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IS U.S. NATIONAL SECURITY PREPARED FOR THE NEXT GEOMAGNETIC POLE REVERSAL?

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by

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements
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Maxwell Air Force Base, Alabama

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ABSTRACT

The Earth's core is undergoing a dramatic change with geomagnetic field strength dropping by 40% over the last 400 years, and satellite observations showing the field weakening ten times faster than previously calculated. These changes are a precursor to a common geological phenomenon known as a geomagnetic polarity reversal, where the north and south magnetic poles of the Earth reverse. Geomagnetic polarity reversals significantly decrease the strength of the magnetic field, thereby considerably increasing the interaction of the solar wind with the Earth's atmosphere and biosphere. The purpose of this research is to answer if the United States is prepared for the impacts to national security resulting from the next geomagnetic polarity reversal.

The report begins with an overview of pole reversals, then evaluates the effects of reversals on United States national security by utilizing six evaluation criteria ranging from infrastructure areas such as the electrical power grid to national response capabilities. The research evaluates the impacts of increases in solar and cosmic radiation and the threat of adverse space weather during a polarity transition on United States national security.

This research concluded that the nation is not prepared for both geomagnetic polarity reversals and adverse space weather. Furthermore, the nation has neglected funding for geoscience and geomagnetism research. Based on the conclusions, this research recommends increasing geoscience and geomagnetism funding, spearheading an international geomagnetic initiative, developing response, recovery and risk plans at the national level and preparing the national infrastructure for the threats posed by pole reversals.

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Section I - Introduction

The Earth's core is in the midst of a significant change. During the last 400 years, the geomagnetic field, or magnetosphere, has declined in strength by a remarkable 40%.[1] Measurements by ESA's SWARM geomagnetism monitoring satellite array have further confirmed this change with measurements indicating the magnetic field is weakening ten times faster than previously predicted.[2] The weakening trend in the magnetic field clearly shows that the Earth's core is undergoing a substantial transformation.

The Earth's geomagnetic field is responsible for both shielding the atmosphere and biosphere from the harmful effects of solar and cosmic radiation, and creating conditions on the surface that are ripe for life. The magnetosphere, then, is the invisible barrier that has played a significant role in protecting the Earth from the harmful effects of space. The importance of this shield is evident when comparing the Earth and Mars. One is a lush planet full of water and life, the other a barren, rocky desert with no magnetic field.

The weakening trend in the magnetic field is a precursor to a common geologic phenomenon known as a geomagnetic polarity reversal, where north and south magnetic poles of the Earth swap positions. While a pole flip may sound benign, the implications extend well beyond a change in polarity. Increases in cosmic and solar radiation bombarding the Earth's surface and a decrease in the magnetic field strength of 90% are a few of the results of the reversal process.[3] The decrease in magnetic field strength would increase vulnerability to catastrophic space weather events and increase cosmic and solar radiation interaction with the atmosphere and surface, leading to infrastructure damages in the trillions of dollars, and the death of untold numbers of Americans. Despite the danger posed by the magnetosphere

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decreasing in strength, geomagnetic polarity reversals have received no attention as a threat to the nation.

The lack of research does not diminish the hazardous consequences a reversal would have on modern society. As such, this research was conducted to answer the following question: *Is the United States prepared for the impacts to national security that would occur during the next geomagnetic pole reversal?* While geomagnetic polarity reversals receive little attention outside the geosciences, reversals have the capability of crippling the nation's interconnected and interdependent infrastructures, posing a threat to national security extending far beyond those predicted by global warming and climate change. Unlike the debate surrounding man-made climate change and global warming, polarity reversals are a proven natural phenomenon that have occurred hundreds of times in the Earth's past, and will happen again in the future.[4]

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Research Framework and Report Overview

This research utilizes an evaluation framework to assess United States national security preparedness for the next geomagnetic polarity reversal. First, the report explains the two impacts resulting from polarity reversals, and then evaluates their effects on United States national security utilizing six evaluation criteria that cover various aspects of the nation's infrastructure. The criteria assess the costs of each impact on national security using a variety of sources, both from academic and government sources. The results of the evaluation will answer whether the United States is ready for the next geomagnetic polarity reversal.

The report is divided into five major sections, starting first with a background section covering the scientific facts and unknowns regarding polarity reversals, then reviews the six evaluation criteria areas, followed by an analysis and assessment of the two pole reversal impacts on United States national security, then completing with conclusions and recommendations. The evaluation framework allows this research to quantify how a geomagnetic polarity reversal would affect United States national security.

The overall purpose of this research is to evaluate United States preparedness for the next reversal event and to highlight the importance of the geosciences outside of climate change and global warming for national security considerations. Because of the damaging effects of pole reversals on national security, the United States should consider reversals a direct threat to the nation, and should devote the time, money and resources needed to unravel the mechanisms creating the Earth's magnetic field. Understanding the Earth's core, geodynamo and magnetosphere should be a top priority for the United States to not only mitigate the hazardous effects of a pole reversal on the nation's infrastructures and national security but to understand better the complex and ever-changing Earth system.

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Section II – Background

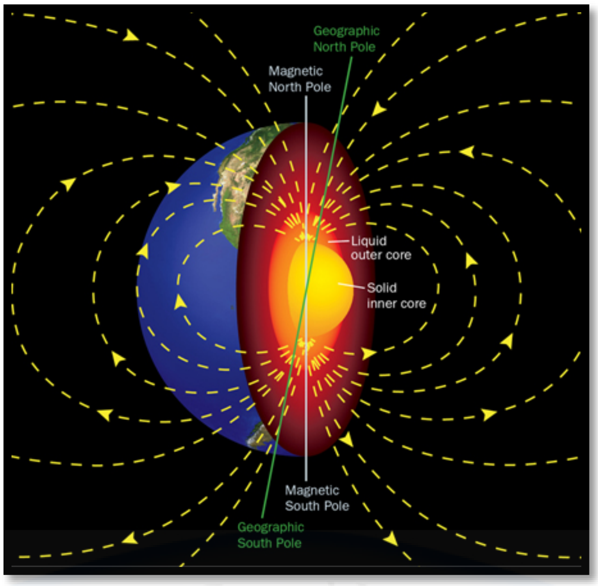

Figure 1. The Earth's Geomagnetic Field.
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(accessed 20 October 2015).

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Origin of the Geomagnetic Field

The Earth's interior consists of four major sections: the crust, mantle, outer core and inner core.[5] The geomagnetic field originates from the Earth's core, creating the equivalent of an axial dipole magnet with both distinct north and south magnetic poles.[6] The highly conductive liquid iron and nickel outer core rotates around the solid iron inner core, and through a combination of heat convection and rotation, creates the Earth's geomagnetic field.[7] This idea, known as the geodynamo, is the prevailing theory on the origin of the Earth's magnetic field.

The geomagnetic field is not a recent phenomenon, however, having been active for at least the last 3.2 billion years.[8] Far from stable and static, the field continually varies in strength, intensity and polarity. Magnetic variations range from periods of seconds and minutes to intervals of 10 million years or more, known as superchrons.[9] The use of magnetic declination on charts and maps is an example of the ever-changing nature of the magnetic field.

Geomagnetic Polarity Reversals and Geomagnetic Excursions

A geomagnetic polarity reversal occurs when Earth's geomagnetic field weakens, and north and south magnetic poles of the Earth flip. The weakening of the field does not always result in a pole reversal, with failed reversal events called geomagnetic excursions occurring in the Earth's history. Polarity reversals are geomagnetic events where the field flips magnetic poles and remains stable for thousands or millions of years, whereas geomagnetic excursions are events where the field weakens and attempts a reversal, but is unsuccessful.[10] While geomagnetic excursions do not succeed in swapping magnetic poles, their effects are indistinguishable from successful polarity reversals until the field polarity changes.

Reversal Frequency

Pole reversals are a familiar part of the Earth system going back millions of years. In fact, during the last 40 million years alone the field has flipped 143 times, with an average reversal rate of once per 250 thousand years for the last 25 million years.[11,12] The last polarity reversal, the Matuyama-Brunhes, occurred over 780 thousand years ago, showing that the Earth could be overdue for a reversal based on the frequency of the last 25 million years.[13] It is also important to note that there have been several geomagnetic excursions occurring since the last full polarity reversal event, which occur at a rate of two to three per million years.[14]

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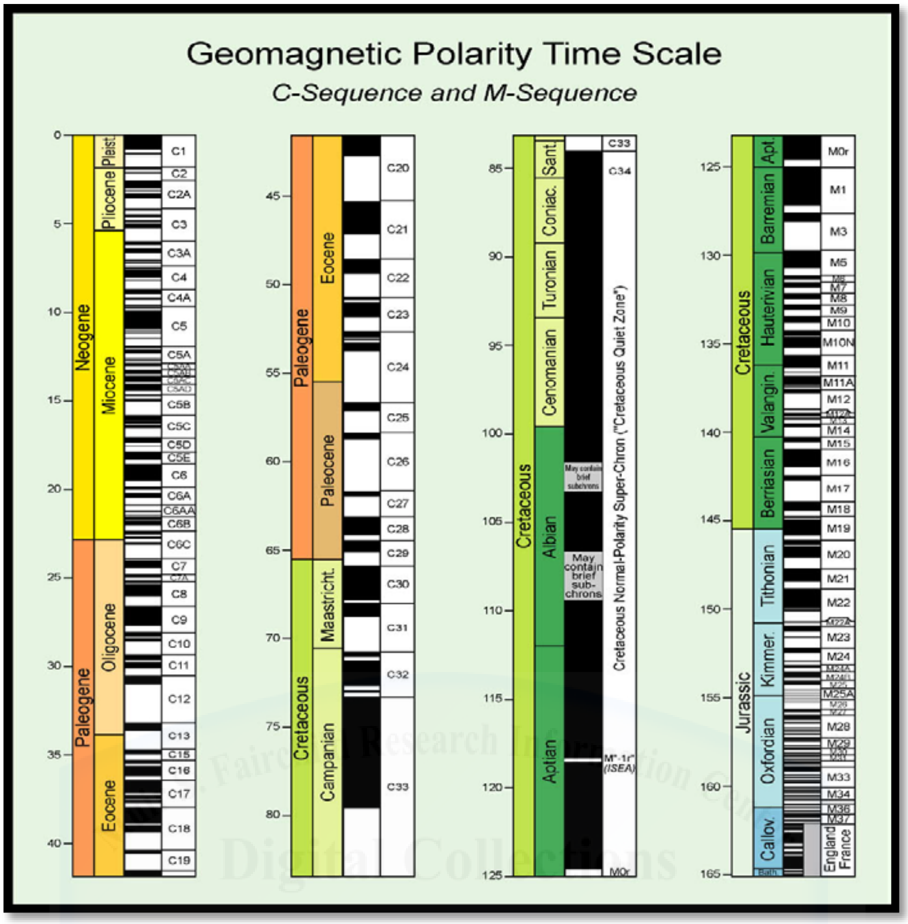

Figure 2. Geomagnetic Polarity Time Scale. Reprinted from *Georgia Tech Geophysics Department*, http://geophysics.eas.gatech.edu/classes/Geophysics/misc/pics/magnetic-time-scale.jpg (accessed 22 November 2015).

