Space Weather

REVIEW ARTICLE
10.1029/2024SW004055

Special Collection:
Impact of Space Weather Events on Transportation System

Key Points:

- Mechanisms of space weather-caused disruptions in critical infrastructure are identified
- The effects of space weather on various transportation modes are examined
- Recommendations for mitigating space weather effects on transportation systems are discussed

Correspondence to:
Z. Wang,
wangzhipeng@buaa.edu.cn

Citation:
Xue, D., Wu, L., Xu, T., Wu, C.-L., Wang, Z., & He, Z. (2024). Space weather effects on transportation systems: A review of current understanding and future outlook. *Space Weather*, *22*, e2024SW004055. https://doi.org/10.1029/2024SW004055

Received 1 JUL 2024
Accepted 27 NOV 2024

Author Contributions:
Conceptualization: Dabin Xue, Lingxiao Wu, Zhipeng Wang, Zhengbing He
Formal analysis: Dabin Xue, Tianhe Xu, Cheng-Lung Wu, Zhipeng Wang, Zhengbing He
Funding acquisition: Zhipeng Wang
Investigation: Tianhe Xu
Methodology: Dabin Xue, Lingxiao Wu, Tianhe Xu, Cheng-Lung Wu, Zhengbing He
Validation: Dabin Xue, Lingxiao Wu, Tianhe Xu, Cheng-Lung Wu, Zhipeng Wang
Visualization: Dabin Xue, Lingxiao Wu, Cheng-Lung Wu, Zhipeng Wang, Zhengbing He
Writing – original draft: Dabin Xue, Lingxiao Wu, Tianhe Xu, Cheng-Lung Wu, Zhipeng Wang, Zhengbing He

Space Weather Effects on Transportation Systems: A Review of Current Understanding and Future Outlook

Dabin Xue[1,2], Lingxiao Wu[3], Tianhe Xu[4], Cheng-Lung Wu[2], Zhipeng Wang[5], and Zhengbing He[6]

[1]Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong, China, [2]School of Aviation, University of New South Wales Sydney, Sydney, NSW, Australia, [3]Department of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Hong Kong, China, [4]Institute of Space Sciences, Shandong University, Weihai, China, [5]School of Electronic Information Engineering, Beihang University, Beijing, China, [6]Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract Space weather events, including solar flares, coronal mass ejections, and geomagnetic storms, have significant effects on various transportation systems. This review provides a comprehensive examination of the current understanding and future outlook of space weather effects on air, maritime, railway, and ground transportation. It explores the mechanisms through which space weather causes communication blackouts, satellite navigation failure, elevated cosmic radiation, and geomagnetically induced currents, leading to disruptions in transportation operations. Historical events are analyzed to underscore the diversity and severity of these impacts. Additionally, this review discusses the anticipated challenges posed by the upcoming solar maximum of Solar Cycle 25 and highlights the need for improved forecasting, mitigation strategies, and resilient infrastructure to safeguard transportation systems against space weather threats. By integrating findings from recent studies and historical data, this review aims to enhance the preparedness and response strategies of the transportation sector in the face of evolving space weather risks.

Plain Language Summary Space weather, which includes events like solar flares, coronal mass ejections, and geomagnetic storms, can seriously affect various transportation systems. This review thoroughly examines how these space weather phenomena impact air, maritime, railway, and ground transportation. It explains how space weather events can cause problems such as communication blackouts, failure of satellite navigation systems, increased levels of cosmic radiation, and geomagnetically induced currents. These issues can disrupt transportation operations significantly. The review looks at past events to show the range and seriousness of these impacts. It also discusses the upcoming solar maximum of Solar Cycle 25 and the challenges it may bring. The review emphasizes the need for better forecasting methods, effective mitigation strategies, and stronger infrastructure to protect transportation systems from space weather threats. By combining recent research and historical data, this review aims to improve how the transportation sector prepares for and responds to the risks posed by space weather. This is crucial for ensuring that transportation systems remain functional and safe despite the challenges posed by space weather.

1. Introduction

Space weather refers to rapid changes in the space environment between the Earth and the Sun, triggered by phenomena such as solar flares, coronal mass ejections (CMEs), and Solar Energetic Particles (SEPs) (Telloni et al., 2020). These environmental changes can have harmful effects on the electricity grid, satellites, avionics, satellite navigation signals, mobile communications, and even air passengers (Royal Academy of Engineering, 2013). The three primary types of space weather are radio blackouts, solar radiation storms, and geomagnetic storms, impacting both Earth- and space-based technologies (Eastwood et al., 2017). A comprehensive summary of space physics can be found in Tsurutani et al. (2022).

1.1. Solar Flares

Intense bursts of electromagnetic radiation from the Sun's surface, are associated with the release of vast energy stored in its magnetic fields. Classified based on their X-ray brightness, solar flares range from A, B, C, and M, to the most powerful X-class, often occurring near sunspots, regions of intense magnetic activity (Bekker et al., 2021). Solar flare radio blackouts, caused by solar flare events, primarily affect High-Frequency (HF) radio

Writing – review & editing: Dabin Xue, Lingxiao Wu, Tianhe Xu, Cheng-Lung Wu, Zhipeng Wang, Zhengbing He

communications used for long-distance and over-the-horizon operations like amateur radio and aviation systems (Frissell et al., 2019). These disruptions can distort or block signals, leading to HF communication blackouts and failures. Additionally, solar flares can induce solar radiation storms, posing radiation hazards to astronauts and high-altitude aircraft passengers, increasing cancer risk and health effects due to higher radiation doses (Meier et al., 2020). Furthermore, radiation storms significantly elevate the risk of Single-Event Effects (SEE) in electronic systems, particularly in space-based and high-altitude operations. While these storms pose some public health concerns, especially for astronauts and frequent flyers, their impact on sensitive electronics and critical infrastructure can be far more severe (Dyer et al., 2003, 2020).

1.2. CMEs

Massive eruptions of plasma and magnetic fields from the Sun's corona, often accompany solar flares (Howard et al., 1985). Geomagnetic storms, triggered by changes in the solar wind, notably from CMEs or high-speed solar wind streams, interact with Earth's magnetosphere, causing fluctuations in the magnetic field and energy deposition into the upper atmosphere (Gerontidou et al., 2018). Classified by intensity, the most severe storms are designated as G5 on the NOAA Space Weather Scale (Berger et al., 2023). These storms cause geomagnetically induced currents (GICs) and disrupt power grids, leading to outages and damage (Belakhovsky et al., 2019; Oughton et al., 2019). Communication and navigation systems, particularly reliant on high-frequency radio waves and satellite technologies, experience disruptions due to ionospheric irregularities, affecting aviation, maritime navigation, and emergency response operations (Astafyeva et al., 2014; Lakhina & Tsurutani, 2016). Moreover, radiation in space poses a major threat to satellites by causing SEE, such as data corruption or hardware failure (Dyer et al., 2017; Selčan et al., 2017). It also leads to long-term degradation through Total Ionizing Dose (TID) and Displacement Damage (DD), which affect satellite components like solar panels and sensors (Ren et al., 2024; Tompros & Mouzakis, 2024). Additionally, spacecraft may encounter increased drag and orbit perturbations, impacting operational efficiency and lifespan (Oliveira et al., 2020).

1.3. SEPs

Primarily, protons and electrons are accelerated during solar flares and CMEs (Klein & Dalla, 2017) to velocities near the speed of light through mechanisms like shock waves and magnetic reconnection in the Sun's atmosphere (Verkhoglyadova et al., 2015). These particles pose significant risks to astronauts, crewed spacecraft, and unshielded satellites, potentially causing acute radiation sickness and increasing the long-term risk of cancer and other health effects (Marov, 2020). Space agencies closely monitor SEP events and implement radiation shielding measures to protect astronauts during space missions. SEPs can penetrate spacecraft materials and electronic components, leading to radiation-induced damage and potential disruptions in onboard systems, jeopardizing mission success and spacecraft longevity (Aminalragia-Giamini et al., 2021). Additionally, SEPs disrupt communication and navigation systems, impacting radio communications, Global Navigation Satellite System (GNSS) signals, and wireless technologies (Knipp et al., 2021).

Modern transportation systems heavily depend on advanced technologies like satellite navigation systems and communication networks, which greatly enhance safety, efficiency, and overall effectiveness (Deng et al., 2023; Monzon et al., 2022). Nevertheless, transportation systems are vulnerable to space weather, as space weather can result in communication blackouts, satellite navigation failure, surveillance failure, increased cosmic radiation, and power grid disruption. Figure 1 illustrates the effects of space weather on transportation systems.

To date, a research gap exists in comprehensively understanding the effects of space weather on transportation systems. While studies have explored specific aspects caused by space weather like satellite navigation failures (Pirjola et al., 2005; Xiong et al., 2016), communication disruptions (Ferguson et al., 2015; Knipp et al., 2016), and elevated cosmic radiation (Hands et al., 2018; Meier & Matthiä, 2014), there is a need for a holistic review considering the interconnectedness of transportation modes and their susceptibility to space weather events. Furthermore, long-term studies assessing the cumulative impacts on transportation infrastructure resilience and operational efficiency are lacking. Additional research is necessary to develop effective mitigation strategies and resilient infrastructure designs to minimize disruptions caused by space weather phenomena. Hence, this systematic review aims to address the following questions.

- How do space weather events cause disruptions in critical infrastructure, including communication systems, GNSS, and power grids?

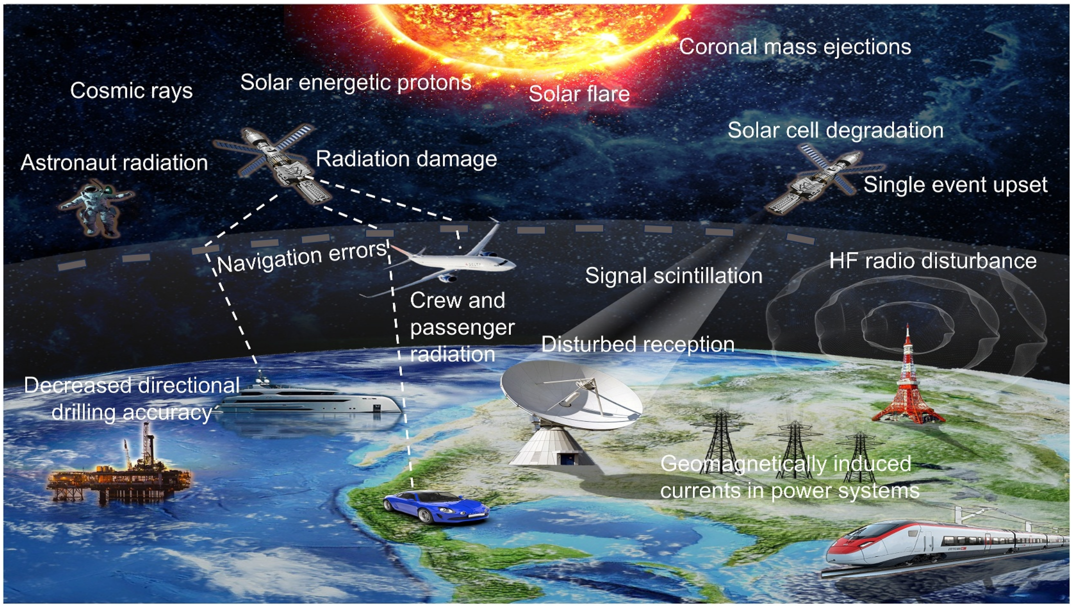


Figure 1. Schematic of the effects of space weather on transportation systems, including air, maritime, railway, and ground transportation.

- How do space weather events affect different modes of transportation, including air, maritime, railway, and ground transportation?
- What measures can be implemented to enhance the resilience of transportation infrastructure against space weather impacts?

The structure of this review is organized as follows: Section 2 highlights several related space weather effects that can affect transportation systems. Section 3 provides a thorough review of the documented and potential effects of space weather on different transportation modes. Section 4 presents various strategies for mitigating and adapting to the negative consequences of space weather on transportation systems. Finally, conclusions and implications are discussed in Section 5.

2. Related Space Weather Effects on Transportation Systems

The duration of space weather impacts can vary widely, spanning from fleeting seconds to enduring spans of many days (Shea & Smart, 2012). Solar activity progresses through an 11-year cycle, with the upcoming solar maximum of Solar Cycle 25 expected in 2025 (Hapgood et al., 2022). Figure 2 presents a brief summary of several notable historical space weather events in September 1859 (Cliver & Dietrich, 2013; Hayakawa et al., 2019, 2023; Hudson, 2021; Love et al., 2024), in May 1921 (Hapgood, 2019; Kappenman, 2006; Love et al., 2019; Lundstedt et al., 2015), in March 1940 (Hayakawa et al., 2022; Love et al., 2023), in August 1972 (Knipp et al., 2018; Tsurutani et al., 2024), in March 1989 (Allen et al., 1989; Balan et al., 2017; Boteler, 2019; Tsurutani et al., 2024), in October 2003 (Shprits et al., 2006; Tsurutani et al., 2006; Villante & Regi, 2008; Wu et al., 2005), in January 2005 (Dorotovič et al., 2008; Orus et al., 2007; Shea & Smart, 2012), in March 2015 (Fagundes et al., 2016; Kassa et al., 2023; Tlatov et al., 2017), and in September 2017 (Amaechi et al., 2021; Hajra et al., 2020; Redmon et al., 2018; Schneider et al., 2018). The most significant impacts of these events highlight the wide-ranging effects of space weather on critical infrastructure and technology. With that, this section explains the related space weather effects on communications, satellite navigation, cosmic radiation, and power grids from the perspectives of physical mechanisms, which can contribute to the understanding of space weather-caused transportation system disruptions.

