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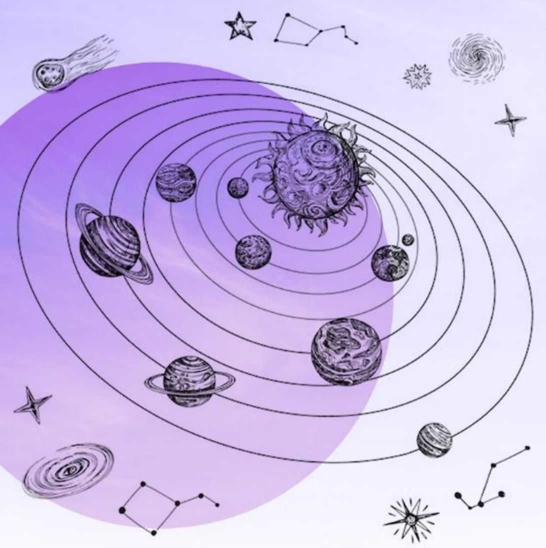
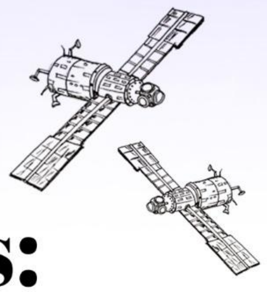
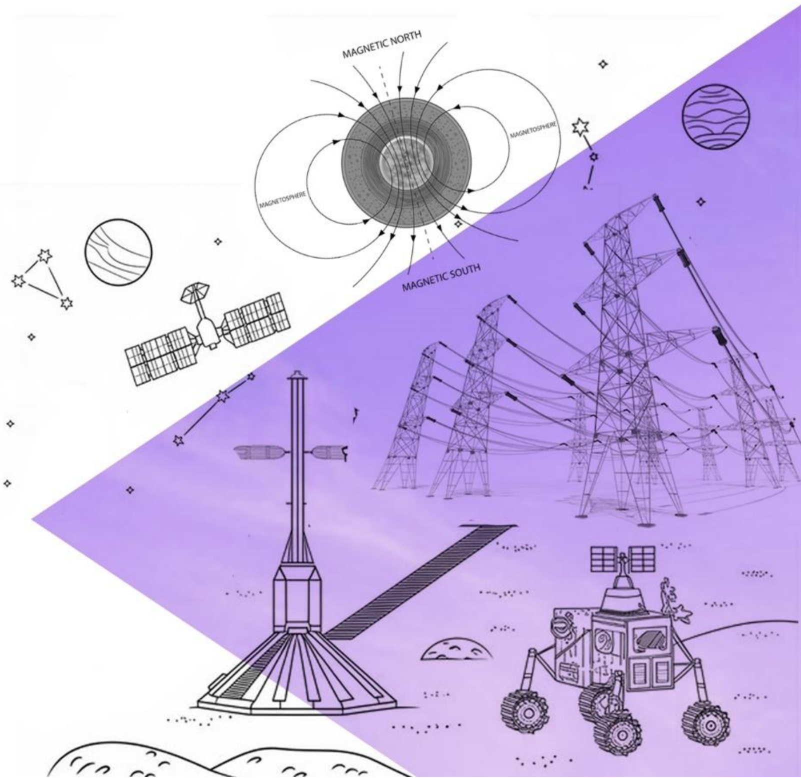




Solar Disruptions: Impact of Geomagnetic Storms on Satellites and Power Grids

Shaza Arif

Research Associate



Working Paper

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Solar Disruptions: Impact of Geomagnetic Storms on Satellites and Power Grids

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Research Associate

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Abstract

Rapid technological advancements are driving innovation across diverse sectors, yet they are also exposing an escalating array of vulnerabilities. Driven by solar activity, geomagnetic storms have emerged as a prominent phenomenon in this context, becoming a major source of concern for space-based and ground-based technological infrastructure. With the growing frequency and intensity of geomagnetic storms, disruptions in Earth's magnetosphere can impact us in consequential ways. Taking a qualitative research approach, the paper explores the impact of geomagnetic activity on technological systems with a focus on satellites and power grids. The findings highlight the disruptive impact of geomagnetic storms and the vulnerabilities of modern systems, along with their broader implications. They also underscore the necessity of robust strategies to address these challenges effectively.

Keywords: Space Weather, Geomagnetic Storms, Technological Infrastructure, Satellites, Power Grids

Introduction

Space weather refers to various phenomena driven by fluctuations in solar activity, which can significantly impact Earth's environment.[1] Among space weather phenomena, geomagnetic storms are particularly important. They are classified as high-impact, low-probability events due to their infrequent occurrence but potentially severe consequences.[2] According to the National Oceanic and Atmospheric Administration (NOAA), 'A geomagnetic storm is a major disturbance of Earth's magnetosphere, the event is often triggered by efficient exchange of energy from the solar wind into the space environment that surrounds the Earth.'[3]

These storms occur from solar wind variations that alter Earth's magnetospheric currents, plasmas, and magnetic fields. They typically arise when high-speed solar winds carry a sustained, southward-directed magnetic field, opposing Earth's magnetic field and triggering geomagnetic disturbances.[4] Ultimately, this facilitates transfer of energy on the dayside of the magnetosphere. The storms are characterised by Coronal Mass Ejections (CMEs) and solar flares.[5] CMEs are characterised by the large-scale expulsion of plasma and magnetic fields from the Sun's corona. Similarly, solar flares are explosions from the solar surface, resulting in bursts of electromagnetic radiations.[6]

The direct impact of geomagnetic storms on humans has historically been limited, which initially confined interest in the phenomenon to scientists and astronomers. However, these storms do pose risks to both space- and ground-based technological infrastructure, making them a growing concern for policymakers and industry.[7]

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1 Hongyi Hu and Zhonghua Xu, "Global-GMDs: The Global Map of Geomagnetic Disturbances," *Software X* 25, (2024):101619, https://www.sciencedirect.com/science/article/pii/S2352711023003151.