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Reversal Timeframes

The timeframes involved with reversals vary, with research in 2014 showing the Matuyama-Brunhes transition completed in less than 100 years, displaying the abrupt and dynamic nature of some reversal events.[15] Additional research conducted in the United States showed field change rates up to 6 degrees per day and 1 degree per week for two reversal events, demonstrating that a rapid directional change of the field is common.[16] There is building evidence and support for the prevalence of rapid directional change during geomagnetic reversals. While reversals can be abrupt events, other research has shown reversals completing on the order of several hundred to several thousand years.[17] The variation in reversal timescales underscores the variable and complex nature of the magnetosphere.

When will the next Pole Reversal Occur?

There is strong evidence suggesting that a transition may be underway, with magnetic field strength levels during the last 150-200 years dropping by a significant 15 percent.[18] Measurements made since the invention of the compass have shown strength levels falling by an astounding 40% over 400 years.[19] Field strength measurements made by ESA's SWARM satellite array add to this building picture of changes in the Earth's core, with data showing the rate of change is occurring ten times faster than previously calculated.[20] If the weakening trend continues accelerating, and the field reverses in the same manner as the Matuyama-Brunhes transition, the Earth could see a flip in a human lifetime.

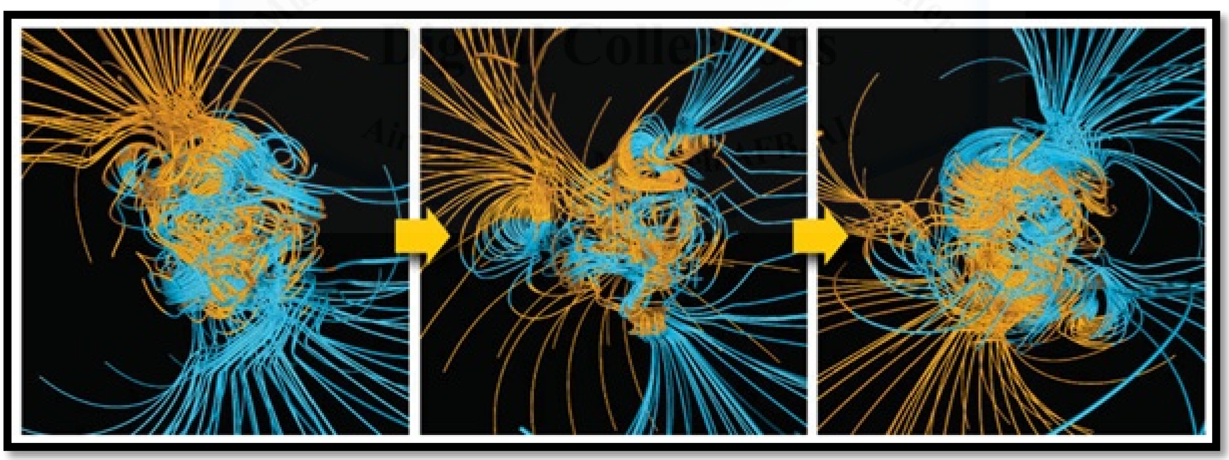

Figure 3. Computer simulation depicting Geomagnetic Pole Reversal. Frame 1 is before the reversal, frame 2 is during the reversal, and frame 3 is after the reversal. Note the tangled and complex nature of the magnetic field in frame 2. Reprinted from *Astronomy.com*, http://www.astronomy.com/-/media/import/images/8/3/0/july-2010-earth_s-magnetic-.jpg?mw=600 (accessed 20 November 2015).

Polarity Reversal Impacts

Pole reversals create two changes to the Earth system that affect the United States: 1) a decrease in geomagnetic field strength, and 2) an increase in radiation entering the atmosphere and biosphere. While there are other possible impacts to include links between reversals, worldwide volcanism, and mass extinctions, they are not included due to the contentious nature of the findings. This section of the report provides a baseline on each reversal impact before beginning the evaluation section. The goal is not to provide a comprehensive overview, but to highlight the pertinent background information for each effect.

Decrease in Field Strength

The most significant change occurring during a reversal is a substantial weakening of the geomagnetic field. Over the course of several hundred to thousand years during the reversal, the magnetic field becomes distorted and weakened.[21] The magnetosphere fluctuates from a geomagnetic dipole to multipolar field, decreasing in strength down to ten percent of its average intensity.[22]

In this transition phase, various north and south polarity regions exist across the globe, creating a magnetosphere that is both non-uniform, irregular and considerably weakened.[23] The magnetosphere is vulnerable to the solar wind as a consequence, resulting in further distortion and abating of the field. The weakening effect also increases the solar wind's interaction with the Earth's atmosphere, contributing to considerable decreases in upper atmosphere ozone and oxygen levels, and increasing atmospheric escape into space.[24] Finally, the weakened magnetosphere drastically increases the susceptibility of the Earth to space weather events, which are already harmful to the Earth with the current relatively stable magnetic field.

The weakening of the magnetosphere is the most significant change occurring in the Earth's magnetic field during a pole reversal.

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Increased Cosmic and Solar Radiation

The geomagnetic field acts a filter against solar and cosmic radiation, protecting both the atmosphere and biosphere from the harmful effects of radiation. The shift from a dipole to a multi-polar field leaves the magnetosphere less efficient at blocking solar and cosmic radiation. The increased amounts of energetic particles interacting with the atmosphere decrease atmospheric ozone, allowing more solar and cosmic radiation to interact with the planet's surface and biosphere.[25] The result from the larger cosmic and solar particle interaction with the atmosphere is reduced ozone and oxygen in the upper atmosphere, and increased radiation exposure at the surface, especially at higher latitudes.[26] Other effects include increased mutation rates and higher amounts of UV radiation interacting with life on the surface.[27] The combination of reduced ozone, oxygen, and increased radiation levels have adverse effects on the biosphere. The Laschamp-Mono Lake geomagnetic excursion event, for example, led to a 20% UV-B radiation increase at latitudes of 40-50 degrees, with atmospheric ozone levels decreasing by 20 to 40%.[28] This research also saw increases in radiation reaching as far south as 30 degrees latitude, or near modern day Florida, which would encompass the majority of the United States.[29] The harmful effects of radiation increases do not represent a direct threat to the United States but create their unique set of issues, which are reviewed in section IV.

Before delving into the evaluation section, it is important to discuss the current state of geomagnetism monitoring programs.

Geomagnetism Monitoring Programs

The United States Geological Survey's (USGS) Geomagnetism Program and the European Space Agency's (ESA) SWARM satellite constellation represent the two most well-funded and active geomagnetism monitoring programs. While regional programs exist, they are not on the same scale or scope for consideration.

The USGS Geomagnetism Program consists of 14 ground-based observation stations that provide 24/7 real-time coverage of the Earth's magnetic field, with the majority of stations based in the United States and its territories.[30] The 14 stations work and cooperate with INTERMAGNET, the International Real-Time Magnetic Observatory Network, which helps in coordinating the work done for collecting geomagnetism data around the globe.[31] The result of the geomagnetism-monitoring program is the ability to monitor the Earth's magnetosphere down to the second, which is extremely helpful during solar geomagnetic storm events, and analyzing other phenomenon associated with the Earth's magnetic field.[32]

The current space-based monitoring system, ESA's SWARM satellite constellation, consists of three satellites that monitor the Earth's magnetosphere from orbit.[33] Providing the most high resolution and accurate measurements of the Earth's magnetic field and crustal magnetic properties, SWARM will help in monitoring and assessing the every changing magnetosphere.[34] The purpose of SWARM is to provide high resolution and extremely accurate measurements of the Earth's magnetosphere, along with regional variations in the crust. It does not provide monitoring data in real time like USGS's geomagnetism monitoring program.

The combination of both monitoring programs allows geologists to monitor and continually assess the on-going changes occurring the geomagnetic field. While unprecedented in their accuracy and speed, these measurement systems nonetheless do not permit any measure of future prediction capability.

Pole Reversal Acknowledgements

Before beginning the evaluation section, it is important to recognize some key issues concerning polarity reversals. Despite huge advancements in technology over the last several hundred years, there is much regarding the Earth system that geoscientists do not know.

The first and most important acknowledgment concerns reversal timeframes and frequency of occurrence. Research has shown that reversals can complete in as little as 100 years or take as long as several thousand years.[35] There is no standard or "normal" polarity reversal, with no two-reversal events being identical in duration due to the periodic and unpredictable nature of the Earth's geodynamo. During the Earth's history, there have been periods of high reversal frequency, as that seen during the last 40 million years, and periods where the field remained stable for millions of years, as during the Cretacious superchron. The core does not reverse at periodic or predictable intervals, making it impossible to forecast the duration and intensity of the next reversal event based on the geological record.

The second acknowledgment is that there is no way to predict a polarity reversal. The technology needed for prediction does not exist, and current measurement systems are passive, in that they only record the strength of the field. Geologists studying reversals are hampered by the time frame of accurate field measurements as well, which go back 400 years and represent less than 0.0001% of the overall age of the Earth at 4.6 billion years old. The most advanced computer systems available today cannot predict or simulate all the complex dynamics of the Earth's core, as the timescales, lengths and inputs needed are impossible to replicate given current technology.[36] While computer simulations have been successful at modeling some aspects of the geodynamo, no system has been powerful enough to model all necessary variables.[37] Until computer processor technology increases in capability, geoscientists can only simulate certain aspects or specific properties of the Earth's core. The issue is complicated further by the inability to access the interior of the Earth. The deepest drill holes on record do not penetrate the Earth's crust, meaning geologists and other geoscientists must interpret seismic waves to build a picture of the Earth's interior. While new methods in seismic tomography have created detailed views of the Earth's interior down to the core-mantle boundary, none have mapped the inner and outer core to the degree needed to confirm the geodynamo theory. Scientific knowledge and technological capabilities limit geologists from being able to predict the next geomagnetic polarity reversal.