2.1. Communication Blackouts

Solar flares can cause communication radio blackouts primarily by affecting the Earth's ionosphere, which is essential for the propagation of radio waves (Yasyukevich et al., 2018). When a solar flare occurs, it emits a broad

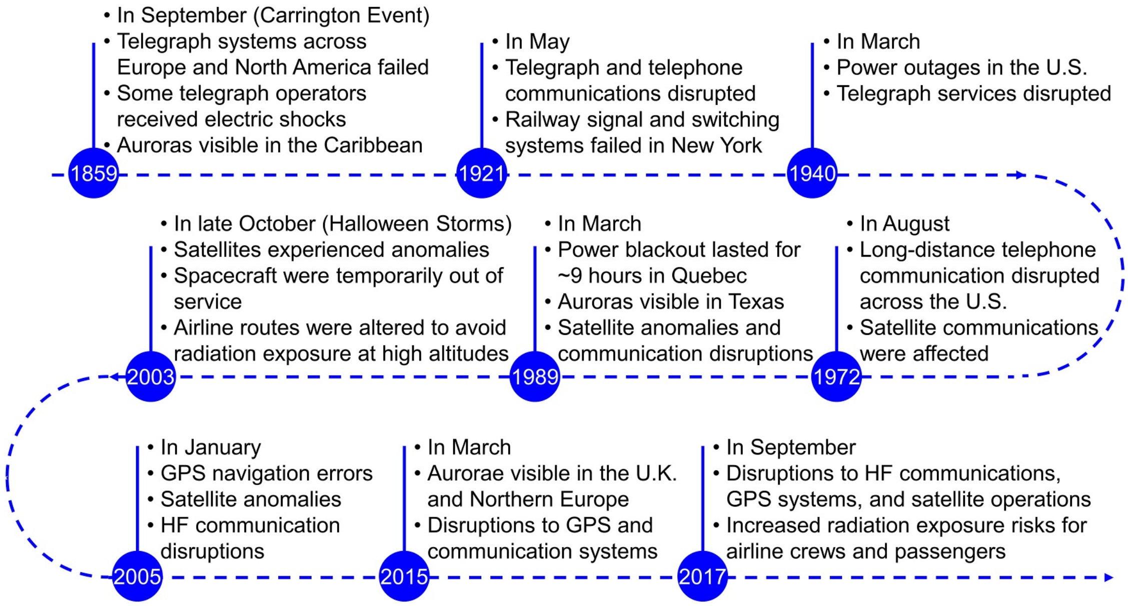


Figure 2. The summary of several notable historical space weather events and their most significant effects on communications, navigation, radiation, and power grids.

spectrum of radiation, including extreme ultraviolet (EUV) and X-rays, which travel at the speed of light and reach Earth in about 8 minutes (Woods et al., 2011). This rapid influx of high-energy radiation significantly increases the ionization levels in the Earth's upper atmosphere, particularly in the ionosphere's D-layer. The D-layer of the ionosphere, located at altitudes between 50 and 90 km, plays a critical role in the propagation of High-Frequency (HF) radio waves, which are used for long-distance communication (Wang et al., 2022). Under normal conditions, the ionosphere reflects these HF radio waves, allowing them to travel beyond the horizon. However, the enhanced ionization caused by solar flares increases the absorption of HF radio waves in the D-layer. This phenomenon, known as a sudden ionospheric disturbance (SID), results in a significant loss of signal strength and can lead to complete radio blackouts on the sunlit side of the Earth (Fagundes et al., 2020). The higher absorption prevents HF radio waves from being reflected back to the ground, thus disrupting long-distance communication.

Moreover, the impact of solar flares on the ionosphere can extend beyond immediate HF communication blackouts. The increased ionization can also affect the E-layer and F-layer, which are higher regions of the ionosphere that influence the propagation of Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves (Bust et al., 2021). These frequencies are crucial for various applications, including aviation, maritime communication, and satellite communication. Enhanced ionization can lead to signal scattering, phase shifting, and overall degradation of signal quality. Additionally, solar flares can cause bursts of radio noise that interfere directly with communication signals. Therefore, the disturbances in the ionosphere caused by solar flares have broad implications for global communication systems, such as shortwave radio broadcasts, GNSS signals, and satellite-based communications.

From the perspective of historical space weather events, the effects on HF communications are more significant than VHF and Satellite Communication (SATCOM). (a) HF service encountered over 2 hours of impairment after the X1.1 (R3 [Strong]) solar flare occurring between 16:29–17:04 UT on 19 October 2003 (NOAA, 2004). (b) On 7 September 2005, solar activity notably affected all HF communications across the United States. However, line-of-sight VHF communication remained largely unaffected (SKYbrary, 2024). (c) Between 4 and 10 September 2017, multiple solar eruptions originating from active region AR12673 resulted in temporary degradation or loss of HF signals on the sunlit side of Earth. Particularly, on 6 September 2017, HF communications experienced a significant outage throughout most of the morning and early afternoon (Redmon et al., 2018). (d) Following the peak of the M2.2 solar flare at 10:28 UT on 28 October 2021, an approximately 12% increase over the background in total electron content was observed, particularly in the latitude range of 20°–40°S of the African sector. Consequently, mid-latitude ionosonde data revealed no echoes from the ionosphere E and F1 layers during the period ~10:25–12:25 UT, constraining complex modes of HF communications (Habarulema

10.1029/2024SW004055

et al., 2022). (e) CMEs were ejected into space following an X5 solar flare erupting from the Sun's surface at 21:55 UT on 31 December 2023, marking the most powerful flare during solar cycle 25 up to that point. Subsequently, this space weather event prompted a warning to high-frequency radio users (Bink, 2024).

2.2. Satellite Navigation Failure

Geomagnetic storms can lead to satellite navigation failures through multiple complex mechanisms. These storms arise when charged particles from the sun interact with the Earth's magnetosphere, inducing significant changes in the Earth's magnetic field and ionosphere. Especially, the most critical impact on satellite navigation systems is the disturbance they cause in the ionosphere (Wang, Li, et al., 2021).

The ionosphere is a layer of the Earth's atmosphere, extending from about 60 km to 1,000 km in altitude, that is ionized by solar radiation (Pavlov, 2014). It plays a crucial role in the propagation of radio signals used by satellite navigation systems. During a geomagnetic storm, the influx of energetic particles increases the density and variability of ionized particles in the ionosphere. This heightened ionization leads to irregularities known as ionospheric scintillation, which can cause rapid fluctuations in the amplitude and phase of the radio signals traveling through the ionosphere (Luo et al., 2020). Scintillation can severely degrade the quality of GNSS signals, leading to increased positioning errors or complete signal loss.

Furthermore, geomagnetic storms can cause large-scale changes in the structure of the ionosphere, creating gradients in the electron density (Li et al., 2021). These gradients can lead to signal refraction and multipath errors, where the satellite signals take multiple paths to the receiver, arriving at slightly different times and angles (Affonso et al., 2022; Wang et al., 2020). This phenomenon degrades the accuracy of the position calculations made by GNSS receivers. The Total Electron Content (TEC) of the ionosphere, which represents the number of free electrons along the path of the GNSS signal, can fluctuate significantly during geomagnetic storms. In particular, the TEC variation on 29 October 2003 is shown in Figure 3. Rapid changes in TEC introduce timing delays in the signals, which GNSS receivers use to calculate distances. These delays can lead to substantial errors in position determination, affecting navigation accuracy (Roy & Paul, 2013; Wang, Xue, et al., 2021).

Additionally, geomagnetic storms can disrupt the satellites themselves. The increased energetic particle flux during such storms can cause temporary malfunctions or permanent damage to satellite electronics (Baker & Bodeau, 2021). This includes the onboard atomic clocks, which are crucial for the precise timing needed for accurate GNSS positioning. Satellite orbits can also be perturbed by increased atmospheric drag, leading to further inaccuracies (Capon et al., 2019). Consequently, geomagnetic storms pose a significant threat to the reliability and accuracy of satellite navigation systems, impacting a wide range of applications from aviation and maritime navigation to military operations and personal navigation devices.

2.3. Elevated Cosmic Radiation

Solar radiation storms significantly increase cosmic radiation levels due to the intense emission of energetic particles from the Sun. These events primarily occur during solar flares or CMEs, which release large quantities of protons, electrons, and heavy ions into space (Norbury et al., 2019). During a solar radiation storm, the Sun emits a burst of high-energy particles, which are accelerated to near-light speeds by the powerful magnetic fields associated with solar flares and CMEs. These particles then propagate through the heliosphere, the bubble-like region of space dominated by the solar wind and the Sun's magnetic field. As they travel, they can penetrate the Earth's magnetosphere and atmosphere, contributing to increased levels of ionizing radiation (Schwadron et al., 2017). This influx of SEPs can significantly enhance the background cosmic radiation, which is normally composed of galactic cosmic rays originating from outside our solar system.

The increase in cosmic radiation due to solar radiation storms is particularly pronounced at higher altitudes and latitudes (Rozanov et al., 2012). The Earth's magnetosphere offers some protection by deflecting charged particles, but this shielding effect is weaker near the poles and at high altitudes, such as those encountered by aircraft and spacecraft (Shi et al., 2013). Consequently, during an SPE, polar regions and high-altitude flight paths experience greater radiation exposure. This poses risks to aviation and space travel, as the elevated radiation levels can affect both human health and electronic systems (Cannon, 2013). For instance, airline crews and passengers on transpolar flights might receive doses of radiation significantly higher than usual, and satellites in

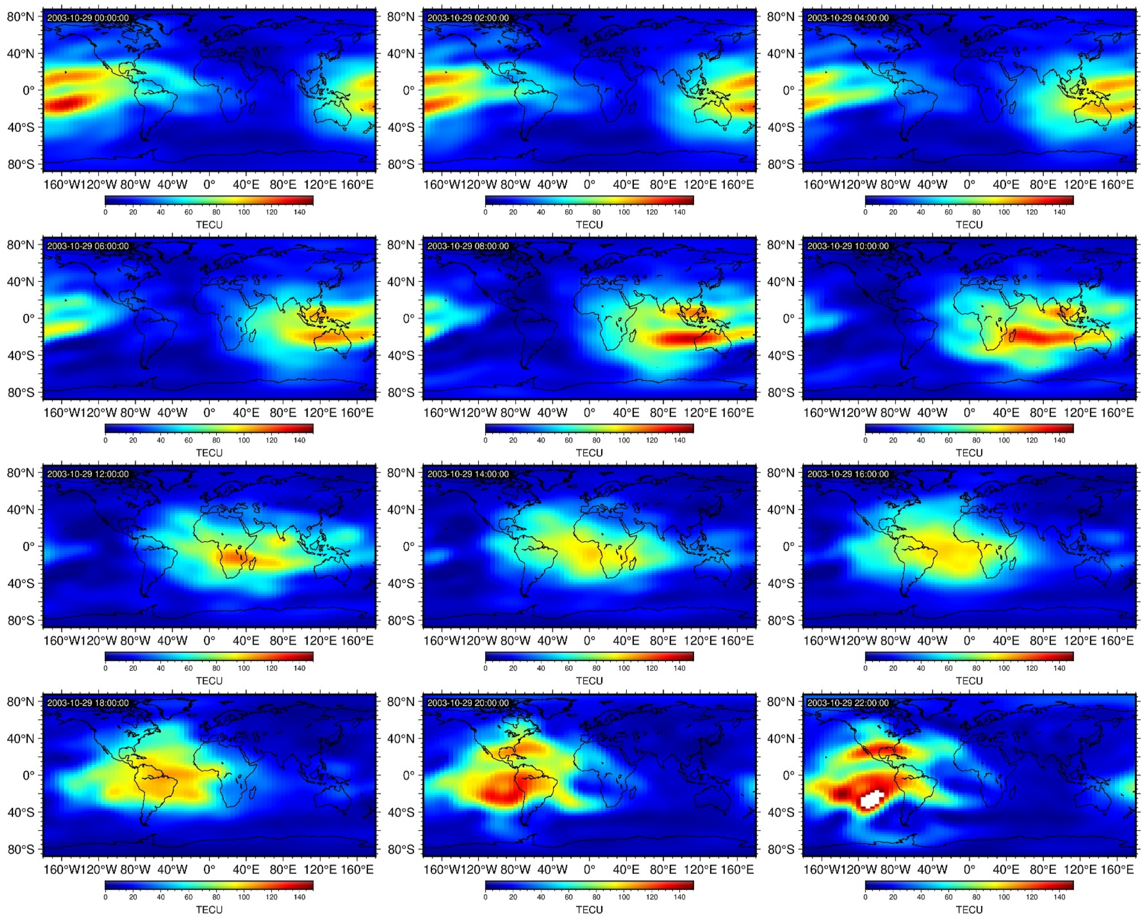


Figure 3. The spatial-temporal changes in TEC on 29 October 2003, with a significant spike in TEC levels over North and South America. A detailed depiction of TEC variations from October 27 to 31, 2003, can be found at https://zenodo.org/records/11112306.

orbit can suffer from increased rates of single-event upsets in their electronic components (Baker & Bodeau, 2021).

Moreover, solar radiation storms can lead to secondary radiation effects (Obermeier et al., 2011). When high-energy particles from an SPE interact with the Earth's atmosphere, they can produce secondary particles through a process called atmospheric cascades. These secondary particles, including neutrons and muons, contribute to the overall radiation environment and can penetrate deeper into the atmosphere than the primary SEPs. This phenomenon enhances the radiation dose at altitudes typically used by commercial aviation, further increasing the risks during intense solar events.

