

# SPACE-WEATHER EFFECTS ON CRITICAL INFRASTRUCTURE ON EARTH

■ Sven Wedemeyer<sup>1</sup>, Magnar Gullikstad Johnsen<sup>2</sup>,  
Patrick Antolin<sup>3</sup>, Jonathan Rae<sup>3</sup> and Stefaan Poedts<sup>4</sup>

■ <sup>1</sup>Roseland Centre for Solar Physics, University of Oslo, PO Box 1029, Blindern 0315 Oslo, Norway

■ <sup>2</sup>Tromsø Geophysical Observatory, UiT the Arctic University of Norway, 9037 Tromsø, Norway

■ <sup>3</sup>Northumbria University, Ellison Place Newcastle upon Tyne, NE1 8ST, UK

■ <sup>4</sup>Centrum voor mathematische Plasma-Astrofysica, Departement Wiskunde,  
Celestijnenlaan 200 B, 3001 Leuven, Belgium // UMCS, Lublin, Poland

■ DOI: <https://doi.org/10.1051/epn/2025511>

Space weather refers to both the dynamic conditions in interplanetary space driven by the Sun and its subsequent impact on the near-Earth environment. Space weather can disrupt or destroy ground- and space-based infrastructure. Although not fully understood, its significance is growing rapidly with our increasing dependence on modern technology.

FIG. 1: The Northern Lights or Aurora Borealis pictured over a transformer station in Scandinavia (Credit: AI generated image, diffus.me)

### The solar origins of space weather

The Sun – our dynamic life-giving host star – is shaped by the interplay between the plasma and magnetic fields that continuously emerge from the solar interior. Its atmosphere is a source of both continuous outflowing plasma — the solar wind — and explosive transient events such as solar flares and coronal mass ejections (CMEs). These phenomena are central drivers of space weather [1].

Solar flares – sudden releases of energy triggered by the sudden, explosive reconfiguration of the Sun’s complex magnetic field – result in the rapid acceleration of particles and the emission of electromagnetic radiation, spanning from radio waves to X-rays and gamma rays. The X-ray and ultraviolet radiation can reach Earth within minutes, disturbing the ionosphere and affecting communication and navigation systems.

CMEs are vast eruptions of magnetised plasma, carrying billions of tons of material into space. When directed toward Earth, a CME can interact with our planet’s magnetosphere, driving geomagnetic storms, which, depending on the CME’s orientation, are the most impactful manifestations of space weather.

Alongside flares and CMEs, high-energy solar energetic particles (SEPs) represent another threat. As recently highlighted by ESA’s Solar Orbiter, SEPs can be produced by flares, reaching Earth within tens of minutes, but also in CME shocks while propagating towards Earth. SEPs pose hazards to astronauts, satellites, communication, and even aviation at high latitudes.

### Impacts on critical infrastructure

Modern society relies heavily on ground- and space-based infrastructure sensitive to space-weather effects (Fig. 2). Satellites and space-based assets are directly exposed. Enhanced radiation during solar storms can damage electronic components, degrade solar panels, and increase satellite drag in low-Earth orbit through heating and expansion of the upper atmosphere, as illustrated by the near total loss of a Starlink satellite batch in 2022 [2,3], would disrupt services ranging from GNSS (Global Navigation Satellite System) positioning (better known as GPS), navigation, and timing to Earth observation and global communications. Polar flight routes, commonly used for long-distance travel, are also vulnerable: solar storms disrupt high-frequency radio communication and increase radiation exposure for crews. Communication and navigation systems are primarily affected by ionospheric and geomagnetic disturbances caused by interactions of the solar wind with the magnetosphere-ionosphere system. GNSS signal degradation impacts sectors relying on precise positioning—aviation, shipping, agriculture, and autonomous vehicles—as well as those dependent on accurate timing, such as financial markets and railway systems.

