Solar Storms: Protecting Your Operations Against the Sun's 'Dark Side'

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4/08/2010

Introduction

Recent scientific information indicates that an extreme solar storm cycle activity producing Geomagnetically-Induced Currents (GIC) is predicted to peak again in 2012. Some scientists are warning that the GIC from sunspots and solar flares could cause significant damage to the electrical grid, telecommunication and other devices. Compared to disruption of the electrical grid from natural hazards and other sources, GIC related damage and disruption to the power distribution grid has the potential to have a very broad footprint across a large region for an extended period with possible cascading societal and economic impact. On the other hand, this 2012 prediction could be a rather benign "non-event" similar to Y2K. Even if 2012 is a non-event, the threat of solar storms and associated space weather risks are rare but real and should not be ignored. Such an event does not have any precedence for comparison for the potential severity of impact. It can be considered an unrecognized catastrophic risk due to our increased reliance on technology today.

This paper provides background on the hazards associated with solar storms based on a review of available information from a variety of reliable resources and explores potential loss scenarios from Geomagnetically-Induced Currents (GIC) associated with solar storms activity.

What is the hazard?

The sun's core is continuously undergoing nuclear fusion and is periodically blowing electrified solar gas (plasma) and Coronal Mass Ejections (CME). According to the current body of knowledge about the sun, violent solar storm events occur when the sun's strained solar magnetic field suddenly snaps to a new configuration and releases massive amounts of energy with intense flashes of light, radiation and CME. The solar storms result in three specific environmental disturbances, namely geomagnetic storms (disturbances in earth's geomagnetic field due to gusts of solar winds), solar radiation storms (elevated radiation levels due to high-energy particles) and radio blackouts (disturbances in earth's ionosphere due to X-ray emissions from the sun).

Space weather refers to these violent transfers of matter and energy from the sun to the earth. This phenomenon is better known as the "Solar Storms." Although solar storms occur periodically, their intensity and frequency vexes and vanes on an average 11-year cycle (9-14 years cycles) with some high peaks and some low peaks for number of sunspots and storms during each cycle. At the solar minimum, the estimated occurrence of a CME event is about one event every five days compared to about 3.5 events per day at the solar maximum. Not all CME events produce significant adverse impact on the electric power grid or the telecommunication network on earth. Although more events occur at or near the Solar MAX, any single solar CME event during the entire cycle can cause adverse impact on earth, depending on its severity and trajectory for arrival on earth.

CME's have strong embedded magnetic fields. They travel towards earth with high velocity and contain atomic particles from the sun, including electrically charged, high-energy atomic particles such as protons and electrons, hydrogen nuclei and large quantities of helium, iron and nickel nuclei. The shock wave of atomic particles from CME interacts with the earth's magnetic field to generate geomagnetic storms (disturbances) in the earth's magnetic fields based on the rate of change. This results in Geomagnetically-Induced Currents (GIC's) in many electrical systems. Spectacular northern and southern lights displays (Aurora Borealis and Aurora Australis) are visible but are harmless examples of this phenomenon around the earth's poles. In periods of solar minimums, they are observed only the in higher latitudes near the North and South Poles. During periods of intense storms, the aurora ovals move to lower latitudes with observations of auroras observed as far away south as equatorial regions during more intense storm events.

Although all of the effects of solar storms are not fully understood, significant research has occurred in recent years to improve our understanding through extensive observations and measurements. The results from this research have also helped to improve scientists' modelling and forecasting abilities for short and long-term predictions. GIC's in the earth caused by these solar storms can seriously affect the safety and performance of critical infrastructure assets, such as high frequency telecommunication, electrical power grid, space satellites; data centers, GPS navigation and aviation just to name a few. An extended interruption to the electrical power grid can cause cascading loss impact at the primary, secondary and tertiary levels including its collateral societal and economic impact encompassing almost all segments of business.

Monitoring and forecasting

Research and monitoring of solar activity is a high priority for many stakeholders worldwide. In the US, along with the US Air Force, the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA) is the primary agency that is responsible for monitoring and reporting on space weather activities. With a fleet of satellites (SOHO, twin STEREO, ACE and others), they are developing technical and scientific capabilities for real time monitoring and forecasting in near-real time as the watch (1-3 days), warning (less than a day) and alert (real time). The latest in these efforts is the launch of the Solar Dynamics observatory (SDO), which is expected to improve our monitoring and predictive capabilities. NOAA has also developed a Space Weather Scale[1] based on severity levels similar to hurricanes. Geomagnetic Storms are rated G1 (Minor) to G5 (Extreme), Solar Radiation storms are rated S1 to S5 and Radio Blackouts are rated R1 to R5.