Furthermore, radiation-caused SEE can significantly impact modern transportation systems, particularly as vehicles become more reliant on advanced electronics and automation. In aerospace, SEEs can disrupt critical avionics, navigation, and communication systems, leading to potential safety risks (Dyer et al., 2006). As a result, some autonomous vehicles and advanced driver-assistance systems may experience temporary malfunctions or incorrect actions, such as sudden braking or steering errors. Additionally, SEEs may affect power management systems in electric and hybrid vehicles, potentially leading to hardware failures. As transportation becomes more connected and automated (Yang et al., 2017), mitigating SEE risks through redundancy, error correction, and radiation-hardened components is crucial for safety and reliability.

2.4. Geomagnetically Induced Currents

The primary mechanism for geomagnetic storms to affect power grids lies in the induction of electric currents in long conductors such as power lines and transformers (Švanda et al., 2020). During a geomagnetic storm, the rapid changes in the Earth's magnetic field induce electric fields in these conductors. These induced electric fields, in turn, generate electric currents that can flow through the power grid infrastructure. These GICs can have significant impacts on power grids (Gil et al., 2023). First, GICs can saturate transformers, reducing their efficiency and capacity. This saturation can persist for extended periods, affecting the stability and reliability of the grid. Second, GICs can also cause voltage fluctuations and imbalances in the grid, potentially leading to equipment damage and failures (Boteler, 2019).

Moreover, GICs can interact with the grid's protection systems, potentially causing them to malfunction or trip. This can lead to widespread power outages, especially if multiple transformers are simultaneously affected. The simultaneous saturation of transformers across the grid can result in a cascade of failures, further exacerbating the disruption (Kappenman, 2018). The severity of the power grid disruption depends on several factors, including the strength of the geomagnetic storm, the configuration and design of the power grid, and the presence of mitigating measures. However, even moderate geomagnetic storms have the potential to disrupt power grids, especially if the grid is not adequately protected or designed to withstand such events. For example, at the China Hebei East traction power supply substation, the maximum GIC recorded was 1.08 A during the geomagnetic storm on 17 March 2015 and 1.74 A during the geomagnetic storm on 23 June 2015 (Liu et al., 2016). A study of the Mexican grid shows that even at low latitudes, GICs can induce an additional current effect of 10–75 A at the edge of the grid, no matter the main orientation of the geoelectric fields (Caraballo et al., 2020).

3. Transportation System Disruptions

Space weather can affect satellite operations, disrupt communication, navigation, and surveillance systems, induce electrical currents in power grids, and pose radiation hazards to airline crew and passengers. This section provides a thorough review of the space weather effects on different transportation systems. Figure 4a illustrates the relationship between keywords based on the published papers sourced from the Web of Science using VOSviewer software, highlighting the interconnected themes in space weather research. The effects of space weather on various transportation systems are depicted in Figure 4b, demonstrating the varying degrees of impact. Among these, air transportation is identified as the most sensitive to space weather, due to its heavy reliance on satellite-based navigation and communication systems which are highly susceptible to solar activity and geomagnetic disturbances. By exploring these various aspects, we can comprehensively understand the complicated relationship between space weather events and transportation systems.

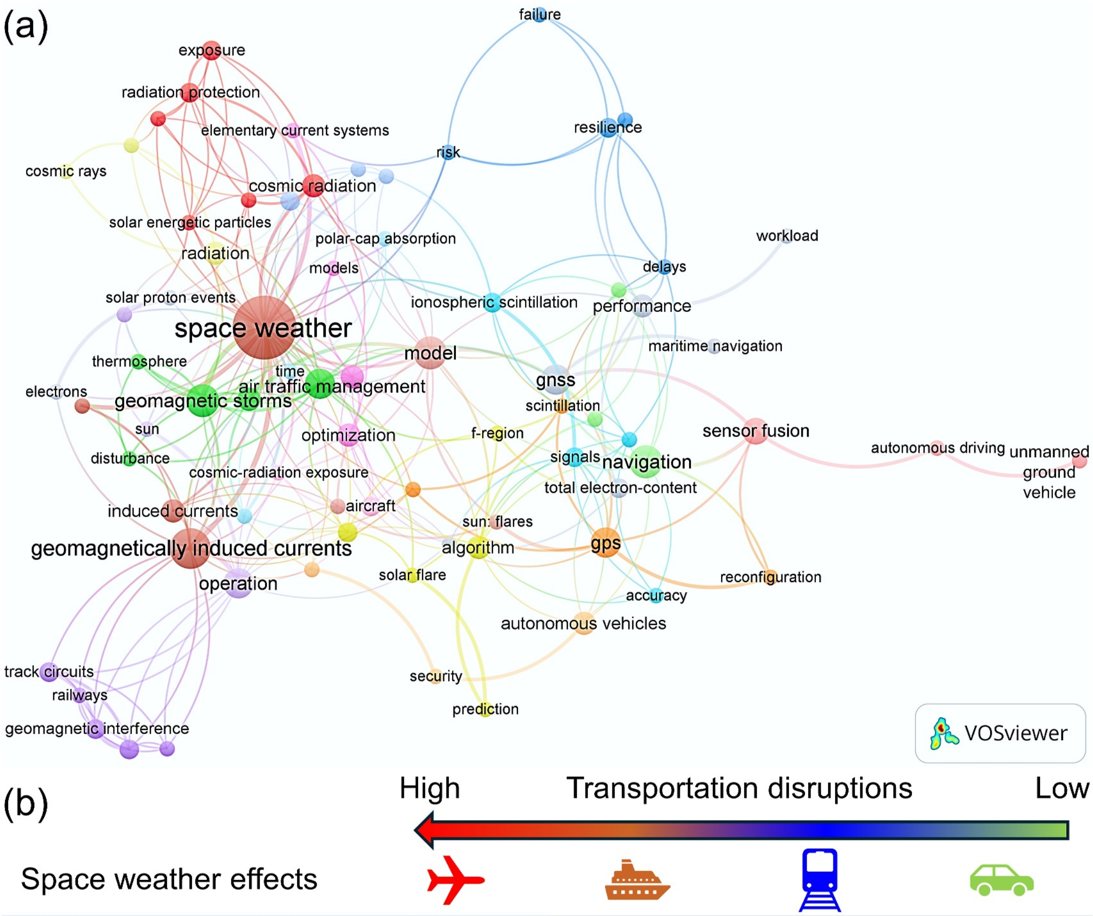
3.1. Air Transportation

Air transportation is highly sensitive to space weather effects, and these effects are HF communication blackouts, satellite navigation failure, surveillance failure, and elevated cosmic radiation.

3.1.1. HF Communication Blackouts

The VHF is the primary channel used for communication between pilots and aviation staff at ground stations. Specifically, pilots employ the Aircraft Communications Addressing and Reporting System (ACARS, 131.550 MHz) to communicate with airline dispatchers (Smith et al., 2018). Additionally, the Controller Pilot Data Link Communication (CPDLC, 118.000–136.975 MHz) facilitates communication between pilots and Air Traffic Control Officers (ATCOs) (Lin et al., 2012). Notably, when aircraft fly over the polar region, HF becomes the only means of communication, as satellite communications are unavailable north of 82°N due to the orbit inclination of geostationary satellites (Sauer & Wilkinson, 2008).

However, Polar Cap Absorption (PCA) events, caused by the ionization of the polar D-region ionosphere by SEPs, can lead to HF communication blackouts for aircraft flying north of 82°N, significantly affecting their normal operations (Fiori et al., 2022). For example, in response to the two-hour HF communication disruptions on 19 October 2003, three polar flights from New York to Hong Kong) were rerouted to routes with more favorable Datalink and SATCOM, resulting in an additional fuel consumption of 26,600 pounds and a reduction of over 16,500 pounds of cargo. Additionally, due to poor communications on 30 October 2003, extra air traffic controllers were required to manage air traffic (NOAA, 2004). On 6 September 2017, there was a notable outage in HF communications during much of the morning and early afternoon (Redmon et al., 2018). Additionally, French civil aviation authorities reported a 90-min loss of HF radio contact with an aircraft lacking CPDLC equipment, occurring off the coasts of Brazil and French Guiana (Rutledge & Desbios, 2018).



Communication blackouts	√	√	√	√
Satellite navigation failure	√	√	√	√
Surveillance failure	√	√	--	--
Elevated cosmic radiation	√	--	--	--
GICs	--	--	√	√

Figure 4. (a) Overlay visualization of keywords based on the VOSviewer software. (b) The effects of space weather on different transportation systems, "√": obvious effects based on transportation research experience, "--": unobvious effects.

Based on the assumption of a one-day duration for HF communication blackouts and utilizing 2019 polar flight data, Xue, Yang, Liu, and Yu (2023) calculated an economic loss estimate of €2.20 million if all polar flights were canceled. However, focusing solely on the daily count of 18 polar flights with trajectories crossing the north polar region above 82°N, simulation results indicate economic costs of €0.88 million for cancellations, €0.18–0.56 million for rerouting, and €0.85 million for scheduling adjustments (Xue et al., 2024).

3.1.2. Satellite Navigation Failure

Satellite navigation offers the potential to enhance flight efficiency and reduce fuel consumption by allowing for reduced separation distances between aircraft, enabled by the Area Navigation (RNAV) capability (Enge et al., 2015). RNAV, a navigation method allowing aircraft operation along any desired flight path rather than fixed point-to-point routes defined by ground-based aids (López-Lago et al., 2020), enables closer flight paths. Furthermore, satellite navigation aids in facilitating continuous descents toward landing airports and adjusting speeds to synchronize with other arriving flights (Xue et al., 2021). However, the performance of satellite navigation systems can be significantly compromised by space weather, posing safety risks to flights reliant on satellite navigation. In such instances, ground-based navigation systems like Very High-Frequency Omnidirectional Range (VOR), Distance Measuring Equipment (DME), and Non-Directional Beacon (NDB) would need to be utilized (Jakšić & Janić, 2020), potentially reducing airspace capacity and causing imbalances between flight demand and airport capacity (Sandamali et al., 2021).

In prior studies, Xue, Yang, and Liu (2022) conducted simulations using forecasted flight data for Hong Kong Airport in 2030 to examine the impacts of satellite navigation failures on various flight parameters such as cancellations, ground delays, airborne delays, and flight diversions. Economic losses were estimated to range from €3.18 million to €4.18 million, which is related to the lead time forecast for satellite navigation failure. Subsequently, Xue, Yang, Liu, and Yu (2023) analyzed the repercussions of the Halloween storm event in 2003 on the top 50 busiest airports in the Continental United States, estimating economic costs stemming from Area Navigation and Continuous Descent Approach (CDA) failures to be €2.43 million. Furthermore, in a subsequent study (Xue, Yang, Liu, & Cong, 2023), considering the projected flight volume for the Greater Bay Area (GBA) of China in 2025, simulation results revealed potential economic costs amounting to tens of millions of Euros, depending on the duration of satellite navigation failure and the time intervals for ground navigation-based landings.

3.1.3. ADS-B and Radar Surveillance Failure

Air traffic management heavily relies on radar systems and Automatic Dependent Surveillance-Broadcast (ADS-B) technology for aircraft tracking and maintaining safe separations. ADS-B out systems, installed onboard aircraft, continuously transmit ADS-B messages at 1,090 MHz, which are then received by ground ADS-B receivers and other aircraft equipped with ADS-B In-system (Ali et al., 2014). Subsequently, these signals are relayed to air traffic control centers, where flight statuses are displayed for air traffic management. However, disruptions in GNSS caused by space weather events can impede ADS-B functionality, given its reliance on GNSS. In addition, space weather events can occasionally lead to the failure of radar-based surveillance, despite being relatively rare. For instance, Marqué et al. (2018) documented an incident on 4 November 2015, where an exceptionally intense solar burst at a radio frequency of approximately 1 GHz caused significant radar disturbances in the air traffic control systems of Belgium, Norway, Greenland, and Sweden, because radar antennas were inadvertently pointed toward the Sun during the solar burst event. Especially, Sweden was affected for about an hour and reduced aircraft movement as accurate information about aircraft was not going to the controllers.

When both radar and ADS-B systems become unavailable, procedure control serves as a fallback mechanism, necessitating an even higher aircraft separation standard. This, in turn, results in reduced airspace capacity and places greater workload demands on air traffic controllers (ICAO, 2016). Additionally, disruptions in surveillance systems can increase the workload and stress for air traffic controllers, further complicating air traffic management during adverse conditions. A sudden surge in workload may compromise efficiency levels and exacerbate fatigue among air traffic controllers, thereby increasing the likelihood of human errors (Loft et al., 2023). The impact of space weather on the operational efficiency of air traffic controllers is challenging to quantify precisely. Nevertheless, its significance cannot be overlooked, as any resultant human-induced accidents could have severe consequences.

3.1.4. Elevated Aviation Radiation Exposure

Aircrews, considered occupational radiation workers by the Federal Aviation Administration (FAA), face significant exposure during high-altitude flights (Bagshaw, 2008). Therefore, airline dispatchers must consider cumulative crew radiation when scheduling flights. Regulatory bodies suggest limits, such as 20 mSv per year averaged over 5 years for aircrews and 1 mSv per year for the general public (ICRP, 2016), with a specific radiation limit of 0.5 mSv during pregnancy (NCRP, 2013).

