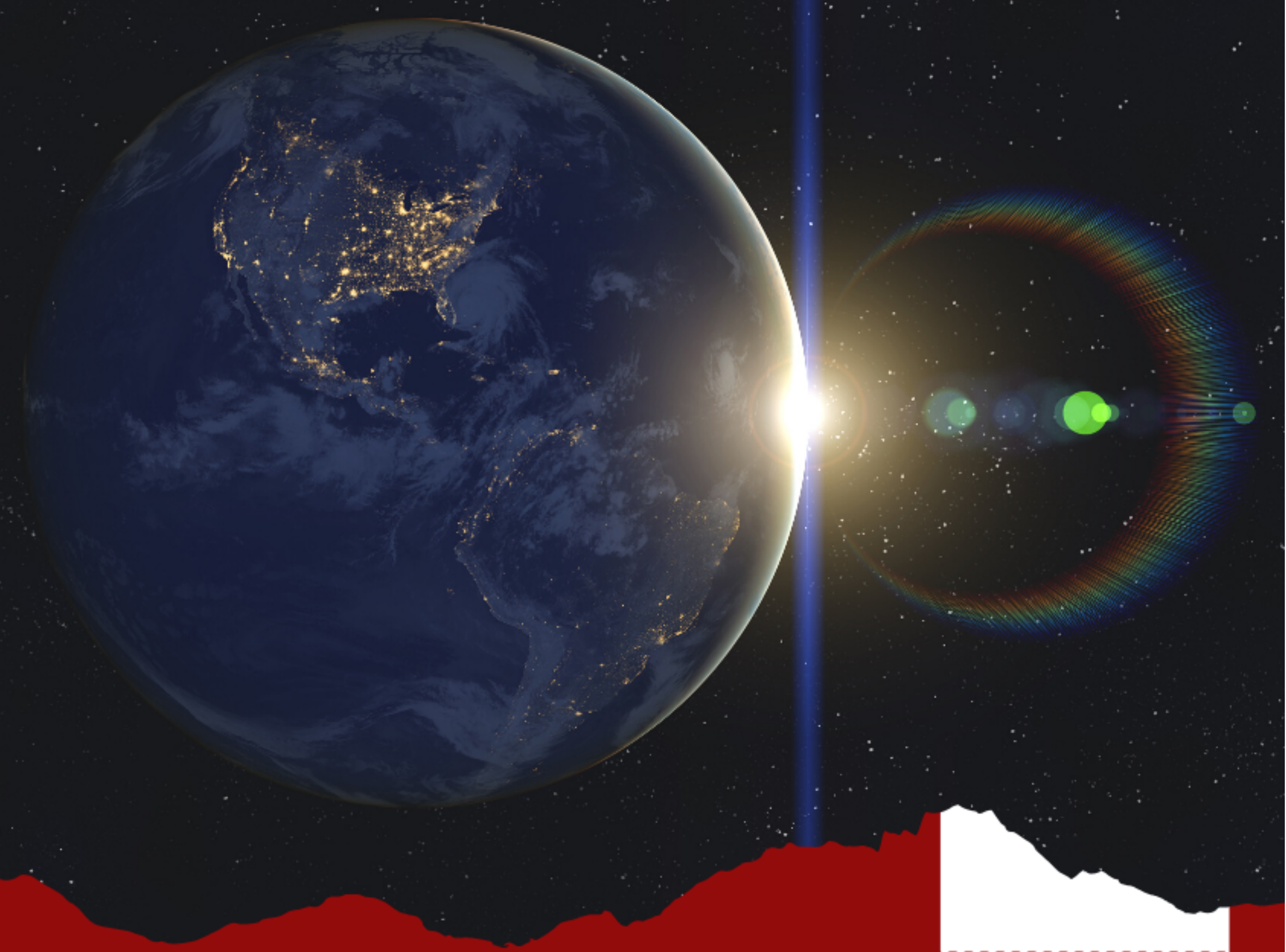

US Security Threatened by Solar Storm Impacts on Earth- and Space-Based Technologies

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Executive Summary

In 1859 the strongest recorded solar storm disrupted telegraph systems around the globe. Today, solar storms not only impact current communication systems but the electrical grid, GPS, and satellites. If an extreme solar storm similar in strength to the 1859 Carrington Event occurred today, the consequences for US security could be severe as many critical services and capabilities depend on the earth- and space-based technologies that would be affected. The probability that a Carrington Event level storm will occur is low, but statistically, one will occur. It is not a matter of if but when, and therefore the issue cannot be overlooked.