The understanding of the Earth is both constrained by technological capabilities and by the length and complexity of measurements. Knowing when the next reversal will occur and predicting its timeframe for completion are two areas outside current scientific capabilities. As such, this research is left setting reversal parameters that may not mirror those during the next geomagnetic pole reversal.

Section III – Evaluation Research Criteria

The evaluation criteria selected for this research have a focus grounded at the national level. The research focuses on assessing the impacts to United States national security by evaluating six major areas for each effect discussed:

1. Communication Systems
2. Satellite Constellations
3. Electrical Power Grid
4. Agriculture and the Food Chain
5. Economic Infrastructure
6. Response Preparedness

With each impact area, the report evaluates the damages to national security based on the six criteria. After the evaluation, the report assesses United States preparedness for the next geomagnetic polarity reversal. While not an all-inclusive list, the criteria provide a means of evaluating the various impacts occurring to United States national security resulting from pole reversals.

This research has covered the science behind the Earth's geomagnetic field, the details of geomagnetic polarity reversals, and the evaluation criteria; it is now time to analyze how geomagnetic polarity reversal impacts would affect United States national security.

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Section IV – National Security Impacts

This portion of the report evaluates two impact scenarios involving pole reversal effects. The first scenario discusses how extreme space weather would damage United States national security during a reversal, and the second examines the effects occurring in the biosphere from increased levels of solar and cosmic radiation. This research assumes a polarity reversal timeframe where the magnetic field begins a significant decrease in strength and rapid directional change now, with the reversal process taking several hundred years to complete.

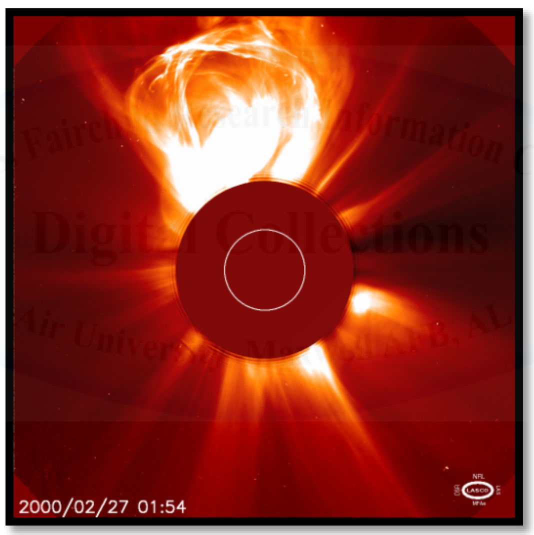

Figure 4. SOHO image of Coronal Mass Ejection. Reprinted from *EarthSky.org*, http://earthsky.org/space/what-are-coronal-mass-ejections (accessed 22 November 2015).

Severe Space Weather Event

The most serious pole reversal effect is the weakening of the geomagnetic field, which decreases in strength by 90 percent during the reversal process.[38] With a reversal lasting several hundred years, the greatest threat to United States national security would arise from adverse space weather. While the term space weather extends beyond the Sun's influence to include charged particles, cosmic rays, and other phenomena, this research focuses on the danger posed by coronal mass ejections (CMEs).[39] CMEs are enormous clouds of charged plasma with magnetic fields ejected into space from the Sun's corona.[40] These plasma clouds crash into the Earth's magnetosphere, causing geomagnetic storms, which disturb and distort the magnetic field.[41] CMEs create both geomagnetic storms and geomagnetically induced currents, which have devastating impacts on electrical components and other aspects of the infrastructure.[42] While CMEs are only a part of the space weather environment, they pose the greatest risk to the Earth during the reversal period.

The strongest CME to hit Earth in the modern era was the 1859 Carrington event, which disrupted telegraph services around the northern hemisphere causing machines to catch fire, operator injuries, and created auroras as far south as Cuba.[43] A more modern example is the 1989 collapse of the Quebec Hydro-Electric plant, which failed in 90 seconds after a solar storm ejection event, leaving millions of Canadians without power for nine hours.[44] This failure occurred despite the CME being only a quarter as strong as the Carrington event in 1859.[45,46] Both events occurred at geomagnetic field strength levels much higher than would be present during a pole reversal.

The likelihood of a CME striking the Earth during a polarity reversal is very high. During the 11-year solar cycle, the Sun produces one ejection per week at solar minimum, with 2 to 3 events per day at solar maximum.[47] In a 200-year period for polarity reversal completion, the Sun would produce a minimum of 10,000 CME events assuming solar minimum numbers, with several superstorm events like the one in 1859.[48] As stated by renowned Physicist Dr. Michio Kaku, the United States is, "…*playing Russian roulette with the Sun. Sooner or later we are going to lose that bet*…" with devastating effects that would push the industrialized world back into the 18th century.[49,50] Coronal mass ejections and other space weather events pose a threat to the Earth with a magnetic field at normal levels, with no research exploring the impact of extreme space weather during a geomagnetic reversal. The Laschamp and Mono Lake geomagnetic excursions provide a means of assessing how the field would change, with radiation and cosmic ray levels increasing in areas as far south as Florida.[51] The effects of any CME event during a reversal would be felt at much farther south latitudes than those experienced with a field at average strength.

It is important to note that the numbers and figures provided are for conditions with an average geomagnetic field strength. Research conducted on severe space weather has not considered the possibility of a drastically weakened geomagnetic field. With the effects of space weather extending farther south and the severity of the impacts increasing, the information provided is a best-case scenario with the real cost likely to be significantly higher.

Communication Systems

The first infrastructure area to suffer from an ejection event during a pole reversal would be the communications infrastructure. The consequences would extend from cell phone services to radio communications systems, to satellite-based C2, to systems utilized by land-based assets, aircraft and ships at sea. The weakened magnetic field would allow an ejection to interfere more with HF, UHF, VHF and satellite timing signals, resulting in experiences more severe than the 2003 Halloween solar storm, which disrupted the FAA's GPS WAAS navigation system for 30 hours.[52] Frequency blackout regions closer to the poles would force airlines to reroute aircraft from the quicker polar routes to slower options farther south, incurring significant costs in increased flight hours and fuel.[53] Military operations would suffer much as they did when a minor solar storm hit during Operation DESERT STORM, which disrupted call for fire requests for several hours in combat.[54] Communications that rely on the ionosphere for the propagation of radio waves would encounter difficulties due to the instabilities created in the atmosphere by

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the mass ejection.[55] Cell phones and devices utilizing cellular connections would have communications interrupted as well, due to the disruption of GPS timing signals needed for current cell network function.[56] These effects do not even take into account the possibility of satellites and ground stations losing power, or suffering irreparable damage in the geomagnetic storm triggered by the CME.

A best-case scenario would be lost communications across a wide area of the United States for several hours in the event of a short duration mass ejection event. A worst-case scenario would see the effects of the CME and resulting geomagnetic storm destroying communications satellites and the electrical power grid, which could take out communications capabilities for weeks or months. The reduced ability of United States forces to communicate would have detrimental effects on operations not only in the United States but around the world. Military operations and first responders would have communications difficulties during and after the ejection event. Areas such as ICBM missile field defense and flying operations critical for the security of the nation would have communications capabilities severely hampered or destroyed due to the effects of the CME. Assuming a worst-case Carrington CME strike, the United States would have difficulties with communications systems for weeks, if not months. United States command and control capabilities would certainly suffer due to the effects of the solar storm.

The impacts to communications systems are only the tip of the iceberg for damaging effects to United States national security.

Satellite Infrastructure

The world's satellite constellations would be extremely vulnerable to severe space weather during a reversal. With an estimated 250 satellite constellations representing an investment of $75 billion dollars and revenue stream of $25 billion to $80 billion dollars per year, the satellite grid is one of the most expensive pieces of the United States infrastructure.[57,58] The decreased strength of the magnetic field would expose satellites to the full brunt of a CME event. With a field reduced down to 10% of its average strength, the magnetosphere would allow larger amounts of radiation from the solar wind to interact with satellites.[59]

Numerous issues would arise well before any space weather event hit the Earth. The time dedicated to dealing with satellite anomalies, which under normal conditions comprises around 40 percent of satellite operators time, would surge under the increased interaction of the solar wind with the magnetosphere.[60] Failures of satellites would increase due to electrostatic spacecraft charging from fluctuations in the solar wind, which would also swell in numbers under the weak field conditions.[61] The weakening of the magnetosphere would allow more radiation to interact with the atmosphere, with a corresponding increase in temperature and density, causing more satellites to de-orbit and burn up.[62] The decreasing strength of the magnetosphere would cause increased satellite failures, equipment anomalies and satellite de-orbits well outside those experienced in this last century.

A CME event as strong as Carrington occurring with an average strength geomagnetic field would cause an estimated $100 billion dollars in damage, triggering satellite failures, de-orbits, and degradation of any systems that survived the event.[63] The solar panels of existing satellites would sustain damage from energetic particles, causing power availability decreases and overall diminished operational life spans.[64] This degradation would affect any satellites utilizing solar energy, civilian or military. The estimates for the number of failures vary, with minimum assessments predicting well over 100 hundred satellites failures and de-orbits.[65] No studies have analyzed CME impacts on satellite constellations during a geomagnetic polarity reversal, but the failure rate would undeniably be higher due to the significantly weakened magnetic field and corresponding adverse effects on the upper atmosphere. Therefore, these numbers represent a best-case scenario for impacts to the satellite infrastructure.

The effects on national security would be widespread, with GPS, communications, television, internet and other services performed by the nation's satellite constellations disrupted for hours, days or destroyed by the solar storm. Devices and systems relying on GPS to function, such as oceanic drilling rigs and cell phone logistics tracking networks would fail, as well as various other critical infrastructures in the US which rely on GPS timing signals to operate.[66] There would be impacts for years with increased numbers of satellite failures, de-orbits, and increased operating costs.

In essence, the United States and the world's satellite constellations would be extremely vulnerable to the effects of space weather during the reversal process. The increased costs of operating satellites in the reduced strength magnetosphere environment would economically hurt the United States and other nations. The impact of such an event with a full strength magnetic field already poses a grave risk to the satellite infrastructure, let alone the enhanced effects with a weakened and Mars-like magnetic field. The $100 billion dollar damage cost estimate is a baseline to start from, with the likely damage being much worse.

The dangers of a weakened magnetic field extend to other infrastructure areas as well.