Department of Natural Resources Canada (NARCAN) is responsible for communicating forecasts and warning alerts based on observed data from Canadian Automatic Magnetometer Observatory System (CANMOS) and other worldwide resources. In Europe, the European Space Agency (ESA) and the European Space Weather Portal (ESWeP) are the multi-language integrated outreach and access portals for information. Nordic countries (Finland, Norway and Sweden) have formed a GIC cooperation network at the Lund Space Weather Center. The increased cooperation and collaboration in research, exchange of real time data, forecasts and alerts by these and other agencies is helping to improve our understanding of this risk.

Our recently enhanced monitoring and observation capabilities are helping to improve our understanding of the threat from the solar storms, associated space weather, and their ability to impact electronics and other technology on earth.

Economic impact from prior events

The solar storm event occurring on March 13, 1989 is one of the more recent documented events and it provides some insight into possible scenarios and effects on the electrical grid system. An electrical power blackout caused by a severe solar storm struck Quebec[2]. Several transformers on the Hydro-Quebec electric grid were affected by GIC resulting in a domino effect shutting down the entire grid system. The blackout lasted for 9 hours and affected over 5 million people at an eventual direct cost of over $2 billion. Since the event did not occur in peak load conditions during the daytime hours of summer or winter, the failure did not cascade beyond Quebec into the United States, but it came close. During the March 1989 Quebec storm, over 200 other events were reported in North America, including a transformer at the Salem nuclear plant in New Jersey that was also damaged beyond repair as its insulation gave way from years of cumulative GIC damage.

A power blackout on August 14, 2003[3] unrelated to any solar storm event that lasted 3-5 days covering a large portion of the northeastern US and Canada provides some estimates of vulnerability and business impact from widespread power failure. According to the initial estimates by the North American Electric Reliability Corporation (NERC), economic cost of this blackout in the US and Canada ranged from $ 4 to 10 Billion. Canada lost a net 18.9 million work-hours and the GDP for the month of August in 2003 was down by 0.7%.

In addition to the 1989 event, there have been many other notable recorded solar storm events over the years with anecdotal observations of adverse consequences. Achieved (including news paper accounts) information about many prior events is provided at this URL link:
http://www.solarstorms.org/SRefStorms.html

A few examples of prior events include:

- 1847: telegraph services interruptions in Great Britain
- 1859: largest solar storm known to date called the "Carrington Event" causing an almost complete shutdown of the US telegraph system; Northern Lights so bright that people reportedly could read a news paper at night
- 1881: telegraph lines in Boston and London reportedly operated without batteries due to surging GIC's
- 1921: The New York Railroad storm- major sunspot visible with naked eye through smoked glass, Aurora visible in eastern US as well as from Pasadena CA, Signaling and switching systems out of order and fires reported in New York Central Railroad and Central New England Railroad, Interference with telephone and telegraph traffic over Europe including fires in a telegraph station in Sweden
- 1940: transformer electric power line shutdowns causing a blackout in North America (New England states, NY, Pennsylvania, Minnesota, Quebec and Ontario)
- 1958: transatlantic communication cables, affected, fires in telegraph offices in Sweden and transformer failure in British Columbia Canada
- 1982: malfunction of railway signals in Sweden
- 1994: failure of Canadian ANIK communication satellites on January 20/21, 1994
- 1997: crippling of AT&T's Telstar 401 communication satellite on January 11 1997 adversely affecting the viability of Skynet satellite service reportedly costing several hundreds of millions dollars of loss
- 1998 May: Bangor hydro Electric Co. and Central Maine Power Co. was affected for a short time
- 2000: suspected railway signal malfunction in Norway that resulted in 19 fatalities in a rail accident
- 2003 October: Blackout in Sweden and transformer damage in South Africa

The super storm event from October 22 - November 4, 2003 is considered by many scientists to be a wakeup call about the potential threat that has resulted in mobilization of international efforts by scientists from various disciplines to collaborate and pool their research to improve our understanding of this phenomenon. According to the information on Goddard Space Flight Center[4] website, at least eight shock waves and powerful CMEs impacted earth's magnetic field bringing billions of tons of electrified solar gas (plasma) to earth and raising radiation levels in space near earth above dangerous levels for nearly two weeks. The shock of this storm was reportedly so powerful that the spacecrafts Ulysses and Cassini far beyond earth's orbit also recorded the impact. Advance warnings and prompt precautionary actions after observation of initial events probably helped minimize damage to satellites, electric systems and airlines.

