e.g. aviation) are not yet exclusively reliant upon GNSS and have retained or developed backup technologies and procedures in place to use in situations where GNSS becomes unavailable.

Our stakeholders found it difficult to populate our impact matrix for Mitigating Actions and Asset Damages. They noted that it was theoretically possible to enact different Mitigating Actions in response to a specific space weather event, for example by post-processing GNSS derived data or by making schedule changes, but were uncertain if these options were standard practice. One individual further speculated that such Mitigating Actions might be evoked and be particularly effective for reducing potential impacts of an extreme event. Stakeholders were also unable to identify any potential Asset Damages to GNSS users but noted that they could potentially occur more indirectly via Service Interruptions. The degradation or disruption of navigation information could, in theory and for example, cause moving vehicles such as cars or airplanes to collide with one another or immobile objects. They were unaware, however, of any incidences where this potential impact has occurred to date.

Although these general insights were informative, our stakeholders emphasized that there are many complexities and uncertainties surrounding this topic. They stressed, for example, that the probability of the physical effects (e.g. ranging errors and loss of lock) leading to a Service Interruption and their resulting consequences both vary as widely, and are changing as rapidly, as GNSS use itself. Stakeholders also expressed uncertainties about how these impacts have or will change with time. On one hand, GNSS users may be becoming less susceptible to potential space weather events due to increased understanding and more robust Defensive Investments (e.g. GNSS modernization, enhanced receiver design and engineering). On the other hand, the potential consequences of Service Interruptions may be simultaneously increasing due to the growing number of GNSS uses and users. As the PNT information provided by GNSS technology becomes increasingly relied upon and further embedded into more complex, interdependent systems and processes, a better understanding of the potential impacts will become more challenging and also more pressing.

Table 17. Impact matrix populated during our first round of stakeholder outreach to better understand how the well-studied physical effects of space weather on GNSS users may lead to different categories of social and economic impacts. Bulleted items inside matrix reflect example impacts identified by space weather for both moderate and extreme storms. Question marks denote instances where the physical effect may in theory be able to cause this impact but empirical support is lacking. Additional notes about each of these impacts from our discussions can be found in Table 18 and Table 19.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damage	Service Interruptions	Health Effects
Ranging Errors	•Receiver Design & Engineering •Additional constellations •Augmentation Systems	•Differential Correction?		•Quality Degradation	
Loss of Lock	•Receiver Design & Engineering •Additional constellations •Augmentation Systems	•Schedule Changes?		•Quality Degradation •Outage	

Table 18. Space weather is known to physically affect the transmission of GNSS signals in a variety of ways, with a few examples defined below that are relatively well studied in the scientific and engineering literature. The physical effects of space weather on GNSS satellites are also addressed in another section of this report. We discussed these physical effects with knowledge stakeholders in order to better understand their potential for causing different types of social and economic impacts (Table 19).

Physical Effects	**Definition**	**Notes from Stakeholder Outreach**
GNSS Satellites* (For list of physical effects on satellites, see Table 11).	Any direct impact to GNSS satellites that interferes with the normal operations and/or performance	• GNSS satellites remain military/government investments and therefore may be even more conservatively designed and therefore more robust than many commercial satellites where cost tends to be a bigger constraint and consideration. • Uncertain if any GNSS satellites have been acutely impacted by any space weather event to date. Also uncertain the degree to which historic events may be adding up (chronic impacts). • The increasing number of GNSS constellations in orbit, launched by other countries, can provide redundancy and may increase impact threshold. • GNSS is moving towards dual- and multiple-frequency signals and receivers, increasing impact threshold.
Ranging Errors	Inaccurate Positioning, Navigation, Timing (PNT) information caused by unaccounted for changes in the propagation speed of the GNSS signal through the ionosphere.	• This only affects GNSS users with single-frequency receivers. • This is also caused by other phenomena (e.g. rain, humidity, and physical obstructions) and can be eliminated by using a dual-frequency receiver. • Under normal non-disturbed conditions, the standard positioning accuracy of single- vs. dual-frequency receivers is ~1 meter vs. ~1cm. Large disturbances caused by space weather may be able to reduce the baseline accuracy of single-frequency receivers by one or two orders of magnitude (~10 to ~100 meters) whereas dual-frequency receivers are largely impervious. • The potential that this physical effect will lead to problems is idiosyncratic and depends on many GNSS user details that are not easily generalizable (e.g. specific GNSS application and service requirements). Although ranging errors would cause the most problems for high-accuracy, real-time applications (e.g. off-shore drilling) needing continuously available PNT information of a known quality, these users typically make substantial Defensive Investments. Impacts to them might therefore be eliminated or else occur at a much higher impact threshold.
Loss of Lock	Inability of a GNSS satellite signal to be tracked by a receiver, reducing the number of usable satellites in the sky.	• Susceptibility to this physical effect is receiver dependent. • Loss of lock leads to outage if receiver cannot lock onto at least 4 satellites for positioning and navigation and at least one satellite for timing. • Amount of time to recover from loss of lock is also receiver dependent. Reacquiring a signal can be nearly instantaneous or it can take ~30 mins to an hour to get high-precision services back. • Uncertain how often this will occur during the next solar cycle since there will be many more GNSS constellations/satellites in the sky then.

Table 19. Additional notes from stakeholder discussions on items listed in our final GNSS impact matrix (Table 17)

Impact Category	Examples	Definition	Notes from Stakeholder Outreach
Defensive Investments	Receiver Design and Engineering	A variety of techniques used by GNSS receiver manufacturers to increase GNSS service quality including, for example, special computer algorithms, holdover technologies (e.g. highly accurate internal synchronization devices), increasing the maximum age of corrections, and inertial navigation systems.	• Depends on user needs. • Also varies with geography and becomes especially important in areas where reliability of GNSS signal is a chronic problem (e.g. high-latitudes, equatorial regions). • Holdover capacity is application specific but can range from hours to days. Holdover is invested in for other reasons besides space weather and can be costly. To maintain accuracy for 5 minutes without GNSS signal, for example, may cost ~$100,000.
	Additional constellations	Utilizing GNSS signals broadcasted by more than one GNSS constellation (e.g. GPS built by the U.S., GLONASS built by Russia, DBS built by China, Galileo built by the European Union) to solve positioning calculations.	• Impacts to GNSS signals tend to be more "local" so if satellite signals are used, the impacted signal will have less weight in the GNSS solution. • Less likely for receivers to lose lock since more satellites can be seen at any one time.
	Augmentation Systems	Supplemental systems external to GNSS systems that provide additional data to GNSS users to improve quality of GNSS service. Systems can be ground or space based and can provide a variety of data, for example, GNSS error information and corrections.	• Ground based augmentation services are more local in nature. They also tend to be resource intensive to operate and maintain so some are starting to be decommissioned. • Satellite based augmentation services are more expensive but provide regional coverage (e.g. the Wide Area Augmentation System (WAAS) in U.S. and the European Geostationary Navigation Overlay Service (EGNOS) in Europe). They can also be affected by space weather (e.g. December 2006) but unclear extent to which it may compromise operations. • Corrections sent by satellites can be interrupted for ~5-10 minutes but this can be addressed by increasing the holdover capacity of receivers.
Mitigating Actions	Differential Correction	Decision made to post-process GNSS data to increase its accuracy by comparing measurements taken by more than one GNSS receiver.	• Theoretically possible, but not clear if or under what circumstances this may be done. Users typically worried about having highly-accurate information to inform the appropriate Defensive Investments. • Any automatic, real-time applications of this are covered in our Defensive Investment category (e.g. Receiver Design & Engineering).
	Schedule Changes	In anticipation of possible service degradation and/or service outages, GNSS users may decide to change timing of operations that may be sensitive to potential problems.	• Decision hinges on how costly schedule changes are to end users and may rarely occur, especially if costs are high (e.g. off-shore drilling). • Some third-party GNSS service providers offer their own forecasts of anticipated disruptions to end users to make them aware of risks.
Service Interruptions	Quality Degradation	Any reductions in the quality of information provided by the standard GNSS service.	• There are many different ways to think about the "quality" of GNSS service (e.g. availability, accuracy, continuity, integrity). • Quality needs and therefore impacts from quality vary dramatically from user to user.
	Outage	Inability of GNSS user to receive usable PNT information from GNSS satellites.	• Impact occurs most frequently in high-latitudes and equatorial region. • Uncertain if it has been observed in mid-latitudes regions but this could certainly happen during an extreme event.