Energy infrastructure is particularly at risk. Strong and varying ionospheric currents that occur during geomagnetic storms induce electric fields in the Earth’s crust. These electric fields drive so-called geomagnetically induced currents ●●●

IN THE ART OF MAKING LASERS



**Ampheia.**

**Ultra-low Noise Fiber Amplifiers.**



**C-WAVE.**

**Tunable Lasers.**



**Cobolt.**

**Single & Multi-line Lasers.**



**C-FLEX.**

**Laser Combiners.**



**VALO.**

**Femtosecond Lasers.**

#### High performance – concretely speaking

CW to fs lasers for advanced imaging, detection and analysis. HÜBNER Photonics offers a full range of high performance lasers including single and multi-line Cobolt lasers, widely tunable C-WAVE lasers, C-FLEX laser combiners, VALO femtosecond fiber lasers and Ampheia ultra-low noise fiber amplifiers.



●●● (GICs) [4] through power grids, pipelines, and railway systems via their groundings (Fig. 3). In extreme cases, GICs can damage transformers and trigger large-scale blackouts. The March 1989 geomagnetic storm caused the collapse of the Quebec power grid, while in November 2003, a large area around Malmö in Southern Sweden lost electricity for several hours owing to a geomagnetic storm. Such severe space weather poses a critical risk to Critical National Infrastructure; listed as a medium likelihood, significant risk in the UK National Risk Register<sup>1</sup> alongside risks such as emerging disease outbreaks and other major natural disasters. Several studies have estimated the economic losses of a severe space weather event to be several trillion dollars [5-7; Lloyds of London<sup>2</sup>].

Even moderate but frequent space-weather events collectively amount to a substantial impact. Over the last 10 years, power grid operators in Scandinavia have experienced transformer tripping at least nine times due to moderate or strong space weather. Such events highlight the vulnerability of power systems and their potential

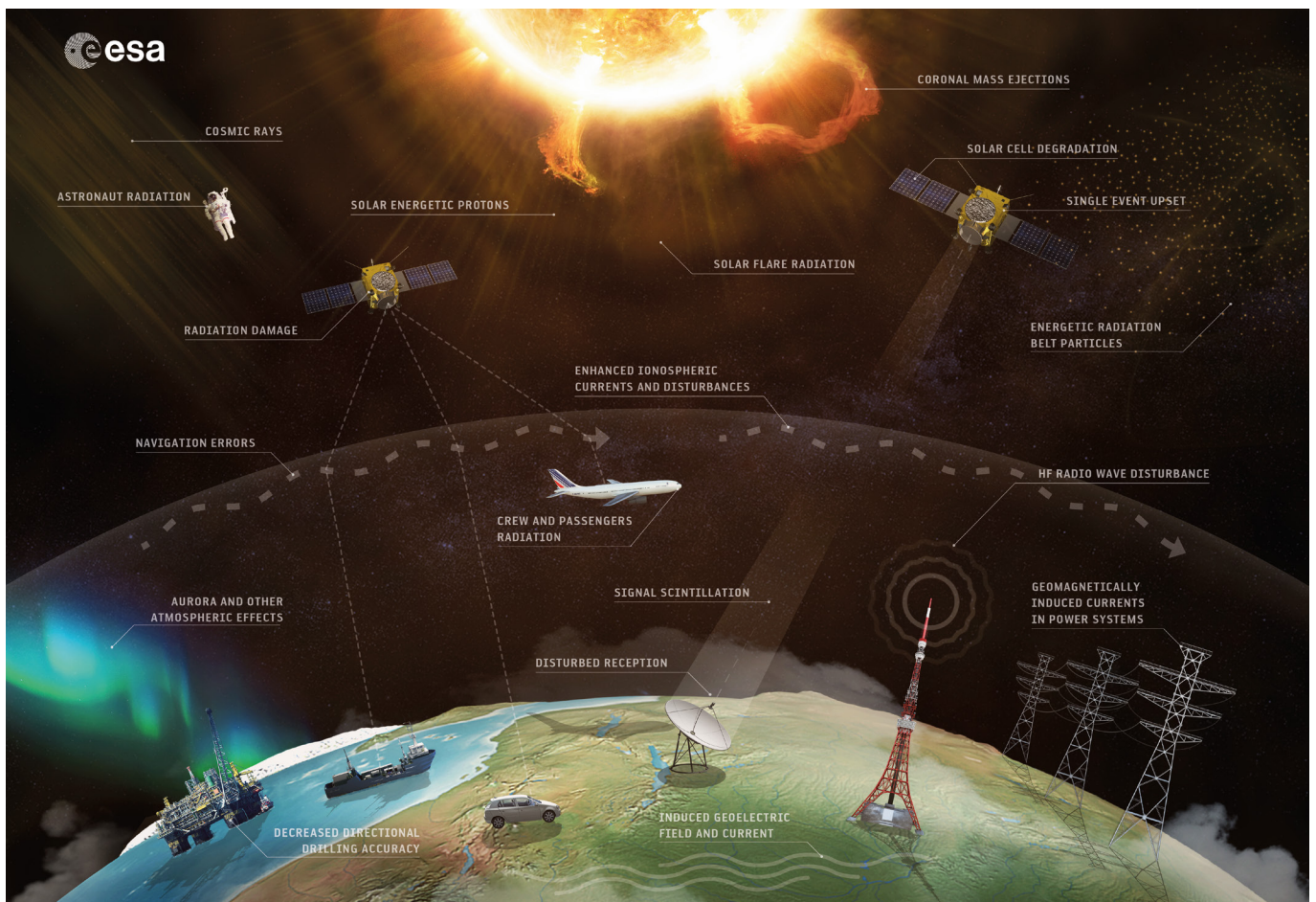
for cascading effects on society. Although not caused by space weather, a transformer fire in March 2025, which grounded all planes out of Heathrow, and the April 2025 blackout on the Iberian peninsula, illustrate the potential impact that severe space weather might have on a modern society. As we evolve as a society, so does our technology, and little is known about the vulnerability of emerging technologies to space weather hazards<sup>3</sup>, such as space-based solar power, the Internet of Things, quantum technologies and nanoscale chips.