Even more disconcerting is the possibility of the earth facing an event of the magnitude similar to what is widely know as "The Carrington Event" in 1859, named after Richard Carrington who observed the initial solar flares by telescope.

Following is an excerpt of the description of that event as found in a NASA article at: http://science.nasa.gov/headlines/y2008/06may_carringtonflare.htm

> On Thursday, September 1, 1859, Richard Carrington - one of England's foremost solar astronomers - was in his private observatory. Just as usual on every sunny day, his telescope was projecting an 11-inch-wide image of the sun on a screen while Carrington skillfully drew the sunspots he saw.
>
> On that morning, he was capturing the likeness of an enormous group of sunspots. Suddenly, as he was watching, two brilliant beads of blinding white light appeared over the sunspots, intensified rapidly, and became kidney-shaped. Realizing that he was witnessing something unprecedented and "being somewhat flurried by the surprise," Carrington later wrote, "I hastily ran to call someone to witness the exhibition with me. On returning within 60 seconds, I was mortified to find that it was already much changed and enfeebled." He and his witness watched the white spots contract to mere pinpoints and disappear.
>
> Just before dawn the next day, skies all over planet Earth erupted in red, green, and purple auroras so brilliant that newspapers could be read as easily as in daylight. Stunning auroras pulsated even at near tropical latitudes over Cuba, the Bahamas, Jamaica, El Salvador, and Hawaii.
>
> Alarmingly, telegraph systems worldwide also went haywire. Spark discharges shocked telegraph operators and set the telegraph paper on fire. Even when telegraphers disconnected the batteries powering the lines, aurora-induced electric currents in the wires still allowed messages to be transmitted.
>
> "What Carrington saw was a white-light solar flareÔa magnetic explosion on the sun," explains David Hathaway, solar physics team lead at NASA's Marshall Space Flight Center in Huntsville, Alabama.

Although electrical outages are common, and we have all experienced them from time to time, the ones caused by solar storms can be very different. They can potentially cover a large region, even an entire continent, extend over a longer period, and thus have a potential for catastrophic business interruption and economic impact. A report published by the National Academy of Science indicates that a storm similar in intensity to the 1859 event today could cost $ 1 to 2 trillion in damage to critical infrastructure and could take 4 to 10 years for recovery and restoration[5].