Solar storms occur when the sun's magnetic field lines become over-twisted and snap, like a rubber band. When the sun's magnetic field lines snap, either an expulsion of plasma with an embedded magnetic field, known as a coronal mass ejection (CME), or electromagnetic radiation, known as a solar flare, is released. If CMEs and solar flares reach Earth they will interact with the Earth's ionosphere and magnetosphere, which can impact technologies on earth and in orbit. CMEs and solar flares can cause damaging currents in the electrical grid, increase atmospheric drag on satellites which can lead to satellite collisions, disrupt the Global Positioning System (GPS) and high frequency (HF) radio signals, and produce radiation that can damage human DNA and satellite electronics. The impacts solar storms have on technology are of significant concern due to the dependence of critical infrastructure and functions on these technologies. Taken together, electrical grid service disruptions, satellite damage, GPS and HF radio communication interruption, and radiation exposure caused by solar storms would have severe national security, economic, and human health and safety consequences.

It is impossible to control the sun's magnetic field and prevent solar storms from occurring. Therefore, to protect critical technology from the effects of solar storms the focus must be on resilience, or how to prevent system failure when a solar weather event does occur. Several resilience measures can be implemented to protect earth- and space-based technologies as well as dependent infrastructure and functions from the impacts of solar storms. Improved solar storm models will help develop more accurate solar storm forecasting and provide a better understanding of how solar storms impact technology in space and on Earth. A range of resilience measures can also be pursued specific to the various technologies impacted such as hardening, upgrading, or updating critical systems, ensuring there is redundancy in systems, and implementing alternative systems to increase diversity in key functions.

Introduction: Solar Storms as Low Probability, High Impact Events

In 1859 the strongest recorded solar storm—named the Carrington Event after Richard Carrington, one of the astronomers who observed and recorded the storm—disrupted telegraph systems around the globe.[1] Electrostatic discharges shocked operators and ignited fires, and induced currents in the telegraph lines allowed messages to be sent even after batteries were disconnected.[2] Today, solar storms not only impact current communication systems but the electrical grid, GPS, and satellites. If an extreme solar storm similar in strength to the Carrington Event occurred today, the consequences for US national, economic, and human security could be severe. Many critical services and capabilities depend on the technologies that would be negatively affected. The probability that a Carrington Event level storm will occur is low; studies published in 2019 by the Autonomous University of Barcelona and in 2020 by University of Warwick placed the probability of an extreme solar storm between 0.46% to 1.88% in the next decade and 0.7% each year, respectively.[3] While the probability at any given moment is very low, statistically, an extreme solar storm will occur.[4] It is not a matter of if but when, and because of this, researchers stress the issue should not be overlooked. A solar storm of this magnitude will have significant consequences and there is currently no way to predict when such a storm will occur, so there will be little time to react when an event does happen.[5]

Solar Storms Threaten Critical Technologies on Earth and in Space

To understand the threat of solar storms it is necessary to understand the mechanics of solar storms. Unlike the Earth which rotates at a constant rate, different areas of the sun rotate at different rates, known as differential rotation, which twists the sun's magnetic field lines over time like a rubber band.[6] This leads to areas of concentrated magnetic field lines which suppress plasma on the sun's surface and prevent convection, causing the temperature to decrease.[7] The areas of low temperature appear as sunspots.[8] Plasma from the sun's surface can move along the twisted magnetic field lines and loop up into the sun's atmosphere to form a structure known as a solar prominence.[9] Solar prominences can reach hundreds of thousands of miles into the sun's atmosphere and persist for several days.[10] When the magnetic field lines become over-twisted, they snap, again like a rubber band, and the material trapped in the solar prominences is released as an expulsion of plasma with an embedded magnetic field, known as a coronal mass ejection (CME).[11] When the over-twisted magnetic field lines snap, they can also release a solar flare or electromagnetic radiation, a form of energy that includes radio waves, microwaves, and very energetic and harmful x-rays and gamma rays.[12]

CMEs and solar flares can be associated with each other but do not have to occur together.[13] Both CMEs and solar flares, along with emitting magnetic field embedded plasma and electromagnetic radiation, accelerate energetic charged particles ejected by the sun.[14] If CMEs and solar flares propagate in the direction of Earth, electromagnetic radiation travels at the speed of light and will arrive at Earth in eight minutes.[15] In less than an hour, energetic charged particles will be the next to reach the Earth.[16] Finally, the CME will reach Earth, in 15 hours to several days depending on the propagation speed.[17] If the radiation, particles, plasma, and magnetic field released by the sun reach the Earth they will interact with the Earth's ionosphere and magnetosphere, which can impact technologies on earth and in orbit.

