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Extreme Space Weather Impact: An Emergency Management Perspective

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Abstract In 2010, the Department of Homeland Security's Federal Emergency Management Agency (FEMA) partnered with the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (SWPC) to investigate the potential for extreme space weather conditions to impact National Security/Emergency Preparedness communications—those communications vital to a functioning government and to emergency and disaster response—in the United States. Given the interdependencies of modern critical infrastructure, the initial systematic review of academic research on space weather effects on communications expanded to other critical infrastructure sectors, federal agencies, and private sector organizations. While the effort is ongoing, and despite uncertainties inherent with this hazard, FEMA and the SWPC did draw some conclusions. If electric power remains available, an extreme space weather event will result in the intermittent loss of HF and similar sky wave radio systems, minimal direct impact to public safety line-of-sight radio and commercial cellular services, a relatively small loss of satellite services as a percentage of the total satellite fleet, interference or intermittent loss of satellite communications and GPS navigation and timing signals, and no first-order impact to consumer electronic devices. Vulnerability of electric power to an extreme geomagnetic storm remains the primary concern from an emergency management perspective, but actual impact is not well understood at present. A discussion of potential impacts to infrastructure from the loss of electric power from any hazard is provided using the 2011 record tornado outbreak in Alabama as an example.

1. Introduction

On 23 July 2012, the NASA STEREO A spacecraft witnessed one of the largest solar eruptions ever recorded [*Baker et al*., 2013]. Fortunately, it was not Earth directed. Had the eruption occurred just 1 week earlier, *Baker et al*. [2013] suggest that Earth could have experienced an extreme geomagnetic storm rivaling the famous Carrington Event of 1859. Modeling by *Ngwira et al*. [2013] suggests that the impact at the surface of the Earth could have been similar to the March 1989 storm that collapsed the Hydro Quebec power grid in Canada. Such storms have the potential to cause disruption to communications, power grids, and other critical infrastructure and represent a hazard that until recent years was almost unknown in the Emergency Management community.

Beginning in 2010, the Department of Homeland Security's (DHS) Federal Emergency Management Agency (FEMA) partnered with the National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC) to investigate the potential for extreme space weather conditions to impact National Security/Emergency Preparedness communications—those communications vital to a functioning government and to emergency and disaster response—in the United States. Given the interdependencies of modern critical infrastructure, the initial systematic review of academic research on space weather effects on communications expanded to other critical infrastructure sectors. By 2012, more than a dozen federal departments and agencies, representatives from major telecommunications services providers, and subject-matter experts and regulators from the electric utilities had partnered in the effort to better understand vulnerabilities to extreme space weather. This article outlines some of the discussions and conclusions of this ongoing effort.

2. Discussion

2.1. What Is Space Weather

The NOAA Space Weather Prediction Center (Figure 1)—the official source of space weather forecasts, alerts, and warnings for the civil and commercial user community in the United States—categorizes various types of space weather in the NOAA Space Weather Scales (http://www.swpc.noaa.gov/NOAAscales/). These include

Figure 1. The NOAA Space Weather Prediction Center in Boulder, Colorado, is the United States Government's official source of space weather forecasts, alerts, and warnings for the civil and commercial user community. (Pictured from left to right: Doug Gore, FEMA Administrator Craig Fugate, Norm Winterowd, William "Bill" Murtagh, and Larry Combs.) (Photo courtesy of Federal Emergency Management Agency (FEMA)).

Radio Blackouts (R), Solar Radiation Storms (S), and Geomagnetic Storms (G) rated on an intensity scale from 1 (minor) to 5 (extreme). In addition, ionospheric disturbances, often associated with geomagnetic storms, can occur independently of the other space weather types and create considerable difficulty to communications and global navigation satellite system signals.