Split forecast

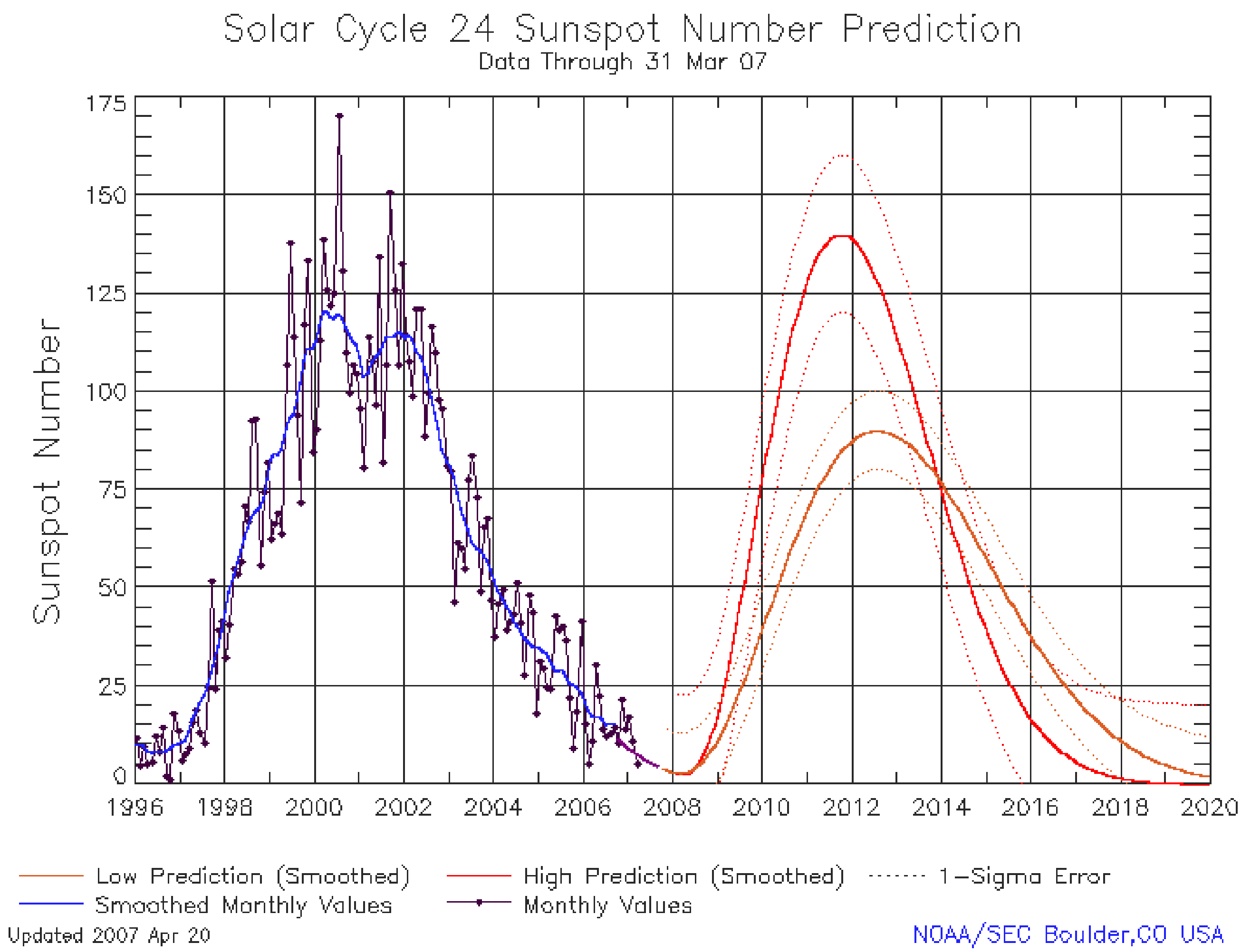
The science of space weather forecasting is still in its infancy in forecasting the overall sunspots and storms activity during a solar cycle (much like the annual hurricane forecast) but it does not claim to predict the timing or the intensity of any individual storms during the cycle.

Based on a revised May 2009[6] prediction by a NASA-sponsored panel of experts organized by NOAA, the Solar Cycle # 24 will peak with below average sunspots (90) activity level around 2013. This is a revision to a split panel prediction in April 2007[7] based on two competing models that had predicted a solar minimum in March 2008 followed by a strong solar maximum in 2011 or a weak solar maximum in 2012.

Based on the historic data, the sunspots activity in a solar cycle ranges 75 to 155. The current solar activity in past 2-3 years is unusually quiet with solar minimum lasting beyond the earlier prediction of 2007 or 2008. This extended quiet period, some call it a lull before the storm. Recently, however, the sun is showing signs of significant activity pointing to a start of new solar cycle # 24. According to the chart below (First Solar Cycle 24 Prediction- by NOAA Space Weather Prediction Center), the low prediction of number of sun spot activity (90) is expected to be the second lowest (78 in 1928) on record.

However, the panel is split right down the middle. Based on an alternate 2007 high prediction scenario for sunspot activity (around 140 œ 20) supported by the precursor observations and locations of recent solar activities, some panel scientists are still predicting storm intensity from this cycle to be similar to the Carrington Event. The surprise discovery of a large breach (similar to the ozone layer hole) in earth's protective magnetosphere against solar wind and energetic particles by NASA's probes from THEMIS spacecraft in June 2007 may also be contributing to the split prediction of stronger geomagnetic storms in cycle #24. The panel has made solar cycle predictions only twice prior to this for cycles #22 and #23 that included severe storms in cycle #23 .They were closer on the timing then intensity. It should be noted that the accuracy and reliability of a prediction improves once the new solar cycle actually begins. NOAA Space Weather Prediction Center would continue to update their prediction as the cycle #24 progresses.

First Solar Cycle 24 Prediction April 2007[8]



The paper explores potential vulnerabilities and risks expected for certain industry segments and critical infrastructure. In case of a repeat of a solar MAX event of the 1859 Carrington event, or even 1921 event, the cost of direct impact, other collateral impact, including the societal and economic impact in today's technology-dependent world, could be catastrophic. Although the potential for occurrence of such an extreme event may be rare, the threat and the vulnerability of electrical distribution and telecommunication are very real that cannot and should not be ignored. It will be a challenge to quantify the economic impact due to the unprecedented nature of this risk, difficulties in data gathering and lack of a consistent methodology.