Electrical Power Grid

Next to the costs of damages to the satellite infrastructure, the electrical power grid represents the next infrastructure area with significant vulnerabilities. A CME hitting with the strength of the 1859 Carrington event during a polarity reversal could send over half of the United States back into the 18th century, leaving millions without electricity for days, weeks or years. With the increase in the interaction of energetic particles with the atmosphere extending down to 30 degrees latitude, a larger portion of the electrical power grid would have contact with geomagnetically induced currents created by the geomagnetic storm.[67] Current estimates of damage to the power grid during a massive CME event place at least 130 million Americans without power for 12-24 hours, assuming no significant damage to the nation's extremely high voltage (EHV) transformers.[68] However, damage is likely to occur to a considerable number of these high voltage transformers with a substantially weakened magnetic field, driven by the higher prevalence of geomagnetically induced currents, which overload EHV transformers and other electrical components.[69] Out of an estimated 2000 EHV transformers in the United States, a minimum of 350 could face irreparable damage or failure.[70,71] The greatest probability of long-term harm to the power grid is created through the destruction of these EHV transformers, as the cost per unit ranges from $2 to $7.5 million dollars, with times approaching 12 months or longer for manufacture; any widespread damage of the electrical grid could have grave repercussions for the nation.[72,73] It would take months or years before the damaged transformers could be replaced, with initial efforts to restore power hampered by the existing electrical failures disrupting everything from the delivery of water to fuel.[74] Even with a best-case scenario of half of the affected population regaining power within 12 to 24 hours, there would still be 60 million or more Americans without electricity for weeks, months or years.[75]

The costs of widespread power outages and regions without electricity for months would be extremely harmful to the country. For example, in a single four-hour blackout in France, an estimated $1 billion dollars was lost; in the August 2003 blackout affecting the Northeast United States, an estimated $10 billion dollars was lost.[76,77] Damages from widespread power outages affecting half of the United States population could cost the nation $1 to $2 trillion dollars in the first year alone, with recovery times approaching ten years or more.[78] These estimates are also contingent upon the effects occurring at 50 degrees latitude, which is much higher than the 30 degrees of latitude where the effects would extend down to during a geomagnetic pole reversal.[79]

The lack of shielding exposes more of the nation's power grid to the brunt of the CME and leads to an increase in the number of affected Americans past the 130 million estimate. To speculate on the exact increase in affected areas and damage to the United States is beyond the capability of this research, but would certainly be worse.

The effects would also extend to military and national security organizations. With power outages extending into months and possibly years for a large portion of the nation, vital military installations, and government agencies would feel the effects. Government services in the affected regions would cease function until restoration of power. With battery backups and generators only lasting up to 7 days, bases and installations would have to find ways of obtaining fuel, water, and other necessities shut off by the electrical failures.[80] Military bases rely more on privatized electrical power delivery than at any time in the nation's history.[81] Without water, fuel, sanitation services and electricity to execute the mission, many facilities and organizations would need to get creative to maintain operational effectiveness. The country would be vulnerable as it focused on the worst national disaster in United States history.

The failure of the electrical grid in a Carrington style event during a polarity reversal would cost a minimum of $2 trillion dollars with at least 60 million Americans in a complete electrical blackout for months. Months, years and decades would pass before a full recovery could occur in the electrical power grid.

The effects would extend to other infrastructure areas as well.

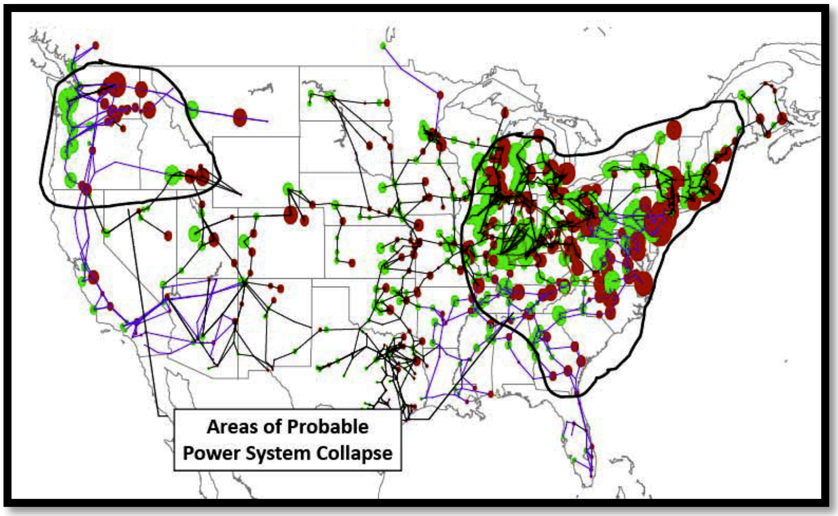

Figure 5. Areas of Power System Collapse. The lines indicate areas of the power grid likely to collapse during a Carrington style coronal mass ejection event. Reprinted from *NASA Science News,* http://science.nasa.gov/science-news/science-at-nasa/2009/21jan_severespaceweather/ (accessed 22 November 2015).

Agriculture and the Food Chain

The nation depends on electricity to produce and consume food. A culture of omnipresent grocery stores, pervasive refrigerators, just in time grocery deliveries and electrically powered agriculture means the nation is highly susceptible to any long-term power outage.

Food without refrigeration can stay fresh for only a few days, with most grocery stores depending on weekly deliveries of refrigerated products, showing that food distribution to the affected populations would be hard hit. Additionally, many regions in the country depend on electrically driven center pivot irrigation systems to grow crops. This, combined with a lack of water, gasoline, and other necessities has the potential for grave consequences. Many Americans have enough food to last a week, but the impacts of a long-term electrical blackout would extend for months, possibly leading to food starvation and anarchy in the regions hit hardest by the CME. With 12% percent of the nation living without extended food stores for more than one day, and a minimum of 130 million Americans affected by a Carrington style event hitting during a reversal, there is the potential for millions of deaths.[82] Scenes of looting and fighting as seen in Hurricane Katrina could be the norm in areas without food, water, and necessities for an extended period. A large number of Americans would die due to the extent and severity of the disaster.

It is hard to ascertain the exact impact an electrical power outage would have on the nation's agriculture. Modern agricultural equipment is dependent on the electrical and satellite infrastructure to operate; GPS devices, electronic soil monitors and computer driven GIS solutions power the modern farmer and his equipment.[83] A simultaneous blackout of GPS signals and loss of electrical energy could end or severely hamper agricultural production in vast areas of the nation. As the majority of the country's crop growing regions extend above 30 degrees latitude, they would feel the effects of any mass ejection event. With 40% of the crops produced in the nation with center-pivot systems, there is the potential for both significant economic losses, and the inability to produce crops, as many regions utilizing the center-pivot systems were not able to support crops with rainwater before their invention.[84] The nation's dependence on electricity and new technologies is a tremendous vulnerability, even in the agricultural sector of the infrastructure.

The impacts of a large ejection event occurring in the midst of a polarity reversal has the potential to create the greatest humanitarian crisis in the nation's history, and could lead to riots, looting, and anarchy in the affected regions. It is impossible to say with certainty how many Americans could die during such an event, but it is highly likely that the 12% of the 60 million Americans without power would be very vulnerable to starvation.[85] Defeating the cascading effects of a total electrical blackout would require a national response that is both well prepared and well-coordinated.

While the impacts to agriculture, communications, electrical and the satellite infrastructures are severe, the economy would be one of the areas hardest hit.

Economic Infrastructure

The combined effects of losses in the satellite, electrical and agricultural infrastructures resulting from a worst-case CME event hitting the Earth during a reversal could spell disaster for the nation's economy. The August 2003 blackout affecting the Northeast United States, which lasted for two days and affected 45 million Americans, totaled an estimated $10 billion dollars in lost revenue.[86] Estimates of the economic impact with a full strength geomagnetic field begin at $2 trillion dollars in the first year alone.[87] This estimate, which is based on 130 million Americans seeing the effects of adverse space weather, is likely lower than would be seen during a geomagnetic polarity reversal. It is very likely the real economic loss would be at least several trillion dollars in the first year alone, not including the costs extended over years and possibly decades to obtain a full recovery. The combined impacts to the satellite, communications, and electrical infrastructure would see costs resulting from the event lasting decades.

All economic activities dependent upon electricity and the internet would cease to operate in the aftermath of the blackout. Stock exchanges, gas stations, grocery stores, websites and telecommunications industries would all suffer or stop due to the effects of satellite damage and electrical blackout. Key global trade links running on undersea fiber optic cables would see damage, severing global internet and commerce ties.[88] The airline industry would have to deal simultaneously with hazardous space weather effects in flight and seek to continue operations to locations without electrical power.[89] Satellite, power, and communications companies would incur costs over $100 billion dollars through damages to equipment and replacement expenses in the years and decades after the event.[90] The hub of trade and activity in the modern era, the internet, would halt in the affected areas. Nearly every aspect of the interconnected and electrified modern society would see detrimental effects from a Carrington-class mass ejection event hitting the Earth during a pole reversal.

In short, the impacts to the United States would easily exceed $2 trillion dollars in the first year alone.[91] This figure does not take into account the cumulative effect of the weakened magnetic field, which would incur increased costs over time with satellite, communications and power infrastructures failures brought on by the increased penetration and interaction of the solar wind with the magnetosphere and atmosphere. Predicting the severity of long-term effects and lasting economic damage is hard to ascertain, but would most definitively be debilitating for at least several years after the event.

Response Preparedness

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The nation is ill prepared to handle a disaster on the scale of a CME direct hit during a geomagnetic reversal. Despite the known threat of space weather on the nation's interconnected and electrically dependent infrastructures, there has been hardly any action during the last several decades. The government is hampered by a lack of any national risk assessments for geomagnetic storms, space weather events or pole reversals.[92] Furthermore, there is no office coordinating the work of developing risk mitigation and analysis measures within the federal government.[93] A federal intra-agency response plan for geomagnetic and space weather events does not exist at the current time. Furthermore, the nation still does not have a long-term all hazards considered power outage response or recovery plan, both of which would help in preparing for any space weather events with or without a degraded geomagnetic field.[94]

While the NOAA's Space Weather Prediction Center and the Air Force's Weather Agency provide space weather event prediction capabilities for civilian and government agencies, the data is still limited by the enormous volume of space and sparse coverage of ground-based assets.[95] While the USGS geomagnetism-monitoring program provides measurements of the Earth's magnetosphere during space weather events, it does not have any capability for predicting the future behavior of the magnetic field. The NOAA, Air Force, and USGS products provide a means of preparing and predicting for some aspects of a worst case space weather scenario but are ineffective due to deficiencies in the nation's infrastructures. The electrical power infrastructure lacks the ability to both monitor and assess the strength of geomagnetically induced currents and the ability to control power generation, transmission and distribution across the nation during geomagnetic storm events.[96] The inability to coordinate mitigation actions across the nation's overloaded power grid would contribute to system collapse. Furthermore, there is still debate in the scientific community regarding how space weather events would affect infrastructure areas.[97]

The nation further suffers from response and recovery plans unprepared for the scope and scale of the disaster. With over 130 million Americans impacted by a worst-case CME event hitting during a reversal, FEMA, DHS, and other government agency responses would simply be unable to cope with the vast logistics needed to provide water and food to the affected areas. Current products at FEMA and DHS do not factor in widespread power failures in areas such as the Northeast corridor of the United States, which would be vulnerable to any space weather events during a polarity reversal. Command and control for response and recovery operations with long-term electrical power failures, limited satellite communications, and infrastructure collapse would be ineffective or severely hampered. If the Hurricane Katrina and Sandy disasters are a measure of response capabilities, then it is likely that FEMA and other responding organizations would have difficulties with communications and organizing relief efforts.[98] The Hurricane Sandy relief efforts epitomize the difficulties, with FEMA personnel sitting for four days after the event due to poor organization and command and control.[99] Even though the scale of the disaster was much smaller than a blackout affecting 130 million Americans, many citizens were still without power and water for three months after the event, with some even living in tent cities.[100] If the same lack of organization and command and control were to prevail in the aftermath of a large solar storm event, then tens of millions of Americans would be without clean water, sanitation services and power for months or years.