5.3 Cost Estimates

In order to translate our findings into quantitative cost estimates that capture the most concerning and potentially largest impacts, we conducted a second round of stakeholder outreach. Although this additional input helped us quantify the potential impacts from Service Interruptions (~$4 million to ~$8 million for the moderate event scenario and ~$100 million to ~$600 million for the extreme event scenario), we received much less guidance from our stakeholders on this sector compared to others. The input gained from our additional outreach is nonetheless provided below alongside a description of how it influenced the derivation of our cost estimates. Note that our estimate are conservative since they only capture how GNSS outages may reduce the economic benefits provided by GNSS to a sub-set of applications where there has been a relative large penetration of the technology. Although the potential costs would certainly be much higher if we included other types of impacts from GNSS outages (e.g. health and safety, environment, etc.), we were unable to find adequate information on these topics to propose defensible estimates [*Leveson*, 2015a]. Our cost estimates are also preliminary and rely upon an early quantitative analysis of this topic and data from 2013 [*Leveson*, 2015a]. There was not enough publically available information on this study to be able to use updated and current numbers for 2016. Given the rapid increase in GNSS usage in the intervening years, impacts estimated herein may therefore be understated.

Table 20. Simplified GNSS impact matrix, with the focus of our cost estimate highlighted in yellow. The presence (or absence) of a circle denotes where we were able to connect a given physical effect to a particular impact category during our first round of stakeholder outreach (see Table 17 for a list of items represented by each circle). Closed circles denote that the physical effect is known, from direct past experience, to cause impacts of that particular category. Open circles indicate that the physical effect may cause that particular type of impact but the linkage presently lacks empirical support.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damages	Service Interruptions	Health Effects
Ranging Errors	●	○		●	
Loss of Lock	●	○		●	

5.3.1 Service Interruptions

We estimate that a moderate event may cost GNSS users ~$4 to ~$8 million (Table 21) whereas a more extreme event may cost ~$100 million to $600 million (Table 22). Our stakeholders emphasized that the potential impacts from a GNSS Service Interruption varies as widely and changes as rapidly as GNSS use itself. Our cost estimate therefore builds off a recent study that quantifies the benefits of GNSS (GPS) to the U.S. [*Levenson et al.*, 2015a; 2015b]. We assume that a moderate and extreme space weather event both lead to a GNSS outage that imposes costs to end users by reducing these economic benefits. Note that GNSS provides additional, non-market benefits (e.g. health and safety, environment) that we were unable to capture due to insufficient quantitative information of this topic [*Leveson et al.*, 2015]. We were also unable to find enough information to capture any societal costs resulting from potential impacts to our nation's critical infrastructure (e.g. chemical, communications, energy, financial services, informational technology, water and waste water, etc.) (for the complete list of 16, as defined by the Department of Homeland Security (DHS), see

Table 23). Our cost estimates are therefore incomplete and should be updated when such pertinent information becomes available. At present, our numbers should therefore be interpreted as conservative estimates of potential costs.

5.3.1.a. Moderate Event Scenario

We estimate that a moderate space weather event may cost end users of GNSS in the U.S. ~$4 to ~$8 million. This estimate captures the costs of an event that is able to cause a ~1 hour GNSS outage across the U.S. and that impacts different types of end users to various degrees. It is based on a historic consideration of past events that have impacted GNSS users, important differences between users in their susceptibilities to an event, and the economic benefits of GNSS to a representative set of applications.

Our first step involved considering past historic space weather events in order to develop a moderate scenario for the duration and extent of the GNSS signal disruption. Stakeholders pointed us to the Halloween storm in 2003 and the December 2006 event as key events with notable impacts to GNSS users. Although we located a number of detailed scientific analyses of these events [e.g. *Chen et al.,* 2005; *Cerruti et al.,* 2006; *Cerruti et al.,* 2008], we found limited and anecdotal documentation about their actual impacts. During the 2003 Halloween storm, for example, one report states that surveying activities on land, in the air, and at sea were delayed and drilling operations were either postponed or cancelled [e.g. *NOAA*, 2004]. Although our stakeholders provided order of magnitude cost estimates of these impacts of ~$10,000 to ~$100,000 per day, it is unclear how long these delays and cancellations lasted and how widespread they were (or could be). We therefore reviewed the more detailed scientific analyses of these events to develop a GNSS outage scenario for our moderate event. Specifically, during the 2003 Halloween Storm, a series of solar radio bursts caused GNSS receivers worldwide to intermittently lose lock for periods of time from minutes [*Chen et al.,* 2005] up to hours [*Astafyeva et al.,* 2014]. Airlines were also unable to use the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS) for precision approaches for a total of ~25 hours over two days during the Halloween 2003 storm (e.g. for ~15 hours on October 29 and ~11 hours on October 30) [e.g. *NOAA,* 2004; *Doherty et al.,* 2004]. We were unable to determine, however, if this ~1 day long interruption caused substantive impacts (e.g. flights were delayed) or if it was more of a nuisance (e.g. pilots reverted to alternate landing procedures). During the December 2006 event, GNSS receivers on the sunlit side of the Earth were disrupted for tens of minutes [*Cerruti et al.,* 2008] up to ~1 hour [e.g. *Carrano et al.,* 2009]. Similar to the Halloween 2003 storm, however, we found limited documentation on how this event in turn impacted GNSS users. To reflect these historical observations, our moderate scenario therefore envisions a space weather event that disrupts GNSS signals across the entire U.S. for ~1 hour. Note that this assumes that the GNSS service ceases and resumes with the space weather disruption. Moreover, it seems as if we have not experienced a "moderate" storm that has significantly impacts GNSS users since the U.S. made GNSS [Global Positioning Service (GPS)] freely available in 2000. It is therefore hard to establish potential impact thresholds if we have not yet experienced significant impacts.

Our next step was to determine what percentage of GNSS users within the U.S. may incur an outage as a result of this disruption. Stakeholders emphasized that the susceptibility of different GNSS users to any given space weather event varies dramatically from user-to-user and for a given user, from location-to-location. There are at least nine types of GNSS applications at present with substantial economic benefits including precision agriculture, construction, surveying, transportation (including air, rail, maritime, and road), timing, and consumer location-based services (LBS)

[*Levenson,* 2015a]. Although each of these applications is comprised of a diverse GNSS user base, it is possible to make some generalization about typical users susceptibilities within each application. We classified users within each of these applications as having either low, medium, or high quality GNSS service needs by reviewing key GNSS performance parameters listed for different GNSS market receivers [*European GNSS Agency,* 2016]. These parameters include accuracy, availability, continuity, integrity, robustness, continuity, indoor penetration, time to first fix, latency, and power consumption [see Annex I in *European GNSS Agency,* 2016]. We used *accuracy* and *continuity* as our quality indicators since they most directly correspond to the effects of space weather on the GNSS signal (Table 18). Specifically, ranging errors and loss of lock can both degrade accuracy whereas loss of lock can interfere with continuity. We then mapped our nine different types of GNSS applications of focus to their mass markets and noted whether user priorities for both accuracy and continuity are either lower or higher (Table 21). Recall that our stakeholders also reported a large range in GNSS receiver price and quality, from ~$10 to more than ~$100,000 per receiver. To reflect the fact that users needing different quality services generally purchase receivers of different qualities that will vary in their susceptibilities to a given disturbance, we assume that the disruption occurring in our moderate event scenario causes as outage impacted ~100% of users with the low quality GNSS needs, 10% of users with medium quality GNSS needs, and 1% of users with high quality GNSS needs (e.g. users with lower quality needs purchase less expensive receivers that are more vulnerable to events whereas those with higher quality needs purchase more expensive receivers that are less vulnerable to disruptions).

Our final step is to compute the costs of this outage scenario to different GNSS applications. *Levenson et al.,* [2015a] estimate that the economic benefit of GNSS enabled technologies across these nine different applications may total ~$37.1 to ~$74.5 billion per year (Table 21). We assume that our moderate event imposes costs to these GNSS users by reducing these total annual benefits by an amount that is proportional to the length of the outage (~1 hour) and the percentage of application users within the U.S. that are impacted. Our calculations assume that the event happens during working hours and these benefits, and therefore costs, accrue during the eight hour working day rather than over a full 24 hour day. Summing our results across all applications suggests a cost to these applications that varies by multiple orders of magnitude but may collectively total ~$4 to $8 million, with largest costs (~$3 to $6 million) for mass market users of GNSS enabled Consumer Location Based Services (for additional details, see Table 21). Note that this approach ignores the potentially important insight that some of these applications may be able to absorb a ~1 hour disruption without being impacted by it. Certain applications may be impacted by GNSS outages of any non-zero duration whereas other may not be impacted until it exceeds some threshold length. It is unclear, for example, if a ~1 hour outage would or would not reduce the annual economic benefits of GNSS across all of these applications (e.g. a ~1 hour outage that results in a delay for air transportation may prove large whereas the same ~1 hour outage that results in a delay of fertilizing, watering, or seeding for precision agriculture may be inconsequential). We were unable to find enough information about this topic to incorporate this potentially important point into our current cost estimate. As mentioned in the beginning of this section, this approach produces a conservative estimate of the potential economic impact of the event since it only captures how an outages may reduce the economic benefits provided by GNSS to a sub-set of applications where there is enough information to quantify and there has been a relative large penetration of the technology. It is furthermore conservative because it is built off a study that assesses only a subset of users within each application (e.g. estimate of precision agriculture only considers benefits to grain farming). Although the costs may be much higher if we include other types of impacts from GNSS outages (e.g. health and safety, environment, etc.), we were unable to find enough information on these topics to propose defensible numbers.