Electrical power transmission grids and transformers

Although we still do not fully understand it, there has been a significant amount of research on the effects that geoelectric fields and geomagnetically-induced currents have on transformers and high-voltage power lines. Some of the possible transmission lines related risk factors may include directional orientation of transmission grid lines (east west or north south), their lengths, and conductor resistance. In addition to their function, aging and deployment, examples of transformer related risk factors include type, design, windings, resistance and grounding.

GIC causes a voltage differential between grounding points (grounding entry points for GIC) in transformers and power lines. This voltage anomaly leads to transformer saturation and possible overheating, shutdown or even destruction of the equipment. The earth's conductivity and earth grounding points in transmission lines can have adverse consequences for power lines. Researchers suggest that power lines in areas with ingenious rocks with high electrical resistivity are also at increased risk. Higher northern latitude areas of North America are also vulnerable. The average working lifetimes of transformers are reported to be shorter in regions with greater geomagnetic storm activity. The Northeastern region of US with the highest rates of detected geomagnetic activity led with 60% more failures in transformers. This transformer failure rate reportedly follows the 11-year solar cycle. This may also be due to cumulative effects of GIC on the aging electric grid infrastructure in North America.

By one estimate[9], the US electrical grid system consists of 6,000 generating units, over 800,000 kilometers of transmission lines and 12,000 major substations, many low-voltage distribution transformers and more than 100 control centers. With its innumerable number of grounding connections, each can serve as a potential GIC entry point into the grid that can lead to potential failure scenarios.

The interconnected nature of electrical grids and cumulative effects of GIC over long distances is a major vulnerability that can result in rapidly cascading failure and this can challenge any protection and emergency response measures. Although utilities generally have some spare transformers, large scale failures in power grids will present serious challenges for the availability and replacement of damaged transformers (at costs over $ 10 million each and extended lead times for replacement) and other critical grid components. This may also lead to extensive collateral damage and extended business interruption in on-going operations in many power-dependent industries, including metals, food, pharmaceuticals, healthcare and many more industries. On-site emergency power generators may help with a safe and an orderly shutdown of critical operations that would be necessary for several industries but may not be adequate for an extended interruption.

Mitigation measures:

The modern electrical grid is interconnected for efficient transmission of large quantities of power over a large distributed network. However, that same interconnectedness that makes an electric power grid efficient for distribution also makes it extremely vulnerable to cascading catastrophic failures.

The US Congress funded a vulnerability assessment research under the National Defence Authorization Act to evaluate the impact of an electromagnetic pulse (EMP) from a high altitude nuclear detonation by a terrorist event on the nation's critical infrastructure including the electric grid. "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical Infrastructures" was published in April 2008 and provides much insight in this potential threat and national vulnerability. The same study also discussed EMP associated with Geomagnetically-induced currents. GIC from solar storms is classified as an E3 event, meaning EMP duration of greater than 1 second and is capable of causing damage to large transformers and system-wide blackouts.

The Federal Energy Regulatory Commission (FERC) is an independent federal regulatory agency in the Department of Energy responsible for regulating several aspects of distribution of electricity, oil and natural gas. Under the Energy Policy Act of 2005, NERC also received an expanded role to ensure mandatory reliability standards. The North American Electric Reliability Corporation (NERC) has been designated as the electrical reliability organization (ERO) for implementation of mandated standards for critical infrastructure reliability protection. NERC is developing a joint government/industry steering committee to study the vulnerability of electric grid. Its charter will be to continue the risk assessment efforts, mitigation recommendations from the EMP vulnerability report and to develop a strategy and direction for future action plans. NERC will also coordinate these plans with the Canadian government authorities.

Currently there are no official mandatory US or international codes and regulatory requirements for electric utilities to enhance the protection from GIC from solar storms. Research on protection measures by industry groups and the scientific community suggests that a combination of system hardening and operational mitigation strategies may provide the best potential for mitigation of risks. System hardening involves modifying/retrofitting the power grid to block or reduce GIC in key transformer assets in the grid. Operational mitigation measures will consist of various operational measures for grid load management responding to solar storm warnings and alerts, including temporary removal of key assets and shutting down portions of grid.

System and critical assets hardening appears to be an effective and feasible approach accomplished by installation of a passive device or a circuit to block or reduce the GIC flowing into the grid. Although individual transformers and other equipment on the grid can be retrofitted for protection against GIC, the current grid system is not designed for any large-scale protection. According to a Department of Homeland Security (DHS) report[10], the estimated cost of retrofitting more than 5000 key large transformers in the US grid would be around $ 150 million. Aging transformers and grid infrastructure present additional challenges. In comparison to the cost of a catastrophic failure of entire grid, the retrofit cost appears to be reasonable but some of the approaches are still conceptual with no specific device available for retrofit or mandated in any codes or regulations.