Geomagnetically Induced Currents in Electrical Grid

When the magnetic fields embedded in the plasma of a CME interact with the Earth's magnetosphere—the region in the near-Earth space environment dominated by the Earth's magnetic field—they create intense, time-varying currents in the magnetosphere and ionosphere, the part of the Earth's upper atmosphere where solar radiation ionizes atoms and molecules, creating a layer of electrons.[18] The variations in the currents cause rapid changes in the magnetic field which induces an electrical field on the Earth's surface, a process known as Faraday's Law of Induction.[19] The electric field generates currents, known as geomagnetically induced currents (GICs), in conductors on the ground such as electrical grids, pipelines, communication systems, and railway systems.[20] It is these GICs that disrupted telegraph lines around the globe during the Carrington Event. In the modern electrical grid, GICs can cause service disruption, and worse, permanently damage transformers, which are critical components of the electrical grid.

Service disruptions occur when GICs trip grid protection systems. Electrical grid protection systems consist of sensors that monitor different properties such as temperatures of transformer cores, variability of power levels, and induction fields.[21] These inputs are then used to automatically redistribute power to stabilize the system.[22] However, GICs can overload the protection system and cause the system to automatically trip by disconnecting the electrical generation from the transmission network in order to self-protect, which results in a loss of power.[23] This occurred in 1989 during an event known as the March 1989 solar storm that was only about one fifth the strength of the Carrington Event.[24] GICs tripped the Hydro-Quebec transmission grid protection system and caused a blackout throughout the Canadian province of Quebec that lasted over nine hours before the electrical grid could be restarted, as it is difficult to restart an electrical grid from full stop.[25] No blackouts occurred in the US during the March 1989 solar storm, but over 200 electrical grid anomalies were recorded.[26]

Transformer damage occurs when GICs cause transformer cores to overheat and damage internal components.[27] An example of this occurred at the Salem Nuclear Plant in New Jersey during the March 1989 solar storm, when GICs produced enough heat in a transformer core to melt internal components and permanently destroyed the transformer.[28]

Atmospheric Drag on Satellites

In addition to generating GICs, the currents in the ionosphere caused by CMEs and energetic charged particles add energy in the form of heat to the upper atmosphere, which causes the upper atmosphere to expand.[29] Large increases in atmospheric density occur as low-density layers of air are replaced with higher density layers of air that were previously at lower altitudes.[30] Satellites in low Earth orbit (LEO) that were previously in the lower density regions are pushed into high density regions where they experience a stronger drag force due to increases of atmospheric density.[31] The large increase in drag slows satellites down and decreases the satellites' altitude, changing their orbit.[32] This leads to "lost" satellites, or satellites that are not where they are expected to be.[33] Other artificial objects in LEO such as space debris also experience increased drag and can become "lost" as well.[34] This occurred after the March 1989 solar storm when hundreds of artificial objects in LEO had to be reidentified and their new orbits recorded.[35]

It is critical to know where satellites and other objects in LEO are to prevent collisions. The United States Space Surveillance Network (US SSN) tracks all artificial space objects to prevent collisions, but if satellites are "lost" this becomes impossible.[36] Collisions have the potential to directly damage a satellite as well as create more space debris and start a chain reaction known as the Kessler Syndrome, in which a collision creates space debris that leads to more collisions which creates more space debris.[37] In the worst case scenario, the debris field could become so dense that any spacecraft that leaves Earth's atmosphere would be destroyed, which would prevent new satellites from being placed in orbit and halt space exploration.[38]

Ionosphere Disturbances and Radio Signals

The added energy in the ionosphere also increases the ionosphere's Total Electron Content (TEC), the total number of ionospheric electrons between a radio transmitter and receiver.[39] GPS radio signals between the satellite and ground receiver travel through the ionosphere. The increased TEC causes a longer delay of the GPS signal as it passes through the ionosphere, leading to less accurate positioning unless the GPS receiver's internal ionospheric model is updated to account for the increased and variable TEC.[40] The mismatch between the actual TEC after a CME and the TEC model inside the GPS receiver can cause both position and timing errors. The timing errors are negligible for most applications, but position errors can be significant and impact navigation and any other system that requires precision location measurements such as surveying, agriculture, and construction.[41] During a series of solar storms in 2003 known as the Halloween storms, GPS errors disrupted commercial and military aircraft navigation and ocean and land surveys.[42] This paper is focused on GPS, the US global navigation satellite system (GNSS), but other GNSSs would similarly be impacted by solar storms.

