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# Impacts of Geomagnetic Storms on Power Systems, Communications and Navigation, and Low-Earth-Orbit Satellite Operations, with Mitigation Strategies

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**Abstract.** Geomagnetic storms affect power system stability, wireless communication and navigation, and low-Earth-orbit satellite operation via magnetosphere-ionosphere-thermosphere coupling. This paper has selected three representative works and systematically compared their research objects, data sources, model construction methods, main results and countermeasures in this study. Geomagnetically induced currents increase transformer reactive power losses and reduce small-signal damping; ionospheric electron density and irregularities cause radio attenuation, scintillation and GNSS positioning errors; and an elevated thermospheric density leads to increased satellite drag and orbital decay. The three studies have recommended optimising neutral-point blocking devices, building frequency-band-specific monitoring and early warning systems, and adding neutral-density forecasting, respectively. These ways are only suitable for small-scale regional samples. They are lack of standardised quantitative indicators, and they have not been widely verified by now. Therefore, this paper proposes the integration of multi-regional observations, standardised evaluation indicators and real-time data assimilation to improve the operational feasibility of geomagnetic storm risk assessment and early warning.

**Keywords:** geomagnetic storms; geomagnetically induced currents; wireless communication and navigation; low-Earth-orbit satellites.

## 1. Introduction

Changes in the magnetosphere, ionosphere and thermosphere due to solar activity will have different impacts on ground-based and near-Earth orbit technological systems. According to the Space Weather Roadmap of the world, infrastructure is increasingly vulnerable to disturbances; therefore, all areas need to strengthen observation and forecasting [1]. Recently, 29 magnetometers were employed in Northern Europe to map geoelectric fields and, in conjunction with measured GICs, the risk assessment results were verified [2]. Time-varying geomagnetic fields induce geoelectric fields via Faraday's law in power grids and drive geomagnetically induced currents (GICs) in transformers. Earlier studies have included stability modelling, reliability standards and subsurface conductivity structures [3]–[6].

Research in Communications and Navigation primarily studies the effects of ionospheric electron density, absorption, scintillation, etc., on HF, VHF, L-band, GNSS and other frequencies, as well as mitigation measures such as monitoring, integrity assessment and augmentation systems [7][8]. Research on low-Earth-orbiting satellites has focused on orbital decay caused by an increase in neutral density and atmospheric drag due to heating of the thermosphere during geomagnetic storms. In 2022, the loss of Starlink satellites led researchers to compare empirical models, physics-based models and satellite drag data [9][10]. The three regions for study use different data, indicators and verification methods, so their results cannot be directly incorporated into a unified risk management system.

Three representative studies are selected in this paper to compare the effects of geomagnetic storms on power grids, communications and navigation, and low-Earth-orbit satellites, along with their corresponding mitigation measures. First, it presents the research questions, data, models and results of each study; second, it analyzes the limitations of regional representativeness, quantification methods and empirical validation; finally, it puts forward recommendations such as multi-source

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observation, unified metrics and real-time data assimilation. By considering the three impact paths at the same time, this paper will determine the scope of current mitigation measures and provide a foundation for space weather risk assessment in power-grid dispatch, communication support and satellite missions.

## 2. Research on the Impacts of Geomagnetic Storms on Technological Systems

### 2.1. Impacts of Geomagnetic Storms on Small-Signal Stability in Power Systems

Si et al. have studied the impact of geomagnetically induced currents on small-signal stability in power systems and proposed a way to optimise blocking devices. Fig. 1 shows the mechanism and results [3]. The study treated transformer reactive power losses as nodal loads and, by integrating power-flow analysis, eigenvalue analysis and geomagnetic storm data from 1989 to 2018, constructed a fuzzy model. Mengdong Power Grid was selected as the case study, and then sensitivity analysis, principal component analysis, K-means clustering and a genetic algorithm were used to determine device locations. The joint-sensitivity scheme reduced reactive power losses from 4383.96 Mvar to 1084.36 Mvar and the risk index from 0.86 to 0.34, it can be seen that this method enhances damping and reduces the number of devices required.