Although operational mitigation measures are feasible, they will have to rely on the accuracy and timeliness of forecasting /alerts of solar storm activities and consensus on coordinated policies, procedures, maintenance schedules and best practices. These operational and grid management mitigation strategies may include removal of specific critical assets and generating capacity from the grid to reduce the risk and even consider load shedding or limited blackout to prevent cascading catastrophic grid failures. Such a strategy may be feasible but real time monitoring and improving the short-term forecasting abilities and coordination of such a rapid response strategy may present major challenges.

Subsequent to the Quebec blackout in 1989, the Northwest Power Coordinating Council (NPCC) approved the document C-15 "Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems" on April 10 1989 that has been updated several times (review cycle of three years) including the latest revision date of January 11 2007. It relies on continual alerts from the Solar Terrestrial Dispatch (STD) and a communication software package Geomagnetic Storm Mitigation System (GSMS). The document discusses recommended operating procedures for grid management and back up communication procedures commensurate with solar and GIC activity levels (Kp index) in STD alerts.

Since the 1989 blackout, Hydro-Quebec has installed transmission-line series capacitors at a cost of over $ 1.2 billion and has improved its real time measurement, monitoring and communication capability for grid management. Most utilities in susceptible regions have relied on similar guidelines and limited contingency plans but they have not been tested fully and may not be sufficient for a rapid response to any large-scale cascading grid failure.

It is not clear if any other global industry-wide efforts for system hardening and operational mitigation strategies are under consideration at this time. As discussed earlier, NERC is planning to organize stakeholder workshops to develop any such action plan for future consideration.

Microelectronics

Investigations have shown that particle showers from solar storms radiation can affect the performance of digital microelectronics systems causing increases in "soft errors" based on altitude as well as geomagnetic latitude and longitude. The effects on micro and nanoscale electronic components are not fully understood. These soft errors are generally spontaneous and non-reproducible and can lead to unexplained computational errors in computer performance.

Electronics used in harsher space environment is susceptible to two kinds of radiation effects. Cumulative effects are gradual changes that degrade the performance of digital microcircuits over time. Single-event effects (SEEs) result in destructive or nondestructive effect. Non-destructive effects are spontaneous circuit level effects that can result in loss of data or control. Destructive effects generally result in sudden failure of a device, which can be catastrophic in case of a critical application.

Mitigation measures:

Gradual degradation of performance of electronics in harsh radiation environments can be mitigated by incorporating proper shielding and control of operating conditions. Other possible approaches for mitigation of risk can include use of radiation-hardened devices or derating a device for application in a harsh environment. Since the single-event effects (SEEs) and soft error rates (SERs) are spontaneous and not reproducible, they are harder to understand and prevent. The mitigation measures generally focus on anomaly detection and redundancy check before taking any action on data input. This is one of the risks that will be most likely to affect the performance of electronics in "Supervisory Control and Data Acquisition" (SCADA) that are commonly used in many large distributed systems and infrastructure segments, such as electric grid, railroad signaling systems and telecommunication.

Space and aviation

The impact of solar storms on space and aviation can be significant. The effects can range from damage and malfunctioning of satellites and instrumentation from specific CME events to that of possible long-term radiation effects on interplanetary flights. Damage to space probes like Pioneer and Voyager I have provided some insight into areas of concerns ranging from failures and anomalies, including repeated resetting /restart of electronics and instruments and transient surges causing phantom commands to poor time keeping functions on GPS satellites. Long-term space objects like the International Space Station (ISS) and Hubble telescope are particularly vulnerable, and have to be periodically moved to different orbits to counter the orbit decay and the adverse impact of solar storm activities and associated radiation.

A multidisciplinary scientific study sponsored and funded by the European Commission in 1994 published their report in 1999. The study indicates that, for aircrafts in polar flight routes, the passengers and the crews are exposed to higher levels of radiation, especially during periods of storm activity. There are proposals to monitor radiation exposure to aircraft crews using radiation dosimeters similar to occupation radiation exposure monitoring. Solar storm activity also affects the on-board electronics and communication in aircrafts and satellites and increases the SER and SEE.