2 Wadih Naim, Patrik Hilber and Ebrahim Shayesteh, "Impact of Geomagnetic Disturbances on Power Transformers: Risk Assessment of Extreme Events and Data Availability," *Life Cycle Reliability and Safety Engineering* 11 (2022): 11-18, https://doi.org/10.1007/s41872-021-00179-8bid.

3 National Oceanic and Atmospheric Administration, "Geomagnetic Storms," accessed November 10, 2024, https://www.swpc.noaa.gov/phenomena/geomagnetic-storms.

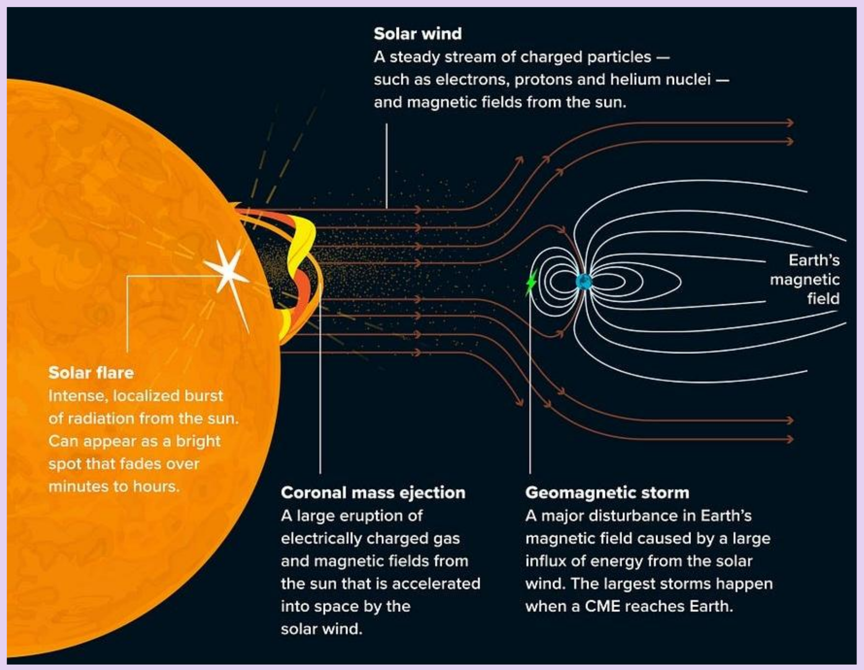
4 Ibid.

5 Jeongheon Kim, Young-Sil Kwak Changsup Lee, Jaewook Lee et al., "Observational Evidence of Thermospheric Wind and Composition Changes and the Resulting Ionospheric Disturbances in the European Sector during Extreme Geomagnetic Storms," *Space Weather Space Climate* 13, no.24 (2023):1- 14,https://www.swsc-journal.org/articles/swsc/full_html/2023/01/swsc230018/swsc230018.html.

6 Daisy Dobrijevic, "Coronal Mass Ejections: What are they and How do they form?" *Space,* June 24, 2022, https://www.space.com/coronal-mass-ejections-cme.

7 Amit Jain, Richa Trivedi, Sudhir Jain, "Effects of the Super Intense Geomagnetic Storm on 10-11 May, 2024 on Total Electron Content at Bhopal," *Advances in Space Research* 75, no.1 (2024): 953-965, https://www.sciencedirect.com/science/article/abs/pii/S0273117724009499.

Figure I: Key Concepts



Source: Ayman Miazi, "Solar Storms on Steroids: Coronal Mass Ejections and the Threat to Global Technology," *Medium,* December 7, 2022, https://medium.com/predict/will-a-coronal-mass-ejection-cause-a-multi-trillion-dollar-catastrophe-d1829e3fe0a5.

Geomagnetic storm-induced fluctuations can also affect Earth's environment, particularly by disrupting ecosystems that support technological infrastructure.[8]

In an increasingly interconnected world, technology serves as the foundation of the economy, security, and global connectivity. Its deep integration into daily life has amplified the potential consequences of geomagnetic activity, heightening the risk of disruptions at various scales. As a result, technological systems have become more vulnerable to geomagnetic storms, posing critical challenges for scientists, policymakers, and society at large.

This paper examines the impact of geomagnetic storms on modern technology, focusing on satellite systems and power grids. It draws on past and recent cases to illustrate real-world implications and concludes with recommendations to mitigate these challenges. By addressing risks and potential solutions, the study encourages multidisciplinary research and policy development to prepare for future space weather disruptions. In terms of methodology, this is a qualitative study that relies on secondary data sources, including books, dissertations, reports, research papers, and websites. Journal articles were sourced from Web of Science, Scopus, and Google Scholar using keywords like 'geomagnetic storms,' 'impact on technology,' 'satellites,' and 'power grids.' Abstracts of 60 articles were reviewed, with 50 selected for in-depth

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8 Olga Khabarova and Colin Price, "Importance and Challenges of Geomagnetic Storm Forecasting," *Astronomy and Space Sciences* 11, (2023): 1-9, https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2024.1493917/full.

analysis. To ensure relevance, most articles from the time period 2022–2024 were used. Case studies support the arguments, and thematic analysis groups recurring ideas into broader categories and sub-themes.

One limitation of the study is its narrowed scope, which focuses on two broad areas, satellites and power grids, due to their central role in technological infrastructure. This focus ensures a more precise analysis while maintaining the paper's intended scope.