The study by FEMA/NOAA determined that space weather events of intensities of 1–3 on the SWPC scale generally do not have a significant impact on daily government operations in the continental United States. The greatest threat to infrastructure was found to be from Category 4 and 5 storms and in particular a Category 5 Geomagnetic Storm which could significantly impact electric power. Geomagnetic storms occur when a blast of solar plasma with embedded magnetic fields, called a Coronal Mass Ejection (CME), erupts from the sun and strikes the Earth's magnetic field. The most potentially destructive CMEs are generally launched from near the center of the solar disk as seen from the Earth, are Earth directed, massive, very fast moving, and have a predominately southward-oriented magnetic field [*National Research Council* (*NRC*), 2008].

2.2. Frequency of Extreme Space Weather

Understanding of extreme space weather impacts on modern technologies is limited. Table 1 from the study provides a partial list of the most significant impacts over the last 170 years. Some in the space weather community have suggested that events such as the great storm of 1921 may occur once in every 100 years, though definitive evidence for this is still lacking. A recent report from *Lloyd's* [2013] placed the recurrence of a Carrington level event capable of causing significant impact at once in every 150 years. Importantly, like other natural hazards, extreme solar events can occur at any time—as the 23 July 2012 event demonstrates—and a single sunspot group may produce multiple extreme storms as defined on the SWPC scale.

2.3. Warning Time

Because of the approximately 2 weeks that sunspots take to transit the visible face of the sun, sunspot regions capable of producing extreme events are often visible for several days. The SWPC issues daily forecasts containing narrative and probabilities for large events, but the science of space weather prediction has not progressed to the point where extreme events can be reliably predicted. The SWPC issues a watch for geomagnetic activity predictions, a warning when a storm condition is expected, and an alert when actual impact crosses established geomagnetic storm thresholds [*SWPC*, 2007].

Table 1. Extreme Space Weather Events With Recorded Impact on Earth

Date	Event
1847	"Anomalous current" noted on telegraph line between Derby and Birmingham, England. First recorded impact of space weather on technology [*Lanzerotti*, 2001].
August 28–29, 1859	Telegraph service disrupted in many parts of the world by geomagnetic superstorm [*Boteler*, 2006; *Green and Boardsen*, 2006; *Humble*, 2006].
September 1–2, 1859	Carrington event among the largest recorded solar storms in the last 500 years. Telegraph service disrupted in many parts of the world and some reported fires in telegraph stations [*Boteler*, 2006; *Green et al.*, 2006; *Humble*, 2006].
May 13–16, 1921	A series of large storms disrupted telegraph service in the U.S. and Europe, caused fires and disrupted train service in New York, and burned out undersea cables [*The New York Times*, 1921a, 1921b; *Cortie*, 1921].
March 13, 1989	Geomagnetic storm collapsed Hydro Quebec power grid in approximately 90 s and left 9 million people without power; 83% of power was restored within 9 h; "Electric utilities across the northern latitudes of the U.S. also experienced transformer damage, depressed voltages, and the forced tripping of several voltage control devices" [*NERC*, 1990].
October 19 – November 7, 2003	"Halloween Storms" interrupted GPS, blacked out high frequency (HF) radio, forced emergency procedures at nuclear power plants in Canada and the Northeastern United States [*NRC*, 2008], and may have damaged several large electrical power transformers in South Africa [*Gaunt and Coetzee*, 2007].

As an example, if a massive event occurred that produced all three types of extreme space weather, the SWPC would issue an immediate ALERT for an extreme solar flare Radio Blackout (R5) event (the solar flare energy arrives at the Earth at the speed of light, and thus with no warning). Within a short time, the SWPC would also issue a WARNING for a Solar Radiation Storm (solar energetic charged particles, predominantly electrons and protons) giving the anticipated arrival time at Earth of $>$10 MeV protons, the expected intensity, and the duration of the warning period. The WARNING would be updated to reflect S5 as the lower thresholds were crossed and the S5 likelihood increased. Meanwhile, NASA spacecraft would capture data on the size, direction, and speed of the coronal mass ejection which would feed modeling software that can predict the arrival time of the CME at Earth. Based on this information, a WATCH for a severe to extreme Geomagnetic Storm (G4 or greater) would be issued typically 15–30 h before the storm onset.