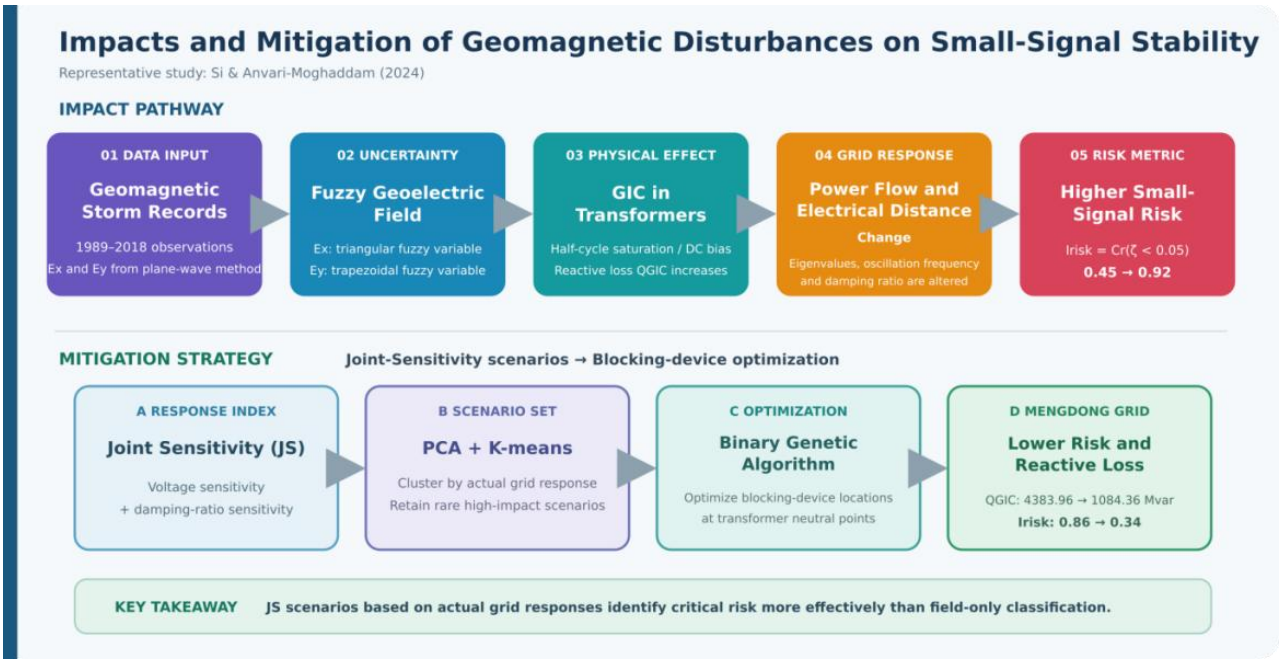


**Fig. 1** Effects of geomagnetic disturbances on small-signal stability in power systems and the mitigation process. ( Picture credit : Original)

### 2.2. Impacts of Space Weather on Radio Communications and Navigation

Ishii et al. have established a space weather drivers-ionospheric responses-signal impacts framework to compare the effects of solar flares, polar cap absorption, ionospheric storms and plasma bubbles on HF, VHF, L-band and GNSS signals [7].The study categorizes the disturbances based on the affected area, duration and forecast lead time, and lists countermeasures such as receiver parameter adjustment, integrity monitoring and satellite-or ground-based augmentation, as shown in Fig. 2. According to the above study, these disturbances have different spatial and temporal scales and respond differently to different frequencies. Existing methods can reduce only some propagation errors, while forecasting remains limited by the ionosphere's non-stationarity and insufficient observations.