The ionosphere is also impacted by x-ray and ultraviolet radiation released by solar flares, which increases ionization in the lower-altitude, higher-density layers. Increased ionization in the higher-density layers leads to absorption and degradation of high frequency (HF) radio signals and can cause radio blackouts.[43] During the 2003 Halloween storms, HF radio communication interference forced the Department of Defense to cancel a maritime mission.[44]

Energetic Charged Particles and Indirect Effect on Aircraft in Polar Regions

When energetic charged particles accelerated by CMEs and solar flares reach Earth, they are guided by the Earth's magnetic field towards the north and south pole where they penetrate the atmosphere.[45] Like the radiation released by solar flares, the energetic charged particles increase ionization around polar regions which causes polar radio blackouts.[46] Additionally, the particles can reach the cruising altitude of aircraft around the poles, which can damage aircraft electronics and be harmful to humans.[47] Energetic charged particles can cause single event effects (SEE) in aircraft avionics, where a single energetic particle causes an electrical disturbance in a circuit that can range from nondestructive to destructive.[48] Energetic charged particles can also damage the DNA of humans in the aircraft, which can cause severe health problems including cancer.[49] During solar storms, including the 2003 Halloween storms and a 2012 solar storm, commercial airlines sometimes have had to cancel or reroute polar flights because of radio blackouts and the risk of radiation exposure.[50] Polar flights have become increasingly common between North America and Asia; in 2016 there were over 14,000 polar flights.[51] Additionally, it is probable that polar flights are important for military and intelligence purposes.

Radiation Impacts on Satellites

Energetic charged particles can also damage satellites through single event effects and charging, as well as cumulative degradation. SEE, described in the previous paragraph, impact satellite electronics as well as aircraft electronics. SkyTerra-1, a telecommunication satellite, experienced a three-week outage after a SEE during a March 2012 solar storm disrupted two sensors which caused the onboard computer to enter safe mode.[52] A complete reboot and systems check were required to bring the satellite back online.[53] Surface charging is a phenomenon that takes place due to the accumulation of low energy electrons on satellite surfaces, while internal charging is the result of high energy electrons that penetrate satellite shielding and accumulate on internal insulators and electrically isolated conductors.[54] The build-up of electrons both on the satellite's surface and on internal satellite components can result in electrostatic discharges (ESD), which can damage electronic components and solar arrays as well as disrupt onboard communication and navigation systems.[55] Additionally, ESDs from surface charging can damage surface materials such as thermal coatings, while ESDs from internal charging can damage internal insulating materials. A study published in 1998 by the Aerospace Corporation analyzed 299 records of spacecraft anomalies caused by space weather events between 1971 and 1997 and found that 133 were caused by surface or internal charging events, the largest contributor of anomalies ranging from minor anomalies to four loss of missions.[56]

Cumulative effects of energetic charged particles lead to gradual degradation of electrical components both internal to the satellite and on its surface, including solar arrays.[57] Two effects result: displacement damage, wherein energetic particles displace atoms in electrical components from their lattice sites; and total ionizing dose (TID), or the accumulation of trapped charges in insulating regions of electrical components due to ionization by energetic particles.

Infrastructure and Functions Critical to US Security Depend on Threatened Technologies

The impacts solar storms have on technology are of significant concern due to the dependence of critical infrastructure and functions on these technologies. The following sections discuss the consequences of solar storm impacts on US national, economic, and human security.

Electrical Grid Service Disruptions and Damage

Disruption and damage to the electrical grid can have severe consequences due to the near-absolute dependence of critical infrastructure on electricity and the interdependence of infrastructure systems. Electrical grid disruption can result in the direct or cascading failure of functions critical to national, economic, and human security including electrical power, water supply, sanitation services, communication, transportation, healthcare and emergency services, financial, food production, government services, and military services and capabilities.[58] A recent study published in 2017 estimated the economic loss per 24 hour day for an extreme solar storm that affects the electrical grid in most states (about 66% of the US population) and found that the potential economic loss would be $45.1 billion per day to the US economy, plus $7 billion per day to the global economy.[59] This estimate only envisions a scenario in which the US is impacted—if a solar storm had multinational effects, the estimated costs would likely significantly increase, particularly the global economic cost.[60]

The figure of $45.1 billion is the just the estimated loss for one day, which might occur if a service disruption that triggers a grid protection system occurs and there is only a daylong blackout. If a blackout is caused by serious damage to multiple transformers, however, it could last several months to over a year. There is a limited availability of spare transformers in the US as each transformer costs several million dollars and transformers are often custom designed.[61] A study by the Cambridge Center for Risk Studies in 2016 found that there are spares for less than 10% of US transformers.[62] This is a significant concern as the lead time for a new transformer is between 5 and 16 months without supply delays or transportation issues and between 18 and 24 months if there is high demand.[63] If the blackout lasted for months to years, the catastrophic economic toll and societal reverberations would quickly add up.