One critical piece of information will be missing: the orientation of the magnetic field inside the CME. The most potentially destructive CME would have a strong and predominately southward-oriented magnetic field. The NASA Advanced Composition Explorer (ACE) spacecraft measures the CME's magnetic orientation [*NASA*, 2013]. ACE, located sunward of the Earth by ~1.6 million km, can provide ~15–20 min warning before a fast-moving CME arrives at the Earth. The SWPC will issue a Geomagnetic Storm WARNING after the CME reaches ACE and key CME parameters are known.

The study noted that this creates a potentially challenging environment for messaging to the public. A fast-moving CME can arrive at the Earth in as little as 17 h. The CME associated with the Carrington storm of 1859 arrived at the Earth in just 17 h and 40 min after erupting off the Sun [*Koskinen and Huttunen*, 2006]. The 23 July 2012 event that occurred on the opposite side of the Sun reached the Earth equivalent distance in ~19 h [*Baker et al.*, 2013]. Many news media outlets receive the same email products from the SWPC as do government agencies and will know that an extreme event has occurred within minutes of the eruption. However, the magnetic orientation of the CME will not be known until it reaches the ACE spacecraft many hours later. Even if the CME has a predominately southward magnetic orientation, no operational models currently exist to predict specific locations or severity of impact on Earth. Table 2 provides a synopsis of warning times, duration, and primary impact of space weather as summarized by the SWPC in the study. FEMA does provide general guidance for space weather events which can inform public messaging on its Ready.gov website (http://www.ready.gov/space-weather).

2.4. Space Weather Impacts

2.4.1. R5 Extreme Solar Flare Radio Blackout

Electromagnetic energy from a solar eruption travels at the speed of light from the Sun to the Earth. X-ray and ultraviolet photons strike the upper atmosphere, produce additional ionization in the ionosphere, and cause absorption and frequency deviation in high frequency (HF, 3–30 MHz) radio signals and fadeout, noise, and phase change in other frequency bands [*Tulunay and Bradley*, 2004]. These effects render HF and similar sky wave communications on the Earth's daylight side essentially unusable for 1–3 h [*SWPC*, 2005]. Microwave

Table 2. Space Weather Warning Times, Duration, and Primary Impacts

	Warning Time	Duration	Primary Extreme Event Impact
Radio blackout (R)	None (speed of light)	Minutes–3 h	- Loss of HF radio communications on the Earth's daylight side. - Short-lived (minutes to an hour) loss of GPS. - Interference on civilian and military radar systems.
Radiation storm (S)	30 min to several hours	Hours to days	- Satellite operations impacted. Loss of satellites possible. - HF blackout in polar regions. - Increased radiation exposure to passengers and crew in aircraft at high latitudes.
Geomagnetic storm (G)	17–90 h	1–2 days	- Possible bulk electric power grid voltage collapse and damage to electrical transformers. - Interference or loss of satellite and sky wave radio communications due to scintillation. - Interference or loss of Global Positioning System (GPS) navigation and timing signals. - Satellite operations impacted.

emissions can also create noise in communications satellites and Global Positioning System (GPS) signals which can act as "natural jamming" that lasts for up to an hour [e.g., *Cerruti et al*., 2008].

Terrestrial line-of-sight very high frequency (VHF, 30–300 MHz), ultra high frequency (UHF, 300 MHz–3 GHz), and microwave signals that comprise the vast majority of public safety radio communications in the U.S. will not be significantly impacted by such an event. This includes line-of-sight VHF air-to-ground communications used for search and rescue and HF groundwave transmissions out to 10–60 miles. Additionally, major U.S. wireless providers stated that this is also true for cellular communications. There is one caveat: The *Royal Academy of Engineering (RAE)* [2013] concluded that cellular base stations could experience increased noise from Solar Radio Bursts (SRB) occurring at dawn and dusk for the parts of the network facing the sun. Due to design similarities, this same potential for increased noise from SRBs occurring at sunrise and sunset would also exist for public safety radio base station antennas facing the sun.