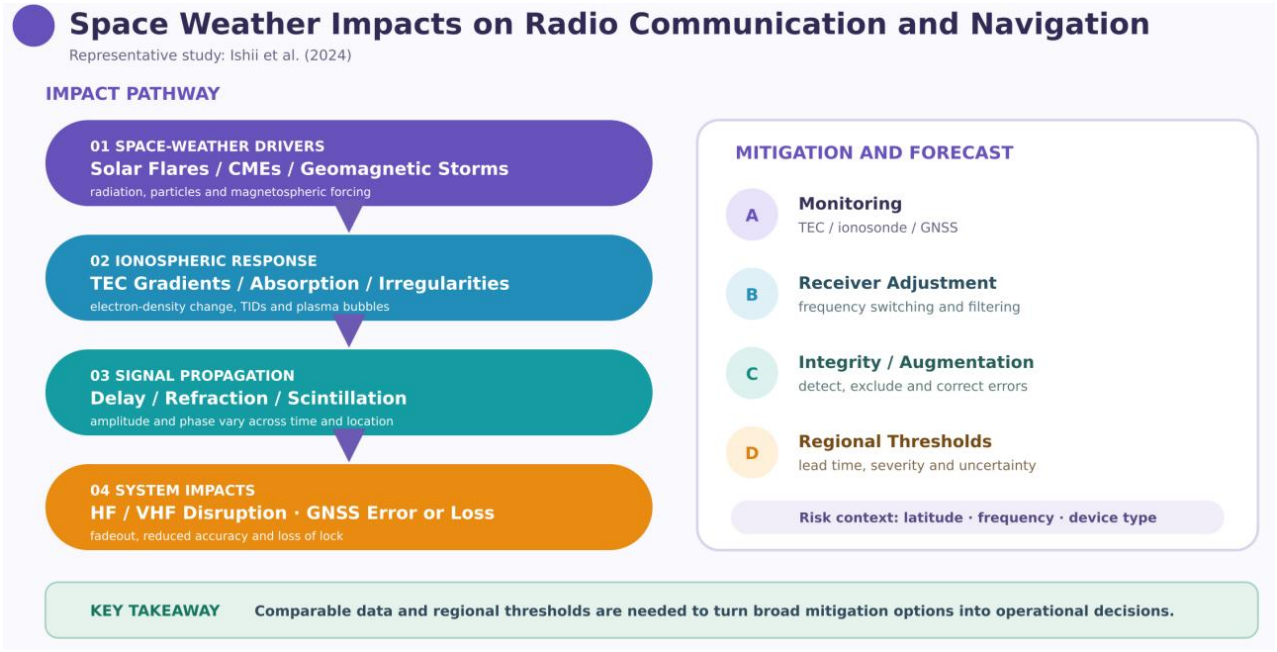


**Fig. 2** Pathways through which space weather affects radio communications and navigation, and the mitigation framework.( Picture credit : Original)

### 2.3. Impacts of Geomagnetic Storms on Low-Earth-Orbit Satellite Operations

Fang et al. used SpaceX's loss of 38 Starlink satellites in 2022 as a case study. Combine NOAA solar wind and geomagnetic observations, SpaceX orbital data and WAM-IPE numerical simulations to estimate the along-track neutral atmospheric density [9]. Fig. 3 is the event chain. As shown in the figure, two consecutive Kp = 5 geomagnetic storms increased the density by about 50%–125% at altitudes of 200–400 km. The NRLMSISE-00 empirical model used before launch did not fully account for the disturbance, and WAM-IPE was more consistent with the drag proxy data from the surviving satellites. Based on the above results, the study proposes adding neutral-density forecasts to launch and orbit-raising decisions..