### Energy systems as a critical vulnerability

Energy infrastructure – as the backbone of modern society – is highly exposed to space weather. The impact of GICs on power systems depends on geomagnetic latitude, geology, and grid design. High-voltage transformers are particularly vulnerable, as sustained GICs can cause overheating and lead to irreversible failure. Most modern transformers have safety systems that trip them before damage occurs, but this can still lead to cascading grid failures and regional blackouts [8-9].

The energy sector is increasingly aware of these risks. Many operators now monitor geomagnetic activity and apply mitigation strategies, such as load reduction or grid reconfiguration, during storms [10]. Despite these efforts, vulnerability remains. A storm comparable to the

▼ FIG. 2: Space weather events due to solar flares and CMEs release radiation, high-energy particles that disturb Earth's magnetosphere and drive geomagnetic storms. These storms induce ground currents that threaten power grids, with past events causing blackouts in Québec (1989), transformer damage in New Zealand (2021), and tripping in Sweden (2023). Europe's interconnected grids are particularly vulnerable. Beyond power systems, space weather also affects satellites, navigation, aviation, and human spaceflight. (Credit: ESA/Science Office).



1859 Carrington Event could cause widespread, long-lasting power disruptions across continents, resulting in costs of up to \$2.7 trillion (16% of EU GDP) [7].

Pipelines are also affected by GICs, which accelerate corrosion and shorten their lifespan—a slower but significant long-term impact of space weather.

### Forecasting space weather: current status and challenges

Accurate and timely forecasts are crucial for mitigation, but major challenges remain in understanding the sources of space weather. The mechanisms driving flares, CMEs, and the solar wind involve complex interactions of magnetic fields and plasma across wide spatial and temporal scales, down to how magnetic fields reconfigure, release energy, and accelerate particles. While the solar wind shapes the interplanetary medium through which CMEs travel, limited knowledge of its properties leads to uncertainties of  $\pm 16$  hours in CME arrival times at Earth, undermining forecast reliability. Predicting CME impact and magnetic configuration is particularly difficult, since geoeffectiveness depends largely on magnetic structure, which can only be measured near Earth, leaving warning times short.