Table 21. Cost estimates reflecting a GNSS outage, as envisioned in our moderate event scenario, that lasts ~1 hour and impacts a broad spectrum but different percentage of GNSS users across the U.S.

GNSS Application[1]	Receiver Market[2]	User Priorities[2]		Quality Needs[3]	% of Users with Outage[4]	Range of Benefits (Billions/yr)[1]	Estimated Costs	
		Accuracy	Continuity				To Application	To Market
Consumer Location-Based Services	Mass Market	Low	Low	Low	100%	$7.3-18.9	$3-6 m	$3-6 m
Timing	High precision, timing & asset management solutions	High	Low	Medium	10%	$0.025-0.050	$900-2000	$1-2 m
Precision Agriculture		High	Low			$10-17.7	$0.3-0.6 m	
Surveying		High	Low			$9.8-13.4	$0.3-0.5 m	
Construction		High	Low			$2.2-7.7	$0.08-0.3 m	
Fleet Vehicle Telematics		High	Low			$7.6-16.3	$0.3-0.6 m	
Maritime Transport	Transport & Safety Liability Critical Solutions	High	High	High	1%	$0.106-0.263	$400-900	$800-2000
Air Transport		High	High			$0.119-0.168	$400-$600	
Rail Transport		High	High			$0.010-0.100	$30-$300	
					Total	$37.1-74.5	~$4-8 m	

[1]Information provided in *Leveson, 2015a* unless otherwise noted. Annual benefits represent mid-range values.

[2]Information derived from GNSS User Technology Report [*European GNSS Agency*, 2016], which describes different GNSS receiver markets and identifies their user priorities in terms of key performance parameters. Here, these three mass markets are mapped to different applications [*Leveson*, 2015a] and note whether the most relevant performance parameters for space weather impacts, accuracy and continuity, are of high or low priority to these users. For information on Mass Markets see p. 31, on Transportation & Safety Liability Critical Solutions see p. 40, and on High Precision, Timing & Asset Management Solutions see p.53.

[3]Applications where users have accuracy/continuity needs that are low/low, high/low, and high/high are assumed to need low, medium, and high quality GNSS services respectively.

[4]Stakeholders reported a large range in GNSS receiver price and quality, from ~$10 to ~$100,000 per receiver. To reflect the fact that users needing different quality services generally purchase receivers of different qualities that will vary in their susceptibilities to a given disturbance, we assume that the event causes an outage to 100%, 10%, and 1% of users with low, medium, and high service quality needs respectively.

5.3.1.b. More Extreme Event Scenario

Under more extreme conditions, we estimate space weather impacts that could cost GNSS users within the U.S. ~$100 million to ~$600 million. Our extreme scenario follows the methodology outlined for our moderate event scenario but assumes that the outage will instead last for ~1-3 days [*Cannon et al.,* 2013; *Hapgood et al.,* 2016] and impacts an order of magnitude more users than in our moderate event scenario (Table 1).

Table 22. Cost estimates reflecting a GNSS outage, as envisioned in for the extreme event scenario, that lasts ~1-3 days and impacts a broad spectrum but different percentage of GNSS users across the U.S.

GNSS Application	Receiver Market	Quality Needs	% of Users with Outage	Range of Benefits (Billions/yr)	Estimated Costs	
					To Application	To Market

Consumer Location-Based Services	Mass Market	Low	100%	$7.3-18.9	$20-200 m	$20-200 m
Timing	High Precision, Timing & Asset Management Solutions	Medium	100%	$0.025-0.050	$0.07-0.4 m	$80-500 m
Precision Agriculture				$10-17.7	$30-100 m	
Surveying				$9.8-13.4	$30-100 m	
Construction				$2.2-7.7	$6-60 m	
Fleet Vehicle Telematics				$7.6-16.3	$20-100 m	
Maritime Transport	Transport & Safety Liability Critical Solutions	High	10%	$0.106-0.263	$0.03-0.2 m	$0.06-$0.4 m
Air Transport				$0.119-0.168	$0.02-0.1 m	
Rail Transport				$0.010-0.100	$3,000-$80,000	
				Total	~$100-600 m	

In addition to being a conservative estimate for all previously mentioned reasons, note that GNSS enabled technologies are becoming more and more integral to our nation's Critical Infrastructure [e.g. *Caverly*, 2011]. For example, we found a preliminary report stating that 11 out of 16 components of our nation's Critical Infrastructure were, as of 2011, reliant upon GNSS technologies (Table 23) (e.g. internal systems that allow them to run for a specific length of time without GNSS) [e.g. *Caverly*, 2011]. However, we were unable to find information describing these dependencies in sufficient detail to analyze potential impacts of an event. Note that this report also provides information of different holdover capacities (e.g. internal systems that allow them to run for a specific length of time without GNSS), which are all commensurate in length with the low-end of our outage duration (~1 day) and smaller than our high-end (~3 days). Although this suggests the potential for societal impacts, we were unable to find more information on how these holdover capacities may have changed over the last 6 years [i.e. since *Caverly*, 2011]. SWAP efforts to establish benchmark GNSS outage scenarios are not yet complete [*Executive Office of the President*, 2017] but will be followed by a comprehensive vulnerability assessment of our nation's Critical Infrastructure to such benchmarks [*Space Weather Action Plan*, 2015]. While there is not currently enough information to assess the impacts of potential GNSS outages via effects on Critical Infrastructure, it will be important to estimate the costs when these other studies conclude and in light of their light findings.

Table 23. U.S. Critical Infrastructure is reliant on GNSS technologies so the potential societal impacts of an extreme event on the U.S. may be large but is currently unknown.

Critical Infrastructure (CI) Sector[1]	Reliant on GNSS[2]?	Holdover Capacity (Hours)[2]
Chemical	Yes	1
Commercial Facilities		
Communications	Yes	24+
Critical Manufacturing	Yes	1.7
Dams	Yes	1
Defense Industrial Base	Yes	1.7
Emergency Services	Yes	24+
Energy	Yes	1
Financial Services	Yes	<0.24-1.7
Food and Agriculture		
Government Facilities		
Healthcare and Public Health		
Information Technology	Yes	1
Nuclear Sector	Yes	1
Transportation Systems	Yes	24+
Water and Wastewater Systems		

[1]https://www.dhs.gov/critical-infrastructure-sectors
[2]Assessment of reliance is based on sectors where GNSS timing information was identified by DHS as essential (Caverly, 2011)
[3]In order to determine if a Critical Infrastructure (CI) sector is impacted by a moderate and extreme event, the sector must (1) be reliant on GNSS and (2) the outage duration for the moderate (1 hour) and extreme (1 day) space weather scenarios must be greater than the sector's holdover capacity.

5.4 GNSS References

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6. Aviation

6.1 Impact Mechanisms

During space weather events, increases in both electromagnetic and particulate radiation may affect aviation in various ways [*Jones et al.,* 2005; *Cannon et al.,* 2013; *Baker and Lanzerotti,* 2016]. Increases in electromagnetic radiation may diminish the capabilities of various aircraft **communication** and **navigation** systems that are fundamental to airplane operations. This may occur, for example, if the ionosphere becomes highly ionized and attenuates rather than reflects the High Frequency (HF) radio waves that airborne planes use to send and receive critical information. Communication and navigation capacities may similarly be diminished when electromagnetic radiation from a space weather event introduces sufficient noise to significant lower signal-to-noise ratios [*Jones et al.,* 2005; *Cannon et al.,* 2013; *Baker and Lanzerotti,* 2016]. Effects may also result from enhanced levels of particulate radiation given its ability to penetrate matter and deposit energy. Neutrons, for example, are thought to be particularly effective at penetrating and depositing energy inside the silicon microchips that control a growing number of airplane electronic ("avionic") equipment. Such effects involve an individual incident neutron and are therefore referred to as Single Event Upsets (SEUs) or **avionic upsets** [*Dyer et al.,* 2000; *Normand,* 2001; *Campbell et al.,* 2002; *Dyer,* 2002]. SEUs may cause either soft or hard errors such as bit flips or circuit latch-ups and burn-outs. Particulate radiation can also penetrate human cells and may directly break down deoxyribonucleic acid (DNA) strands in tissue or produce free radicles in biological tissues that may alter cellular functions. Space weather is therefore also potentially hazardous to those onboard aircraft where potential **radiation exposure** at high dose rates received at airplane altitudes may be significant [*Butikofer et al.,* 2008; *Dyer et al.,* 2003; *Langtos and Fuller,* 2003; *Getley et al.,* 2005; *Getley et al.,* 2010], potentially leading to adverse health outcomes such as increases in the risk of cancer and lower cognitive ability of unborn fetuses.