Air transportation experiences the highest radiation exposure compared to other transportation modes. Pilots, crewmembers, and frequent flyers encounter heightened levels of cosmic radiation during flights, especially at high altitudes where shielding from the Earth's magnetosphere and atmosphere is reduced. Long-haul flights, like those over Polar Regions, are particularly prone to increased cosmic radiation. To mitigate aviation radiation exposure, airlines traditionally make measures such as canceling flights, lowering altitudes, or rerouting, at the cost of more fuel consumption or economic losses (Koops, 2017).

Based on the findings from Matthiä et al. (2015), lowering flight altitudes for a transatlantic flight (Seattle-Cologne) from 41,000 ft to 28,000 ft, resulted in the maximum reduction in effective dose by 42%, decreasing from 119 to 68.7 μSv during the ground-level event on 13 December 2006. However, this reduction was accompanied by increased fuel consumption, rising by 4.8% from 53.9 to 56.5 tons, and an extension of flight duration by 4.7% from 9.9 to 10.37 hr. According to (Fujita et al., 2021), a Ground-Level Enhancement (GLE) event significant enough to warrant a change in flight conditions occurs approximately once every 47 years when adhering to dose and dose-rate regulations. However, this frequency is reduced to once every 17 years under more stringent conditions. Their conservative estimation suggests that the annual risks associated with countermeasure costs can amount to up to approximately $1.5 thousand for daily operated long-distance flights. Moreover, Saito et al. (2021) conducted an analysis utilizing the atmospheric radiation storm event that occurred on 20 January 2005, focusing on a flight route from New York to Tokyo to assess its economic impacts. Their findings indicate that to mitigate radiation hazards, fuel consumption for twin-engine, wide-body jet passenger aircraft increases by 39–69 tons (33%–58%) when flight altitude restrictions are imposed. Moreover, when constraints are applied to both aircraft altitude and latitude, both flight time and fuel consumption experience increases of 2.2–2.8 hr (17%–20%) and 32–48 tons (27%–41%), respectively. As lowering flight altitudes always increases fuel consumption, Xue, Yang, Liu, et al. (2022) proposed a multi-objective optimization model aiming to determine the optimal flight altitude and speed to minimize the weighted sums of cosmic radiation dose and fuel consumption. The simulation focuses on a scenario involving heightened cosmic radiation during a typical Tokyo to London flight due to a space weather event. Findings indicate that this model effectively lowers fuel consumption while satisfying cosmic radiation safety thresholds endorsed by the European Union. The economic advantages of this approach may vary between $4,556 and $0.35 million. After that, by assuming space weather like the Halloween storm in 2003 occurred in 2019, the total flight cancellation cost would be €49.97 million if the cosmic radiation limit for one flight trip is set to 500 μSv. In contrast, if the limit is set to 1,000 μSv, the total flight cancellation cost would be reduced to €2.77 million (Xue, Yang, Liu, & Yu, 2023).

Furthermore, SEE can present a significant risk to autonomous air transportation by disrupting critical systems such as navigation, communication, and onboard decision-making algorithms. These disruptions, caused by temporary faults or permanent damage to flight control systems, can potentially lead to loss of control or system failure. Given that autonomous air vehicles depend heavily on sensors, communication links, and real-time data processing, SEE can compromise the accuracy and reliability of these components, affecting overall safety and mission success.

3.2. Maritime Transportation

Maritime transportation also relies heavily on GNSS for navigation and HF/VHF for communication, making it vulnerable to space weather effects. Geomagnetic storms can cause GNSS inaccuracies, leading to navigation errors that are particularly problematic in congested or narrow waterways. Disruptions to AIS, which operates on VHF, can affect vessel tracking and collision avoidance. However, the slower pace and larger operational space of maritime transportation allow for more time to react to space weather forecasts and adjust operations accordingly.

3.2.1. Communication Blackouts

Maritime transportation relies heavily on HF and VHF radio communications for long-distance and short-range communications, respectively (Alqurashi et al., 2022). Solar flares and geomagnetic storms can cause ionospheric disturbances that degrade these radio signals. HF communications, essential for over-the-horizon communication, are particularly vulnerable. During heightened solar activity, the ionosphere becomes highly ionized, leading to increased signal absorption and reflection anomalies. These impacts are exacerbated at high latitudes, where ionospheric disturbances are both intense and frequent, resulting in sporadic and unreliable communication. Such disruptions pose significant maritime operational risks, especially in emergencies where reliable communication is critical.

3.2.2. Satellite Navigation Failure

GNSS provides the precise positioning data that modern ships depend on for navigation, route planning, and collision avoidance (Zhang et al., 2021). Geomagnetic storms can induce rapid and severe fluctuations in the ionosphere, causing delays and distortions in the signals received from satellites. This results in positional errors that can reduce the accuracy of GNSS from a few meters to tens of meters, as detailed in the research by Panda and Gedam (2016). Sufficiently strong space weather events can impact radio-based navigation and communication systems, magnetic compass performance, and power systems, potentially disrupting maritime navigation operations (Grant et al., 2012). Such inaccuracies are particularly dangerous in narrow or congested waterways, near ports, and during adverse weather conditions where precise navigation is paramount.

3.2.3. AIS Failure

The Automatic Identification System (AIS) relies on VHF radio signals to exchange ship positions, identities, and navigation data (Yang et al., 2019). Solar flares and geomagnetic storms cause ionospheric disturbances, increasing signal noise and degrading VHF channels, which can lead to intermittent or complete AIS signal loss, causing gaps in real-time tracking. Berdermann et al. (2018) indicated that during solar flares, AIS message traffic spikes due to GNSS tracking issues, indicating prolonged effects on AIS transponder software. These disruptions compromise situational awareness for ship operators and maritime authorities, increasing navigational hazards, collision risks, and operational inefficiencies. Additionally, GNSS disruptions impair AIS functionality, leading to unreliable vessel tracking and decision-making delays, especially in poor visibility or heavy traffic areas.

3.3. Railway Transportation

Railway transportation is generally less affected by space weather than air and maritime transport. Although modern railways rely on GNSS for precise timing, signaling, and radio communication for train control and coordination (Johnsen & Veen, 2013; Rahimi et al., 2022; Righetti et al., 2020), the fixed nature of railway networks and the availability of alternative terrestrial communication systems can reduce the impact of space weather to some extent. However, these systems depend on electrical power, making them vulnerable to disruptions from GICs during severe geomagnetic storms.

3.3.1. Signal Anomalies

Railway infrastructure and operations can be affected by induced electrical currents during severe space weather (Krausmann et al., 2015). Studies of railway operations at magnetic latitudes above 50° have shown that induced and/or stray currents from the ground during strong magnetic storms result in increased numbers of signaling anomalies (Eroshenko et al., 2010; Ptitsyna et al., 2008; Wik et al., 2009). These anomalies can be categorized into “right side” failures, where green signals erroneously turn red, and “wrong side” failures, where red signals erroneously turn green (Patterson et al., 2024). The latter is a more hazardous failure mode, as it may create a collision risk (Boteler, 2021). Based on two example railway lines in the United Kingdom, relays are most susceptible to “wrong side” failures when a train is at the end of a track circuit block, and the geoelectric field threshold at which “wrong side” failures can occur is lower than that for “right side” failures (Patterson et al., 2023b). These failures are expected to recur over timescales of several decades (Patterson et al., 2023a).

3.3.2. Power System Disruptions

In addition, GICs significantly can also impact railway transportation by interfering with traction power supply systems (Taran et al., 2023). Railway tracks, being long metallic conductors, can experience induced currents during geomagnetic disturbances. These GICs can flow through the rails and enter the traction power substations, causing transformer saturation, increased magnetization currents, and overheating. For example, the March 1989 geomagnetic storm caused transformer saturation and the failure of ∼1,000 MVA Generator Set Up (GSU) transformers on the 500 kV transmission grid (Naim et al., 2022). Such disruptions can lead to immediate service interruptions and necessitate costly repairs and maintenance, undermining the reliability and safety of railway operations.

3.4. Ground Transportation

Space weather has the least impact on ground transportation compared to other modes due to the fundamental differences in their reliance on space-dependent technologies. Ground transportation systems, including cars, trucks, and buses, are minimally dependent on satellite-based navigation and communication systems (Liu et al., 2022; Shi et al., 2022). These vehicles primarily rely on terrestrial infrastructure such as roads, traffic signals, and ground-based communication networks, which remain largely unaffected by space weather events.

Unlike aviation and maritime transport, which rely heavily on satellite-based GNSS for navigation and timing, ground transportation can operate effectively with traditional methods and infrastructure.

However, in the long term, some potential effects of space weather on ground transportation need to be mentioned. Satellite navigation failure can significantly impede vehicle operation, affecting safety, efficiency, and reliability. In modern vehicles, which heavily rely on satellite-based navigation systems for route guidance and positioning, such failures can lead to a loss of accuracy and reliability in navigation information (Pilipenko et al., 2023). This can result in misinterpretation of routes, delays, and potential safety hazards for drivers and passengers. Moreover, autonomous vehicles, reliant on precise satellite data for localization and path planning, may experience disruptions in their autonomous functions, potentially compromising their ability to navigate safely (Jing et al., 2022). In emergencies, the impact of satellite navigation failure can be particularly severe, hindering the ability of emergency responders to navigate swiftly to incident locations.

In addition, power grid disruptions can have profound effects on vehicle operation, particularly with the increasing electrification of transportation. Electric vehicles (EVs) rely on an uninterrupted power supply to recharge their batteries and sustain operation. In the event of a power grid disruption, charging infrastructure may become unavailable, limiting the ability of EV drivers to recharge their vehicles, and potentially stranding them without power (Acharya et al., 2020). This can result in disruptions to transportation services, affecting both individual drivers and commercial fleets. Furthermore, grid failures may also impact traffic management systems, such as traffic lights and road signage, leading to traffic congestion and safety hazards on road networks (Li et al., 2014).

4. Discussions and Mitigation Strategies

The resilience of different transportation modes to space weather effects varies significantly. Specifically, air transportation is the most vulnerable due to heavy reliance on satellite-based systems and HF communications. Maritime transportation is also affected but to a lesser degree. Railway transportation shows moderate resilience with fixed infrastructure and alternative communication options. Ground transportation is the most resilient, relying more on terrestrial navigation and communication systems, and experiencing the least direct impact from space weather. Space weather events, though rare, have substantial global destructive potential. Limited data hinder a thorough understanding of the impact on transportation systems due to infrequent extreme events spanning decades to centuries. Given the impossibility of preventing such events, this review outlines three Key Measures to mitigate their effects on transportation infrastructure, ensuring safety and efficiency.

4.1. Key Measure One

Improving space weather forecast and monitoring systems is crucial for enhancing the resilience and safety of global technological infrastructure (ICAO, 2019). Specifically, space weather forecast centers play a crucial role in monitoring and predicting space weather events that can impact various technological systems on Earth. Accurate and timely forecasts can help mitigate the adverse effects of space weather on critical systems such as communication networks, navigation systems, power grids, and transportation networks (Smith et al., 2022). In Europe, the European Space Agency (ESA) leads efforts to monitor and forecast space weather. They employ sophisticated observational networks and advanced modeling tools to track solar wind patterns, CMEs, and geomagnetic storms, contributing to early warning systems (ESA, 2020). NOAA's Space Weather Prediction Center (SWPC) in the United States can provide real-time space weather alerts and forecasts. It utilizes data from space-based observatories, including those from the Solar Dynamics Observatory (SDO) and geostationary satellites (Bain et al., 2023). In Canada, the Canadian Space Weather Forecast Center (CSWFC) plays a pivotal role, leveraging the country's unique geomagnetic vantage points to study auroral and ionospheric phenomena (Marshall et al., 2020). Meanwhile, Russia's Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN) conducts extensive research on space weather, focusing on high-latitude impacts and satellite navigation systems (Borchevkina et al., 2020). In addition, the Chinese Meridian Project (CMP), a key initiative funded and developed by the Chinese government, aims to comprehensively monitor the space environment through an extensive ground-based network (Wang et al., 2024). Currently, space weather advisory services are provided by four global centers: the Pan-European Consortium for Aviation Space Weather User Services (PECASUS), SWPC, the Australia-Canada-France-Japan (ACFJ) consortium, and the China-Russia (CRC) consortium (Sergeeva et al., 2023). These centers operate on a 2-week rotational basis, with one center on duty while the others serve as primary backup, secondary backup, and maintenance centers. By providing early warnings, these improved systems enable better preparedness and response strategies, reducing the risk of disruptions and economic losses.

4.2. Key Measure Two

Strengthening the resilience of critical systems such as communication, navigation, surveillance, signaling, and power grids is crucial in mitigating the adverse effects of space weather on transportation networks. This can be achieved through several measures. For communication systems, this involves incorporating redundancy and failsafes to ensure continuous operation during space weather disturbances (Sabaliauskaite et al., 2024). Then, enhancing navigation systems, especially those reliant on GNSS, includes developing alternative positioning methods and improving the robustness of satellite infrastructure (Chen et al., 2023; Wang et al., 2023). For example, Ground Based Augmentation System (GBAS) can contribute to resilient aircraft navigation service (Zhu et al., 2024). Surveillance systems need to be fortified with advanced sensors and algorithms to maintain operational integrity (Chiocchio et al., 2020). Railway signal systems should be designed to withstand geomagnetic interferences (Pan et al., 2020). Lastly, power grids should be upgraded with protective technologies like geomagnetic shielding and adaptive control mechanisms to prevent disruptions caused by geomagnetically induced currents (Lopes et al., 2020). By implementing these comprehensive strategies, the transportation sector can better withstand the challenges posed by space weather events, ensuring safety and reliability.