Given the response efforts for Hurricanes Sandy and Katrina, combined with the lack of adequate planning and action products at FEMA and DHS, it is unlikely that the nation would be able to respond adequately to any large-scale disaster scenario. Simply stated, the scale and scope of the disaster exceed any existing planning products available, with past response efforts calling into question the capability of the government to respond to a disaster affecting over half of the nation's population.[101]

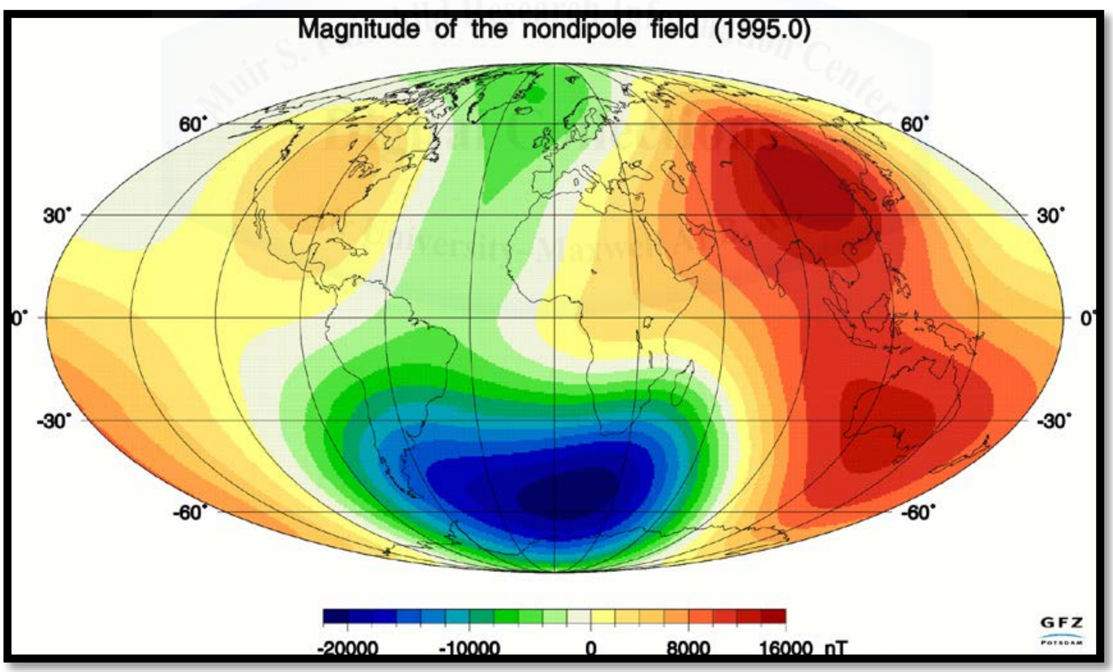

Figure 6. Magnetic Map of the Earth. Note the non-uniform nature of the geomagnetic field, especially over the South Atlantic region. Reprinted from *Helmholtz Centre Potsdam GFZ, German Research Centre for Geosciences*, http://op.gfz-potsdam.de/champ/media_CHAMP/luehr_1_nondipolar.gif (accessed 22 November 2015).

Increases in Cosmic and Solar Radiation

While extreme space weather events like the 1859 Carrington CME pose the greatest risk to the nation during a reversal, the weakening of the magnetosphere by itself is still dangerous for national security. A weakened geomagnetic field increases solar and cosmic radiation interacting with the atmosphere and biosphere. The weakening is significant for two reasons: 1) the increased interaction of the solar wind and space weather with the magnetosphere, atmosphere, and biosphere, and 2) increased levels of UV radiation reaching as far south as 30 degrees latitude.[102]

While the impacts are not as severe as the previous scenario, they nonetheless would have detrimental effects on national security.

Communication Systems

Increases in radiation entering the Earth's atmosphere would have adverse effects on communications systems based on the changes in the magnetosphere. While the real risk to the communications infrastructure comes from CMEs striking the Earth, there would still be impacts arising from the reduced strength magnetic field.

The weakening of the magnetosphere by up to 90% and the dynamic nature of the Sun ensure that the Earth would see more effects from small-scale solar events.[103] Galactic cosmic rays, solar flares and radiation storms from the sun would have varying effects on communications systems. Small scale space weather events would likely cause problems such as ionospheric scintillation, which are fluctuations in the atmosphere caused by ionization that would impair HF and other communications that utilize the atmosphere to propagate radio signals.[104,105] Radio blackout events resulting from the emission of x-rays and extreme ultraviolet radiation from the Sun would interact to a greater degree with the atmosphere,

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increasing the frequency of outages.[106] With approximately 2,000 emissions per 11-year solar cycle, there would be many opportunities during a 200-year reversal period for these events to disable and disrupt communications systems.[107] Communications interruptions, as a result, would be more commonplace during the reversal period.

The communications difficulties encountered during operation DESERT STORM are an analog for how operations would be impaired in an environment with a weakened magnetosphere. The 41-day conflict witnessed over 80 solar flares that interrupted UHF and SATCOM communications for minutes and hours at a time.[108] Routine outages of communications could be common as the magnetic field weakens, triggering less reliability for critical systems used in war and during peacetime operations. In particular, the airline industry would have to re-route flights to avoid blackout areas, which not only incurs costs but adds to flight safety dangers. Whether on land, sea, air or space, communications would see disruptions during the reversal period.

While the costs associated with such cumulative damage and interruptions are hard to quantify, they would undoubtedly incur economic and operational expenses in the civilian and military sectors. The net result of a weakened magnetic field would be increased frequency and duration of communications blackouts around the world, not just in the United States.

Satellite Infrastructure

The greatest potential for damage to national security during a reversal resides in the satellite infrastructure. Increased amounts of solar and cosmic radiation interacting with satellite constellations would add costs to the construction and operation of satellite systems.

With a normal strength magnetosphere, operators already see 40% of their time devoted to fixing anomalies associated with space weather events; electrostatic discharge, solar panel degradation and atmospheric changes leading to de-orbit are a few of the issues that would increase in severity during a polarity reversal.[109] Satellite designs are built based on predetermined rates of degradation; any significant rise in radiation would reduce the 15-year average operational life of satellite systems.[110] Solar flares would pose the greatest threat to satellite constellations outside of CME events during the reversal process. During a two-century period, the Sun would eject over 40,000 M to X-class flares.[111] While flare events are smaller in their impact than large CMEs, they still damage satellite operations. The 2001 Bastille Day X-Class flare event is an example of how smaller scale flares can negatively affect satellite operations, with GPS position errors approaching 20 to 40 meters for several hours.[112] Position errors of this degree are more than enough to negatively affect navigation for air, maritime and land-based assets. The warfighter would see the effects as well, with systems reliant on GPS for targeting or navigation being much less efficient due to position errors approaching 120 feet. The FAA's GPS WAAS navigation system and other systems that rely on satellites would see similar effects, although the duration and extent of the impact would be less than that experienced during a large CME event.[113] During a 200-year reversal with normal solar activity, there would be at least 3,500 X-Class flares with the same potential as the Bastille Day event.[114] With a geomagnetic field filtering less radiation from the solar wind and allowing the charged particles to interact with the atmosphere to a larger degree, it is likely that lower class flare events would produce more damage.

The net result is an increase in damage to satellite constellations with minor space weather events, with a corresponding increase in the cost to build, launch and maintain satellites. While it is impossible to estimate an exact value, it is evident that a weakened magnetosphere would not only lead to an increase in the price to operate in space, it would render those systems less reliable.

While the satellite infrastructure would be damaged by a weakened magnetosphere, the electrical power grid represents another infrastructure area that would be vulnerable.

Electrical Power Grid

Along with the satellite infrastructure, the power grid is susceptible to damage resulting from a geomagnetic reversal. More specifically, the frequency and duration of geomagnetically induced currents and localized magnetic fields could enhance and increase damage from space weather events.

The transition geomagnetic field would have numerous north and south polarity regions distributed across the globe. The effect would be a greater ability for geomagnetic storms caused by space weather to induce ground level electric fields, which drive geomagnetically induced currents.[115] As transformer failures correspond with increases in solar activity, a decrease in geomagnetic field strength would lead to increased failure rates.[116] While it is impossible to say how many transformers could fail, the failure rate would correspond directly with activity of geomagnetically induced currents. Even a small increase in geomagnetically induced current activity related to solar storms would cause damages in the electrical grid of millions of dollars per year, assuming only a few transformers are damaged.

An increase in severity and frequency of geomagnetically induced currents damaging the electrical grid is the likely result of a weakened geodynamo. More transformer failures, blackouts, and damage to the interconnected electrical power grid are the results of such a change in the Earth's geodynamo.

While the weakening of the magnetosphere would incur costs on the satellite, communications, and electrical infrastructure areas, there could be damaging effects to the food chain as well.