2.4.2. S5 Extreme Solar Radiation Storm

Solar ions and protons moving at very high speeds can arrive at the Earth in tens of minutes and can build in intensity over several hours to an S5 (extreme) level. These energetic charged particles can damage electronic spacecraft components. *Odenwald et al*. [2005] calculated that an 1859-like event impacting the Earth could result in a ~50 times increase in the anomalies normally experienced across the entire satellite fleet, particularly for satellites in geostationary orbits (GEO) and medium-earth orbits (MEO) that are less atmospherically shielded than low-earth orbit (LEO) satellites. (Note: government and public safety communications utilize satellites at GEO and LEO; the Global Positioning System is at MEO.) This would create a challenging environment for ground controllers attempting to mitigate problems and could result in the temporary or permanent loss of service for some satellites [*Odenwald et al*., 2005]. Additionally, an S5 storm can add 3–5 years of equivalent radiation exposure to solar panels, potentially degrading many older satellites below their minimum operating power and resulting in a potential loss of ~15% of the satellite fleet [*Odenwald et al*., 2005]. *RAE* [2013] recently stated that, based on the 2003 storm, "up to 10% of satellites could experience temporary outages lasting hours to days" and that "Very old satellites might be expected to start to fail in the immediate aftermath of the storm. . . ."

When presented with these figures during the study, commercial satellite industry representatives disputed their severity and pointed to the relatively low number of satellites damaged or lost in significant radiation storms during the space age. However, it is important to note that there have been no S5 events since 1974 when proton measurements began on Geostationary Operational Environmental Satellite (GOES) spacecraft.

Regardless, government and private-sector organizations can mitigate the potential impact by contracting satellite services from vendors with access to multiple satellites, and by using diverse satellite receivers that rely upon different satellites or satellite constellations. The Department of Defense indicated that it does not anticipate significant disruption to GPS satellites from an extreme radiation storm.

2.4.3. G5 Extreme Geomagnetic Storm

Extreme geomagnetic storms produce two effects that are of primary interest to government and critical infrastructure owners, operators, and customers in the U.S.: scintillation of communication signals that pass through the ionosphere and the impact of geomagnetically induced currents (GIC) on electric power utilities. (GIC can also affect other conducting structures such as pipelines and railways, but that was not covered in the FEMA/NOAA study.)

2.4.3.1. Scintillation

Scintillation is interference with radio and microwave signals that pass through or reflect from the Earth's ionosphere, and its effects are greatly enhanced during geomagnetic storms when the ionosphere is typically disturbed. Scintillation can degrade or even prevent signals to and from satellites and sky wave radio systems [*Tulunay and Bradley*, 2004]. Lower frequencies are more impacted than higher frequencies. Many portable satellite phones and receivers used by government and emergency personnel operate in the L-band (1–2 GHz). The study concluded that these communications systems could be impacted for 7–12+ h by scintillation effects. As usable satellite frequency increases, S-band (2–4 GHz), C-band (4–8 GHz), X-band (8–12 GHz), and K-band (12–40 GHz) are progressively less impacted by scintillation effects and may operate successfully during an extreme geomagnetic storm, if satellite service is available.

The Global Positioning System operates in the L band. Organizations that rely on GPS for location and timing signals may experience significant disruption. For example, loss of GPS timing signals of greater than two hours may force some cellular and public safety radio base stations into "island mode." These base stations would be unable to hand off calls to another base station for mobile users moving between coverage areas, and users near the edge of coverage areas may experience interference from adjacent base stations or loss of service.