In addition to severe economic loss, electrical grid outages would also have a significant toll on human health and safety. In 2003, an electrical grid failure, unrelated to solar storms, caused a blackout for 50 million people throughout the northeastern US and southeastern Canada that lasted two days.[64] A study published in 2012 estimated the mortality risk in New York City during the 2003 blackout and found that the mortality for accidental deaths increased by 122% and the mortality for disease-related deaths increased by 25%.[65] Deaths would likely increase as blackout length increased due to a lack of water, food, and medicine; power for medical devices; hypothermia or heat stroke; inability to contact emergency services; and slower response time for emergency responders.[66] Crime would likely also increase as blackouts provide opportunities for theft, fraud, and exploitation—and, similar to emergency responders, it would be difficult to contact law enforcement and officers would be slower to respond.[67] If a large-scale blackout were to last for several months to years, societal institutions including law enforcement and local government would face such strain that they would likely become ineffective and could even face collapse.[68] In this worst case scenario, not only would a large-scale, long-term electrical grid outage have severe economic and human health and safety consequences, but it might transform political authority and societal organization, with rule of law observance and enforcement being taken upon by individuals rather than structured institutions.

Satellite Damage

Damage to satellites either due to collisions with "lost" objects in orbit or the effects of energetic charged particles could have severe impacts as satellites provide capabilities critical to national, economic, and human security including position, navigation, and timing (PNT); intelligence, surveillance, and reconnaissance (ISR); communication; space situational awareness (SSA); earth environmental monitoring; and missile defense.[69] A study published in 2017 by Abt Associates estimated that during an extreme solar storm, 10 to 100 satellites globally could be lost and the global economic impact would be between $4 billion and $200 billion, which includes both asset cost and potential revenue loss.[70] Around 40% of satellites are owned or operated by the US, placing the estimated US economic impact between $2 billion and $80 billion.[71]

In addition to the economic cost, the loss of capabilities that these satellites provide could have severe consequences for the US military and Intelligence Community (IC). PNT satellites provide precision strike information, operation synchronization, and track assets and forces.[72] ISR satellites provide military, diplomatic, and economic intelligence information that supports Department of Defense and intelligence agencies' operation planning and execution.[73] Satellite communication supports command and control and gives government and intelligence agencies means to convey instant orders and maintain situational awareness.[74] Earth environmental monitoring provides weather, geospatial, and maritime information that supports operation planning and targeting.[75] SSA provides data on space debris and adversaries' space assets as well as space weather observations.[76] Missile defense relies in part on satellites to monitor critical regions, and space-based sensors are often the first to detect a missile launch.[77] Damage to satellites that the US military and Intelligence Community depend on could disrupt operations, intelligence collection, and missile defense, creating critical vulnerabilities in US national security.

Satellite capabilities also support commercial, disaster response, and scientific applications that can have additional economic and human security impacts. Satellite communication provides television broadcasts directly to homes and to central stations and internet access and voice communication to rural areas.[78] Weather, geospatial, and marine data from earth environmental monitoring benefits weather forecasting, agriculture and water resource management, infrastructure and transport management and development, energy and mineral resource management, disaster response and risk reduction, climate change monitoring, and ecosystem and biodiversity monitoring.[79] PNT services are integrated into most critical functions and infrastructure. Timing is critical for communication networks, financial networks, banking systems, electrical grids, traffic signals, and rail signals[80] (position and navigation applications will be discussed in the next subsection).

GPS, HF Radio Communication, and Radiation Exposure Disruptions

Global Positioning System (GPS), high frequency (HF) radio communication, and radiation exposure disruptions can have a variety of national, economic, and human security impacts. As discussed in the previous subsection, the US military and Intelligence Community relies on position and navigation capabilities which are provided by GPS. Additionally, the US military utilizes HF radio for aircraft and maritime communication as well as in military operations.[81] As in the case of damage to GPS satellites, if GPS and HF radio signals are degraded, operations could be disrupted which can create vulnerabilities in national security.