Agriculture and the Food Chain

An increase in radiation could have detrimental consequences for human life and the food chain. The first and most notable effect of a weakened magnetic field deals with ozone and oxygen in the upper atmosphere, which filter out the majority of radiation from space. The combination of weak magnetic field and regular solar flare storms could deplete the atmosphere's ability to filter out ultraviolet radiation for several years. An analog to what the nation could face are the Laschamp-Mono Lake geomagnetic excursion events, which saw UV radiation increases of 40% at latitudes of 40-50 degrees.[117] Ozone losses reached 40% in the upper atmosphere, leading to surges in radiation at northern latitudes in the United States and Europe.[118] The decrease in ozone was the result of the weakened field, which allowed solar flares and CMEs to strip away ozone and oxygen in the upper atmosphere.[119]

Even a small reduction in ozone could have harmful consequences, with research showing a 1% reduction in ozone corresponding to a 3% increase in skin cancer rates, and a 1-2% increase in melanoma mortality.[120] With space weather effects extending down as far as 30 degrees latitude, or near present day Florida, and the majority of the United States exposed to increases in radiation, a 40% decrease in ozone levels in the atmosphere could create a significant rise in skin cancer rates and deaths.[121,122] The damages would extend to other areas as well, with more cardiac deaths and dementia cases reported after geomagnetic storms.[123] Skin cancer, cardiac deaths and cases of dementia would all increase during a pole reversal event.

The food chain would see faunal extinctions of small organisms called Radiolaria in the ocean correlating to reversal events.[124] It is unclear how this would affect the food chain for humans, but could have more far-reaching effects within the ocean food chain. A more salient risk to the food chain comes in the form of radiation, with increased UV-A/B radiation correlating to stunted crop growth, tissue damage and smaller plant yields.[125] While not all species of plants are damaged by radiation, it is possible that a substantial surge of UV-A/B radiation entering the biosphere could have widespread adverse effects on plant growth, especially at higher latitudes.

The larger amounts of radiation entering the biosphere has the potential to increase skin cancer rates and would pose a threat to small ocean creatures and some species of plants, although it is unlikely the damages would harm national security to any significant degree.

Economic Infrastructure

A reversal would negatively affect the nation's economy during the reversal period. The satellite and electrical infrastructures could see spikes in operating and equipment costs easily in the millions of dollars. Airlines could see cost increases brought on by outages of navigation systems and by having to re-route flights due to radiation hazards in the atmosphere. With the cost of a commercial satellite averaging $500 million dollars and the cost per diverted or re-routed flights costing anywhere from $10,000 to $100,000 dollars per event, there is the potential for economic injuries to rise into the millions of dollars during the reversal period.[126] The satellite infrastructure would be hit hard with an average economic gain of a satellite over its lifetime topping $1 billion dollars; even a few losses of satellites could increase the economic impact on the nation.[127] With only a fraction of the potential economic damage areas considered, the price to the country over the reversal period could easily top several billions of dollars.

While the effects of a weakened magnetosphere are not damaging enough to compromise the national security of the United States, they would still incur economic losses, especially to the electrical and satellite infrastructures, which could see millions to billions of dollars in losses.

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Response Preparedness

The nation would likely be able to respond to the damages brought on by a weakened geomagnetic field without a large space weather event. Electrical power failures and satellite damages, while increasing in frequency and severity, would not create any widespread disaster scenarios. Furthermore, the increases in skin cancer and mutation rates would not pose a significant hazard. Regional and national response plans from FEMA, DHS, and other organizations are capable of handling these small scale blackouts created by solar flare events, and could respond within their current capabilities. The cumulative effects occurring during the geomagnetic reversal would likely see several minor blackout events as the most severe side effect of the reversal.

While the weakening of the magnetosphere has the potential to damage United States national security, it would not pose a direct threat to the nation in the end.

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Section V – Conclusions

It is clear that the geomagnetic field plays an irreplaceable role in protecting the atmosphere and biosphere of the Earth. Coronal mass ejections, solar flares, galactic cosmic rays and other space weather events that are normally filtered by an average strength geomagnetic field become an increasingly larger problem with a magnetosphere at ten percent of average strength.[128]

American society is especially susceptible to any decrease in magnetic field strength, with many important aspects of modern civilization relying on satellites and the electrical power grid to operate. Electricity keeps food fresh, pumps water, and is essential in filtering wastewater to reduce disease. It also runs irrigation and agricultural equipment, powers the internet, provides heating and cooling, and intertwines with all aspects of day-to-day life. The satellite infrastructure has revolutionized warfare and allowed for precise navigation for oceanic drilling rigs, farm equipment, and all number of GPS-enabled devices. The nation is dependent upon electricity and the technologies it enables to power the economy, navigation, communications systems, agriculture and a myriad of other infrastructure areas. Any significant disruption in electrical energy delivery and access would devastate the nation.

A large CME hitting the Earth during a reversal would be the worst natural disaster to strike the country in its history. Satellite damages would be a minimum of $100 billion dollars, electrical infrastructure damages would exceed $1 billion dollars, and the nation would lose $2 trillion dollars in the first year alone in economic losses. National security would suffer as FEMA, DHS, and other federal agencies struggled to deal with an electrical power blackout affecting over half of the nation's population. 60 million Americans would be without electricity for weeks, months or years. The effects would detrimentally affect everything from water delivery to sanitation services, to communications capabilities, to the provisioning of food in the affected areas. A full recovery could take years or decades and would be unlike anything seen in the history of the nation.

Even without a once or twice per century Carrington CME event hitting the Earth during a reversal, the nation would still be at the mercy of solar weather. Solar flares, radio blackouts, increases in radiation and small ejection events would each impose a different set of damages on the nation. Satellite infrastructure and electrical power grid damages could easily extend into the billions of dollars. Crops grown in northern regions could see yields reduced through cellular damage brought on by increased UV radiation. Skin cancer rates would increase exponentially as the atmosphere's ozone and oxygen were steadily stripped away by solar flares and the solar wind. While not as devastating for the nation, a weakened magnetosphere would incur cumulative damages on the nation into the billions of dollars.

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The background evidence of geomagnetic pole reversal frequency, the weakening trend in the magnetosphere, and the known harmful effects of space weather paint a picture of disastrous consequences the likes of which have never been seen by the nation before. Earthquakes, tsunamis, volcanoes, hurricanes and other natural phenomena have far less impact than a reversal could have on the nation.

With the background information, evidence and data in mind, there are three conclusions drawn from this research report: 1) The country is not prepared for the next geomagnetic pole reversal, 2) The magnetic field safeguards the nation, and 3) Prediction capabilities are lacking.

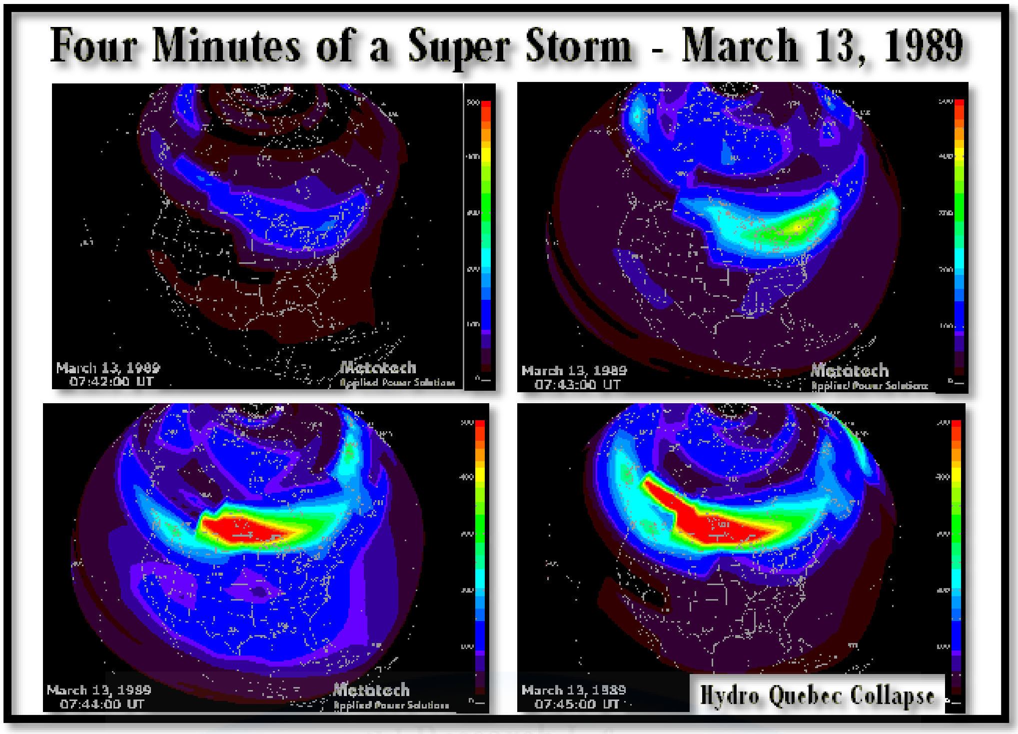

Figure 7. 1989 Solar Storm Progression. Images depict the progression of the March 1989 Quebec Solar Storm. Reprinted from *Metatech Corporation*, http://www.metatechcorp.com/aps/AAAS_Press_Brief.htm (accessed 22 November 2015).

Conclusion #1: The Nation is Not Prepared

The nation is ill-prepared and extremely vulnerable to the impacts created as a result of geomagnetic polarity reversals. Despite the massive threat of space weather and the clear signs of a rapidly weakening magnetosphere, the nation has moved at a slow pace to address the threat. The President's October 2015 *National Space Weather Strategy* and *National Space Weather Action Plan* finally addresses the issue and sets the framework for dealing with space weather, but national response would be ineffective if a mass ejection event were to happen now. FEMA and DHS do not have the planning products, frameworks or capabilities in place to deal with such a large-scale event. There is also a troubling lack of national risk assessments considering geomagnetic reversals or adverse space weather as a threat to the nation. The country has done nothing to research, prepare or plan for the next geomagnetic reversal, despite building evidence that a reversal may occur in the near future. This fact, combined with FEMA's inability to handle events like Hurricane Katrina and Sandy has shown how vulnerable the nation is to large-scale disasters. Organizational dysfunction and the mishandling of the response and recovery efforts would likely lead to the affected areas suffering from lack of clean water, sanitation services and food, likely leading to riots and the deaths of many Americans.

The emergency response capabilities are not the only area that is unprepared for the effects of a polarity reversal. The electrical power grid and satellite infrastructure stand to lose billions of dollars from losses brought on by a weakened magnetic field alone. Geomagnetically induced currents and normal space weather events would destroy or damage satellites and burn up costly EHV transformers. Changes in the ionosphere would routinely disable and disrupt communications around the globe. Crops in the higher latitudes would see damage with farmers having to seek out more robust plant species to stay in business. The electrical grid would be especially vulnerable as it continues the path to more interdependence. An inability to monitor and assess geomagnetically induced currents and adjust power transmission across the nation would lead to widespread damages.[129] The satellite infrastructure would be vulnerable with systems designed for lower levels of radiation failing with the increased interaction of the solar wind with the Earth's atmosphere.