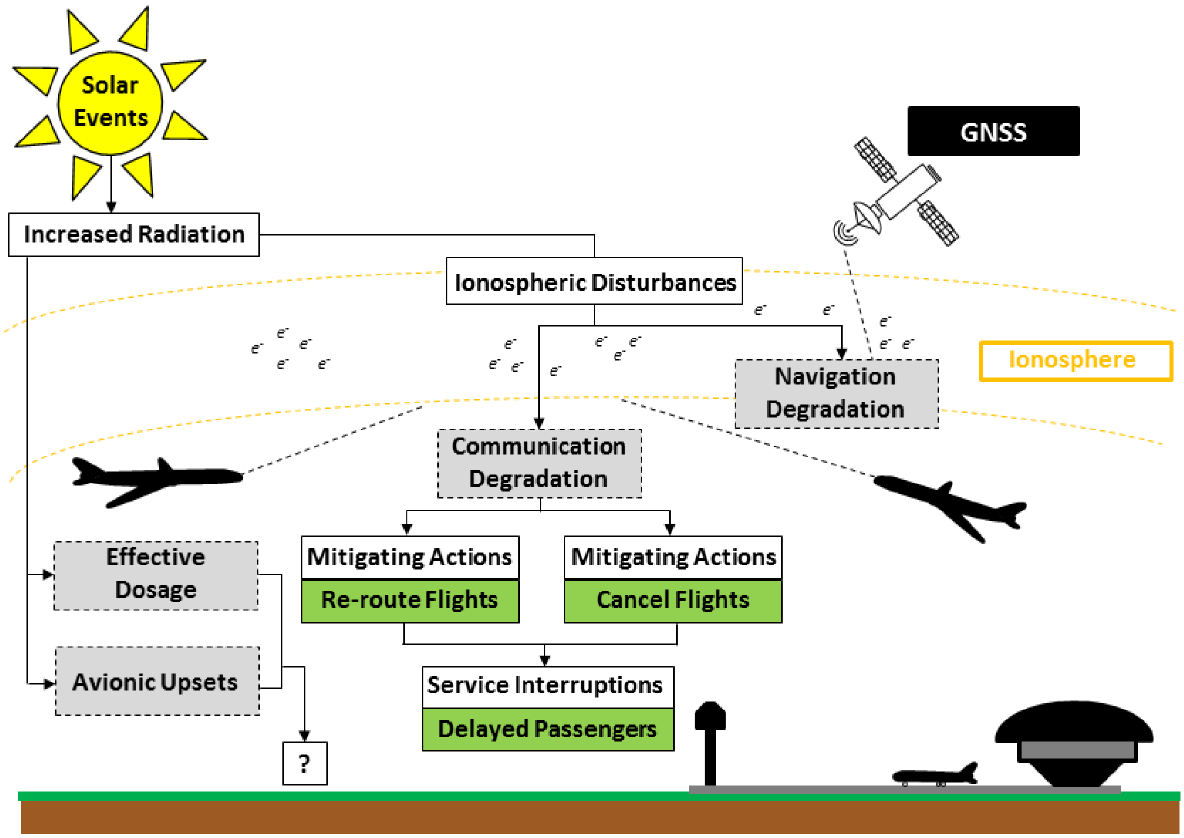

Figure 8. Impact mechanism diagram for aviation outlining the primary causal pathways from a solar event to physical effects (grey boxes) that can in turn cause a variety of social and economic impacts (green boxes). Note that our illustration depicted is not to scale, not comprehensive, and should be revised with future input from stakeholders to ensure it captures largest potential concerns.

6.2 Stakeholder Perspectives on Impacts

Our first phase of stakeholder outreach involved hour long phone calls with 6 individuals with expertise on space weather and aviation. We used our impact matrix to guide these conversations and to systematically collect input on the known physical effects of space weather on aviation and the types of impacts that each may cause. Our final impact matrix is presented below (Table 24) along with additional and important insights from these conversations, including definitions and notes on the various physical effects (Table 25) and impacts (Table 26). The remainder of this section provides a high-level overview of what we learned from these stakeholder discussions.

Depending on roles and responsibilities, industry stakeholders emphasized different concerns about the known physical effects of space weather on aviation (Table 25). Airplane manufactures, for example, were most concerned about safeguarding airplane electronics ("avionics") against Single Event Upsets (SEUs). Although critical avionic equipment and circuits are rigorously designed and tested to minimize the potential problems that SEUs can cause, they explained how this hazard is continuously evolving in complexity alongside other industry trends such as the increasing dependence on aircraft computers, shrinking chip sizes, and increasing flight altitudes. Airplane operators on the other hand were primarily concerned about space weather's potential to disrupt different communication technologies, especially High Frequency (HF) radio which to date remains an important mode of communication especially along polar and oceanic routes. Many stakeholders noted that the nature of this effect may change in the future, as satellite communication technology which has different vulnerabilities to space weather (e.g. see Link Disruptions in the Satellite section) is increasingly adopted across the industry. Stakeholders working more directly on a range of aircraft safety issues expressed unknown but potentially growing risks from the increasing role of GNSS in airplane navigation combined with the decommissioning of ground based navigation aids around the world. And lastly pilots, flight attendants, and representatives throughout the industry also expressed concerns about exposure to enhanced level of radiation that could occur if flying at altitude during a space weather event.

Stakeholders were able to readily populate our impact matrix with many examples across the different impact categories (Table 26). Stakeholders spoke at length about the substantial number of Defensive Investments made across the industry that protect against the impacts of space weather events but also stressed that such investments are made to ensure and enhance the safety and efficiency of airplane services against all-hazards (e.g. terrestrial weather, bird strikes, terrorists, etc.). Stakeholders with experience working in polar-regions were most familiar with space weather and noted that potential disruptions to HF radio often prevent airlines from flying planned schedules or routes since the inability of an aircraft to be in continuous contact with Air Traffic Control (ATC) violates Federal Aviation Administration (FAA) law. Although rerouting airplanes around regions where HF radio may be disrupted can be considered an effective Mitigating Action, stakeholders noted that it tends to be costly to airlines in terms of additional fuel, reduced cargo, landing fees, and employee workloads. They also reported a drop in the number of occasions of this occurring in the recent past, due to the relatively calm recent solar conditions. Depending on the circumstances, airlines may also opt to delay or cancel flights depending on where and how long the disturbance lasts. Although infrequently enacted for space weather reasons, all Mitigating Actions are a routine part of the business and are frequently enacted for a variety of reasons and directly cause Service Interruptions for passengers who will then arrive late at their destinations. Although many stakeholders were concerned about potential Health Effects, they stressed that the scientific connection between radiation exposure and health outcomes (e.g. cancer) remain heavily debated and largely uncertain. Many airlines nonetheless take simple precautionary actions such as temporarily lowering cruising altitude if it does not jeopardize aircraft safety for other reasons (e.g. surrounding airspace is uncrowded and sufficient fuel is aboard to compensate for decreased fuel efficiency).

Table 24. Impact matrix populated during stakeholder outreach to better understand how the known physical effects of space weather (Table 25) on aviation can cause different types of impacts. Items in the matrix reflect example impacts and stakeholder perspectives on the differences between impacts that might occur during moderate (normal text) compared to more extreme (italic text) space weather conditions. Question marks denote instances where the physical effect may in theory be able to cause this impact but empirical support is lacking. *Additional details pertaining to a select set of these impacts can be found in Table 26.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damage	Service Interruptions	Health Effects
Communication	• Personnel training • Maintenance of alternative procedures* • Redundant technologies* • Situational Awareness	• Preflight planning • Aircraft schedule/route changes*	• *Accidents?**	• Delays*	
Navigation	• Personnel training • Maintenance of alternative procedures* • Redundant technologies* • Augmentation systems	• Alternative procedures	• *Accidents?**	• Delays*	
Avionic Upsets (SEUs)	• Design & Engineering • Avionic testing • Redundant technologies*	• Equipment inspections • Alternative procedures	• Equipment failure • *Accidents?**		
Effective Dose	• Situation awareness • Inflight measurements	• Preflight planning • Reduce altitude • Post-event analysis • *Aircrew schedule changes*		• Delays*	• Cancer* • Lower Cognitive Ability*

Table 25. Definitions of key effects of space weather on aviation that includes notes from stakeholder interviews on current status and future of each specific impact.