Forecasting space weather requires a deeper understanding of its solar origins, particularly CME initiation and propagation, the complex, nonlinear coupling of the solar wind with Earth's magnetosphere and ionosphere/thermosphere. Geomagnetic indices, such as Kp and Dst, provide broad measures of activity, but translating these into actionable infrastructure warnings remains a significant challenge. Progress depends on combining advanced models with dense local and continental sensor networks to monitor geomagnetic storms and assimilate data into larger geospace models.

### Prospects for improved forecasting

Ongoing and future efforts hold promise for advancing space-weather forecasting. Ground-based networks of research infrastructure sensors, such as GNSS receivers, neutron monitors, atmospheric radars, magnetometers, solar radio burst monitors, and solar telescopes, are being enhanced and expanded to serve as monitoring infrastructure, thereby increasing our space weather situational awareness. A key avenue is the launch of new space missions to monitor the Sun, interplanetary space, and near-Earth space. Future missions at strategic vantage points, such as ESA's Vigil mission, would allow continuous monitoring of solar activity on the far side of the Sun and provide earlier warnings of Earth-directed eruptions. Other magnetospheric mission ●●●

<sup>1</sup> <https://www.gov.uk/government/publications/national-risk-register-2025>

<sup>2</sup> <https://www.lloyds.com/insights/futureset/futureset-insights/systemic-risk-scenarios/extreme-space-weather/economic-impact>

<sup>3</sup> <https://doi.org/10.25398/rd.northumbria.29594696.v1>

## Efficient Leak-Testing with VD810 Compact Vacuum Meters

Leak testing plays a vital role across scientific and industrial domains—from aerospace engineering to vacuum systems in laboratories. It enables early detection of defects and supports continuous quality assurance during both research and production.



### Precision Measurement with Modern Vacuum Meters

Modern leak-testing equipment, such as compact vacuum meters, allows for high-precision measurement and documentation. The Thyracont VD810 compact vacuum meter is a prime example

of how advanced sensor technology supports this essential task.

The VD810 reliably measures absolute and relative pressure in the rough vacuum range from 2000 to 1 mbar (abs.) and -1060 to +1200 mbar (rel.). Its chemically resistant piezo-ceramic sensor with FKM sealing is resistant to contamination, making it ideal for demanding industrial or laboratory conditions.

### Smart, Intuitive Operation

The VD810 is designed for both precision and ease of use. Its intuitive membrane keypad and menu-guided interface simplify operation, while the integrated data logger records multiple measurement series with real-time clock timestamps. Data can be easily transferred to PCs or tablets via USB-C or optional Bluetooth® LE. An intelligent energy management system extends battery life, with convenient charging via USB-C on a PC or standard USB power adapters.

### Reliable Quality Assurance

The VD810 compact vacuum meter achieves reliable and efficient leak testing — ensuring highest quality standards in industry and research. ■

### For more information, contact:

Thyracont Vacuum Instruments  
<https://thyracont-vacuum.com/en>  
 Phone: +49 851 95986-0

●●● concepts, such as the ESA SWORD mission, are still in earlier stages. Ground-based measurements of GICs are sporadic, but they are increasingly being installed on power networks worldwide.

Advances in numerical modelling are equally important. More sophisticated models, combined with data assimilation techniques, aim to improve flare eruption and CME propagation forecasts in this coupled system, as well as predict the response of the radiation and ionosphere-thermosphere to such space weather drivers, and the ground impacts of these drivers. Machine learning is increasingly used to recognise patterns in solar data, predict flare probabilities and their consequences in Earth's system. Integrating these methods with traditional physics-based models could lead to more robust and reliable forecasts.