Geomagnetic Storms and their Impact on Modern Technologies

Geomagnetic storms are characterised by the interaction of energetic particles from the Sun with the Earth's magnetic field that leads to disruptions in the ionosphere, 100 to 1000 km above our planet.[9] The storms are measured on the G-scale, ranging from G1 (moderate storm) to G5 (extreme storm).[10] Such developments can have notable impacts on both space-based and ground-based technological infrastructure. The following section of the paper will discuss the impact of geomagnetic storms on two key areas:

1. Satellites
2. Power grids

Geomagnetic Storms and Satellites

The number of satellites has expanded exponentially, driven by the commercialisation of space. Currently, over 10,000 active satellites are in orbit, reflecting growing dependence on space-based infrastructure.[11] Geomagnetic storms have a direct impact on the satellites in several ways, as discussed in the following section:

Atmospheric Drag

Geomagnetic storms cause heating and expansion in the thermosphere, increasing atmospheric density[12] and drag on satellites.[13] As a result, satellites must perform

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9 Government of Canada, "Space Weather Effects on Technology," accessed November 14, 2024, https://www.spaceweather.gc.ca/tech/index-en.php.

10 Rositsa Miteva and Susan Samwel, "Catalog of Geomagnetic Storms with Dst Index ≤ −50 nT and their Solar and Interplanetary Origin (1996–2019)," *Atmosphere* 14, no.12 (2023): 1744-1769, https://www.mdpi.com/2073-4433/14/12/1744.

11 Eric Mack, "There Are 10,000 Active Satellites in Orbit. Most Belong To Elon Musk," *Forbes,* July 19, 2024, https://www.forbes.com/sites/ericmack/2024/07/19/theres-now-10000-active-satellites-in-orbit-most-belong-to-elon-musk/.

12 William Parker and Richard Linares, "Satellite Drag Analysis During the May 2024 Gannon Geomagnetic Storm," (paper, arXiv, 2024), https://arxiv.org/pdf/2406.08617.

13 National Oceanic and Atmospheric Administration, "Satellite Drag," accessed November 20, 2024, https://www.swpc.noaa.gov/impacts/satellite-drag#:~:text=In%20addition%20to%20these%20long,density%2C%20increasing%20drag%20on%20satellites.

manoeuvres to maintain their orbits, depleting onboard fuel.[14] Older satellites, with weaker propulsion systems, may deorbit prematurely, while newer ones, though more resilient, face a shortened operational lifespan, making them more vulnerable to future geomagnetic events.[15]

Case Study I: February 2022 Space X Starlink Satellites

On 3 February 2022, SpaceX launched 41 satellites into orbit with a perigee of approximately 210 km, intending to raise them to 550 km.[16] However, within a day, many began deorbiting, resulting in the loss of 38 satellites over the next few days.[17] Subsequent studies found that the satellites deorbited because the launch location was directly affected by a geomagnetic storm, which increased atmospheric drag. The research also highlighted that even moderate geomagnetic activity, combined with factors such as low-altitude orbital insertions and satellite design, can have major consequences, resulting in financial losses worth millions of dollars.[18] The event demonstrated that satellite insertion in relatively lower perigee made the satellites considerably more vulnerable given that atmospheric drag is closer to Earth.

Case Study II: May 2024 Geomagnetic Storm

On 10 May 2024, a powerful G-5 class geomagnetic storm sent shock waves through Earth's ionosphere, causing massive disruptions. This storm was one of the first major events in the new era of low Earth orbit satellite operations, where commercial small satellites play an increasingly prominent role.[19] Before the storm, the decay rate of object (satellites) was approximately 38 metres per day. During the storm, however, it surged more than fourfold to 180 metres per day highlighting the severe impact of increased atmospheric drag on low Earth orbit satellites.[20] Analysis of open-access data from the U.S. Space Force revealed that more than 5,000 satellites had to manoeuvre during the storm. Nearly all Starlink satellites performed orbit-raising

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14 Parker and Linares, "Satellite Drag Analysis During the May 2024 Gannon Geomagnetic Storm."

15 Denny Oliveira, Eftyhia Zesta and Dibyendu Nandy , "The 10 October 2024 Geomagnetic Storm May Have Caused the Premature Reentry of a Starlink Satellite," (paper, arXiv, 2024), https://arxiv.org/html/2411.01654v1.

16 Thomas Berger, Marie Dominique, Greg Lucas, Vishal Ray et al., "The Thermosphere Is a Drag: The 2022 Starlink Incident and the Threat of Geomagnetic Storms to Low Earth Orbit Space Operations," *Advanced Earth and Space Science* 21, no.3 (2023): 1-13.

17 Daniel Billett, Magnus Ivarsen, Elisabetta Iorfida and Eelco Doornbos, "The 2022 Starlink Geomagnetic Storms: Global Thermospheric Response to a High-Latitude Ionospheric Driver," *Space Weather* 22, no.2 (2024):1-16, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023SW003748.

18 Oshita Baruah, Souvik Roy, Suvadip Sinha and Erika Palmerio, "The Loss of Starlink Satellites in February 2022: How Moderate Geomagnetic Storms Can Adversely Affect Assets in Low Earth Orbit," *Space Weather* 22, no.4 (2024): 1-15, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023SW003748.

19 Tereza Pultarova, "May Solar Superstorm Caused Largest 'Mass Migration' of Satellites in History," *Space.com*, July 19, 2024, https://www.space.com/may-solar-storm-largest-mass-migration-satellites.