Physical Effects	Definition	Notes from Stakeholder Outreach
Communication	Any degradation or interruption in the signal used to transmit information to/from an aircraft and therefore can potentially cause the degradation or disruption of communication systems.	• Most frequently a problem for routes still reliant on High-Frequency (HF) radio (e.g. polar, high-latitude, and oceanic). These routes are also some of the most profitable in an industry with small margins. • Importance of effects in the polar region is relatively recent, starting after Russian airspace opened in 2001 and after long-haul aircraft with sufficient ranges were built. • Communication problems could decrease in future if more airlines move away from HF radio to usage of satellite communications. Currently, these services (e.g. IRIDIUM or INMARSAT) are proving beneficial. • Communication problems could also decrease if industry adopts technologies with Ka-frequencies. Ka-frequencies are not currently utilized due to problems with rain fade but the industry is actively working to overcome issues due to their higher bandwidths. • Potential decreases could be offset by increase in air travel. Impacts in future could still increase if a larger number of airplanes/people are impacted by an event.
Navigation	Any degradation or interruption in the signal used to transmit information to/from an aircraft that can potentially cause the degradation or disruption, or failure of navigation systems.	• A number of navigation systems utilized by an airline can be impacted (e.g. Radar, Satcom) but main concern is interruption to GPS-based navigation (e.g. WAAS). • Impact largely unknown due to recent increase in GNSS over recent years. It may cause a real problem or just be nuisance creating more workload for pilots. • Although less frequently observed in mid-latitude areas, problems have most potential to be problematic here given the higher volume and density of air traffic. Navigation problems only apply to approaches/landings and may be growing issue due to decommissioning of ground based navigation aids.
Avionic Upsets (SEUs)	A random, non-permanent soft error in the digital systems that are the foundation of airplane electronic ("avionic") equipment.	• SEUs are a well-studied and understood phenomenon that engineers expect to happen and therefore design accordingly (e.g. radiation hardened microchips, voting systems in circuits, and error detection/correction software). • SEUs have potential to cause problems in digital electronics but infrequently do. • The more critical a system is, the more engineering goes into it. Avionic equipment must surpass tight standards and often undergo testing and accreditation by third parties to ensure the integrity of their performance at inflight conditions. Unclear the degree to which space weather events are addressed by industry design standards. • Problem is likely to increase in future due to technological trends including increased usage of electronics, the miniaturization of silicon chips, and use of commercial off-the-shelf technologies. • SEUs are also caused by internal processes (e.g. interconnect coupling) so determining precise cause of any given SEU is hard. • Cabin equipment manufacturers are starting to put time and effort into SEUs because glitches in performance of entertainment equipment can degrade airline brand.
Effective Dose	Absorbed ionizing radiation dose weighted for the radio-sensitivity of each organ and the type/energy of radiation.	• Largest exposure in polar/high-latitude regions and on long haul flights. • Very sensitive topic, empirical evidence linking exposure to effects is lacking. Uncertainties lead to wide variety of responses within industry. • Stewardesses and pilots have mixed concerns, caring about potential health issues but also potential loss of work (e.g. restricted hours or early retirement) if regulations were established. • Problem is likely to remain and be key concern in future since, unlike other impacts, there is no foreseeable technological fix (e.g. shielding thickness required would be uneconomical). • Unlikely that the scientific uncertainties will be resolved in near future. Certain airlines nonetheless take issue serious even though there are no regulations in place about annual dose limits. • Exposure levels may increase in future if airlines continue trend of offering longer and higher altitude flights. On the other hand, exposure levels may decrease if more airlines start considering exposure in route and schedule planning for flights or key personnel (e.g. pilots, stewardesses).

Table 26. Additional details on a select set of space weather impacts in our impact matrix (Table 10) identified during stakeholder outreach.

Impact Category	Examples	Definition	Notes from Stakeholder Outreach
Defensive Investments	Maintenance of alternative procedures	Retaining the capacity for a range of alternative procedures (e.g. non-precision approaches) under sub-optimal operating conditions requires infrastructure, published information (e.g. book, maps, etc.), and trained personnel.	• Very expensive but invested in due to range of hazards faced by industry. • Space weather events are more likely to change take-off and landing procedures rather than inflight procedures. • Key personnel are trained to follow specific procedures if a given condition arises. Although helpful against potential problems caused by single event effects, tends to be more relevant for communication/navigation problems. For example, fall back on traditional navigation aids if space weather renders GNSS navigation unavailable. On an event-by-event basis, the additional workload for personnel may be more of a nuisance than costly.
	Redundant technologies	Airlines are required by law to have multiple systems that can be used to maintain continuous communication and navigation capabilities.	• Very expensive but invested in due to range of hazards faced by industry and fundamental importance of safety. • Capabilities of redundant (e.g. backup) technologies are still very high and automatically enacted so their utilization is typically seamless.
Mitigating Actions	Aircraft schedule and route changes	Deciding to delay an aircraft from taking off or to fly a different route than planned in anticipation or reaction to a space weather event.	• Most often a precautionary decision based on information provided by SWPC or other commercial providers. • Delays are usually minor since many events tend to be short lived. • Most common for polar routes and high-latitude routes where it may occur a couple to a handful of times per year. May happen more frequently in future as we transition from solar minimum to maximum. • A variety of factors need to be considered and downstream logistics need to be coordinated. Economic consequences become non-linear if changes cause crew to run out of workable hours.
Asset Damages	Accidents	Any incident resulting in physical damage to an aircraft due to space weather.	• Could in theory happen due to physical effects (inability to communicate, failure of critical equipment, or erroneous positioning/navigation information). Not clear that this has ever happened to industry. • Would be a hard to attribute to space weather, especially for moderate sized events.
Service Interruptions	Delays	Passengers on aircraft arrive late to destinations when airlines make various Mitigating Actions (e.g. delays, reroute changes) to reduce risk of space weather impacts.	• Not clear how often it happens, especially outside polar-regions. • Notable example was a relatively recent event in Sweden. Airspace was shut down since due to solar interference with radar systems. • Costs increase quickly for rerouting if crew runs out of time and there are no replacements (e.g. in remote areas)
Health Effects	Cancer	Increase in risk of cancer due to elevated exposure received while at airplane altitudes. Potentially relevant components of health cost include direct treatment costs (e.g., hospital bills), the costs of pain and suffering, the costs of lost life-years, and lost earnings.	• Most relevant for those spending a lot of time in air (e.g. pilots, stewardesses, frequent flyers) or those in the air during a severe event. • Now that internet services are offered in flight, informed passengers may access space weather alerts and advocate from cabin that pilots reduce altitudes. It is not clear how frequently this happens but it is a concern. • Health concerns may not outweigh lost income concerns if limits were set (e.g. early retirement). • Large uncertainties about actual exposure (e.g. not measured onboard aircraft but estimated/modeled) and linkages lead to diverse opinions. • Could lead to class action lawsuits although not clear if currently happening for this reason.
	Lower Cognitive Ability	Increase in risk that unborn children in utero will have lower cognitive ability due to exposure received while at airplane altitudes.	• Large uncertainties about linkages lead to diverse opinions. • Could lead to class action lawsuits although not clear if currently happening for this reason.

6.3 Cost Estimates

In order to translate our findings into quantitative cost estimates reflective of the most concerning and potentially largest impacts, we conducted a second round of stakeholder outreach. Most stakeholders suggested that we focus our quantification on impacts stemming from how space weather events affect High Frequency (HF) radio communication. This effect therefore underpins the costs estimates we developed for Mitigating Actions (~$400,000 to ~$5 million for our moderate event scenario and ~$1 million to ~$30 million for our more extreme event scenario) and Service Interruptions (~$900,000 to ~$5 million for our moderate event scenario and ~$6 million to ~$200 million for our more extreme event scenario). The cost estimates for Mitigating Actions capture the costs of rerouting planes away from polar-regions during a moderate event and canceling flights in the continental U.S. under a more extreme scenario. Since these Mitigating Actions disrupt normal air traffic, our cost estimates of Service Interruptions therefore consider how these decisions in turn impact airline passengers in terms of their lost time. Although we examine the impacts stemming from potential disruptions to High Frequency (HF) Radio, note that this impact may decrease in the future as the industry continues to lessen its reliance on this communication technology. Key insights gleaned from our second round of stakeholder conversations are provided below alongside a description of how they influenced the derivation of our cost estimates.