4.3. Key Measure Three

Implementing targeted traffic management strategies can significantly enhance the resilience of transportation systems against space weather impacts. These strategies include developing dynamic rerouting protocols that adjust to real-time space weather data, ensuring that flights and vessels avoid affected areas. Advanced traffic control systems equipped with predictive analytics can optimize the flow of air, maritime, and ground traffic, reducing congestion and minimizing delays caused by disruptions (Sridhar et al., 2008). In aviation, this might involve preemptively adjusting flight paths and altitudes to minimize exposure to increased cosmic radiation and communication blackouts (Buzulukova & Tsurutani, 2022; Jones et al., 2005). For maritime and railways, strategic scheduling adjustments and the use of alternative routes can maintain service continuity (Ahuja et al., 2005). Additionally, integrating space weather alerts into traffic management systems allows for timely decision-making and coordinated responses. By adopting these comprehensive traffic management strategies, transportation networks can maintain operational efficiency and safety, even during severe space weather events. Dynamic rerouting, adaptive signal control, and pre-established contingency plans are essential to ensure continued transportation operation and safety. For illustration, Figure 5 highlights these potential methods and recommendations for mitigating the effects of space weather on transportation systems from the perspectives of Key Measure two and Key Measure three.

Notably, effective mitigation of space weather effects requires a balance among improving space weather monitoring and forecasts (Georgoulis et al., 2024; Ishii et al., 2024; Vourlidas et al., 2023; Zheng et al., 2024), strengthening critical system resilience (Firdhous & Karuratane, 2018; Liu et al., 2020; Zhang et al., 2023), and optimizing operational measures (Hu et al., 2024; Lai et al., 2022; Sun et al., 2021; Zamanifar & Hartmann, 2020), with the latter two relying in part on accurate space weather forecasts. The specific technology and the relative costs of mitigation will dictate the best way forward. Technological mitigation often depends on the particular application, while forecasting involves both general and application-specific components. Addressing this challenge will be a significant undertaking for the scientific community and will require collaboration with engineering and business sectors to achieve effective solutions.

5. Conclusions

This systematic review has provided a comprehensive overview of the intricate relationship between solar-terrestrial interactions and their impacts on transportation systems. Through the synthesis of existing research literature and empirical evidence, we have elucidated the multifaceted effects of space weather phenomena on aviation, maritime, rail, and ground transportation.

Our analysis has stressed the critical importance of understanding and mitigating the effects of space weather on transportation infrastructure and operations. We have demonstrated that disruptions to satellite-based navigation,

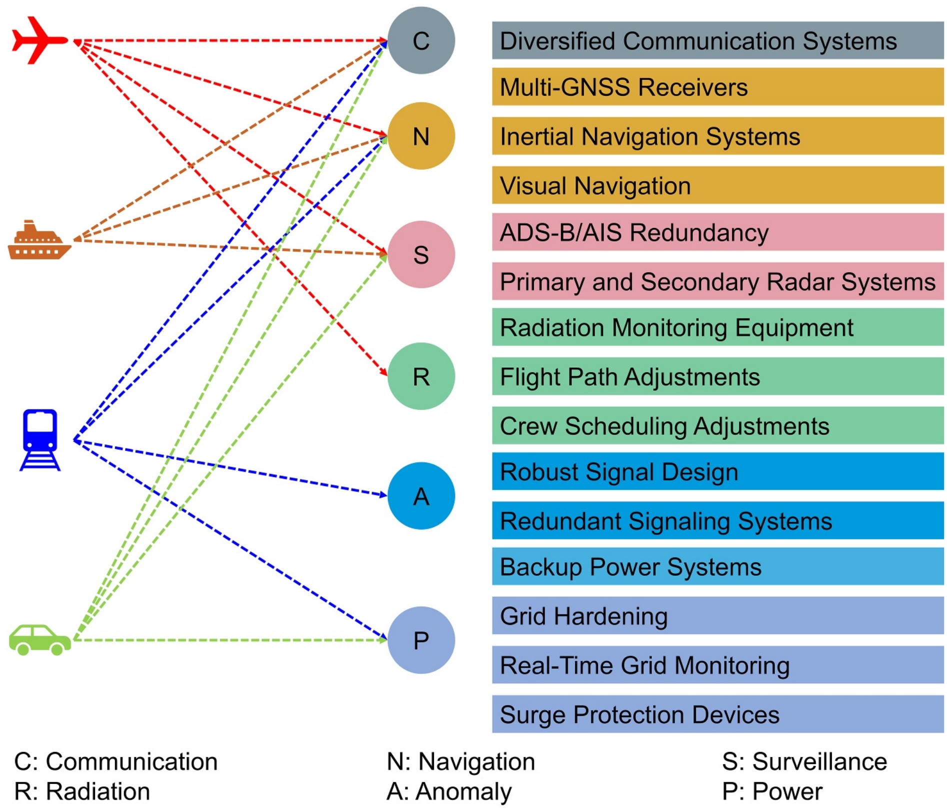


Figure 5. Specific key points for ensuring continued transportation operation from critical system resilience and operation management measures.

communication, and power distribution networks can pose significant challenges to transportation resilience, safety, and efficiency, with potential ramifications for economic productivity and societal well-being.

Furthermore, this review has highlighted the need for proactive risk management strategies and resilient infrastructure design to enhance the preparedness and response capabilities of transportation organizations in the face of space weather threats. By leveraging advanced forecasting techniques, real-time monitoring systems, and contingency planning measures, transportation stakeholders can mitigate the impact of space weather events and ensure the robustness and reliability of global transportation networks.

Moving forward, future research efforts should focus on addressing knowledge gaps and advancing predictive capabilities in space weather forecasting models, with a particular emphasis on developing tailored solutions for the transportation sector. Collaboration between academia, industry, and government agencies will be essential to facilitate knowledge exchange, data sharing, and technology transfer initiatives aimed at enhancing space weather resilience across the transportation ecosystem.

Data Availability Statement

The TEC data were obtained from IGS (https://cddis.nasa.gov/archive/gnss/products/ionex/).

Acknowledgments

This work was supported by the National Key Research and Development Program of China (Grant 2023YFB3907001), the National Natural Science Foundation of China (Grants U2233217, 62371029).

References

Acharya, S., Dvorkin, Y., Pandžić, H., & Karri, R. (2020). Cybersecurity of smart electric vehicle charging: A power grid perspective. *IEEE Access*, *8*, 214434–214453. https://doi.org/10.1109/ACCESS.2020.3041074

Affonso, B. J., Moraes, A., Sousasantos, J., Marini-Pereira, L., & Pullen, S. (2022). Strong ionospheric spatial gradient events induced by signal propagation paths aligned with equatorial plasma bubbles. *IEEE Transactions on Aerospace and Electronic Systems*, *58*(4), 2868–2879. https://doi.org/10.1109/TAES.2022.3144622

Ahuja, R. K., Cunha, C. B., & Şahin, G. (2005). Network models in railroad planning and scheduling. In *Emerging Theory, Methods, and Applications* (pp. 54–101). Informs. https://doi.org/10.1287/educ.1053.0013

Ali, B. S., Ochieng, W., Majumdar, A., Schuster, W., & Chiew, T. K. (2014). ADS-B system failure modes and models. *Journal of Navigation*, *67*(6), 995–1017. https://doi.org/10.1017/S037346331400037X

Allen, J., Sauer, H., Frank, L., & Reiff, P. (1989). Effects of the March 1989 solar activity. *Eos, Transactions American Geophysical Union*, *70*(46), 1479–1488. https://doi.org/10.1029/89EO00409

Alqurashi, F. S., Trichili, A., Saeed, N., Ooi, B. S., & Alouini, M.-S. (2022). Maritime communications: A survey on enabling technologies, opportunities, and challenges. *IEEE Internet of Things Journal*, *10*(4), 3525–3547. https://doi.org/10.1109/JIOT.2022.3219674

Amaechi, P. O., Akala, A. O., Oyedokun, J. O., Simi, K., Aghogho, O., & Oyeyemi, E. O. (2021). Multi-instrument investigation of the impact of the space weather events of 6–10 September 2017. *Space Weather*, *19*(12), e2021SW002806. https://doi.org/10.1029/2021SW002806

Aminalragia-Giamini, S., Raptis, S., Anastasiadis, A., Tsigkanos, A., Sandberg, I., Papaioannou, A., et al. (2021). Solar energetic particle event occurrence prediction using solar flare soft X-ray measurements and machine learning. *Journal of Space Weather and Space Climate*, *11*, 59. https://doi.org/10.1051/swsc/2021043

Astafyeva, E., Yasyukevich, Y., Maksikov, A., & Zhivetiev, I. (2014). Geomagnetic storms, super-storms, and their impacts on GPS-based navigation systems. *Space Weather*, *12*(7), 508–525. https://doi.org/10.1002/2014SW001072

Bagshaw, M. (2008). Cosmic radiation in commercial aviation. *Travel Medicine and Infectious Disease*, *6*(3), 125–127. https://doi.org/10.1016/j.tmaid.2007.10.003

Bain, H., Copeland, K., Onsager, T., & Steenburgh, R. (2023). NOAA space weather prediction center radiation advisories for the international civil aviation organization. *Space Weather*, *21*(7), e2022SW003346. https://doi.org/10.1029/2022SW003346

Baker, D. N., & Bodeau, M. (2021). *Effects of space radiation on contemporary space-based systems I: Single event upsets, spacecraft charging, degradation of electronics, and attenuation on fiber cabling* (pp. 3–11). Space Weather Effects and Applications. https://doi.org/10.1002/9781119815570.ch1

Balan, N., Ebihara, Y., Skoug, R., Shiokawa, K., Batista, I., Tulasi Ram, S., et al. (2017). A scheme for forecasting severe space weather. *Journal of Geophysical Research: Space Physics*, *122*(3), 2824–2835. https://doi.org/10.1002/2016JA023853

Bekker, S., Ryakhovsky, I., & Korsunskaya, J. (2021). Modeling of the lower ionosphere during solar X-ray flares of different classes. *Journal of Geophysical Research: Space Physics*, *126*(2), e2020JA028767. https://doi.org/10.1029/2020JA028767

Belakhovsky, V., Pilipenko, V., Engebretson, M., Sakharov, Y., & Selivanov, V. (2019). Impulsive disturbances of the geomagnetic field as a cause of induced currents of electric power lines. *Journal of Space Weather and Space Climate*, *9*, A18. https://doi.org/10.1051/swsc/2019015

Berdermann, J., Kriegel, M., Banyś, D., Heymann, F., Hoque, M., Wilken, V., et al. (2018). Ionospheric response to the X9. 3 flare on 6 September 2017 and its implication for navigation services over Europe. *Space Weather*, *16*(10), 1604–1615. https://doi.org/10.1029/2018SW001933

Berger, T., Dominique, M., Lucas, G., Pilinski, M., Ray, V., Sewell, R., et al. (2023). The thermosphere is a drag: The 2022 star link incident and the threat of geomagnetic storms to low earth orbit space operations. *Space Weather*, *21*(3), e2022SW003330. https://doi.org/10.1029/2022SW003330

Bink, A. (2024). 'Strongest' solar flare since 2017 detected: Here is what to know. https://thehill.com/homenews/nexstar_media_wire/4384088-strongest-solar-flare-since-2017-detected-heres-what-to-know/

Borchevkina, O., Korenkova, N., Leshchenko, V., Klimenko, M., Karpov, I., Radievskii, A., et al. (2020). Complex of radiophysical, geomagnetic, and meteorological observations (IZMIRAN), Kaliningrad Branch. *Russian Journal of Physical Chemistry B*, *14*(5), 883–891. https://doi.org/10.1134/S1990793120050176

Boteler, D. H. (2019). A 21st century view of the March 1989 magnetic storm. *Space Weather*, *17*(10), 1427–1441. https://doi.org/10.1029/2019SW002278

Boteler, D. H. (2021). Modeling geomagnetic interference on railway signaling track circuits. *Space Weather*, *19*(1), e2020SW002609. https://doi.org/10.1029/2020SW002609

Bust, G. S., Liles, W., & Mitchell, C. (2021). *Space weather influences on HF, UHF, and VHF radio propagation* (pp. 153–163). Space Weather Effects and Applications. https://doi.org/10.1002/9781119815570.ch7

Buzulukova, N., & Tsurutani, B. (2022). Space Weather: From solar origins to risks and hazards evolving in time. *Frontiers in Astronomy and Space Sciences*, *9*, 1017103. https://doi.org/10.3389/fspas.2022.1017103

Cannon, P. S. (2013). Extreme space weather—A report published by the UK royal academy of engineering. *Space Weather*, *11*(4), 138–139. https://doi.org/10.1002/swe.20032

Capon, C., Smith, B., Brown, M., Abay, R., & Boyce, R. (2019). Effect of ionospheric drag on atmospheric density estimation and orbit prediction. *Advances in Space Research*, *63*(8), 2495–2505. https://doi.org/10.1016/j.asr.2019.01.013

Caraballo, R., González-Esparza, J., Sergeeva, M., & Pacheco, C. (2020). First GIC estimates for the Mexican power grid. *Space Weather*, *18*(2), e2019SW002260. https://doi.org/10.1029/2019SW002260

Chen, X., Luo, R., Liu, T., Yuan, H., & Wu, H. (2023). Satellite navigation signal authentication in GNSS: A survey on technology evolution, status, and perspective for BDS. *Remote Sensing*, *15*(5), 1462. https://doi.org/10.3390/rs15051462

Chiocchio, S., Persia, A., Santucci, F., Graziosi, F., Pratesi, M., & Faccio, M. (2020). Modeling and evaluation of enhanced reception techniques for ADS-B signals in high interference environments. *Physical Communication*, *42*, 101171. https://doi.org/10.1016/j.phycom.2020.101171