20 Parker and Linares, "Satellite Drag Analysis During the May 2024 Gannon Geomagnetic Storm."

manoeuvres, a sharp increase from the baseline of approximately 300 per day.[21] These large-scale manoeuvres added further complexity to collision avoidance efforts, which were already challenged by position errors induced by the storm.[22] At an altitude of 1,200 miles, LEO satellites and space debris were observed drifting toward Earth at a rate of 590 feet (180 metres) per day due to increased atmospheric drag. In response, thousands of spacecraft simultaneously fired their thrusters to counteract altitude loss and regain stable orbits. The storms produced remarkable changes/disturbance in satellite trajectories, compounding existing challenges in low Earth orbit operations.[23]

Such large-scale manoeuvres create potential collision risks, as avoidance systems have limited time to predict and adjust to rapidly changing satellite trajectories. With multiple satellites shifting unpredictably, the likelihood of miscalculations and near-misses substantially increases.[24] The event also highlighted growing vulnerabilities associated with the rising number of satellites in space; and the critical need for enhanced propulsion capabilities to ensure satellite survivability.

Equipment Damage

High-energy particles generated by geomagnetic storms can penetrate satellite shielding, causing damage to onboard equipment.[25] Radiation exposure further degrades electronics, potentially leading to severe operational disruptions.[26] Over time, the cumulative effects of radiation may necessitate more frequent satellite replacements to maintain functionality and reliability.

Degradation of Radio Signals

While satellite damage is a notable risk, it is generally mitigated by design, as most satellites are built to withstand such events. However, the disruption of radio signals poses a greater challenge. A major consequence of geomagnetic storms is their interference with radio communication, as these storms cause the absorption and reflection of radio waves, leading to signal degradation and loss.[27] These scenarios lead to rapid signal fluctuations and unplanned propagation paths, with signals

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21 Jacinta Bowler, "Thousands of Satellites had to Suddenly Maneuvre During May's Solar Storm," *ABC News,* July 24, 2024, https://www.abc.net.au/news/science/2024-07-24/aurora-geomagnetic-storm-satellites-spacelink/104100052.

22 Jeff Foust, "Geomagnetic Storms Cause "Mass Migrations" of Satellites," *Space News*, December 11, 2024, https://spacenews.com/geomagnetic-storms-cause-mass-migrations-of-satellites/.

23 Parker and Linares, "Satellite Drag Analysis During the May 2024 Gannon Geomagnetic Storm."

24 Foust, "Geomagnetic Storms Cause 'Mass Migrations' of Satellites."

25 Government of Canada, "Space Weather Effects of Technology."

26 Olga Khabarova and Colin Price, "Importance and Challenges of Geomagnetic Storm Forecasting," *Astronomy and Space Science* 11, (2024): 1-25, https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2024.1493917/full.

27 Erin Kayata, "A Geomagnetic Storm is Hitting the Northern Part of the U.S. Here's how the Solar Event May Impact You," *Northeastern Global News*, October 10, 2024, https://news.northeastern.edu/2024/10/10/geomagnetic-storm-effects-technology/.

reproducing or multiplying in unexpected directions. Such degradation of radio signals impacts Global Navigation Satellite System (GNSS) systems, which are heavily dependent on stable radio signals.[28]

Ionospheric disruptions during geomagnetic storms can cause unpredictable GNSS signal propagation, reducing system accuracy and reliability.[29] Superstorms, in particular, can greatly impact GPS performance, with Total Electron Content (TEC) fluctuations increasing by 4 to 40 times compared to quiet periods.[30] TEC refers to the total number of electrons between a radio transmitter and receiver. Higher TEC leads to increased disruption of radio waves.[31] As a result, navigation systems across land, air, and maritime operations are adversely affected.

Case Study III: Aviation and GNSS Errors

A recent study analysed the impact of geomagnetic storms on airplane crashes between 1919 and 2023 yielding interesting insights. The highest number of accidents occurred during the equinox months of March and September, extending into October, while fewer accidents were recorded during the solstice months of June and December. Another key finding was that storms occurring during the declining phase of Solar Activity Cycles (SACs) influenced accident rates, suggesting a potential correlation between solar activity and aviation safety.[32]

During intense solar storms, GNSS signals used for aircraft instrument approach procedures can be intermittently disrupted. In such cases, pilots may need to switch to alternative navigation systems, which, while equally safe, are often less efficient, potentially impacting flight operations and scheduling.[33]

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28 National Aeronautics and Space Agency, "Space Technology", accessed November 15, 2024, https://www.jpl.nasa.gov/nmp/st5/SCIENCE/effects2.html#:~:text=Solar%20storms%20cause%20damage%20to%20communication%20systems.&text=During%20geomagnetic%20storms%20some%20radio,amateur%20radio%20is%20frequently%20disrupted.

29 Yifan Wang, Yunbin Yuan, Min Li and Ting Zhang, "Effects of Strong Geomagnetic Storms on the Ionosphere and Degradation of Precise Point Positioning Accuracy during the 25th Solar Cycle Rising Phase: A Case Study," *Remote Sensing* 15, no. 23 (2023):1-17, https://www.mdpi.com/2072-4292/15/23/5512.

30 Elvira Astafyeva and Yu Yasyukevich, *Geomagnetic Storms, Super-storms, and their Impacts on GPS-based Navigation Systems* 10, no.47 (2014): 508-525, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2014SW001072.

31 National Oceanic and Atmospheric Administration, "Total Electron Content," accessed February 28, 2025, https://www.swpc.noaa.gov/phenomena/total-electron-content#:~:text=The%20Total%20Electron%20Content%20(TEC,radio%20signal%20will%20be%20affected.

32 Ukte Aksen, Umit Deniz, Goker Erdinc Timocin and Cagatay Akcay, "The Effect of Geomagnetic Storms on Aircraft Accidents between the Years 1919–2023 in Civil Aviation," *Advances in Space Research* 73, no.1 (2024): 807-830, https://www.sciencedirect.com/science/article/abs/pii/S0273117723008943.