Position and navigation functions are integrated into many commercial applications to improve productivity across the economy.[82] Applications include en-route and approach navigation for aircraft, ocean and in-shore navigation, as well as port approaches and docking for ships, in-car and autonomous vehicle navigation, commercial fleet management, cargo and package tracking, precision agriculture, construction, mining, and surveying and mapping.[83] If these services were disrupted for any significant amount of time, there would be massive economic consequences as productivity would be reduced. Disruption to HF radio would also have economic consequences as commercial aircrafts use HF radio for aircraft-to-ground voice communication and ships use HF radio for ship-to-shore communication, distress calls, and weather broadcasts.[84] Disruptions to position and navigation functions and HF radio could also impact human health and safety as they are integrated into emergency response applications including emergency vehicle location, dispatch, and navigation as well as aviation, maritime, and ground search and rescue.[85] Additionally, the loss of navigation and communication for aircraft and ships can be hazardous, particularly in controlled airspaces and ports.[86]

It is difficult to accurately quantify the full economic and human impact of GPS, HF radio, and aircraft radiation exposure disruptions since it is difficult to obtain accurate information on each of the myriad different applications and users that use these technologies, but a clear takeaway is the reality that much of what society has come to see as modern life is hyperconnected to and reliant on these functions, especially GPS.[87]

Resilience Measures to Protect Critical Technologies from the Impacts of Solar Storms

When considering how to design resilient systems, the first step is often to consider the concept of *resistance*, or ways to prevent the threat from manifesting in the first place. Since it is impossible to control the sun's dynamics and prevent solar storms from occurring or to redirect CMEs and solar flares away from Earth, the focus must instead be on *resilience*, or how to prevent system failure when the threat does occur. Several resilience measures can be implemented to protect technology, dependent functions, and infrastructure from the impacts of solar storms. Improved solar storm models provide a resilience measure universal to all technologies impacted; then there are resilience measures specific to various different technologies such as hardening, upgrading, or updating the system; ensuring there is systemic redundancy—multiples of components that can perform a key task; and implementing alternative systems to increase diversity, or a variety of systems that can perform a key task.

Improved Solar Storm Models

A resilience measure that can help protect all the technologies impacted by solar storms is improved solar storm models. Despite advancements in solar storm knowledge, including a better understanding of the ionosphere due to TEC measurements taken from GPS satellites, there are still many gaps.[88] Many "known unknowns" exist regarding the sun, the upper atmosphere, solar storm formation and propagation, and solar storm impacts on Earth including the initial structure of CMEs at the sun's surface and the relationship between solar flares and CMEs.[89] There are also likely many "unknown unknowns." Only in the past 15 years were interactions between solar storms and weather on Earth discovered.[90] An incomplete understanding of solar storms requires guesses and interpolations to be made in models, which reduces their accuracy. To improve solar storm models, more data is required. Funding is needed for more observation satellites monitoring critical areas such as the sun and the Earth's magnetosphere as well as research on the physics behind solar storm formation, propagation, and impact on Earth.[91] Small satellites should be considered for some solar storm monitoring applications as they are less expensive than traditional observation satellites and can be deployed in constellations to provide distributed observations.[92]

Solar storm models are important because they provide a better understanding of how solar storms impact technology in space and on Earth, which leads to a better understanding of how to protect these technologies from the impacts of solar storms. Additionally, an increased understanding of the sun itself and how solar storms form and propagate improves solar storm forecasting. As mentioned towards the beginning of this report, solar flares arrive at Earth within minutes and energetic charged particles arrive shortly after, which provides very little time to prepare once a solar flare is observed. CMEs arrive to Earth in 15 hours to a few days, but determining how capable a CME is of causing a geomagnetic disturbance on Earth depends on the polarity of the magnetic field embedded in the plasma.[93] This cannot be determined until the CME is around 30 minutes away from Earth, which does not provide much warning.[94] The ability to accurately forecast a solar storm further in advance gives operators and users that rely on technology more time to prepare for the impact.

Preparation time allows electrical grid operators to postpone maintenance to ensure as many critical lines are available as possible to reduce strain if one portion of the grid fails, implement operational procedures to shift electrical loads and bring in reserve power to increase system stability, and disconnect vulnerable transformers or even shut down the entire grid to protect equipment.[95] For functions and infrastructure that rely on the electrical grid, advanced warning allows for time to transition to on-site emergency power generation. Advanced warning provides applications that rely on GPS and HF radio systems the opportunity to prepare for outages and switch to alternative systems if available.[96] Advanced forecasting is also an effective resilience measure to protect aircraft from radiation exposure, as with advanced warning airlines can avoid polar routes and reroute flights to avoid the threat and continue safe operation.