Cliver, E. W., & Dietrich, W. F. (2013). The 1859 space weather event revisited: Limits of extreme activity. *Journal of Space Weather and Space Climate*, *3*, A31. https://doi.org/10.1051/swsc/2013053

Deng, X., Wang, L., Gui, J., Jiang, P., Chen, X., Zeng, F., & Wan, S. (2023). A review of 6G autonomous intelligent transportation systems: Mechanisms, applications and challenges. *Journal of Systems Architecture*, *142*, 102929. https://doi.org/10.1016/j.sysarc.2023.102929

Dorotovič, I., Kudela, K., Lorenc, M., & Rybanský, M. (2008). On 17–22 January 2005 events in space weather. *Solar Physics*, *250*(2), 339–346. https://doi.org/10.1007/s11207-008-9222-8

Dyer, A., Hands, A., Ryden, K., Dyer, C., Flintoft, I., & Ruffenach, A. (2020). Single-event effects in ground-level infrastructure during extreme ground-level enhancements. *IEEE Transactions on Nuclear Science*, *67*(6), 1139–1143. https://doi.org/10.1109/TNS.2020.2975838

Dyer, C., Hands, A., Ford, K., Frydland, A., & Truscott, P. (2006). Neutron-induced single event effects testing across a wide range of energies and facilities and implications for standards. *IEEE Transactions on Nuclear Science*, *53*(6), 3596–3601. https://doi.org/10.1109/TNS.2006.886207

Dyer, C., Hands, A., Ryden, K., & Lei, F. (2017). Extreme atmospheric radiation environments and single event effects. *IEEE Transactions on Nuclear Science*, *65*(1), 432–438. https://doi.org/10.1109/TNS.2017.2761258

Dyer, C., Lei, F., Clucas, S., Smart, D., & Shea, M. (2003). Solar particle enhancements of single-event effect rates at aircraft altitudes. *IEEE Transactions on Nuclear Science*, *50*(6), 2038–2045. https://doi.org/10.1109/TNS.2003.821375

Eastwood, J., Biffis, E., Hapgood, M., Green, L., Bisi, M., Bentley, R., et al. (2017). The economic impact of space weather: Where do we stand? *Risk Analysis*, *37*(2), 206–218. https://doi.org/10.1111/risa.12765

Enge, P., Enge, N., Walter, T., & Eldredge, L. (2015). Aviation benefits from satellite navigation. *New Space*, *3*(1), 19–35. https://doi.org/10.1089/space.2014.0011

Eroshenko, E., Belov, A., Boteler, D., Gaidash, S., Lobkov, S., Pirjola, R., & Trichtchenko, L. (2010). Effects of strong geomagnetic storms on Northern railways in Russia. *Advances in Space Research*, *46*(9), 1102–1110. https://doi.org/10.1016/j.asr.2010.05.017

ESA. (2020). *The Europa directory of International organizations 2020* (22nd ed.). Routledge. https://doi.org/10.4324/9781003138587

Fagundes, P., Pezzopane, M., Habarulema, J. B., Venkatesh, K., Dias, M., Tardelli, A., et al. (2020). Ionospheric disturbances in a large area of the terrestrial globe by two strong solar flares of September 6, 2017, the strongest space weather events in the last decade. *Advances in Space Research*, *66*(7), 1775–1791. https://doi.org/10.1016/j.asr.2020.06.032

Fagundes, P. R., Cardoso, F., Fejer, B., Venkatesh, K., Ribeiro, B., & Pillat, V. G. (2016). Positive and negative GPS-TEC ionospheric storm effects during the extreme space weather event of March 2015 over the Brazilian sector. *Journal of Geophysical Research: Space Physics*, *121*(6), 5613–5625. https://doi.org/10.1002/2015JA022214

Ferguson, D. C., Worden, S. P., & Hastings, D. E. (2015). The space weather threat to situational awareness, communications, and positioning systems. *IEEE Transactions on Plasma Science*, *43*(9), 3086–3098. https://doi.org/10.1109/TPS.2015.2412775

Fiori, R. A., Kumar, V. V., Boteler, D. H., & Terkildsen, M. B. (2022). Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation. *Journal of Space Weather and Space Climate*, *12*, 21. https://doi.org/10.1051/swsc/2022017

Firdhous, M., & Karuratane, P. (2018). A model for enhancing the role of information and communication technologies for improving the resilience of rural communities to disasters. *Procedia Engineering*, *212*, 707–714. https://doi.org/10.1016/j.proeng.2018.01.091

Frissell, N. A., Vega, J. S., Markowitz, E., Gerrard, A. J., Engelke, W. D., Erickson, P. J., et al. (2019). High-frequency communications response to solar activity in September 2017 as observed by amateur radio networks. *Space Weather*, *17*(1), 118–132. https://doi.org/10.1029/2018SW002008

Fujita, M., Sato, T., Saito, S., & Yamashiki, Y. (2021). Probabilistic risk assessment of solar particle events considering the cost of countermeasures to reduce the aviation radiation dose. *Scientific Reports*, *11*(1), 17091. https://doi.org/10.1038/s41598-021-95235-9

Georgoulis, M. K., Yardley, S. L., Guerra, J. A., Murray, S. A., Ahmadzadeh, A., Anastasiadis, A., et al. (2024). Prediction of solar energetic events impacting space weather conditions. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2024.02.030

Gerontidou, M., Mavromichalaki, H., & Daglis, T. (2018). High-speed solar wind streams and geomagnetic storms during solar cycle 24. *Solar Physics*, *293*(9), 1–18. https://doi.org/10.1007/s11207-018-1348-8

Gil, A., Berendt-Marchel, M., Modzelewska, R., Siluszyk, A., Siluszyk, M., Wawrzaszek, A., & Wawrzynczak, A. (2023). Review of geomagnetically induced current proxies in mid-latitude European countries. *Energies*, *16*(21), 7406. https://doi.org/10.3390/en16217406

Grant, A., Shaw, G., & Ward, N. (2012). The effect of space weather on maritime aids-to-navigation service provision. *Annual of Navigation*, *19*(1), 49–66. https://doi.org/10.2478/v10367-012-0005-9

Habarulema, J. B., Tshisaphungo, M., Katamzi-Joseph, Z. T., Matamba, T. M., & Nndanganeni, R. (2022). Ionospheric response to the M-and X-class solar flares of 28 October 2021 over the African sector. *Space Weather*, *20*(8), e2022SW003104. https://doi.org/10.1029/2022SW003104

Hajra, R., Tsurutani, B. T., & Lakhina, G. S. (2020). The complex space weather events of 2017 September. *The Astrophysical Journal*, *899*(1), 3. https://doi.org/10.3847/1538-4357/aba2c5

Hands, A. D., Ryden, K. A., Meredith, N. P., Glauert, S. A., & Horne, R. B. (2018). Radiation effects on satellites during extreme space weather events. *Space Weather*, *16*(9), 1216–1226. https://doi.org/10.1029/2018SW001913

Hapgood, M. (2019). The great storm of May 1921: An exemplar of a dangerous space weather event. *Space Weather*, *17*(7), 950–975. https://doi.org/10.1029/2019SW002195

Hapgood, M., Liu, H., & Lugaz, N. (2022). SpaceX-Sailing close to the space weather? *Space Weather*, *20*(3), e2022SW003074. https://doi.org/10.1029/2022SW003074

Hayakawa, H., Bechet, S., Clette, F., Hudson, H. S., Maehara, H., Namekata, K., & Notsu, Y. (2023). Magnitude estimates for the Carrington flare in 1859 September: As seen from the original records. *The Astrophysical Journal Letters*, *954*(1), L3. https://doi.org/10.3847/2041-8213/acd853

Hayakawa, H., Ebihara, Y., Willis, D. M., Toriumi, S., Iju, T., Hattori, K., et al. (2019). Temporal and spatial evolutions of a large sunspot group and great auroral storms around the Carrington event in 1859. *Space Weather*, *17*(11), 1553–1569. https://doi.org/10.1029/2019SW002269

Hayakawa, H., Oliveira, D. M., Shea, M. A., Smart, D. F., Blake, S. P., Hattori, K., et al. (2022). The extreme solar and geomagnetic storms on 1940 March 20–25. *Monthly Notices of the Royal Astronomical Society*, *517*(2), 1709–1723. https://doi.org/10.1093/mnras/stab3615

Howard, R., Sheeley Jr, N., Koomen, M., & Michels, D. (1985). Coronal mass ejections: 1979–1981. *Journal of Geophysical Research*, *90*(A9), 8173–8191. https://doi.org/10.1029/JA090iA09p08173

Hu, S., Wang, K., Li, L., Zhao, Y., He, Z., & Zhang, Y. (2024). Multi-crowdsourced data fusion for modeling link-level traffic resilience to adverse weather events. *International Journal of Disaster Risk Reduction*, *112*, 104754. https://doi.org/10.1016/j.ijdrr.2024.104754

Hudson, H. S. (2021). Carrington events. *Annual Review of Astronomy and Astrophysics*, *59*(1), 445–477. https://doi.org/10.1146/annurev-astro-112420-023324

ICAO. (2016). Procedures for air navigation and air traffic management Pans-atm Doc 4444. Retrieved from https://store.icao.int/en/procedures-for-air-navigation-services-air-traffic-management-doc-4444

ICAO. (2019). Manual on space weather information in support of international air navigation. Retrieved from https://store.icao.int/en/manual-on-space-weather-information-in-support-of-international-air-navigation-doc-10100

ICRP. (2016). Radiological protection from cosmic radiation in aviation. *Annals of the ICRP*. Retrieved from https://www.icrp.org/publication.asp?id=ICRP%20Publication%20132

Ishii, M., Costa, J. E. R., Kuznetsova, M. M., Andries, J., Gopalswamy, N., Belehaki, A., et al. (2024). Pathways to global coordination in space weather: International organizations, initiatives, and space agencies. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2024.06.017

Jakšić, Z., & Janić, M. (2020). Modeling resilience of the ATC (air traffic control) sectors. *Journal of Air Transport Management*, *89*, 101891. https://doi.org/10.1016/j.jairtraman.2020.101891

Jing, H., Gao, Y., Shahbeigi, S., & Dianati, M. (2022). Integrity monitoring of GNSS/INS based positioning systems for autonomous vehicles: State-of-the-art and open challenges. *IEEE Transactions on Intelligent Transportation Systems*, *23*(9), 14166–14187. https://doi.org/10.1109/TITS.2022.3149373

Johnsen, S. O., & Veen, M. (2013). Risk assessment and resilience of critical communication infrastructure in railways. *Cognition, Technology and Work*, *15*(1), 95–107. https://doi.org/10.1007/s10111-011-0187-2

Jones, J. B. L., Bentley, R., Hunter, R., Iles, R., Taylor, G., & Thomas, D. (2005). Space weather and commercial airlines. *Advances in Space Research*, *36*(12), 2258–2267. https://doi.org/10.1016/j.asr.2004.04.017

Kappenman, J. G. (2006). Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events–An analysis of observational evidence including the great storm of May 1921. *Advances in Space Research*, *38*(2), 188–199. https://doi.org/10.1016/j.asr.2005.08.055

Kappenman, J. G. (2018). Geomagnetic disturbances and impacts upon power system operation. In *Electric Power Generation, Transmission, and Distribution* (pp. 17-11–17-22). CRC Press. Retrieved from https://www.taylorfrancis.com/chapters/edit/10.1201/9781315222424-17/geomagnetic-disturbances-impacts-upon-power-system-operation-john-kappenman

Kassa, Y., Damtie, B., & Tebabal, A. (2023). Ionospheric and magnetic signatures of extreme space weather events of 17 March and 23 June 2015 over the African sector. *Journal of Atmospheric and Solar-Terrestrial Physics*, *243*, 106003. https://doi.org/10.1016/j.jastp.2023.106003

Klein, K.-L., & Dalla, S. (2017). Acceleration and propagation of solar energetic particles. *Space Science Reviews*, *212*(3–4), 1107–1136. https://doi.org/10.1007/s11214-017-0382-4

Knipp, D. J., Bernstein, V., Wahl, K., & Hayakawa, H. (2021). Timelines as a tool for learning about space weather storms. *Journal of Space Weather and Space Climate*, *11*, 29. https://doi.org/10.1051/swsc/2021011

Knipp, D. J., Fraser, B. J., Shea, M., & Smart, D. (2018). On the little-known consequences of the 4 August 1972 ultra-fast coronal mass ejecta: Facts, commentary, and call to action. *Space Weather*, *16*(11), 1635–1643. https://doi.org/10.1029/2018SW002024

Knipp, D. J., Ramsay, A., Beard, E., Boright, A., Cade, W., Hewins, I., et al. (2016). The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses. *Space Weather*, *14*(9), 614–633. https://doi.org/10.1002/2016SW001423

Koops, L. (2017). Cosmic radiation exposure of future hypersonic flight missions. *Radiation Protection Dosimetry*, *175*(2), 267–278. https://doi.org/10.1093/rpd/ncw298

Krausmann, E., Andersson, E., Russell, T., & Murtagh, W. (2015). Space weather and rail: Outlook and finding. https://doi.org/10.2788/211456

Lai, X., Wu, L., Wang, K., & Wang, F. (2022). Robust ship fleet deployment with shipping revenue management. *Transportation Research Part B: Methodological*, *161*, 169–196. https://doi.org/10.1016/j.trb.2022.05.005

Lakhina, G. S., & Tsurutani, B. T. (2016). Geomagnetic storms: Historical perspective to modern view. *Geoscience letters*, *3*, 1–11. https://doi.org/10.1186/s40562-016-0037-4