Within the first hours after onset of a geomagnetic disturbance, HF radio communications may be helped due to enhancement of the ionosphere F layer, but the communications will degrade as the storm progresses. As with a solar flare Radio Blackout event, line-of-sight terrestrial radio should remain usable though it may experience increased noise.

2.4.3.2. Electric Power

Nothing involved with extreme space weather has raised more controversy than the potential impact to the electric power grid from geomagnetic storms, specifically the potential for catastrophic damage to extra high-voltage (EHV) transformers from geomagnetically induced currents. These EHV transformers are responsible for changing electricity generated at power stations and stepping it up to higher voltages for transport on the bulk transmission system for delivery around the country. There are approximately 2000 EHV transformers in the United States [*Kappenman*, 2010]. Many of these are custom built.

Given the dependency of the other critical infrastructure sectors on electric power, no other aspect of space weather impact is more important to understand. In 2008, the *National Research Council (NRC)* cited a Metatech Corporation study that predicted a 1921-like storm could permanently damage 350 EHV transformers in the United States with recovery requiring 4–10 years and trillions of dollars. In 2011, the DHS Office of Science and Technology commissioned the JASON Study by The MITRE Corporation, which questioned the plausibility of the Metatech Corporation study but admitted that "severe damage is a possibility" [*Brenner et al.*, 2011]. The *North American Electric Reliability Corporation (NERC)* stated in a 2012 Interim Report, "NERC recognizes that other studies have indicated a severe [geomagnetic disturbance (GMD)] event would result in the failure of a large number of EHV transformers . . . this report does not support this conclusion." More recently, *Lloyd*'s [2013] suggested that while some EHV transformers may be damaged, the more important factor is the areas served by the transformers that fail. In one scenario, the most populated areas of the Northeast and Mid-Atlantic states could be without power for prolonged periods with domestically produced transformers having manufacturing lead times of 5–12 months and "6–16 months for international suppliers" [*Lloyd*'s, 2013]. In the FEMA/NOAA study, senior engineers from two major electric utilities pointed out that the reports suggesting that widespread damage would occur are based on simulations which assume that at certain GIC levels the EHV transformers will sustain damage. They stated that no testing information has verified that severe GMD events are capable of triggering damage to a large number of EHV transformers.

The North American Power Grid has grown considerably in both size and complexity since the 1921 storm and has not experienced a storm of similar or greater intensity since. Regardless, the studies above generally agree that a repeat of the 1921 storm *could* result in widespread voltage instability and voltage collapse (a.k.a. blackout) in the United States. This could potentially affect more than 100 million people with the greatest vulnerability along the Atlantic Coast, the northern Midwest, and Northwest of the country. Opinions diverge from there, but additional discussions with scientists, engineers, and government experts as part of a federal planning effort in 2011–12 did provide a scenario that advised federal planning.

If a widespread blackout were to occur from a severe geomagnetic disturbance, representatives from the energy sector in the federal planning effort indicated that more than half of customers would see their electric power restored within 12–24 h. Impact to the remaining affected population would depend on how many (if any) EHV transformers are damaged and where they are located. Damage to a few, dispersed EHV transformers is expected to have little or no long-term impact on customers. If failures were concentrated in a tight area or on nearby adjacent lines the impact could be more severe, especially for those major metropolitan areas that import most of their power from the bulk transmission system. It must be noted that, according to the *U.S. Energy Information Administration* [2013], there are approximately 6440 power plants in the United States with at least one generator. While damage to generators and associated infrastructure from extreme space weather is possible, widespread or long-term damage to power plants is not expected [*NERC*, 2012]. Based on this assessment, electric utility providers and government energy experts stated that even in areas where access to bulk power is lost, there will be "islands of power" available to those customers serviced by local power plants.