Improving forecasting also requires closer engagement with stakeholders. Effective space-weather services must be tailored to the specific needs of end-users, such as power grid operators, airlines, satellite operators and companies. This requires interdisciplinary collaboration between scientists, engineers, industry, and policymakers.

### Outlook

Space weather is a growing concern for modern society, as critical infrastructures become increasingly interconnected and technologically dependent. Solar flares, CMEs, and SEPs drive impacts across satellite operations, aviation, communication, navigation, and, in particular, energy infrastructure. Power grids and pipelines are highly vulnerable to geomagnetically induced currents, making energy systems a central concern for preparedness.

Despite advances in observing and modelling solar, heliospheric, and geophysical activity, major challenges remain in forecasting the timing, magnitude, and geoeffectiveness of solar events and their coupling to the magnetosphere-ionosphere-ground system. Progress will require improved solar monitoring, modelling, and interdisciplinary collaboration. With growing awareness, international efforts, emerging technologies, and Artificial Intelligence, there is cautious optimism that space-weather forecasting will become a reliable tool to protect society from the Sun's technological impacts. ■

### About the Authors



**Sven Wedemeyer:** Full professor at the University of Oslo, Norway, councillor of the European Astronomical Society (EAS), studying the Sun's atmosphere and sources of space weather.

**Magnar Gullikstad Johnsen:** Leader of Tromsø Geophysical Observatory and the Norwegian Center for Space Weather at UiT the Arctic University of Norway, expert on geomagnetism, auroral physics, and space weather.

**Patrick Antolin:** Associate Professor at Northumbria University, President of the European Solar Physics Division of the EPS, expert on the solar atmosphere.

**Jonathan Rae:** Professor in Space Plasma Physics at Northumbria University, expert in auroral physics, geomagnetic storms, the Van Allen Radiation Belts, and their space weather impacts.

**Stefaan Poedts:** Full Professor at KU Leuven // UMCS, Lublin, Poland, President of the European Space Weather and Space Climate Association, expert in Space Weather, Solar Physics and Astrophysics.

### References

- [1] *E-SWAN: Space Weather and Space Climate - A timeline*. ISBN(ebook): 978-2-7598-3611-6 DOI: 10.1051/978-2-7598-3610- (2024)
- [2] T. Berger *et al.* 2023. *Space Weather*, 21, e2022SW003330 doi.org/10.1029/2022SW003330 (2023)
- [3] W. Parker and R. Linares, *Journal of Spacecraft and Rockets* **61:5**, 1412 (2024), doi.org/10.2514/1.A36164
- [4] A. Pulkkinen *et al.*, *Space Weather* **15**, 828 (2017), doi:10.1002/2016SW001501
- [5] M. Allcock *et al.* (2025). doi.org/10.25398/rd.northumbria.29594696.v1
- [6] H. den Baeumen *et al.*, *Natural Hazards and Earth System Sciences* **14(10)**, 2749 (2014)
- [7] J. Eastwood *et al.*, *Risk Analysis* **37**, 2 (2017), DOI: 10.1111/risa.12765
- [8] D. Boteler, *Space Weather* **17**, 1427 (2019) doi.org/10.1029/2019SW002278
- [9] L. Bolduc, 2002. *Journal of Atmospheric and Solar-Terrestrial Physics* **64**, (1793) doi.org/10.1016/S1364-6826(02)00128-1
- [10] D. Mac Manus *et al.*, *SpaceWeather* **21**(2023) e2023SW003533 doi.org/10.1029/2023SW003533

► FIG. 3:

Measured GICs and geomagnetic field in mid-Norway during the 3 November 2021 storm: the transformer neutral current (red) ideally should be zero but peaked near 60 A around 21:40 UT, coinciding with a nearby transformer trip. The ~1000 nT geomagnetic variation (green), a rare event, highlights the storm's intensity and strong ionospheric currents. (Credit: SINTEF Energy Research and Dr. Kristian Solheim Thinn.)