33 NavCanada, "How Space Weather and Solar Storms Impact Aviation," October 7, 2024, https://www.navcanada.ca/en/news/blog/how-space-weather-and-solar-storms-impact-aviation.aspx#:~:.

Seasonal variations and space weather account for major impact on the aviation sector. Therefore, authorities must incorporate these factors into risk assessments and operational planning to enhance flight safety and efficiency.

Impact on Power Grids

Geomagnetic storms have affected ground-based systems for over 150 years, with one of the earliest recorded impacts occurring in the 1840s, when they disrupted telegraph operations.[34] These storms can directly impact power grids, which are essential to technological infrastructure. During a storm, fluctuations in Earth's magnetic field create disturbances that induce electric fields on the surface. These fields generate Geomagnetically Induced Currents (GICs), which can flow into power grids and transformers, potentially causing operational disruptions and equipment damage.[35] GICs are intense, low frequency currents that can impact Earth-based infrastructure.[36] Consequently, GIC poses a significant risk to high-voltage transformers that are central components of a power grid.[37]

Transformer Failure

Transformers manage the smooth flow of alternating current (AC). However, when exposed to Direct Current (DC), they can be damaged. Ground-induced currents that are a result of geomagnetic storms can trigger a DC offset in the magnetic flux. Resultantly, this can increase the current flowing through the transformer.[38] The DC offset is likely to trigger saturation in the magnetic core, when the transformer is operated close to its threshold point.[39] GICs can disrupt transformer operations by generating excess heat within the core and windings.[40] This thermal buildup increases the risk of winding and insulation failure, potentially leading to short-circuiting and

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34 David Boteler, Risto Pirjola and Heikka Nevanlinna, "The Effects of Geomagnetic Disturbances on Electrical Systems at the Earth's Surface," *Advances in Space Research* 22, no.1 (1998): 17-27, https://www.sciencedirect.com/science/article/abs/pii/S027311779701096X#:~:text=Geomagnetic%20disturbances%20have%20affected%20electrical,power%20systems%20into%20larger%20networks.

35 Somayeh Taran, Nasibe Alipour, Kourosh Rokni, Hadi Hosseini et al., *Effect of Geomagnetic Storms on a Power Network at Mid-Latitudes* 71, no.11 (2023):5453-5465, https://www.sciencedirect.com/science/article/abs/pii/S0273117723001461#:~:text=The%20geomagnetically%20induced%20current%20.

36 Gurbux Lakhina, Rajkumar Hajra and Bruce Tsurutani, "Geomagnetically Induced Currents," in *Encyclopedia of Solid Earth Geophysics*, ed. Harsh Gupta (Cham: Springer Nature, 2021), 1.

37 Morgan Rivers and Łukasz Gajewski, "Global Transformer Overheating from Geomagnetic Storms," (paper, arXiv, 2023),https://arxiv.org/html/2403.18070v1.

38 Naim, Hilber and Shayesteh, "Impact of Geomagnetic Disturbances on Power transformers: Risk Assessment of Extreme Events and Data Availability," 11.

39 Stanislav Gritsutenko, Nikolay Korovkin, Yaroslav Sakharov and Olga Sokolova, "Assessment of Geomagnetically Induced Currents Impact on Power Grid Modelling," *Magnetism* 3, no.2 (2023):135-147, https://doi.org/10.3390/magnetism3020011.

40 Milad Akbari, "Transformer Thermal Assessment Under Geomagnetically Induced Current Conditions," (PhD diss., York University, Ontario, 2022).

uncontrolled energy release.[41] Such stresses accelerate transformer ageing and may trigger catastrophic failures. Over time, insulation degradation, erosion of magnetic properties, and overall malfunction can further compromise grid stability, increasing the likelihood of widespread power disruptions.[42] In addition to transformer damage, voltage regulation problems and reactive power loss, is also reaction of GIC, causing grid instability.[43] Such events can have profound and cascading effects, resulting in widespread blackouts/ power outages and disruptions. Geomagnetic activity has also led to costly power outages, and damage to transformers in the past as discussed below.[44]

Case Study I : Quebec Blackout 1989

March 1989 witnessed one of the most intense geomagnetic storms of the century. A review of the storm demonstrated that the second ICME was the main trigger for the damage, while the first ICME played a crucial role in clearing its path.[45] This preconditioning effect allowed the second ICME to travel at a much higher speed than it otherwise would have. Consequently, a secondary ICME, potentially originating from a less intense solar flare, became the catalyst for the extreme geomagnetic disturbance. It led to a blackout in Quebec, lasting up to nine hours in most areas and several days in others, affecting six million people.[46] It also caused economic losses of approximately USD 13.2 million and left tens of millions without power.[47]

This clearly shows that geomagnetic storms can have substantial economic impacts by disrupting ground-based infrastructure. Hence, sequential geomagnetic events must be accounted for through continuous space weather monitoring to mitigate potential risks.

Case Study II: Sweden Blackout 2003

In October 2003, southern parts of Sweden witnessed a notable geomagnetic storm. The massive ionospheric convention, coupled with abrupt commencement of the storm and sub-storms, led to massive damage to one of Sweden's high voltage power

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41 Naim, Hilber and Shayesteh, "Impact of Geomagnetic Disturbances on Power Transformers," 14.

42 Tina Reynolds, "Navigating the Storm,"*Clouglobal,* August 3, 2024.

43 Chunming Liu, Anqi Li and Xiyan Guan, "Influence of Geomagnetic Storms on Power System Static Voltage Security," *Electric Power Systems Research* 229, (2024):110139, https://doi.org/10.1016/j.epsr.2024.110139.