There has been confusion in the public sector between GIC and electromagnetic pulse (EMP) from nuclear explosions. Put simply, a geomagnetic storm can induce currents in the ground whose frequency is so low that they require a large receiver—such as the high-voltage transmission lines found in the North American Power Grid—to capture them. Conversely, nuclear EMP has three components ranging from high frequency (E1) which can damage consumer electronics (e.g., computers, smartphones, etc.) to low frequency (E3) which has similarities to GIC. Geomagnetically induced currents do not have an E1 component; thus, they will not directly damage consumer electronics (first-order impact). Such electronics may be damaged if they are unprotected and plugged into electrical outlets during instances of voltage instability (second-order impact).

Experience from numerous natural disasters such as Hurricane Sandy or the Honshu Earthquake in Japan tells us that effects of power loss will build over time. Any technology without backup power will fail immediately (i.e., cable television, phone, internet service, water and gasoline pumps, heating and cooling systems, refrigeration, etc.). Most devices that rely on batteries will fail within 2–24 hours (i.e., smartphones, communications towers, medical devices, etc.). Generator backup power will generally last for 2–7 days without refueling. Demand for generators and fuel will be high and sources may not be locally available. The same may be true for food, drinking water, and medical supplies. If loss of power occurs during excessively hot or cold temperatures, shelter from the environment would become an issue. The larger the impact, the longer it will take federal, state, tribal, and local governments to marshal and deliver resources to all affected areas.

As an example, the following is a partial account from the *Huntsville-Madison County Emergency Management Agency* [2011] following the record tornado outbreaks in 2011 that left the majority of Northern Alabama without power for 5–7 days.

> "Generators were brought in to keep water systems and other infrastructure running. Cell phone coverage was unreliable or interrupted as the backup generators at the cell towers ran out of fuel. Hundreds of thousands of dollars [was] lost to food spoilage at schools and retail businesses as well as families. Traffic backed up as people waited in line to get gas in areas that still had power. Some internet providers were off line for several days. VOIP phone systems were down. Businesses were closed and employees couldn't work. Schools and daycare centers were closed. Many grain mills were out of power for seven days. There was no feed or water for cattle. There was no ventilation for the [chicken] houses. Approximately three million chicken carcasses had to be disposed of. Businesses that could open were only accepting cash. People could not access their bank accounts and credit cards were useless."

3. Conclusion

Despite the uncertainties, several conclusions can be drawn from the FEMA/NOAA study. If electric power remains available, an extreme space weather event will result in the intermittent loss of HF and similar sky wave radio systems, minimal direct impact to public safety line-of-sight radio and commercial cellular services, a relatively small loss of satellite service as a percentage of the total satellite fleet, interference or intermittent loss of satellite communications and GPS navigation and timing signals, and no first-order impact to consumer electronic devices.

The FEMA/NOAA study concluded that vulnerability of electric power to an extreme geomagnetic storm remains the primary concern. Efforts are underway to improve scientific and engineering understanding of the threat, to develop and improve regulations and protective measures, and to provide information on the space weather hazard. The NOAA Space Weather Prediction Center provides daily forecasts, email products, and educational materials (http://www.swpc.noaa.gov/). FEMA provides recommendations for space weather and other hazards on its Ready.gov website (http://www.ready.gov/). NERC commissioned the Geomagnetic Disturbance Task Force to investigate bulk power system reliability implications and develop solutions to help mitigate this risk (http://www.nerc.com/comm/PC/Pages/default.aspx select Geomagnetic Disturbance Task Force from the list). The Federal Energy Regulatory Commission issued a Final Rule for Reliability Standards for Geomagnetic Disturbances in May 2013 (http://www.ferc.gov/whats-new/comm-meet/2013/051613/E-5.pdf). The White House Office of Science and Technology Policy issued a report on space weather observing systems (http://www.whitehouse.gov/blog/2013/04/26/standing-watch-against-space-weather). Finally, the National Space Weather Program provides links to several current efforts (http://www.nswp.gov/nswp_index.htm).

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