Mitigation measures:

The research indicates that a (polar) flight route, altitude and even type of aircraft are some of the risk factors that affect the level of radiation risks to airline passengers and the crews. Based on space weather forecasts, some airlines have considered rerouting of flights from the shorter, high northern polar routes to more southerly or lower-altitude flight paths to reduce the radiation risk against additional cost of longer flights. Although research in recent years has given us more insight into these risks, more studies are needed for exposure monitoring and to determine effective safety measures that reduce the radiation risk to the passengers and the crews.

In addition to the potential health hazards of radiation in high altitude flying, there is also potential risk to onboard, flight-critical subsystems. Commercial aircraft manufacturers like Boeing and Airbus have electromagnetic environment (EME) related qualification practices for design of flight-critical components. They include multiple levels of redundancies for safety critical subsystems, shielded cables and back up analog signal where appropriate. The designs of newer (e.g. Boeing 777) fly-by-wire aircrafts incorporate more electronics than their older counterparts do and EMP immunity cannot be fully assured without more extensive testing.

For satellites and space exploration, the risk of malfunctions and catastrophic damage is real and many satellite anomalies and failures/malfunctions have been attributed to the effects of solar storms. The knowledge gained from research and failure/malfunction investigations are helping improve the protection in designs and administrative measures.

Telecommunications

Telecommunication plays a crucial role in our daily routines and global trade in this technology-dependent world. In addition, telecommunications are also critical in emergencies and during disasters. It also supports voice and data communication including the internet. A number of aspects of telecom activities, including reliability and interconnectivity, are regulated by various governmental agencies in many countries.

As noted in prior events, there have been many documented incidents involving malfunctions and damage to telephone and telegraph systems. Today's telecommunication systems with complex electronics, satellite/radio communication and use of optical fiber and deep-sea cables are much more vulnerable to disruptions from solar activities than the old telegraph systems. Although this area has not been studied in detail, many unexplained interruptions in telecommunication are being attributed to solar and geomagnetic activities. Our modern society is completely dependent on electricity and telecommunication and any large-scale extended failures would have devastating societal and economic impact.

Mitigation measures:

There are many measures in place to help prevent the system from a total collapse in case of a solar storm event. These measures include industry-wide sharing of best practices by industry groups such as Network Reliability and Interoperability Council (NRIC) and others, geographic diversity of a large system, redundant deployment of landlines, and wireless and satellite capabilities providing alternate means that may help prevent the telecom sector from experiencing a total system collapse. That does not mean the telecommunication industry is not vulnerable to massive outages. The digital systems may be sensitive and may be vulnerable to disruptions. More work and investigative research of this sector is needed to assess the status of readiness.

Oil and gas pipe lines

In the case of oil and gas pipelines, there is no acute risk for catastrophic failure. It is primarily a life cycle risk of increased corrosion leading to a reduction in service life. Although specific risks from solar storms to oil and gas pipelines have not been studied in detail when compared to power transmission grids, development of a number of models and studies have been carried out on the effects of geomagnetically-induced currents (GIC) on pipeline corrosion. Compared to short sections, long sections of pipes are generally more susceptible and are isolated electrically by use of insulating flanges. They are protected by insulation and cathodic protection against the risk of corrosion but GIC's may exceed the protection that may result in increased risk of corrosion.

Many risk factors affect the degree of risk. Examples include pipeline construction (material, diameter, bends, branches, insulated flanges and integrity of insulation materials, etc.) and geophysical parameters such as the fluctuations in earth's conductivity and voltage difference between ground and pipeline. The studies confirm the increased risk of corrosion for pipes located in higher latitude areas.

Mitigation measures:
Design of new pipelines should explicitly consider mitigation of various risk factors described earlier. By improving the pipeline insulation, electrical isolation to ground and enhanced cathodic protection with impressed current systems, adverse corrosion effects of geomagnetically-induced currents can be monitored in real time and mitigated to certain extent. The Trans-Alaska pipe line is reportedly better designed for GIC protection than the older Siberian pipeline. Additional pipeline survey, maintenance, and considerably more research are needed for improving our knowledge in this area.

Railways

Railway networks are also vulnerable to malfunction because of voltages generated by the geomagnetically-induced currents. Although other forms of electric transportation, such as trams and electric buses may also be at risk, vulnerability of railway signaling system present significant risks to railways. Although conclusive studies have not been reported, adverse impact on signaling systems can be expected from solar storm activities and we have several examples from prior events. There is also anecdotal evidence of unexplained short circuit damage to rail equipment on high-speed ICE trains in Germany in a few cases.