44 Qihe Shao, Ying Liu, Yinhe Luo and Graham Heinson, "Geoelectric Field Estimations During Geomagnetic Storm in North China from SinoProbe Magnetotelluric Impedances," *Space Weather* 22, no.4 (2022): 1-12, DOI:10.1029/2023SW003758.

45 Tian Zhang, Yusuke Ebihara and Takashi Tanaka, "Nighttime Geomagnetic Response to Jumps of Solar Wind Dynamic Pressure: A Possible Cause of Québec Blackout in March 1989," *Space Weather* 11, no.2 (2023): 1-17, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023SW003493.

46 National Weather Service, "Safety National Program Space Weather and Safety," accessed November 20, 2024, https://www.weather.gov/safety/space.

47 Government of Canada, "Space Weather Effects on Technology."

transmission systems.[48] The storm's impact was seen in an hour-long blackout in the affected areas, leaving approximately 50,000 people without electricity.[49]

Discussion and Analysis

The study of the impact of geomagnetic storms on satellites and power grids helps to identify the disruptions caused by space weather events. Based on the areas identified in the paper, the following section will analyse the findings.

In the realm of space, disruptions in GPS navigation can considerably undermine both civil and military-based systems. Overall, navigation aid losses can impact diverse sectors - airspace, maritime transport, road transport, and electric vehicles could be severely disrupted.[50] In aviation, radio communication and GPS signals can be disrupted via geomagnetic storms, which are crucial for aircraft navigation. Furthermore, the ionospheric irregularities can produce clutter in radar signals. Flights that operate near the polar regions are at a considerably higher risk, given that the effects of geomagnetic storms are much more pronounced. In addition, rerouting and cancellation of flights can have a sizeable economic aspect. Moreover, such disruptions have repercussions for military operations, posing serious national security risk.

The increasing reliance on LEO satellites for critical functions such as communication, navigation, disaster management, weather forecasting, geospatial imaging, internet services, and relief operations has heightened the risks posed by geomagnetic storms. Given their broad applications, these sectors are particularly vulnerable to satellite malfunctions during such events, potentially leading to widespread disruptions.

One example in this regard is the agriculture system. In developed countries such as the United States, modern farming relies heavily on technology. Approximately 80 percent of farmers in the Midwest use basic GPS technology, whereas 50 percent are considerably reliant on GPS. They have been using GPS-guided tractors and systems for plantation, fertilization, harvesting, and monitoring. During the May 2024 storm, GPS-guided tractors demonstrated peculiar behaviour during the geomagnetic activity.[51] This is relevant given that delays in planting or harvesting can lead to lower

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48 Antti Pulkkinen, Sture Lindahl and Ari Viljanen, "Geomagnetic Storm of 29-31 October 2003: Geomagnetically Induced Currents and their Relation to Problems in the Swedish High-voltage Power Transmission System," *Space Weather* 3, no.8 (2005): 1-19, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2004SW000123.

49 Andrew Dimmock, Vanina Lanabere, Lisa Rosenqvist and Emiliya Yordanova, "Investigating the Trip of a Transformer in Sweden During the 24 April 2023 Storm," *Space Weather* 22, no.11 (2024):1-21,https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024SW003948.

50 Council of the European Union, "Solar Storms: A New Challenge on the Horizon," November 21, 2023, https://www.consilium.europa.eu/media/68182/solar-storms_a-new-challenge-on-the-horizon-21-nov-2023_web.pdf.

51 Daisy Dobrijevic, "Powerful Solar Storms are a Nightmare for Farmers - Our Tractors Acted like they were Demon Possessed,"*Space.com*, December 11, 2024,

yields, while recalibrating or repairing GPS systems adds financial strain during already tight seasons.

Given the abundance of satellite designs that are being used for different purposes, the exact behaviour of satellites cannot be anticipated with certainty. However, previous results show that even modest storms indicate a degree of disruption to satellite operations.[52] Hence, based on past incidents, it is important to remain cognizant of more intense storms that can inflict considerably more damage.

An important takeaway is the ever-growing importance of manoeuvrability of satellites vis-à-vis atmospheric drag. This is particularly relevant for mega-constellations, as such storms add complexity to space traffic coordination. Another implication is the potential disruption of satellite launch schedules due to geomagnetic disturbances, leading to delays and increased costs for active space missions. Astronauts and spacecraft face heightened exposure to radiation, raising concerns for the safety of future space exploration.

Power grid systems can have far-reaching effects across various sectors. Blackouts disrupt essential services, including hospitals, industrial operations, the financial sector, and transportation. However, the consequences extend beyond power outages. Geomagnetic storms, for example, can destabilise power grids, resulting in substantial economic losses. As discussed in the paper, the Quebec blackout led to losses worth USD 13.2 million. In today's era, where interdependence is remarkably high, potential events can lead to a much higher economic impact. Furthermore, Northern latitudes, particularly the US and Canada, are at higher risk, given stronger magnetic interactions near the poles.[53] This leads to more stress on the vulnerabilities of power grid infrastructure in those respective areas. In addition, the interconnected nature of grids adds to the risks. Geomagnetic storms can affect interconnected regional infrastructure, damage to which can have cascading impacts leading to disruptions on a global scale.

A crucial consideration for the future is the interconnected vulnerability of satellite systems and power grids. Disruptions in power grids can affect satellite ground stations, which are essential for coordinating satellite operations. Likewise, satellites rely on ground stations for data processing, meaning power outages can delay or impair satellite functionality. At the same time, power grids depend on satellites for communication and grid synchronisation, making them susceptible to disruptions in

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https://www.space.com/theuniverse/sun/wonky-row-crops-and-possessed-tractors-the-surprising-impact-of-solar-storms-on-modern-farming.