Table 27. Simplified aviation impact matrix with the focus of our cost estimates highlighted in yellow. The presence (or absence) of a circle denotes where we were able to connect a given physical effect to a particular impact category during our first round of stakeholder outreach (see Table 25 for a list of items represented by each circle). Closed circles denote that the physical effect is known, from direct past experience, to cause impacts of that particular category. Open circles indicate that the physical effect may cause that particular type of impact but the linkage presently lacks empirical support.

Physical Effects	**Impact Categories**				
	Defensive Investments	Mitigating Actions	Asset Damages	Service Interruptions	Health Effects
Communication Degradation	●	●	○	●	
Navigation Degradation	●	●	○	○	○
Human Exposure		●		○	○
Avionic Upsets	●	○	○	○	○

6.3.1. Mitigating Actions

We estimate that a moderate space weather event may cost the U.S. airlines ~$400,000 to ~$5 million, with a more extreme scenario that may cost ~$1 million to ~$30 million. Our estimates reflect how airlines are apt to respond to the potential loss of HF communication capabilities, and are therefore based on some initial assumptions about the duration and location of potential HF Radio disruptions. In our moderate scenario, a HF Radio outage in the polar-region causes operators to reroute their polar-flights for 1 day. The outage in our more extreme scenarios lasts for 1-3 days and results in the cancellation of ~1-10% of all domestic flights. Our stakeholders emphasized that rerouting or cancelling flights in anticipation or in reaction to an ongoing a space weather event are precautionary measures. They reduce the risk of more serious impacts that could in theory occur, for example accidents or collisions, if airplanes are unable to communicate important information with one another and/or with ground control. However, there is not enough information at this time to defensibly quantify the potential impacts that could results if such Mitigating Actions are not enacted.

6.3.1.a. Moderate Event Scenario

We estimate that a moderate space weather event may cost U.S. airline operators ~$400,000 to ~$5 million. This estimate is based on a series of stakeholder discussions about moderate events, which are known to affect HF communications in polar-regions and therefore only impact airline carriers flying polar routes. According to polar operators, there is a standard industry response to moderate space weather events. When NOAA's Space Weather Prediction Center issues a storm watch that is S3 or greater, they reroute all of their planned polar flights to lower latitudes. They further noted that the pre-flight decision-making process typically occurs in daily increments so it is appropriate to assume that an anticipated event will impact a full day of flights even if the HF disturbance created by a moderate event only lasts for a small fraction of a day. Our cost estimate outlined below therefore involves combining information on the costs of polar rerouting, the number of flights rerouted, and the percentage of polar flights operated by U.S. carriers.

We need to first understand the costs associated with polar rerouting. The most widely cited figure for this Mitigating Action is ~$10,000 to $100,000 per flight [*NOAA*, 2004]. Although it in unclear where this estimate came from, our stakeholders were also somewhat uncertain about the actual costs involved. They reacted to this cited number favorably while noting that ~$100,000 is not typical but is reasonable as an upper limit. They further noted that the reported range captures the increased and variable costs of flying non-polar routes. Longer distances between destinations increases fuel consumption, travel time, and can often require additional stops plus landing fees for refueling and crew changes. This range is also consistent with reported costs savings of example polar flights (Table 28). One stakeholder noted that there are currently ~16 polar-routes, so this table includes a small sample of all polar routes flown by different airlines. We therefore assume the reported range for the costs of polar rerouting of ~$10,000 to $100,000 per flight [*NOAA*, 2004].

Table 28. Example time and cost savings of polar routes for a set of example city pairs.

City Pair[1]	Time Savings[1]	Cost Savings (Canadian $)[1]	Cost Savings (USD)[2]
Atlanta to Seoul	124 minutes	$44,000	~$41,000
Boston to Hong Kong	138 minutes	$33,000	~$31,000
Los Angeles to Bangkok	142 minutes	$33,000	~$31,000
New York to Singapore	209 minutes	$44,000	~$41,000

[1]Source: AMS, 2007
[2]Values converted to 2016 USD based on the mid-year 2004 currency conversion of 0.74605 USD per CAD (www.xe.com) and the U.S. BEA's GDP price deflator value of 1.2505 to adjust from 2004 to 2016 (www.bea.gov).

Our next step involved an assessment of the number of polar flights that would be rerouted. We were able to find a publically available document reporting that there were over 15,000 polar flights in 2015 [*Nav Canada*, 2016]. This suggests that a moderate event impacting polar operations for one day might result in the rerouting of ~41 flights

(=~15,000 flights per year/365 days per year). Our stakeholders noted that polar air traffic is steadily increasing but that such information is not captured and cannot be derived from publically available flight data. The US Bureau of Transportation Statistics dataset, for example, only provides flight counts into and out of airports but does not provide information about the route that these planes took. Such information is logged, however, by different entities responsible for monitoring and controlling polar airspace. Stakeholders at the FAA and those affiliated with the Cross Polar Working Group were able to provide us with more recent and detailed polar flight statistics data by month. In 2016, there were a total of 15,815 polar flights with an average of 40.2-48 flights per day depending on the month (Table 29). Data available for 2017 suggests a slightly higher daily average that ranges from 44.6-50.4 flights per day. To capture the lower and higher end of these recent summary statistics, we simply assume that our moderate event involves the rerouting ~40-50 flights (Table 29). One stakeholder further noted that ~100% of airlines operating polar routes remain reliant on HF communications (they are not equipped with polar satellite communications [e.g. IRIDIUM]) and that ~90% of all polar flights are operated by U.S. carriers. Combining all this information together, suggest rerouting costs to U.S. airlines that may be ~$0.4-$5 million (=$10,000-$100,000 per flight x 40.2-50.4 flights per day x 1 day x 0.90 U.S. flights).

Our estimate does not consider the Southern Polar Region given the absence of U.S. carriers and the smaller volume of air traffic. We also do not consider the costs of rerouting flights away from High-Latitude Regions (e.g. those along the North Atlantic Oceanic Track (NAT OTS) and the Pacific Oceanic Tracks [PACOTS]) since stakeholders note that polar flights constitute the vast majority (>95%) of space weather related rerouting.

Table 29. Statistics of polar flight numbers provided by a stakeholder. Note that these numbers are preliminary and should be critically reviewed and examined for consensus among the different entities that collect polar flight data.

	2016		2017	
Month	Total	Average Daily	Total	Average Daily
January	1,256	40.5	1,470	47.4
February	1,126	40.2	1,268	45.3
March	1,312	42.3	1,401	45.2
April	1,228	40.9	1,337	44.6
May	1,291	41.6	1,562	50.4
June	1,300	43.3	1,410	47.0
July	1,350	43.5		
August	1,441	46.5		
September	1,447	48.2		
October	1,329	42.9		
November	1,274	42.5		
December	1,461	47.1		
Yearly	15,815	40.2-48.2		44.6-50.4

6.3.1.b. More Extreme Event Scenario

Under more extreme conditions, we estimate that a space weather event may cost airline operators ~$1 million to ~$30 million. This estimate assumes disruptions to HF communications that are longer-lasting (e.g. ~1-3 days) and also more widespread, extending to lower-latitudes and impacting ~1-10% of all U.S. domestic flights. Our cost estimate also assumes flight cancellations, rather than rerouting as in our moderate scenario, and is therefore based on the number of cancelled flights and the average per flight costs of cancellations.

In our extreme scenario, we assume disruptions to HF communications that are longer-lasting (~1-3 days) and that extend over a larger geographical area that encompasses the continental US. Airlines may therefore be unable to reroute flights around the disturbed area, as in our moderate scenario, and instead need to prevent flights from taking off until the event and the disturbance pattern it created within the atmosphere and ionosphere have both passed. We assume airlines cancel rather than delay flights because stakeholders note that the former is usually the less costly option, and therefore the preferred Mitigating Action, for more prolonged and more extensive air traffic interruptions as envisioned here. We furthermore assume that the outage only impacts ~1-10% of all U.S. domestic flights. This scenario assumption could be interpreted as the total portion of U.S. airspace that may be disturbed or else the percentage of airlines across the U.S. actually impacted by the disturbance which would depend, for example, on the backup communications onboard individual aircraft (e.g. Satellite communications) and their ability to perform under the disturbed conditions. In 2016, the average number of domestic flights in the U.S. was ~21,000-24,000 flights per day (Table 30). Note that we only consider domestic flights since we were unable to find a cost estimate that considers the cost of canceling international flights. This furthermore suggests that our final cost estimate may be conservative. An event that results in the cancellation of ~1-10% of domestic flights for ~1-3 days would therefore impact ~200-7,000 flights (=0.01-0.10 x 1-3 days x 21,000-24,000 flights per day). According to a recent report, there is no generally accepted cost of cancellations for use in government cost-benefit studies but a reasonable estimate of the fixed cost to aircraft operators is ~$5,000 per flight cancellation [*FAA*, 2016]. This suggests that our extreme scenario might cost U.S. airlines ~$1 million to ~$30 million.