From the power grid, to the satellite infrastructure, to federal disaster response, recovery and planning products, to nation risk assessments, the country is ill-prepared, ill-equipped and will be unable to respond to any large-scale disaster brought on by the weakening of the magnetosphere.

Conclusion #2: The Magnetic Field and Modern Society

The magnetosphere is essential for shielding the atmosphere and biosphere from the harmful effects of space. A field weakened to 10% of average strength would have disastrous consequences for a nation that relies on satellites, communications systems, and an electrical grid to operate everything from the economy to weapons systems used in war.[130] As the nation becomes more dependent upon electronics, the dual threat of a weakened magnetosphere and adverse space weather will only increase. While the Carrington event in 1859 only created inconveniences in communication around the globe, a mass ejection event on the same scale hitting the Earth during a pole reversal today could destroy over half of the electrical power grid, negatively impacting half of the population of the United States, and has the potential to kill tens of millions of Americans. No other natural disaster outside a meteorite impact or massive worldwide volcanism would have the same damaging effects on the nation. To say that the modern, electrified and connected society relies on the protection offered by the magnetic field is an understatement.

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Conclusion #3: Prediction Capabilities

Even with knowledge of the rapid weakening of the magnetic field and the hazards posed by solar weather, the USGS and geoscientists remain unable to adequately predict the behavior of the magnetosphere. The only two large-scale geomagnetism monitoring programs, the USGS's Geomagnetism Monitoring Program and ESA's SWARM satellite constellation, only record field strength with no ability to predict the future behavior of the geodynamo. Computer systems are simply not fast enough to simulate and model all the necessary variables to predict the future behavior of the Earth's core. Geologists can only look back at the last 400 years of accurate measurements, and attempt to predict the future behavior of the magnetic field. Without prediction capabilities, geoscientists will be unable to say if the current weakening trend in the magnetosphere is a precursor to a pole reversal or a geomagnetic excursion. The lack of any prediction capability inhibits planning and preparation efforts that would be essential in mitigating the harmful effects of a polarity reversal. Developing monitoring and prediction capabilities that give insight into the complex behavior of the inner and outer core should be a top priority for geoscientists.

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Section VI – Recommendations

Based on the research evaluation and findings, it is clear that the nation is not prepared for dealing with the negative consequences brought on by geomagnetic polarity reversals. Furthermore, it is also evident the country is not ready to respond to adverse space weather events. Therefore, it is critically important that the country address the threat adequately before a worst-case pole reversal and adverse space weather event occur simultaneously. To address the threat, the nation should focus on the following recommendations: 1) increasing geomagnetism funding, 2) developing the first real-time 3-D view of the Earth's core, 3) developing geomagnetic pole reversal response, recovery and risk plans at the national level, 4) establishing a "Global Geomagnetic Initiative," 5) improving space weather forecasting capabilities, 6) developing national electrical grid control measures, 7) hardening satellites and electrical transformers, and 8) make understanding the Earth a priority. If followed, these recommendations represent a pragmatic and comprehensive approach to addressing the threat posed by geomagnetic polarity reversals.

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Recommendation #1: Increase Geomagnetism Funding

This first recommendation is to significantly increasing funding for both the USGS's Geomagnetism Monitoring Program and geomagnetism research. The 2015 USGS budget allocated $1.8 million dollars for the geomagnetism program, or a mere 0.00072% of the budget allocated for the Global Change Research Program (GCRP), which focuses on human impacts on the environment.[131,132] Furthermore, the geomagnetism program budget has decreased by 10% since the year 2000.[133] To place the geomagnetism budget in perspective, it receives 27 times less funding than the earthquake hazards program, 5 times less funding than USGS's invasive species initiatives, and 1,388 times less funding than the GCRP.[134] A more robust and capable geomagnetism monitoring program both helps monitor the changes in the Earth's core, and aids in measuring the localized variations in the magnetic field created as a result of solar storms. Doubling or tripling the USGS budget for geomagnetism would have the effect of not only increasing the capability to monitor the continual changes within the Earth's core, but would help in measuring and assessing geomagnetic storms created by adverse space weather. By expanding the number of stations and increasing the capability of the existing system, the USGS could provide enhanced data on electrical conductivity of the crust around the nation, and would support efforts to prepare and plan for the next reversal event. Increased funding for this program is essential not only for monitoring the magnetosphere, but helps to mitigate the effects of space weather. A robust and well-funded geomagnetism program is essential in both monitoring the Earth's geodynamo and helping to mitigate the damaging effects of space weather on the nation's infrastructures.

As the Earth's core continues to move closer to a polarity reversal, the nation should emphasize geomagnetism research funding. The geodynamo theory will remain unproven until enough research and scientific advancements occur to determine the origin of the magnetic field. It is important to note that the geodynamo theory has yet to be conclusively proven. Furthermore, there are still many unanswered questions surrounding the behavior of the geodynamo. Reversal timeframes, inner and outer core behavior prior to the reversal process, and how the magnetic field evolves during a reversal are important areas of information essential for preparation and planning efforts that still need more research. Increasing the USGS research budget, grants for geomagnetism research, and supporting INTERMAGNET and other geomagnetic initiatives could pay off both in the short and long-term with a better understanding of the Earth.

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Like global warming and climate change, the nation needs to emphasize the importance of the geosciences with appropriate funding.

Recommendation #2: Develop a Real-Time 3-D View of Earth's Interior

Understanding the interaction between the inner and outer core is essential for discovering how the geodynamo operates. For this reason, the United States should build the world's first real-time 3-D view of the core. This initiative would bear fruit in not only the realm of geomagnetism, but could help in explaining earthquakes, how volcanoes form and evolve, and give a better understanding of the mechanisms involved with plate tectonics. While the USGS Geomagnetism Program provides key information on the strength, orientation and evolving nature of the magnetosphere, it cannot give insight into the interaction of the outer and inner core. As research has shown that variations in heat flow and convection between the inner and outer core create the conditions for a reversal to occur, a real-time 3-D view of the Earth's inner and outer core could give the nation precious months or years to plan and prepare.[135] Having the capability to monitor and assess the changes occurring in the Earth's core in real time would certainly add to the nation's understanding of its behavior and allow for prediction measures.

To accomplish this task, the USGS should receive increased funding for their global seismograph network, invest in quantum computing, and explore new methods of imaging the interior of the Earth. The field of seismic tomography has evolved rapidly in the last several decades with the increased computational power of the personal computer. While the advancements have been significant in the last two decades, the computer systems available today are still not powerful enough to work in real time. Quantum computers, which promise to be many times more powerful than current systems, could be used to help develop an "Earth Observatory" to map, measure and investigate the interior of the Earth. Finally, the nation should invest in new technologies that can be used to image, understand and map the interior of

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the Earth. Increasing the reliability and accuracy of seismic data and increasing computer speeds would go a long way toward allowing geoscientists to predict the behavior of the magnetosphere.

In essence, the purpose of this recommendation is to build an “Earth Observatory” that would focus on monitoring the changes inside the planet. The creation of an observatory focused on the interior of the planet could help predict the future behavior of the core and unlock the mechanisms behind natural phenomena from volcanoes to earthquakes. The creation of an “Earth Observatory” is a critical step in developing the capability to predict the future behavior of the magnetosphere.

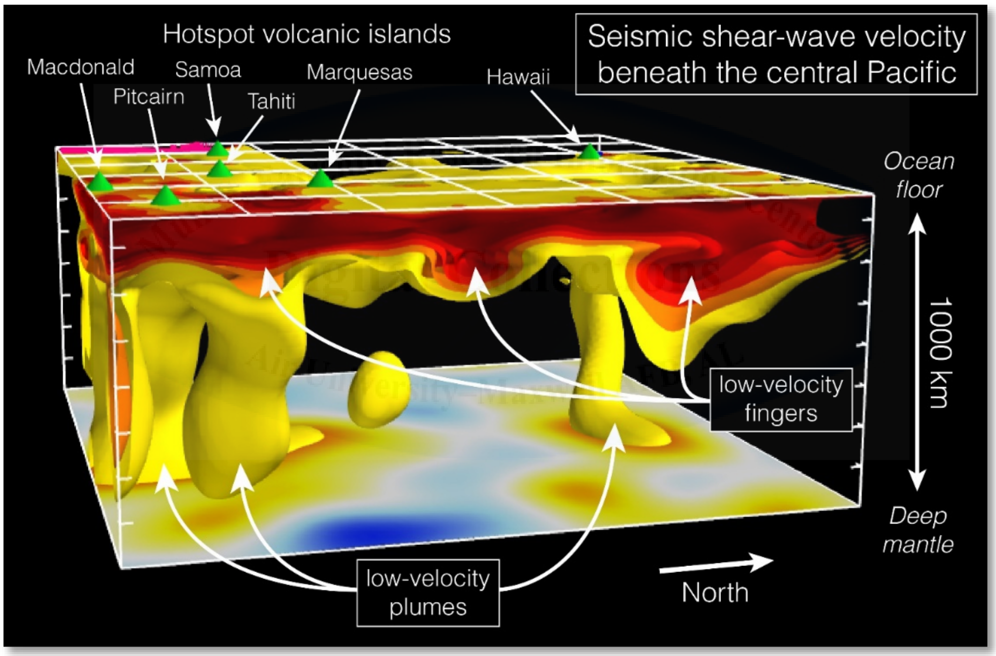

Figure 8. 3-D View of Hawaii Hot Spot. This image shows the current state of seismic tomography capabilities. Reprinted from *Phys.org*, http://cdn.phys.org/newman/gfx/news/hires/2013/1-newmodelofea.jpghtm (accessed 04 December 2015).

Recommendation #3: Develop Response, Recovery and Risk Mitigation Plans

While addressing the funding, measurement and prediction capabilities for pole reversals are important, it will be imperative to develop response, recovery and risk mitigation plans at the national level to mitigate the negative aspects of pole reversals. More specifically, FEMA should analyze the risks associated with pole reversals and include those on the *Strategic National Risk Assessment*. As the *Strategic National Risk Assessment* already includes tsunamis, volcanoes and earthquakes, the inclusion of reversals as another natural threat for consideration is logical. Furthermore, working together FEMA and DHS need to develop intra-agency plans for not only pole reversals, but for adverse space weather. Fortunately, the President's October 2015 *National Space Weather Strategy* does address this concern and calls for FEMA and DHS to work toward creating such products for adverse space weather, although it will be years before the plans are set and implemented.