Mitigation measures:
Many large and geographically distributed infrastructures (water and waste management systems, electric power, traffic signals, mass transit systems, environmental control systems, and manufacturing systems) use "Supervisory Control and Data Acquisition" (SCADA) that collect data and process signals from remote sensors by telemetry for predetermined control actions. SCADA related risks are just not unique to railroad alone as these systems are used in many large distributed systems. Prior experience shows several examples of unexplained rail signal malfunctions. These are probably examples of "soft errors" from single-event effects in SCADA systems in solar storm events.

Industry research has shown that SCADA systems may be vulnerable to EMP and solar storm exposures. When these systems malfunction, it can result in incorrect processing of sensor signal that can lead to incorrect control action. To address critical application requiring a more robust reliability, the SCADA architecture may include redundant signal verification and validation for prioritization of actions to improve the reliability. Unless upgraded, older designs and remote telemetry aspects of SCADA systems in railroads are likely to be vulnerable to malfunctions due to solar storm effects. The mitigation measures are likely to focus on additional vigilance in case of alerts and contingency plans to responds to potential emergencies.

Conclusion

Risk of extreme space weather from solar storms is not a totally new or unknown emerging risk. Our understanding of this risk is based on prior events in last 20-30 years, primarily the 1989 Quebec blackout and the super storm in 2003. The heightened attention at this time is due to a prediction of an extreme solar MAX event in 2012 with a potential to cause large-scale direct and collateral losses, including cascading unknown but potentially catastrophic societal and economic impact. If the 1989 Quebec blackout and the 1859 Carrington Event are benchmarks for adverse outcomes from similar solar storm events in the future, the consequences could be greatly magnified due to our growing dependence on technology, such as electricity, telecommunication and the internet and the cascading nature of interconnected global economy.

Many collaborative workshops are being planned to discuss and develop a strategies for implementation of recommendations from the EMP report. Participation in these workshops will give us a better insight and awareness of industry-wide mitigation measures and preparedness in electric power distribution and other important infrastructure sectors.

Such a mega risk event does not have any precedence for comparison for the potential severity of economic and societal impact. Although there are recorded losses from past events that can give some indications, the severity potential from an extreme space weather event is much greater today. An extreme space weather event today can be an unrecognized catastrophic risk event due to evergrowing dependence on technology in our interconnected global economy. Better understanding of the technical aspects of this threat and interconnected vulnerabilities in various industry segments, such as electric utilities, power distribution, oil and gas pipelines in the energy sector and technology exposures should be a top risk management priority. This must be followed by an assessment of their awareness of this threat, readiness, prioritization of their mitigation strategies and action plans. This will require opening a high-level dialog with a variety of stakeholders and participation in workshops and other forums.

Resources

1. National Research Council: Severe Space Weather Events- Understanding Societal and Economic Impacts Ó Workshop Report: http://www.nap.edu/catalog.php?record_id=12507#toc
2. Science@NASA; Severe Space Weather: http://science.nasa.gov/headlines/y2009/21jan_severespaceweather.htm
3. Department of Homeland Security: Connections and interdependencies across economy: http://science.nasa.gov/headlines/y2009/images/severespaceweather/interdependency.jpg
4. Swiss Re: Space Weather- Hazard to the Earth? http://www.swissre.com/pws/research%20publications/risk%20and%20expertise/risk%20perception/space_weather.html
5. IEEE Spectrum November 2000 http://thayer.dartmouth.edu/spacescience/wl/res/ae/biblio/molinski00.pdf
6. Effects on railroad http://www.arema.org/eseries/scriptcontent/custom/e_arema/library/2000_Conference_Proceedings/00024.pdf
7. Threat Analysis Canada http://www.publicsafety.gc.ca/prg/em/ccirc/2002/ta02-001-eng.aspx
8. Document C-15 "Procedures for Solar Magnetic Disturbances which Affect Electric Power Systems" revised January 11 2007: Northeast Power Coordination Council, New York, NY.
9. John Hopkins APL Technical Digest, Volume 28 Number 1 (2008) - "Harsh Environments: Space Radiation Environment, Effects, and Mitigation" by Richard H. Maurer, Martin E. Fraeman, Mark N. Martin, and David R. Roth.
10. NOAA Space Weather Prediction Center http://www.swpc.noaa.gov/
11. NOAA Space Weather Prediction Center: Education: http://www.swpc.noaa.gov/Education/index.html
12. Lund Space Weather Center http://www.lund.irf.se/
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End notes:

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