Table 30. Monthly statistics describing U.S. Domestic air traffic in 2016.

	2016			
Month	Total Number of Domestic Flight[1]	Daily Average[2]	Total Number of Passengers[1]	Passengers per Flight[3]
January	636,907	~21,000	52,474,764	~80
February	612,287	~21,000	51,112,202	~80
March	697,968	~23,000	61,593,910	~90
April	675,765	~23,000	58,894,484	~90
May	702,507	~23,000	62,751,668	~90
June	713,120	~24,000	64,757,139	~90
July	730,481	~24,000	66,133,058	~90
August	731,594	~24,000	63,497,082	~90
September	672,886	~22,000	58,618,920	~90
October	688,246	~22,000	61,709,276	~90
November	658,300	~22,000	59,270,072	~90
December	662,304	~21,000	59,178,742	~90
Yearly	8,182,365	~21,000-24,000	719,991,317	~80-90

[1]Bureau of Transportation Statistics T-100 Segment data for All Carriers and All Airports. Available at: https://www.transtats.bts.gov/Data_Elements.aspx?Data=1 (flights and passenger data tabs)
[2]Derived by dividing monthly BTS flights numbers by number of days in each month.
3Derived by dividing monthly BTS flight numbers by monthly BTS passenger numbers.

6.3.2. Service Interruptions

In addition to imposing financial costs on the airline industry, space weather events may impact airline end users with estimated costs of ~$900,000 to ~$5 million and ~$6 million to ~$200 million for our moderate and extreme storm scenarios respectively. These cost estimates consider direct impacts to airline passengers who will be delayed because of airline Mitigating Actions, where impacts are assessed using the value of lost time [*Department Of Transportation*, 2016]. Note that there are other end users of airline services, for example, the shipping industry uses airlines to transport freight. There are also other upstream and downstream businesses dependent on airline transport that may be indirectly impacted by these disruptions in air traffic. Although such costs are also involved and important, such topics are beyond the scope of our current analysis.

6.3.2.a. Moderate Event Scenario

We estimate that our moderate event costs airline passengers ~$900,000 to ~$5 million. Recall that our moderate scenario assumes that airlines reroute ~40-50 polar flights (Table 29). Since lower-latitude routes are longer than polar routes, passengers scheduled to fly on these flights would therefore arrive late to their destinations. To derive a cost estimate, we therefore needed to establish the number of passengers impacted by the event, the amount of time they are delayed, and the costs per unit time of their delay.

In order to understand how many passengers may be delayed, stakeholders noted that there are a limited number of aircraft models capable of flying polar-routes and include, for example, those manufactured by Airbus (e.g. models A340, A350, and A380) and by Boeing (e.g. models B744, B77, and B787). Publically available information on these specific aircraft models suggests that one polar flight may carry ~242-615 passengers (Table 31). This suggest that the event may delay ~10,000-30,000 passengers (= ~40.2-50.4 polar flights x ~242-615 passengers per polar flight).

Table 31. Estimated number of passengers transported by various aircraft models flying polar routes.

Manufacturer	Model	# of Passengers
Airbus	A340[1]	250-475
	A350[2]	280-366
	A380[3]	489-615
Boeing	B744[4]	376
	B777[5]	313-396
	B787[6]	242-330
	Range	***242-615***

[1]http://www.aircraft.airbus.com/aircraftfamilies/previous-generation-aircraft/a340family/
[2]http://www.aircraft.airbus.com/aircraftfamilies/passengeraircraft/a350xwbfamily/
[3]https://www.emirates.com/us/english/flying/our_fleet/emirates_a380/emirates_a380_specifications.aspx
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[5]http://www.boeing.com/commercial/777/#/design-highlights/characteristics/777-200er/
[6]http://www.boeing.com/commercial/787/by-design/#/787-10-characteristics

Our next step involved establishing the length of time that these passengers are delayed and the value of their lost time. We assumed that all passengers on these flights are delayed ~124-209 minutes, reflecting lower and upper bounds on the time savings associated with example polar routes (Table 28) [*AMS*, 2007]. Although this information is not a representative sample of all polar routes (i.e. 4 of ~16 routes as previously discussed), we were unable to obtain more precise information from the literature or via stakeholder discussions. We then noted the average value of this lost passenger time at ~$47.10 per person per lost hour (Department of Transportation, 2016). The estimate is also known as the Value of Travel Time Savings (VTTS) and values lost travel time for intercity flights at $36.10 per person per hour for personal travel and at $63.20 per person per hour for business trips. Noting a distribution between personal and business travel that is 59.6% to 40.4%, the weighted average value equates to ~$47.10 per person per lost hour (or $0.785 per minute). Note that the vast majority of polar routes connect the US Eastern seaboard to Asia. If polar routes involve a larger proportion of business-related travel relative to all flights on average, using the average value of lost time may understate the economic impact. Moreover, it is unclear what percentage of people on these flights are U.S. citizens. We therefore simply assume ~90%, to be consistent with our previous assumption about the percentage of polar flights operated by U.S. carriers. Multiplying these estimates together, we arrived at a cost to passengers of $0.9-5 million (=~10,000-30,000 passengers x ~124-209 minutes delayed x ~$0.785 per minute x 0.9 U.S. citizens).

6.3.2.b. More Extreme Event Scenario

Under more extreme conditions, we estimate space weather impacts that could cost U.S. airline passengers ~$6-200 million. This estimate is also based on the value of lost passenger time of ~$47.10 per hour (~$0.785 per minute), as outlined in our moderate event scenario. Recall that our extreme scenario assumes that ~200-6,000 domestic flights are cancelled in the US. This may in turn potentially impact ~80-90 passengers per flight (see Table 30 and footnotes for details). Note that the average lost time per cancellation (e.g. rebooking process, etc.) has been estimated at ~457 minutes per passenger [*FAA*, 2016]. This suggest total costs to passengers of our extreme event that may be ~$6-200 million (=200-6,000 cancelled flights x ~80-90 passengers per flight x 457 minutes per passenger x $0.785 per minute).

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7. Key Findings and Conclusions

This study advances our overall understanding of the potential impacts of space weather and in addition to stimulating timely discussions, provides a solid, tractable foundation for future work. The systematic approach developed for exploring and synthesizing the many qualitative and quantitative complexities of this topic can also be readily applied to other sectors known to be impacted by space weather (e.g. trains, pipelines). Further, this study is based on scientific and engineering literature addressing space weather events, and expert stakeholder understanding of the physical effects and key concerns. Below we summarize several initial key findings from this study:

1. Space weather impacts are a real concern

The concept of "space weather" has advanced over the past decade from something mostly known to space researchers to a topic of concern to policy specialists, public officials, and many in the general public. Specifically, three key policy efforts were recently issued regarding space weather: the October 2016 Executive Order entitled "Coordinating Efforts to Prepare the Nation for Space Weather Events," the "Space Weather Action Plan" issued by the Office of Science and Technology Policy in October 2015, and the "Space Weather Research and Forecasting Act" introduced as Senate Bill 2817 in April 2016. There is also traction internationally, with a handful of other socioeconomic impact studies underway, as well as a United Nations and US workshop on the International Space

Weather Initiative held August 2017. Industry stakeholders contacted for this study demonstrated evidence that space weather has the potential to cause significant impacts and support the development of improved understanding of the hazards, risks, and costs.

2. Stakeholders are interested and committed to helping

Contrary to popular belief, industry stakeholders have been very forthcoming with information; this may be in part related to the fact that they have a vested interest in the quality of the research that is being done. Stakeholders were very responsive to our inquiries. They emphasized the importance and challenges involved and generously provided their time, insights, and feedback to help guide and strengthen our endeavor. Stakeholders were also able to readily discuss and connect the physical effects identified for their sector to our five different impact categories. Many emphasized, however, that almost all of the impacts we identified also apply to other non-space weather hazards. Overall, stakeholders helped shape our ultimate approach and inform our assumptions, and were thrilled that this effort aimed to capture their understanding and perspective on the issue.

3. Impacts are complex and not well understood

The social and economic impacts of space weather intersect the fields of physics, engineering, industry operations, and economics. A limited number of previous studies have assessed the social and economic impacts of space weather. Some of the complexities include modern society's lack of a direct experience of a severe space weather event, the rapidly evolving technological advances, and impacts that are not directly proportional with storm magnitude. Though our study initiated as an economic-centric approach, it was quickly evident that the problem first requires analytical mapping of space weather events and the physical effects by sector to the downstream social and economic impacts. Additionally, stakeholders engaged in this study emphasized that it is intractable at this point in time to rigorously connect the magnitude of a space weather event to our list of physical effects and ultimately to the types and sizes of the impacts that may result. To this end, we developed an analytical framework that accounts for much of the complexity and can accommodate additional information as it is acquired. Our study produced cost estimates using expert opinion and existing data and identified additional research needed to further refines these estimates including the estimation technique.