To develop response, recovery and hazard plans, the country needs to focus on four areas. First, the nation should explore and benchmark the various hazards associated with polarity reversals. Increasing funding for geomagnetism monitoring and research, along with creating an "Earth Observatory" are examples of how to execute this first step. Next, FEMA needs to create response and recovery plans addressing the side effects of polarity reversals to include a large-scale nation-wide blackout affecting over half of the population. Third, the country needs to establish protection and mitigation policies for the electrical power grid and satellite infrastructure. The creation of a national command center for the electrical and satellite infrastructures is an easy solution. Finally, the nation needs to focus on creating the ability to accurately predict the behavior of the Earth's core, and find ways of simulating all aspects of the geodynamo. The establishment of an "Earth Observatory" and focusing on increasing the power of computer systems would help in solving the mysteries of the geodynamo. This framework for action focuses on observing and understanding the Earth, then planning and mitigating the effects of a geomagnetic pole reversal.

In essence, the development of response, recovery, and risk mitigation plans only serves to further the knowledge of the Earth and better prepares the United States for the unpredictable and complex nature of the Earth system.

Recommendation #4: Global Geomagnetic Initiative

In line with efforts to create response, recovery, and risk mitigation plans, the United States should establish a "Global Geomagnetic Initiative." The purpose of this initiative would be two-fold: 1) to gather geoscience expertise on geomagnetism and polarity reversals from around the world, and 2) to standardize instrumentation. The United States has taken the lead on climate change and global warming, and should do the same concerning adverse changes to the Earth system beyond climate. The benefits of such an initiative would range from obtaining more accurate data for magnetic and seismic observation stations, to establishing a community of professionals to realistically and pragmatically address the threat posed by geomagnetic pole reversals. The increased data accuracy from magnetic and seismic observatories alone could easily help in creating better maps of the interior of the Earth, and assist in monitoring the ongoing changes in the Earth's core. Rather than a problem only affecting the United States, geomagnetic polarity reversals are a world problem that will require action from all nations.

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Recommendation #5: Improve Space Weather Forecasting Capabilities

In conjunction with developing an ability to monitor and predict the behavior of the Earth's core, the country should focus on enhancing its space weather forecasting capability. While the NOAA's Space Weather Prediction Center provides solar storm outlooks and other related products, the accuracy of predictions and models is lacking. One look at NASA's Space Weather Prediction Center's CME scoreboard displays the problem, with prediction models from experts varying by six hours or more with their forecast accuracy.[136] Current systems can provide accurate information on the magnetic field of CMEs only 30-60 minutes before the ejection hits the Earth.[137] This is not enough time for the affected areas to react even if the nation was ready for such an event.

Current prediction capabilities rely partly on the Solar and Heliospheric Observatory satellite (SOHO), which is already 20 years old, and computer models to predict the speed and direction of coronal mass ejections.[138] While SOHO has improved the nation's ability to monitor the Sun, forecasts still lead to routine errors of 6 hours or more.[139] While 2015 launch of the Deep Space Climate Observatory (DSCOVR) satellite is a step in the right direction and replaces the aging Advanced Composition Explorer (ACE) satellite, the notification time will still range from 15 to 60 minutes for accurate mass ejection warnings.[140] If a large mass ejection was headed for Earth, 60 minutes would not be enough time to coordinate actions in critical infrastructure areas.

To fix the issue, the nation should launch new and improved satellites capable of accurately forecasting the speed, direction and electrical charge of mass ejection events at least 17 hours before their arrival on Earth, which was the time it took for the 1859 Carrington event to erupt from the Sun and strike the Earth.[141] Even if response and recovery plans were in place, 60 minutes is hardly enough time to coordinate mitigation efforts in the electrical and satellite infrastructures. A more advanced and robust system could mitigate the threat posed by geomagnetically induced currents and geomagnetic storms.

In short, accurate space weather prediction is not only important now but would become increasingly important in an environment where even normal space weather could compromise the integrity of the electrical grid and damage satellites. The nation should seek to launch more deep space monitoring satellites and continue to refine its forecasting techniques to extend out

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predictions beyond the 60-minute current capability. Even a small increase in preparation time could make an enormous difference with mitigation efforts.

Recommendation #6: Develop National Electrical Grid Control Measures

The next recommendation is for the establishment of a national electrical power grid control center. Right now the electrical infrastructure is a patchwork of various private power-generating companies which has become more interconnected and interdependent over the last century. To mitigate the hazardous impacts of geomagnetically induced currents and geomagnetic storms on the nation's electrical transformers, the electrical power industry needs an ability to monitor and assess transformers nationwide. The ability to balance electrical loads from region to region will be essential if at least some of the 350 at risk EHV transformers are to be spared destruction during an intense geomagnetic storm.

The ability for the power grid to react quickly and decisively during a large-scale geomagnetic storm could save portions of the country from having to endure electrical blackouts for months or years. This recommendation, along with improved prediction and monitoring capabilities for the magnetosphere and Sun, could reduce the risk of events in the future. While geomagnetically induced currents and geomagnetic storms would damage and destroy transformers, it is possible some transformers could be saved by load management and faster reactions from power companies.

In essence, the establishment of the capability to monitor and control power across the country would help in reducing the hazards created by adverse space weather in a weakened geomagnetic environment.

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Recommendation #7: Harden Satellites and Transformers

While the recommendation for establishing a national electrical power grid control center and "Earth Observatory" capable of real-time monitoring of the Earth's core would be essential, there are other actions the nation can undertake to reduce the risks associated with geomagnetic polarity reversals. The electrical and satellite infrastructures could both benefit from increased radiation resistance for solar storms and geomagnetically induced currents. Government, military, and civilian satellite operators could quickly start installing and engineering more radiation resistant hardware to mitigate the threat posed by both the weakened magnetosphere and space weather. While the cost per satellite would increase, it would be minuscule in comparison to the overall economic losses and damage associated with a large-scale space weather event. Like satellite systems, the electrical grid could begin the process of hardening to mitigate the effects of geomagnetic storms and geomagnetically induced currents. The only prohibition against such an action is the cost. Since the 1989 Quebec Solar Storm, the Canadian government has spent $1.2 billion dollars to harden the Hydro-Quebec electrical infrastructure.[142] The price tag for hardening large portions of the nation would extend well into the tens of billions of dollars. While this may seem like a steep price tag, a single large mass ejection event could easily exceed this cost in one day, with the associated economic losses reaching into the trillions of dollars. The technology is available to render both the electrical and satellite infrastructures more resistant and capable of withstanding adverse space weather events in a reduced strength geomagnetic environment.

The nation should focus on hardening the electrical grid and satellite infrastructure against adverse space weather now to prepare for the future. Even without a geomagnetic reversal, the United States could see costs in the trillions of dollars making the increased prices to manufacture and harden both systems well worth the effort.

Recommendation #8: Make Understanding the Earth a Priority

Finally, the nation needs to make understanding the Earth system beyond climate a top priority. The USGS, which is the nation's premiere scientific organization dedicated to understanding the Earth, spends a significant portion of its budget and time on climate change, global warming, and other environmental efforts. In the 2015 budget, the USGS budgeted 2.5 times more funding for climate, water, and land-use programs than for the natural hazards program that covers areas from volcanoes to the geomagnetism program.[143] Looking at the USGS Geomagnetism Program, it received 183 times less funding than the water, climate, and land use programs.[144] While understanding the Earth's climate is critically important, it should not overshadow the other Earth hazards that need to be researched and mitigated. The Earth system as a whole, especially beyond climate, remains unpredictable, complex and dynamic. The fact that geologists are still unable to predict volcanoes, earthquakes and the behavior of the geodynamo indicates there is much about the Earth system scientists do not understand. Therefore, the USGS should re-invest in capabilities and bolster funding toward studying and mitigating natural hazards like volcanoes, earthquakes and pole reversals.

Doubling or tripling the USGS budget for Earth system programs and research not related to global warming and climate change would be minute in the overall federal budget. The USGS budget for 2015 was only $1.1 billion dollars, which is nearly 70 times less funding than the Department of Defense's research and development budget, and between 5-7 times less funding than the EPA and NOAA receive.[145,146,147] The USGS should prioritized funding for programs outside of climate research.

Understanding and predicting the behavior of the Earth's core is vital for national security. Without new monitoring systems in place and without an emphasis on the geosciences outside of climate change and global warming, the nation could be caught unprepared for the next geomagnetic polarity reversal. Geology, despite the advancements in science and technology made in the last century, remains a scientific field with many unanswered questions.

Summary

The Earth's geomagnetic field is vital for United States national security. While invisible, this protective shield has allowed life to evolve on Earth and has set the conditions for the creation of advanced human civilizations. Without a strong and active magnetic field, the Earth would be an analog to Mars. As such, understanding the dynamics, mechanisms and future behavior of the geodynamo should be a national priority.

This research highlighted how fragile the nation's infrastructures become when the protection offered by the geomagnetic field is compromised. The increase in technology, the accelerating decrease in magnetic field strength and threat of large-scale adverse space weather are converging together to create the perfect geomagnetic storm. The findings of this research displayed how unprepared the nation is for both dangerous space weather and the next reversal event, and how prediction capabilities for both leave much to be desired.

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If the government does not act now, then the cost of such inaction could be trillions of dollars in economic losses and the deaths of millions of Americans. The recommendations offered by this research are practical examples of how the nation could mitigate and prepare for a cataclysmic pole reversal. By re-focusing funding on geomagnetism programs and geomagnetism research, building the world's first 3-D real-time view of the interior of the Earth, and spearheading a "Global Geomagnetic Initiative," the nation would be able to bolster geomagnetism knowledge and develop prediction capabilities for the Earth's geodynamo. Furthermore, by focusing on improving space weather forecasting capabilities, hardening the satellite and electrical infrastructures, and implementing early warning and control measures, the nation could mitigate the negative impacts of both adverse space weather and polarity reversals.

The development of national response, recovery and risk plans would go a long way toward preparing the nation's emergency response organizations for such a large-scale disaster. Finally, much like the nation has done with climate change and global warming, the United States needs to make understanding the Earth's geodynamo and complex systems a priority. While scientific understanding of the Earth is increasing every day, there is still much regarding the Earth system that technology and science cannot currently explain.

In short, the nation needs to focus on understanding the Earth as an entire system rather than focusing on one particular part, as areas from climate, to earthquakes, to volcanoes and pole reversals remain outside current capabilities to predict and understand. The future survival of the nation will depend on gaining a holistic understanding of the Earth as a complex and variable system. While the 20th century focused on space exploration, the 21st century should focus on gaining an understanding of the complex and dynamic planet Earth.

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