52 Paul Cannon, *Extreme Space Weather: Impacts on Engineered Systems and Infrastructure*, report (London: Royal Academy of Engineering),4, https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf.

53 Allianz, "Here Comes the Sun: The Dangers of Geomagnetic Storms," accessed December 9, 2024, https://commercial.allianz.com/news-and-insights/expert-risk-articles/geomagnetic-storms.html.

space-based infrastructure. This interdependence creates a feedback loop, where geomagnetic storms can trigger cascading failures across multiple sectors, both operationally and economically.

Emerging technologies could play a notable role in countering the impact of geomagnetic storms. In this context, Artificial Intelligence (AI) can help in the prediction of more accurate space weather via Machine Learning (ML) models. Similarly, quantum computing can lead to ultra-secure infrastructure that can boost resilience against future potential threats. The May 2022 geomagnetic storm was cited as one of the strongest solar storm in 20 years. However, the damage it did was relatively less than anticipated.[54] In the future, more intense space weather is expected, increasing the likelihood of greater damage. Predictions indicate that disruptions caused by geomagnetic storms will intensify as the current solar cycle peaks in July 2025, with this trend persisting for the following two years.[55] Hence, these developments underscore the need for proactive preparedness and implementation of adequate measures to mitigate the impacts of potential geomagnetic storms.

Recommendations

In light of the analysis presented in the paper, the following section proposes several recommendations to mitigate the potential impact of geomagnetic storms under two broad categories: space-based and ground-based.

Space-based Recommendations

Prediction of Solar Weather

Space weather prediction systems provide early warnings, allowing satellite operators to initiate protective measures such as shutting down vulnerable systems temporarily. Being able to accurately forecast solar weather is an imperative step toward the next big storm. Space-based observatories (such as NASA's Solar Dynamics Observatory (SDO), Solar and Heliospheric Observatory (SOHO) and Parker Solar Probe), and ground-based facilities (such as Daniel K. Inouye Solar Telescope) need to be better equipped to provide a detailed account of solar activity. Owing to their increasing efficiency, advanced technologies such as ML systems could be employed to make space weather predictions. The models can be trained more efficiently by using data

54 Jonathan O'Callaghan and Lee Billings, "The Strongest Solar Storm in 20 Years Did Little Damage, but Worse Space Weather Is Coming," *Scientific American*, May 15, 2024, https://www.scientificamerican.com/article/the-strongest-solar-storm-in-20-years-did-little-damage-but-worse-space/.

55 Rebecca Mathews, "Can Solar Storms Affect Your Organization? Scientists Believe Geomagnetic Storms Will Increase in the Near Future," *Business Continuity Institute,* September 6, 2024, https://www.thebci.org/news/can-solar-storms-affect-your-organization.html.

gathered from the space-based and ground-based systems to adjust satellite orbits proactively. Furthermore, space agencies such as NASA, ESA and NOAA can collaborate for data sharing and alerts.

Satellite Design and Operations

Resilient Infrastructure

Satellites intended for low Earth orbit insertion should be designed to withstand the cumulative effects of space weather on operational planning. This requires a targeted focus on enhanced shielding and robust electronic components. Fault-tolerant designs and radiation-hardened chips should be prioritised to prevent system failures and protect sensitive onboard systems from geomagnetic disturbances.

High-Thrust Propulsion Systems

To counteract satellite drag, unexpected orbital decay, and extend operational life during geomagnetic storms, satellites should be equipped with high-thrust propulsion systems. These systems enable rapid altitude adjustments, allowing satellites to reach regions of lower atmospheric density and maintain stable orbits in the face of increased drag.

Station-Keeping for Mega Constellations

Tight station-keeping boundaries should be established for LEO constellations to prevent unpredictable orbit phasing. Ensuring seamless operations in congested orbital environments is also essential to minimise collision risks and maintain stability of satellite networks.

Operational Measures

Establishment of live backup systems for navigation, communication and altitude control for seamless operations during periods of disruptions should be explored. Likewise, modalities of shutting down non-critical systems during geomagnetic storms is also an important area which should be addressed. Furthermore, an increasingly important aspect is the manoeuvrability of satellites, which should be tailored to overcome atmospheric drag.

Multidisciplinary Approach

Given the risks involved, there is a need for a multidisciplinary approach. Threats from geomagnetic storms call for increased collaboration between relevant entities. This includes national space agencies, private satellite operators, heliophysics experts, satellite engineers, government regulators, telecommunication providers, and utility operators. A coordinated effort can improve preparedness, response, and resilience.

Government and private entities engaged in transitional space physics research should develop real-time operational capabilities to provide accurate thermospheric temperature, composition, and density data. These capabilities would support future satellite launches, enhance LEO orbital operations, and strengthen global infrastructure against geomagnetic disturbances.

Advanced nations, particularly those in the Northern Hemisphere, which are more experienced in space weather monitoring and satellite infrastructure, should take a leading role in assisting countries in the Global South. This could include sharing space weather forecasts, impact assessments, and response mechanisms to minimise disruptions in vulnerable regions.