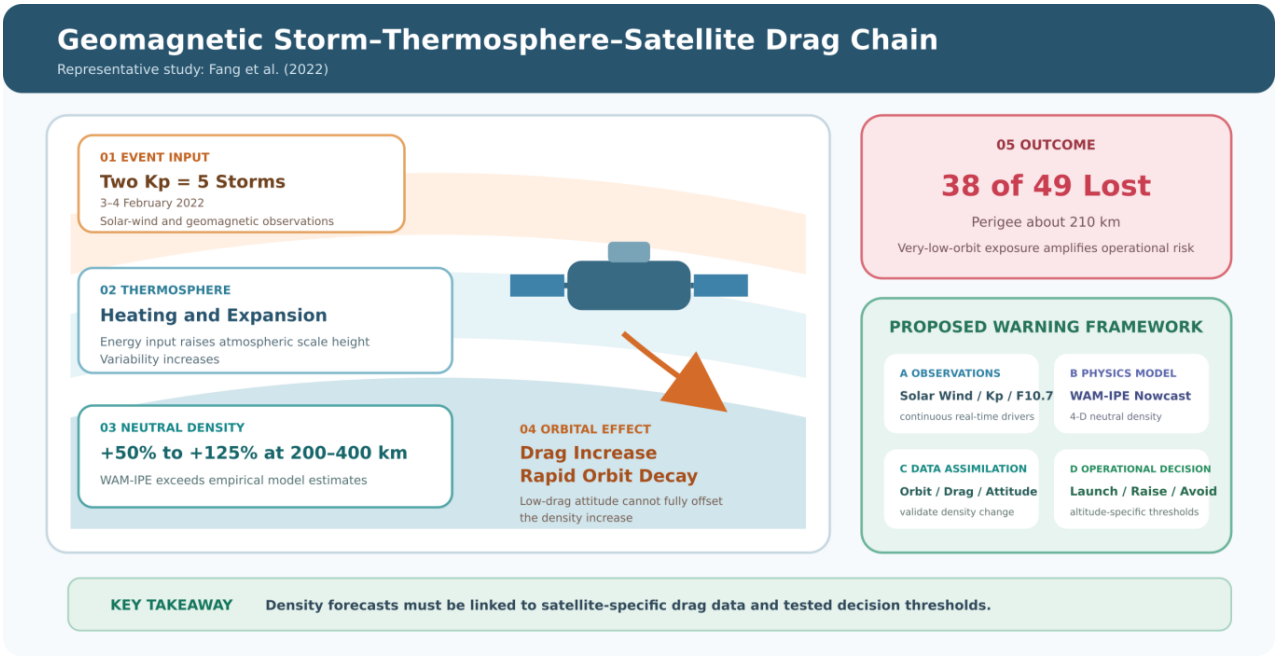


**Fig. 3** Thermospheric density enhancement, increased satellite drag, and the early-warning process under geomagnetic storms. ( Picture credit : Original)

## 3. Analysis of Limitations and Recommendations for Improvement

The three studies have different data and validation methods, and their main problems are the representativeness of the area, quantitative indicators and empirical verification. Table 1 shows the deficiencies of each study and the corresponding paths for correction.

**Table 1.** Main limitations of the three representative studies and recommendations for improvement

| Research area | Main limitations | Recommendations for improvement |
|---|---|---|
| Power systems | Based only on the Mengdong power grid and observations from a single geomagnetic station, the plane-wave and linear small-signal models simplify spatial variations in the geoelectric field and large-disturbance processes, and the effectiveness of blocking devices has been validated mainly through simulated samples.. | Expand case studies to different latitudes, subsurface conductivity structures, and grid topologies; incorporate transformer thermal effects and transient processes; and use historical events and field data from installed devices to evaluate risk reduction and cost. |
| Communication and navigation | Cases from different regions, events and frequency bands are discussed side by side, but errors across systems are not compared using a consistent method during the same geomagnetic storm; there are no common metrics for impact magnitude, duration and early-warning thresholds. | Collect TEC, signal strength, GNSS positioning errors and loss-of-lock rates for the same event simultaneously; establish unified metrics by latitude and frequency band; and compare the measured effectiveness and cost of mitigation methods.. |
| Low-Earth-orbit satellites | The conclusions are based mainly on a single event and a low initial orbit of about 210 km; only drag proxies from 11 surviving satellites are used for comparison, and no absolute density observations from the lost satellites or validation of the warning method have been conducted.. | Expand samples across events, orbital altitudes, and satellite configurations; combine accelerometer, orbit, and attitude data to estimate density; and use historical event replay to test lead time, hit rate, and false-alarm rate. |

## 4. Conclusion

This paper takes three representative studies as cases, and based on their research questions, data, models and results, examines how geomagnetic storms affect power grids, communications and navigation, and low-Earth-orbit satellites, and assesses the deficiencies in the current mitigation measures.

The three conclusions of this paper are: Geomagnetically induced currents increase transformer reactive power losses and reduce small-signal damping; Ionospheric electron density and irregularities cause radio absorption, scintillation and GNSS positioning errors; and enhanced thermospheric density increases satellite drag and accelerates orbital decay. Although the blocking device, receiver and augmentation system have been optimized and neutral-density forecasts have improved, the risk reduction effect is limited by regional conditions, model inputs and validation samples.

Therefore, the following research will construct a multi-regional, multi-event observation database, standardize metrics for impact intensity and early-warning efficiency, and integrate real-time geomagnetic, ionospheric and satellite orbit data into physics-based models. Only after meeting the criteria for thresholds, lead times and false-alarm rates will the research results be used to support power-grid dispatch, communications support and satellite launch decisions reliably.

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