Li, D., Jiang, Y., Kang, R., & Shlomo, H. (2014). Spatial correlation analysis of cascading failures: Congestions and blackouts. *Scientific Reports*, *4*(1), 5381. https://doi.org/10.1038/srep05381

Li, Q., Zhu, Y., Wang, Z., & Fang, K. (2021). A method for automatic detection and characterization of plasma bubbles using GPS and BDS data. *Chinese Journal of Aeronautics*, *34*(5), 195–204. https://doi.org/10.1016/j.cja.2020.10.014

Lin, C. J., Lin, P.-H., Chen, H.-J., Hsieh, M.-C., Yu, H.-C., Wang, E. M.-Y., & Ho, H. L. (2012). Effects of controller-pilot communication medium, flight phase and the role in the cockpit on pilots' workload and situation awareness. *Safety Science*, *50*(9), 1722–1731. https://doi.org/10.1016/j.ssci.2012.04.007

Liu, L., Ge, X., Zong, W., Zhou, Y., & Liu, M. (2016). Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway. *Space Weather*, *14*(10), 754–763. https://doi.org/10.1002/2016SW001411

Liu, R., Ren, Y., Yu, H., Li, Z., & Jiang, H. (2022). Connected and automated vehicle platoon maintenance under communication failures. *Vehicular Communications*, *35*, 100467. https://doi.org/10.1016/j.vehcom.2022.100467

Liu, X., Chen, B., Chen, C., & Jin, D. (2020). Electric power grid resilience with interdependencies between power and communication networks–a review. *IET Smart Grid*, *3*(2), 182–193. https://doi.org/10.1049/iet-stg.2019.0202

Loft, S., Tatasciore, M., & Visser, T. (2023). Managing workload, performance, and situation awareness in aviation systems. In *Human Factors in Aviation and Aerospace* (pp. 171–197). Elsevier. https://doi.org/10.1016/B978-0-12-374518-7.00008-0

Lopes, J. A. P., Madureira, A. G., Matos, M., Bessa, R. J., Monteiro, V., Afonso, J. L., et al. (2020). The future of power systems: Challenges, trends, and upcoming paradigms. *Wiley Interdisciplinary Reviews: Energy & Environment*, *9*(3), e368. https://doi.org/10.1002/wene.368

López-Lago, M., Serna, J., Casado, R., & Bermúdez, A. (2020). Present and future of air navigation: PBN operations and supporting technologies. *International Journal of Aeronautical and Space Sciences*, *21*(2), 451–468. https://doi.org/10.1007/s42405-019-00216-y

Love, J. J., Hayakawa, H., & Cliver, E. W. (2019). Intensity and impact of the New York railroad superstorm of May 1921. *Space Weather*, *17*(8), 1281–1292. https://doi.org/10.1029/2019SW002250

Love, J. J., Rigler, E. J., Hartinger, M. D., Lucas, G. M., Kelbert, A., & Bedrosian, P. A. (2023). The March 1940 superstorm: Geoelectromagnetic hazards and impacts on American communication and power systems. *Space Weather*, *21*(6), e2022SW003379. https://doi.org/10.1029/2022SW003379

Love, J. J., Rigler, E. J., Hayakawa, H., & Mursula, K. (2024). On the uncertain intensity estimate of the 1859 Carrington storm. *Journal of Space Weather and Space Climate*, *14*, 21. https://doi.org/10.1051/swsc/2024015

Lundstedt, H., Persson, T., & Andersson, V. (2015). The extreme solar storm of May 1921: Observations and a complex topological model. *Annales Geophysicae*, *33*(1), 109–116. https://doi.org/10.5194/angeo-33-109-2015

Luo, X., Gu, S., Lou, Y., Chen, B., & Song, W. (2020). Better thresholds and weights to improve GNSS PPP under ionospheric scintillation activity at low latitudes. *GPS Solutions*, *24*, 1–12. https://doi.org/10.1007/s10291-019-0924-1

Marov, M. Y. (2020). Radiation and space flights safety: An insight. *Acta Astronautica*, *176*, 580–590. https://doi.org/10.1016/j.actaastro.2020.03.022

Marqué, C., Klein, K.-L., Monstein, C., Opgenoorth, H., Pulkkinen, A., Buchert, S., et al. (2018). Solar radio emission as a disturbance of aeronautical radio navigation. *Journal of Space Weather and Space Climate*, *8*, A42. https://doi.org/10.1051/swsc/2018029

Marshall, F., Thomson, D., Chave, A., Fiori, R., & Danskin, D. (2020). A characterization of periodicity in the voltage time series of a riometer. *Journal of Geophysical Research: Space Physics*, *125*(7), e2019JA027160. https://doi.org/10.1029/2019JA027160

Matthiä, D., Schaefer, M., & Meier, M. M. (2015). Economic impact and effectiveness of radiation protection measures in aviation during a ground level enhancement. *Journal of Space Weather and Space Climate*, *5*, A17. https://doi.org/10.1051/swsc/2015014

Meier, M. M., Copeland, K., Klöble, K. E., Matthiä, D., Plettenberg, M. C., Schennetten, K., et al. (2020). Radiation in the atmosphere-A hazard to aviation safety? *Atmosphere*, *11*(12), 1358. https://doi.org/10.3390/atmos11121358

Meier, M. M., & Matthiä, D. (2014). A space weather index for the radiation field at aviation altitudes. *Journal of Space Weather and Space Climate*, *4*, A13. https://doi.org/10.1051/swsc/2014010

Monzon, B. V., Ortiz, F., Herrero, G. S., & Lagunas, E. (2022). Enhanced communications on satellite-based IOT systems to support maritime transportation services. *Sensors*, *22*(17), 6450. https://doi.org/10.3390/s22176450

Naim, W., Hilber, P., & Shayesteh, E. (2022). Impact of geomagnetic disturbances on power transformers: Risk assessment of extreme events and data availability. *Life Cycle Reliability and Safety Engineering*, *11*(1), 11–18. https://doi.org/10.1007/s41872-021-00179-8

NCRP. (2013). Preconception and prenatal radiation exposure: Health effects and protective guidance. Retrieved from https://www.apfa.org/wp-content/uploads/2017/12/preconception-and-prenatal-radiation-exposure.pdf

NOAA. (2004). Intense space weather storms October 19 - November 07, 2003. Retrieved from https://repository.library.noaa.gov/view/noaa/6995

Norbury, J. W., Slaba, T. C., Aghara, S., Badavi, F. F., Blattnig, S. R., Clowdsley, M. S., et al. (2019). Advances in space radiation physics and transport at NASA. *Life Sciences and Space Research*, *22*, 98–124. https://doi.org/10.1016/j.lssr.2019.07.003

Obermeier, A., Ave, M., Boyle, P., Höppner, C., Hörandel, J., & Müller, D. (2011). Energy spectra of primary and secondary cosmic-ray nuclei measured with TRACER. *The Astrophysical Journal*, *742*(1), 14. https://doi.org/10.1088/0004-637X/742/1/14

Oliveira, D. M., Zesta, E., Hayakawa, H., & Bhaskar, A. (2020). Estimating satellite orbital drag during historical magnetic superstorms. *Space Weather*, *18*(11), e2020SW002472. https://doi.org/10.1029/2020SW002472

Orus, R., Cander, L. R., & Hernandez-Pajares, M. (2007). Testing regional vertical total electron content maps over Europe during the 17–21 January 2005 sudden space weather event. *Radio Science*, *42*(03), 1–12. https://doi.org/10.1029/2006RS003515

Oughton, E. J., Hapgood, M., Richardson, G. S., Beggan, C. D., Thomson, A. W., Gibbs, M., et al. (2019). A risk assessment framework for the socioeconomic impacts of electricity transmission infrastructure failure due to space weather: An application to the United Kingdom. *Risk Analysis*, *39*(5), 1022–1043. https://doi.org/10.1111/risa.13229

Pan, P., Hu, H., Xiao, D., Song, Y., & He, Z. (2020). An improved controlled-frequency-band impedance measurement scheme for railway traction power system. *IEEE Transactions on Industrial Electronics*, *68*(3), 2184–2195. https://doi.org/10.1109/TIE.2020.2972469

Panda, S. K., & Gedam, S. S. (2016). Evaluation of GPS standard point positioning with various ionospheric error mitigation techniques. *Journal of Applied Geodesy*, *10*(4), 211–221. https://doi.org/10.1515/jag-2016-0019

Patterson, C., Wild, J., & Boteler, D. (2023a). Modeling the impact of geomagnetically induced currents on electrified railway signaling systems in the United Kingdom. *Space Weather*, *21*(3), e2022SW003385. https://doi.org/10.1029/2022SW003385

Patterson, C. J., Wild, J. A., Beggan, C. D., Richardson, G. S., & Boteler, D. H. (2024). Modelling electrified railway signalling misoperations during extreme space weather events in the UK. *Scientific Reports*, *14*(1), 1583. https://doi.org/10.1038/s41598-024-51390-3

Patterson, C. J., Wild, J. A., & Boteler, D. H. (2023b). Modeling "wrong side" failures caused by geomagnetically induced currents in electrified railway signaling systems in the UK. *Space Weather*, *21*(12), e2023SW003625. https://doi.org/10.1029/2023SW003625

Pavlov, A. (2014). Photochemistry of ions at D-region altitudes of the ionosphere: A review. *Surveys in Geophysics*, *35*(2), 259–334. https://doi.org/10.1007/s10712-013-9253-z

Pilipenko, V. A. E., Chernikov, A., Soloviev, A. A., Yagova, N. V., Saharov, Y. A., Kudin, D. V., et al. (2023). Influence of space weather on the reliability of the transport system functioning at high latitudes. *Russian Journal of Earth Sciences*, *23*(2), 2008–2034. https://doi.org/10.2205/2023ES000824

Pirjola, R., Kauristie, K., Lappalainen, H., Viljanen, A., & Pulkkinen, A. (2005). Space weather risk. *Space Weather*, *3*(2). https://doi.org/10.1029/2004SW000112

Ptitsyna, N., Kasinskii, V., Villoresi, G., Lyahov, N., Dorman, L., & Iucci, N. (2008). Geomagnetic effects on mid-latitude railways: A statistical study of anomalies in the operation of signaling and train control equipment on the east-siberian railway. *Advances in Space Research*, *42*(9), 1510–1514. https://doi.org/10.1016/j.asr.2007.10.015

Rahimi, M., Liu, H., Cardenas, I. D., Starr, A., Hall, A., & Anderson, R. (2022). A review on technologies for localisation and navigation in autonomous railway maintenance systems. *Sensors*, *22*(11), 4185. https://doi.org/10.3390/s22114185

Redmon, R., Seaton, D., Steenburgh, R., He, J., & Rodriguez, J. (2018). 2017's geoeffective space weather and impacts to Caribbean radio communications during hurricane response. *Space Weather*, *16*(9), 1190–1201. https://doi.org/10.1029/2018SW001897

Ren, Y., Zhu, M., Xu, D., Liu, M., Dai, X., Wang, S., & Li, L. (2024). Overview on radiation damage effects and protection techniques in microelectronic devices. *Science and Technology of Nuclear Installations*, *2024*(1), 3616902–3616917. https://doi.org/10.1155/2024/3616902

Righetti, F., Vallati, C., Anastasi, G., Masetti, G., & Di Giandomenico, F. (2020). Failure management strategies for IoT-based railways systems. In *2020 IEEE International Conference on Smart Computing* (pp. 386–391). SMARTCOMP. https://doi.org/10.1109/SMARTCOMP50058.2020.00082

Roy, B., & Paul, A. (2013). Impact of space weather events on satellite-based navigation. *Space Weather*, *11*(12), 680–686. https://doi.org/10.1002/2013SW001001

Royal Academy of Engineering. (2013). Extreme space weather: Impacts on engineered systems and infrastructure. Retrieved from https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf

Rozanov, E., Calisto, M., Egorova, T., Peter, T., & Schmutz, W. (2012). Influence of the precipitating energetic particles on atmospheric chemistry and climate. *Surveys in Geophysics*, *33*(3–4), 483–501. https://doi.org/10.1007/s10712-012-9192-0

Rutledge, R., & Desbios, S. (2018). Space weather focus: Impacts of a severe space weather event on aviation operations. *World Meteorological Organization Commission for Aeronautical Meteorology (CAeM) Newsletter*, *1*. https://mailchi.mp/f7811e0713c9/wmo-caem-newsletter-issue-12018#Item%2019

Sabaliauskaite, G., Bryans, J., Jadidbonab, H., Ahmad, F., Shaikh, S., & Wooderson, P. (2024). TOMSAC-Methodology for trade-off management between automotive safety and cyber security. *Computers and Security*, *140*, 103798. https://doi.org/10.1016/j.cose.2024.103798

Saito, S., Wickramasinghe, N. K., Sato, T., & Shiota, D. (2021). Estimate of economic impact of atmospheric radiation storm associated with solar energetic particle events on aircraft operations. *Earth Planets and Space*, *73*, 1–10. https://doi.org/10.1186/s40623-021-01377-5

Sandamali, G. G. N., Su, R., Sudheera, K. L. K., & Zhang, Y. (2021). A safety-aware real-time air traffic flow management model under demand and capacity uncertainties. *IEEE Transactions on Intelligent Transportation Systems*, *23*(7), 8615–8628. https://doi.org/10.1109/tits.2021.3083964

Sauer, H. H., & Wilkinson, D. C. (2008). Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons. *Space Weather*, *6*(12). https://doi.org/10.1029/2008SW000399