While a globally integrated early warning system for geomagnetic storms does not yet exist, foundational elements are already in place through NOAA, the European Space Agency (ESA), the International Civil Aviation Organization (ICAO), and other entities. A well-structured North-South collaboration could bridge existing gaps, helping vulnerable regions prepare for and mitigate geomagnetic storm disruptions. Several global early warning systems[56] already exist for other critical issues, demonstrating the feasibility of a dedicated Global Geomagnetic Storm Early Warning System (GGS-EWS). Under such a system:

1. Entities like NOAA, ESA, International Telecommunication Union (ITU), and World Meteorological Organization (WMO) could collaborate to provide real-time, globally accessible alerts on geomagnetic disturbances. Space weather is increasingly discussed in UN COPUOS (Committee on the Peaceful Uses of Outer Space) and UNOOSA (UN Office for Outer Space Affairs), making these platforms suitable for advancing global coordination efforts.
2. A central AI-driven prediction and data-sharing system could aggregate geomagnetic activity data, process risk assessments, and disseminate region-specific warnings to vulnerable nations. A regional pilot initiative (e.g., Africa or South Asia) under ITU/WMO leadership could test the feasibility and scalability of AI-driven early warnings.
3. Advanced nations, with space weather monitoring capabilities, could assist developing countries by sharing forecasts, mitigation strategies, and response protocols.
4. Governments could incorporate geomagnetic storm risks into energy, satellite, and aviation resilience planning to minimise disruptions.

Given the precedent set by existing global early warning systems, a dedicated system for geomagnetic storms is both feasible and necessary. A well-coordinated GGS-EWS would strengthen global preparedness, prevent cascading failures across critical

[56] UN's Early Warnings for All (EW4All); WMO's Multi-Hazard Early Warning Systems; FAO's Global Information and Early Warning System (GIEWS); Water, Peace, and Security Partnership's Global Early Warning Tool, etc.

sectors, and support developing nations in building resilience against future space weather events.

Ground-based Recommendations

Monitoring of Geomagnetically Induced Currents (GICs)

Installing GIC monitoring systems in high-risk areas is essential for accurately measuring and forecasting induced current intensity. This can help anticipate grid vulnerabilities and mitigate potential transformer failures. GIC blockers or reducers could be deployed to protect critical infrastructure from excessive current surges. Early warnings may also be integrated with load management strategies to proactively reduce strain on the grid and minimise disruptions during geomagnetic storm events.

Transformer Upgradation for Grid Resilience

Enhancing grid resilience requires the deployment of upgraded transformers designed to withstand the effects of GICs. Advanced transformer designs should incorporate robust insulation systems and materials that improve durability against prolonged exposure to induced currents. As discussed earlier, blocking filters can be integrated to regulate GIC flow within the power grid, preventing excessive current accumulation. This approach helps mitigate the risks of overheating and insulation breakdown caused by geomagnetic storms, thereby safeguarding grid integrity and ensuring continuous operability.

Reinforcing Grid Infrastructure

The potential damage from GICs can also be circumvented by reinforcing the grid infrastructure. Power utilities can explore redundant transmission paths and diversification of power sources to reduce dependency on specific transmission lines, thereby minimising grid vulnerabilities. In this context, shorter transmission lines could be used in high-risk areas. Likewise, microgrids that can operate independently of each other are also a potential remedial measure. Another potential measure is grid reconfiguration during geomagnetic storms to strategically adjust power flow and manage load distribution, protecting vulnerable components such as transformers. By enhancing grid flexibility and resilience, these measures can help mitigate GIC-related threats and ensure uninterrupted power supply during extreme space weather events.

Operational Measures

Temporary Shutdowns

Temporary shutdowns of vulnerable components when an intense storm is expected could be an effective measure. This involves identification of facilities that are considerably more prone to risks and subsequently deactivating or isolating them during periods of increased geomagnetic storm events. This, in turn, leads to a lesser probability of overheating and insulation breakdown.

Load Management

Potential risks to transformers can be mitigated using optimal load management during a geomagnetic storm. Effective load management could lead to maintaining a controlled current flow and temperature below the operational threshold. Consequently, in such a scenario, a GIC-induced DC offset is less likely to cause transformer failure. After the identification of high-risk areas, more prone to GIC-related stress, the power supply could be rerouted to less affected areas.

Communication Protocols

The evolving risks posed by geomagnetic storms highlight the need for robust communication frameworks, standardised protocols, and coordinated response strategies. A concerted approach among key stakeholders, particularly Regional Transmission Operators (RTOs), is essential to ensure timely information exchange and effective crisis management. Strengthening cross-sector coordination between power utilities, space weather monitoring agencies, and government regulators will enhance grid resilience and enable a proactive response to geomagnetic disturbances. Risk assessments and modeling studies could serve as important factors in subsequent collective actions, and coordinating responses can enhance resilience against such events. Prompt knowledge sharing can enable concerned entities to streamline their operating procedures, safeguarding critical infrastructure.

Hence, the harmful impacts of geomagnetic storms can be reduced through a collective approach that includes a combination of effective monitoring, cross-cutting technology, and international cooperation. Given increasing reliance on modern technology and the potential of geomagnetic storms in the future, there is a pressing need to ensure maximum preparedness before the next storm hits.

Conclusion

Geomagnetic storms have become a critical risk to society due to the threats they pose to both space-based and ground-based infrastructure. The increasing vulnerabilities of satellites and power grids, two important components that underpin the contemporary technological ecosystem, highlight the increasing risks associated with space weather disturbances. Satellites face increasing atmospheric drag, equipment damage, degradation of radio signals, and space coordination challenges. Likewise, impacts of geomagnetic storms can lead to overheating and insulation breakdown of transformers, voltage regulation issues, and blackouts.

This interdependence of space-based and ground-based systems amplifies the risks posed by geomagnetic storms. Their cascading effects can damage critical sectors such as navigation, communication, transportation, agriculture, essential services etc. leading to both operational disruptions and economic losses. To mitigate these risks, a pragmatic, multi-layered strategy, such as a dedicated Global Geomagnetic Storm Early Warning System (GGS-EWS), ought to be considered.

By integrating advanced monitoring, infrastructure resilience, and international collaboration, into policy frameworks, industry practices, and global efforts, nations can proactively mitigate the disruptive effects of geomagnetic storms, ensure long-term resilience, safeguard technological systems, and minimise economic fallout in an increasingly space-dependent world.

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