4. Demonstrated value of defensive investments and SWPC science

The estimated costs of proactive measures that prevent impacts are low compared to the impacts that could be realized during space weather events. Our cost estimates suggest that preventative expenditures associated with Defensive Investments and Mitigating Actions tend to be small relative to the much larger potential costs that result from the other impact categories including Asset Damage, Service Interruptions, and Health Effects. These *proactive* costs are an indication that such investments might payoff, though we did not explore the reduction in economic impacts enabled by Defensive Investments or Mitigating Actions. Scientific research on space weather contributes knowledge that is essential for designing and engineering robust and safeguarded systems Stakeholders discussed the central importance of space weather products and services as trigger points for Mitigating Actions such as the forecasts and alerts provided by NOAA's SWPC (Figure 1). Many stakeholders also noted that a severe event may cause disproportionate impacts in regions that do not experience more moderate space weather events since they lack the familiarity, training, and preparedness that accompanies more frequent exposure to potentially hazardous conditions.

5. Applicability of study to the value of NOAA's investments and to inform program planning

This study has implications to help inform the value of science and forecasting investments and to improve the focus of investments relevant to societal outcomes (e.g. areas subject to significant impacts). A necessary first step in assessing the value of improving NOAA's forecasting capabilities is the ability to estimate the economic impacts. These economic impacts cannot be estimated without understanding the impact of space weather across key technological sectors. Only after these impacts are understood, a value chain linking research and forecast investments to societal outcomes can then be produced and used to make decisions about where to invest. Specifically, NOAA can prioritize investments in new products and services that demonstrate a clear linkage to improving societal outcomes. This effort is the critical first step towards developing an approach for transparently establishing priorities that maximize societal value.

Additionally, the analytical framework developed in this study identifies some initial information on who uses NOAA's products, services, data and science; how they use it; and how they benefit from it. While specific NOAA staff might have access to this information, a concerted effort should be made to identify the information that is being collected, how it can be used in programmatic evaluation and planning, and how to make it accessible. One possible approach discussed amongst the study team and relevant for this study is to release the final report with a request and mechanism that will allow anyone to respond to the findings. This might entail, for example, the establishment of a dedicated email account or Google Form inviting feedback and comments. This would allow a wider variety of individuals to constructively contribute their knowledge and thoughts to this effort. This repository of input could help establish future collaborates and also provide a wealth of ideas for future work to pursue.

8. Recommended Next Steps

The goals of this initial NOAA effort were to capture, synthesize, and share what is currently known about the social and economic impacts of space weather. In order to advance our collective understanding of this important but not well studied topic [*Eastwood et al.*, 2007], we encourage others to challenge, expand, and refine what is presented herein. We furthermore recommend the following next steps that we think are essential for this is to become a more tractable research problem that others can productively contribute their knowledge and expertise to. Next steps are listed in order of priority, with short-term steps requiring relatively less effort that escalate into longer-term steps requiring more substantial effort.

Critical Review

This interdisciplinary study spans a large number of scientific, engineering, and economic topics. We tried our best to carefully include essential technical details and key concepts from each of these fields into our analysis. Although our effort was guided by extensive input and iterative feedback from stakeholders and experts, it is important for this report to be further critically reviewed by knowledgeable individuals not yet engaged. To this end, the study team will be submitting this work to a journal for publication at the conclusion of this project. In addition to the critiques and revisions that will accompany the peer-review process, contributing our analysis to the literature is essential for stimulating much needed research interest and attention on this topic.

Discuss Findings

This initial effort attempts to fill a large knowledge gap that is essential to other ongoing efforts and timely discussions within the U.S. and abroad. The contents of this report should be considered preliminary and this document viewed as a tool for stimulating critical discussions that need to occur within and across different technological sectors, institutions, and disciplines. To this end, we recommend that NOAA and/or other entities use this document as a mechanism for soliciting input, fostering dialogue, and building the working relationships necessary for advancing our understanding of this important but challenging real-world issue. This could occur, for example, via round table discussions, the establishment of a dedicated email account, and/or an online community forum. It is essential to create a variety of easy opportunities for a wider variety of individuals to contribute their knowledge and this would also help foster future collaborations.

Establish Best Practices

The growing recognition of space weather's ability to cause social and economic impacts has led to a handful of recent and concurrent studies on the topic by other countries and research institutions [e.g. *National Research Council*, 2008; *Biffis and Burnett*, 2017; *Oughton*, 2017; *Luntama et al.*, 2017]. Our study team has had limited but insightful interactions with representatives of these other efforts. At the 2017 Space Weather Workshop, for example, we came together for a day-long exchange to better understand similarities and differences in terms of project scopes, challenges, and methodologies. We collectively agreed that at the conclusions of our independent efforts, it would be fruitful to more thoroughly debrief and discuss our experiences as well as compare and contrast our different studies including approaches and findings. This could, for example, lead to a clear articulation of the various challenges inherent to this type of an analysis and the establishment of best practices for studying space weather impacts. This can help guide those wishing to conduct similar studies, allowing them to learn and build from these early efforts. This is also important since some of these efforts are not yet, and may not become, publically available.

Conduct Case Studies

This study establishes an initial, transparent methodology for deriving quantitative estimates of various categories of impacts across our four different sectors of interest. Our effort was in part restricted by our inability to find well documented, detailed accounts of impacts observed during historic space weather events. A more extensive consideration, application, and verification of our estimation techniques to the impacts that we have collectively observed as a society, in the form of case studies, should be central to future efforts. At this point in time, for example, it is unclear whether or not the information necessary for this recommended next step exists and/or is publically available. Clearly establishing what needs to be known in the advent of an event will enable the rapid collection, rigorous assessment, and quantitative reporting of impacts associated with any future events. This has been essential for strategically managing and responding to other natural hazards (e.g. hurricanes, tornados, earthquakes, tsunamis, etc.). This is especially timely since we are entering a new solar cycle, with an anticipated upswing in solar activity.

Analyze Sensitivity

This study identifies key variables and parameters that need to be known in order to estimate impacts. In many instances, we were unable to find the appropriate data for constraining these inputs and therefore relied upon expert best judgement or used order of magnitude assumptions based on available but coarse information sources. A more robust exploration of estimate sensitivity and parameter space would help diagnose where more detailed information is necessary for reducing the uncertainties in our cost estimates. For example, it would be helpful to at the very least understand which inputs change our cost estimates by factors versus by orders of magnitudes.

Add Context

This study explored the full spectrum of potential impacts and then, considered in more depth those that seemed to be the most significant as identified by stakeholder discussions. Before refining these estimates or proposing additional estimates for impacts not quantitatively covered in our report, we recommend adding context to the numbers presented herein. This could include an assessment of how potential costs compare to other costs within the industry including those imposed by other natural hazards and also how these costs may be increasing or decreasing with time to better understand what issues may be growing or diminishing within these industries. Such context is essential for truly understanding the importance of these impacts and can help establish clear priorities for future research.

Update Estimates

Research on this topic requires a sustained attention and iterative effort for it to advance and keep pace with our growing technical understanding of space weather and our modern society's rapidly evolving dependence on potentially vulnerable technologies. Impacts not only depend on technologies but also on various business and governmental changes. The opening of Russian airspace for polar flights, for example, introduced new airline vulnerabilities to moderate space weather events. Policies instated across the power sector, including those by Federal Energy Regulatory Commission (FERC) and National Energy Regulatory Commission (NERC), may soon reduce the probability of impacts to electricity across all sized space weather events. A better understanding of impacts will occur through many different U.S. Space Weather Action Plan (SWAP) efforts including the finalization of benchmarks for an extreme event [*Executive Office of the President,* 2017] and the vulnerability assessments of our nation's Critical Infrastructure [*Executive Office of the President,* 2015a,b]. Keeping pace with change and incorporating the results of concurrent efforts is essential if this work is to stay current and relevant to decision making and policies.

Explore Interdependencies

This study independently considers impacts to the U.S. of space weather events resulting from four different technological sectors. We did not consider impacts that may result, for example, due to the known effects of space weather on other important sectors (e.g. trains, pipelines, etc.). We also did not consider potentially more catastrophic scenarios due to the known coupling between different sectors and also different space weather phenomena. Nor did we explore any of the international dimensions of this problem, including impacts that may result abroad as a result of U.S. impacts or else impacts that may result in the U.S. due to the impacts of space weather on other countries. These additional considerations and complexities should be carefully examined and considered as we begin to better understand impacts across different sectors and across different countries.

8.1 References

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