For other technologies, however, while the ability to implement immediate response procedures may reduce some of the impact of solar storms, most of the immediate response procedures are still disruptive and do not address the root issue of vulnerabilities in critical technologies. Improved understandings of solar storms and enhanced solar storm models should not just be used to improve solar storm forecasting but also to build resilience into critical technologies themselves, which will be discussed in the following subsections.

Electrical Grid Resilience

Current electrical grids have protection systems, but as was highlighted by the Quebec blackout during the March 1989 solar storm, these systems can still cause service disruptions. There are several other resilience measures that can be implemented to protect the electrical grid from solar storm impacts without causing service disruptions. The first measure is to "harden" the electrical grid, or physically protect the electrical grid from the impacts of solar storms without disruption. One way to harden the electrical grid is to install GIC absorbing or blocking devices. One such device is a neutral blocking device (NBD), a mature, tested, and validated technology that automatically protects transformers from GICs.[97] NBDs provide a metallic path to ground transformers during normal operations and an Alternating Current (AC) effective path to ground transformers when a CME is impacting the Earth, which prevents the flow of GICs through transformers.[98] It is estimated that it would cost less than $4 billion dollars to install these devices at critical US transformer substations, which is negligible compared to the $45.1 billion/day cost of a large-scale, long-term blackout caused by a severe solar storm.[99] A second way to harden the electrical grid is to replace older, vulnerable transformers with models that are more resilient to the effects of GICs.[100] This option is more expensive as new transformers cost several million dollars, but is still a fraction of the cost of a large-scale, long-term blackout. A third resilience measure is to increase the number of spare transformers held in reserve to improve redundancy in case of disruption or destruction of live transformers. Furthermore, rather than just stock up on traditional transformers which are expensive, designed for specific systems, and difficult to transport, there is currently research to develop transformers that are interchangeable, modular, and rapidly deployable.[101]

An additional resilience measure that should be implemented along with the previously mentioned measures is investment in Small Modular Nuclear Reactors (SMRs) as a backup power source. SMRs are designed to start up without receiving any power from the electrical grid, store fuel on-site for at least a decade, operate connected to the grid and independently, and withstand solar storms, electromagnetic pulses (EMPs), natural disasters, and cyberattacks.[102] SMRs can be used to create microgrids, which are localized grids that under normal circumstances are connected to the main electrical grid but if needed can be disconnected from the main grid and operate in island mode.[103] Microgrids can be integrated into critical sectors such as hospitals, emergency services, water supply, sanitation services, fuel stations, and military bases so that if there is a blackout critical functions will still be provided. The goal is that electrical grid hardening will prevent solar storm-induced blackouts, but if a hardening measure or unprotected part of the grid fails it is important to have an alternative, backup power source. In addition, SMR microgrids could provide essential backup power if there were a blackout caused not only by solar storms but also electromagnetic pulses (EMPs), natural disasters, or cyberattacks. Additionally, when connected to the main grid, SMRs can provide a clean, reliable energy generation source.

Satellite Resilience

Multiple measures can be implemented to improve satellites' resilience against solar storm radiation effects. Currently, the most effective measure to protect satellites from radiation is to radiation-harden the satellites or physically protect the electronics within the satellite from radiation.[104] Radiation-hardening techniques include insulating and shielding circuits.[105] Further research and modeling is needed to determine the level of hardening required for a satellite to survive an extreme solar storm. A study published in 2018 modeled the electron flux of an extreme energetic charged particle scenario and found that about 2.5 mm of shielding would be needed to meet the NASA recommendation for internal charging currents, which is greater than is typically used; therefore, such a scenario would likely result in most spacecraft experiencing electrostatic discharges that cause temporary or permanent satellite loss.[106] More of these types of studies should be funded and used to guide industry standards for satellite hardening.