Schneider, N. M., Jain, S. K., Deighan, J., Nasr, C.-R., Brain, D. A., Larson, D., et al. (2018). Global aurora on Mars during the September 2017 space weather event. *Geophysical Research Letters*, *45*(15), 7391–7398. https://doi.org/10.1029/2018GL077772

Schwadron, N. A., Cooper, J. F., Desai, M., Downs, C., Gorby, M., Jordan, A. P., et al. (2017). Particle radiation sources, propagation and interactions in deep space, at Earth, the Moon, Mars, and beyond: Examples of radiation interactions and effects. *Space Science Reviews*, *212*(3–4), 1069–1106. https://doi.org/10.1007/s11214-017-0381-5

Selčan, D., Kirbiš, G., & Kramberger, I. (2017). Nanosatellites in LEO and beyond: Advanced Radiation protection techniques for COTS-based spacecraft. *Acta Astronautica*, *131*, 131–144. https://doi.org/10.1016/j.actaastro.2016.11.032

Sergeeva, M. A., Gonzalez-Esparza, J. A., Gatica-Acevedo, V. J., Gonzalez, L. X., Corona-Romero, P., Aguilar-Rodriguez, E., et al. (2023). On some challenges for national and global space weather services. *Remote Sensing*, *15*(19), 4839. https://doi.org/10.3390/rs15194839

Shea, M., & Smart, D. (2012). Space weather and the ground-level solar proton events of the 23rd solar cycle. *Space Science Reviews*, *171*(1), 161–188. https://doi.org/10.1007/s11214-012-9923-z

Shi, H., Zhou, Y., Wang, X., Fu, S., Gong, S., & Ran, B. (2022). A deep reinforcement learning-based distributed connected automated vehicle control under communication failure. *Computer-Aided Civil and Infrastructure Engineering*, *37*(15), 2033–2051. https://doi.org/10.1111/mice.12825

Shi, Q., Zong, Q.-G., Fu, S., Dunlop, M., Pu, Z., Parks, G., et al. (2013). Solar wind entry into the high-latitude terrestrial magnetosphere during geomagnetically quiet times. *Nature Communications*, *4*(1), 1466. https://doi.org/10.1038/ncomms2476

Shprits, Y., Thorne, R., Horne, R., Glauert, S., Cartwright, M., Russell, C., et al. (2006). Acceleration mechanism responsible for the formation of the new radiation belt during the 2003 Halloween solar storm. *Geophysical Research Letters*, *33*(5). https://doi.org/10.1029/2005GL024256
SKYbrary. (2024). Impact of space weather on aviation. Retrieved from https://skybrary.aero/articles/impact-space-weather-aviation
Smith, A., Forsyth, C., Rae, I., Garton, T., Jackman, C., Bakrania, M., et al. (2022). On the considerations of using near real time data for space weather hazard forecasting. *Space Weather*, *20*(7), e2022SW003098. https://doi.org/10.1029/2022SW003098
Smith, M., Moser, D., Strohmeier, M., Lenders, V., & Martinovic, I. (2018). Undermining privacy in the aircraft communications addressing and reporting system (ACARS). *Proceedings on Privacy Enhancing Technologies*, *2018*(3), 105–122. https://doi.org/10.3929/ethz-b-000294042
Sridhar, B., Grabbe, S. R., & Mukherjee, A. (2008). Modeling and optimization in traffic flow management. *Proceedings of the IEEE*, *96*(12), 2060–2080. https://doi.org/10.1109/JPROC.2008.2006141
Sun, H., Wang, Y., & Xue, Y. (2021). A bi-objective robust optimization model for disaster response planning under uncertainties. *Computers and Industrial Engineering*, *155*, 107213. https://doi.org/10.1016/j.cie.2021.107213
Švanda, M., Mourenas, D., Žertová, K., & Výbošt'oková, T. (2020). Immediate and delayed responses of power lines and transformers in the Czech electric power grid to geomagnetic storms. *Journal of Space Weather and Space Climate*, *10*, 26. https://doi.org/10.1051/swsc/2020025
Taran, S., Alipour, N., Rokni, K., Hosseini, S. H., Shekoofa, O., & Safari, H. (2023). Effect of geomagnetic storms on a power network at mid latitudes. *Advances in Space Research*, *71*(12), 5453–5465. https://doi.org/10.1016/j.asr.2023.02.027
Telloni, D., Carbone, F., Antonucci, E., Bruno, R., Grimani, C., Villante, U., et al. (2020). Study of the influence of the solar wind energy on the geomagnetic activity for space weather science. *The Astrophysical Journal*, *896*(2), 149. https://doi.org/10.3847/1538-4357/ab91b9
Tlatov, A., Shramko, A., Chernov, Y. O., Strelkov, M., & Naga Varun, E. (2017). Space weather parameters: Modeling and prediction from the data of groundbased observations of solar activity. *Geomagnetism and Aeronomy*, *57*(7), 854–858. https://doi.org/10.1134/S0016793217070210
Tompros, D., & Mouzakis, D. E. (2024). Space environment effects on equipment and structures—Current and future technologies. *The Journal of Defense Modeling and Simulation*, *21*(3), 283–291. https://doi.org/10.1177/15485129211033038
Tsurutani, B., Mannucci, A., Iijima, B., Guarnieri, F., Gonzalez, W., Judge, D., et al. (2006). The extreme Halloween 2003 solar flares (and Bastille Day, 2000 flare), ICMEs, and resultant extreme ionospheric effects: A review. *Advances in Space Research*, *37*(8), 1583–1588. https://doi.org/10.1016/j.asr.2005.05.114
Tsurutani, B. T., Sen, A., Hajra, R., Lakhina, G. S., Horne, R. B., & Hada, T. (2024). Review of the August 1972 and March 1989 (allen) space weather events: Can we learn anything new from them? *Journal of Geophysical Research: Space Physics*, *129*(7), e2024JA032622. https://doi.org/10.1029/2024JA032622
Tsurutani, B. T., Zank, G. P., Sterken, V. J., Shibata, K., Nagai, T., Mannucci, A. J., et al. (2022). Space plasma physics: A review. *IEEE Transactions on Plasma Science*, *51*(7), 1595–1655. https://doi.org/10.1109/TPS.2022.3208906
Verkhoglyadova, O. P., Zank, G. P., & Li, G. (2015). A theoretical perspective on particle acceleration by interplanetary shocks and the Solar Energetic Particle problem. *Physics Reports*, *557*, 1–23. https://doi.org/10.1016/j.physrep.2014.10.004
Villante, U., & Regi, M. (2008). Solar flare effect preceding Halloween storm (28 October 2003): Results of a worldwide analysis. *Journal of Geophysical Research*, *113*(A3). https://doi.org/10.1029/2008JA013132
Vourlidas, A., Turner, D., Biesecker, D., Coster, A., Engell, A., Ho, G., et al. (2023). The NASA space weather science and observation gap analysis. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2023.06.046
Wang, C., Xu, J., Chen, Z., Li, H., Feng, X., Huang, Z., & Wang, J. (2024). China's ground-based space environment monitoring network—Chinese Meridian Project (CMP). *Space Weather*, *22*(7), e2024SW003972. https://doi.org/10.1029/2024SW003972
Wang, H., Wang, Z., Fang, K., Dan, Z., & Zhu, Y. (2023). An airborne ionospheric correction approach for single-frequency BDSBAS. *IEEE Transactions on Geoscience and Remote Sensing*, *61*, 1–20. https://doi.org/10.1109/TGRS.2023.3315743
Wang, J., Shi, Y., Yang, C., & Feng, F. (2022). A review and prospects of operational frequency selecting techniques for HF radio communication. *Advances in Space Research*, *69*(8), 2989–2999. https://doi.org/10.1016/j.asr.2022.01.026
Wang, Z., Li, T., Li, Q., & Fang, K. (2021). Impact of anomalous ionospheric gradients on GBAS in the low-latitude region of China. *GPS Solutions*, *25*, 1–13. https://doi.org/10.1007/s10291-020-01038-2
Wang, Z., Xue, K., Wang, C., Zhang, T., Fan, L., Hu, Z., et al. (2021). Near real-time modeling of global ionospheric vertical total electron content using hourly IGS data. *Chinese Journal of Aeronautics*, *34*(2), 386–395. https://doi.org/10.1016/j.cja.2020.07.023
Wang, Z., Yin, Y., Song, D., Fang, K., Li, Q., & Li, X. (2020). Dual smoothing ionospheric gradient monitoring algorithm for dual-frequency BDS GBAS. *Chinese Journal of Aeronautics*, *33*(12), 3395–3404. https://doi.org/10.1016/j.cja.2020.04.030
Wik, M., Pirjola, R., Lundstedt, H., Viljanen, A., Wintoft, P., & Pulkkinen, A. (2009). Space weather events in July 1982 and October 2003 and the effects of geomagnetically induced currents on Swedish technical systems. *Annales Geophysicae*, *27*(4), 1775–1787. https://doi.org/10.5194/angeo-27-1775-2009
Woods, T. N., Hock, R., Eparvier, F., Jones, A. R., Chamberlin, P. C., Klimchuk, J. A., et al. (2011). New solar extreme-ultraviolet irradiance observations during flares. *The Astrophysical Journal*, *739*(2), 59. https://doi.org/10.1088/0004-637X/739/2/59
Wu, C. C., Wu, S., Dryer, M., Fry, C., Berdichevsky, D., Smith, Z., et al. (2005). Flare-generated shock evolution and geomagnetic storms during the "Halloween 2003 epoch": 29 October to 2 November. *Journal of Geophysical Research*, *110*(A9). https://doi.org/10.1029/2005JA011011
Xiong, C., Stolle, C., & Lühr, H. (2016). The Swarm satellite loss of GPS signal and its relation to ionospheric plasma irregularities. *Space Weather*, *14*(8), 563–577. https://doi.org/10.1002/2016SW001439
Xue, D., Hsu, L.-T., Wu, C.-L., Lee, C.-H., & Ng, K. K. (2021). Cooperative surveillance systems and digital-technology enabler for a real-time standard terminal arrival schedule displacement. *Advanced Engineering Informatics*, *50*, 101402. https://doi.org/10.1016/j.aei.2021.101402
Xue, D., Liu, Z., Zhang, D., Wu, C.-L., & Yang, J. (2024). Optimizing polar air traffic: Strategies for mitigating the effects of space weather-induced communication failures poleward of 82°N. *Space Weather*, *22*(12), e2024SW004136. https://doi.org/10.1029/2024SW004136
Xue, D., Yang, J., & Liu, Z. (2022a). Potential impact of GNSS positioning errors on the satellite-navigation-based air traffic management. *Space Weather*, *20*(7), e2022SW003144. https://doi.org/10.1029/2022SW003144
Xue, D., Yang, J., Liu, Z., & Cong, W. (2023). Forward-looking study of solar maximum impact in 2025: Effects of satellite navigation failure on aviation network operation in the greater Bay area, China. *Space Weather*, *21*(12), e2023SW003678. https://doi.org/10.1029/2023SW003678
Xue, D., Yang, J., Liu, Z., & Wang, B. (2022b). An optimized solution to long-distance flight routes under extreme cosmic radiation. *Space Weather*, *20*(12), e2022SW003264. https://doi.org/10.1029/2022SW003264
Xue, D., Yang, J., Liu, Z., & Yu, S. (2023). Examining the economic costs of the 2003 Halloween storm effects on the North Hemisphere aviation using flight data in 2019. *Space Weather*, *21*(3), e2022SW003381. https://doi.org/10.1029/2022SW003381
Yang, C. D., Ozbay, K., & Ban, X. (2017). Developments in connected and automated vehicles. *Journal of Intelligent Transportation Systems*, *21*(4), 251–254. https://doi.org/10.1080/15472450.2017.1337974

Yang, D., Wu, L., Wang, S., Jia, H., & Li, K. X. (2019). How big data enriches maritime research–a critical review of Automatic Identification System (AIS) data applications. *Transport Reviews*, *39*(6), 755–773. https://doi.org/10.1080/01441647.2019.1649315

Yasyukevich, Y., Astafyeva, E., Padokhin, A., Ivanova, V., Syrovatskii, S., & Podlesnyi, A. (2018). The 6 September 2017 X-class solar flares and their impacts on the ionosphere, GNSS, and HF radio wave propagation. *Space Weather*, *16*(8), 1013–1027. https://doi.org/10.1029/2018SW001932

Zamanifar, M., & Hartmann, T. (2020). Optimization-based decision-making models for disaster recovery and reconstruction planning of transportation networks. *Natural Hazards*, *104*(1), 1–25. https://doi.org/10.1007/s11069-020-04192-5

Zhang, W., Yang, Y., Zeng, A., & Xu, Y. (2023). Robust BDS/5G integrated positioning based on resilient observation model. *Advances in Space Research*, *71*(10), 4006–4017. https://doi.org/10.1016/j.asr.2022.12.042

Zhang, X., Wang, C., Jiang, L., An, L., & Yang, R. (2021). Collision-avoidance navigation systems for maritime autonomous surface ships: A state of the art survey. *Ocean Engineering*, *235*, 109380. https://doi.org/10.1016/j.oceaneng.2021.109380

Zheng, Y., Jun, I., Tu, W., Shprits, Y., Kim, W., Matthiä, D., et al. (2024). Overview, progress and next steps for our understanding of the near-earth space radiation and plasma environment: Science and applications. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2024.05.017

Zhu, Y., Tang, H., Wang, Z., Guo, K., Wang, S., & Wang, Y. (2024). Performance evaluation of tropospheric correction model for GBAS in China. *GPS Solutions*, *28*(3), 1–15. https://doi.org/10.1007/s10291-024-01646-2