A second resilience measure against solar storm radiation effects is redundancy, both at a component level and satellite level.[107] The goal of redundant electronics components is that if one component is damaged by radiation, the reserve component can take over and the satellite can continue to operate as normal. Similarly, the goal of redundant satellites is that if one satellite fails because of radiation damage, there is one or more satellites available to take over its functions. For applications where small satellites are realistic, this would be an excellent resilience measure. Constellations of small satellites that provide similar functions could be deployed so that if a few failed, the satellite constellation function would still operate as normal. Not only would these constellations protect satellite operations if some failed from radiation damage, but also if some were destroyed by adversary antisatellite technology.[108] It is important to be mindful of small satellite radiation hardening, though, as the reduced size of the electronics increases their vulnerability to radiation effects.[109]

While it is known that radiation from solar storms affects satellites, there is still uncertainty about the level of this threat due to a lack of satellite anomaly sharing within the industry, likely because governments and industry do not want to advertise anomalies for security and economic reasons.[110] This makes it difficult to determine the threat level. A further complication is that the sun has been relatively "quiet" for the past decade, which makes it difficult to determine if decreases in the number of reported anomalies is due to the space environment, a lack of reporting, or improved radiation hardening.[111] To improve anomaly sharing, a database of satellite anomalies caused by solar storms should be developed. The National Oceanic and Atmospheric Administration (NOAA) developed this type of database, but it has not been updated since 1993.[112] To address security and economic concerns, an anonymous database could be developed that does not identify a specific satellite/organization with the anomaly but still provides information about the anomaly and the sun and space environment at the time of the anomaly. This would provide a better idea of the threat level and help guide how best to protect satellites from solar storm radiation effects.

A measure that can be implemented to improve satellite resilience against increased atmospheric drag during a solar storm is increased understanding and improved prediction capabilities of atmospheric drag during solar storms.[113] If the atmospheric drag can be forecasted and predicted accurately, then satellites and space debris are less likely to become "lost," which reduces the risk of collisions that could cause the Kessler Syndrome.

GPS and HF Radio Resilience

Resilience measures to reduce GPS outages and preserve PNT functions from the effects of solar storms are active areas of research. One promising area of research is to develop the capability to recalibrate and update GPS receivers' internal ionospheric models during a solar storm so that the internal TEC model matches the actual increased and varied TEC environment.[114] Since the difference between a receiver's TEC model and the actual TEC environment is what causes GPS disruptions, if this can be reduced the GPS service disruptions would be reduced. Another area of research is the development of an alternative, ground-based PNT system—a system on Earth that provides similar PNT capabilities to GPS satellites—to preserve PNT capabilities if GPS is disrupted by ionospheric disturbances. There is ongoing research to reconfigure, combine, and improve existing navigation systems such as enhancing LORAN-C, a long-range, ground-based navigation system decommissioned in 2010 due to the superior capabilities of GPS, as well as develop new PNT systems to achieve accurate, global ground-based PNT capabilities.[115] Not only would an alternative, ground-based PNT system preserve PNT capabilities if GPS were disrupted by ionospheric disturbances, but also if GPS is disrupted by malicious ground-based attacks such as jamming or spoofing.

A resilience measure to preserve communication functions during solar storms for systems that use HF radio is to ensure that these systems have reliance on multiple higher frequency communications pathways. Due to the constraints of physics, HF radio signal degradation cannot be prevented, but higher frequency signals such as ultra-high frequency (UHF) and X band are less affected by ionospheric disturbances.[116] If there is a radio blackout at one frequency, it is often possible to switch to a higher frequency to maintain communication.

Resilience Through Collaboration

Resilience against the impacts of space weather cannot be achieved without government, academic, private sector, and international collaboration. Collaboration is needed for both the innovation and implementation of resilience measures. The sun has produced relatively few significant solar weather events over the past decade, so the threat of a solar storm has not been a priority concern for most industries.[117] Additionally, there are few standards and requirements to implement solar storm resilience measures, so industry is not incentivized to proactively implement resilience measures such as hardening or redundancy.[118] Applicable government agencies must take responsibility and work with industry to develop standards and requirements, assign responsibility, and establish plans of action to implement resilience measures. Collaboration between government, academic, and the private sector through shared resources and expertise is needed to increase observation capabilities, improve solar storm models, and continue to develop innovative solutions to protect technologies impacted by solar storms. Solar storms do not just impact the US but the entire world, and many countries have programs to study solar storms and build resilience against an inevitable future event. The US should collaborate with international partners to increase observation capabilities, share data, compare models, and develop innovative resilience measures.

Solar storms will disrupt functions and infrastructure that all parts of modern life rely on, so both government and the private sector must commit to building resilience in critical infrastructure and functions against the dangerous effects of solar storms. As noted at the beginning of this report, it is not a matter of if but when the next extreme solar storm will occur, and it is in the nation's best interest to build resilience before such a storm occurs in order to protect US national, economic, and human security. If the US does not act proactively to address the threat of solar storms, the nation could face an unrecoverable disaster that fundamentally changes society.

Endnotes

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