When the Space Weather Threat Becomes Reality

In May 2024, Earth found itself in the path of the most powerful solar storm to head in our direction for over 20 years. Although the Gannon Storm didn't cause any major power outages or other serious incidents, over time reports surfaced of a diverse range of impacts. Taken together, these underscore the importance of the many space weather activities currently underway globally, from studying the Sun to mitigation planning. OpenSpace spoke to Simon Machin from the Met Office and Alexi Glover from the European Space Agency to find out the current state of space weather activities.

The phenomena that we collectively refer to as 'space weather' are not new. The Sun has been emitting solar flares, radiation storms and coronal mass ejections (CMEs), and causing geomagnetic storms and other disturbances, for billions of years, as far as we can tell. However, the effects of these phenomena didn't matter to most people until the digital age, when we became increasingly reliant on power and communications networks, and services provided by satellites such as positioning, navigation and timing (PNT).

The first 'major' recorded impact on technology was in 1859 due to what is known as the Carrington Event – this is the most powerful solar storm to impact Earth on record. Geomagnetically induced currents caused telegraph operators to receive shocks and continental telegraph lines were destroyed by fires. In the 20th century, solar storms had varying levels of impact, including a geomagnetic storm in 1989 that caused communications blackouts, a major power outage in Quebec, Canada, and the loss of positional knowledge for over 1,000 space objects for nearly a week. But the intensity of the Sun's activity rises and falls across an 11-year cycle, and not every 'peak' sees a notable event on Earth. As a result, even after the 1989 storm, concern around space weather waned once more.

In the end, it took the Halloween storms of 2003 to emphasise just how serious the impacts of space weather could be. As a consequence of multiple flares and CMEs, many satellites experienced anomalies, with anecdotal evidence suggesting that the majority of satellites in low Earth orbit (LEO) were temporarily 'lost' as their positions altered and had to be reestablished; there was also one total loss and 10 cases of loss of operational service for more than a day.[1, 2] Aircraft flights were diverted away from the poles to lower latitudes to avoid radiation, there was a power outage in Sweden and GPS systems were seriously affected, including those used for deep-sea and land drilling, and surveying.[3, 4]

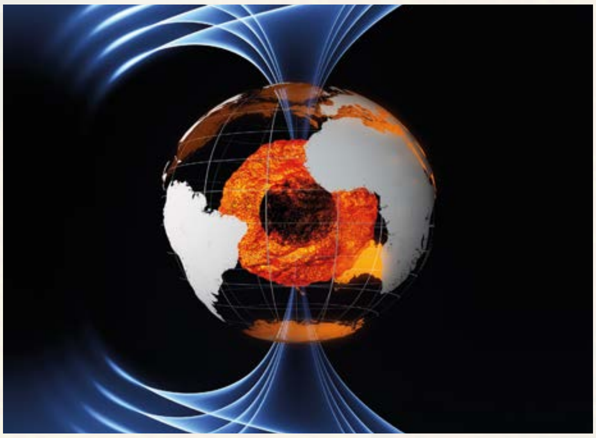
Since then, organisations around the world have set up or enhanced programmes to gather related data in space and on land, and to study the Sun and the effects of its behaviour. The ultimate goal is to create a space weather forecasting system analogous to the terrestrial weather forecasts we now take for granted. In the meantime, we need to continue to improve our ability to mitigate the effects of space weather events.

What's the problem?

Space weather describes the interaction of phenomena caused by solar activity with the Earth's magnetosphere, atmosphere and ground, and with technology and engineered systems, such as satellites, aircraft, power cables and electronic systems. Each of the phenomena can cause different impacts, including loss of radio signals caused by solar flares, power outages due to geomagnetic storms emanating from CMEs, and disruption to satellite operations from radiation storms.

There are too many potential impacts of space weather events and mitigating actions to describe in a single article – a report published earlier this year on Severe Space Weather Impacts on UK Critical National Infrastructure, led by Starion as part of the UK's Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) project, runs to over 100 pages. Lloyd's, the insurance marketplace, estimates that the global economy could be exposed to losses of US$2.4 trillion over a 5-year period – or up to US$9.1 trillion in the most extreme scenario – from the threat of a hypothetical solar storm.[5]

As a result, there are many projects assessing the threats to space-, ground-, sea- and air-based infrastructures and systems, and potential mitigations. In the European Union (EU), the EU Space Programme's Space Situational Awareness component includes a Space Weather Events (SWE) subcomponent. In March 2025, the Commission adopted its 'Implementing Decision' for the selection of a space weather service under SWE. The UK Government has been particularly active with the SWIMMR programme, given that the UK is further north than many other European countries and therefore more at risk in terms of ground- and sea-based systems.



Earth's magnetic field. Image © ESA/AOES Medialab

Meanwhile, the European Space Agency (ESA) is actively engaged in a broad range of space weather projects and activities. "Space weather has the ability to impact a large number of technologies and systems that form part of our everyday lives, and many aspects of our critical infrastructure," says Alexi Glover, ESA Space Weather Service Coordinator. "Our Space Safety Programme is developing new sources of data and service capabilities geared towards increasing the resilience of our society to space weather impacts."

ESA's projects include the development of the Space Weather Payload Data Centre (SWE PDC), which is being led by Starion. Alexi Glover explains: "The new PDC in development is intended to be a flexible and scalable system carrying out Level-1 data processing for ESA's space weather hosted payload missions and beyond. In future, the PDC will also support further elements of the Distributed Space Weather Sensor System [D3S] under development, plus the Vigil mission due to launch in 2031.

"The SWE PDC will make processed Level-1 data available in near real-time to the Space Weather

Service Network for further Level-2/3 data processing into space weather products. The PDC project will also implement the SWE Data Hub capability, replacing and extending the current Space Weather Database [SWEDB] functionality, enabling the storage, retrieval, analysis and visualisation of data in support of space weather services and their users."

The PDC will be scalable, secure (zero trust) and cloud native. With more space weather missions in development, including Vigil and Aurora, it's essential that the ground segment is scalable in order to store, process and disseminate the growing volume of data, and can integrate new data types.

The project will also include the development of enhancements for the current SWE Data System that supports the ESA Space Weather Service Network. This provides an overview of current space weather conditions and a set of domain-specific dashboards for areas such as spacecraft, aviation, pipeline and power systems operation services. The enhancements will support improved user interfaces and will also provide additional tools to facilitate visualisation and access to ESA Space Weather Network data products that are typically hosted at federated sites operated by organisations across the space weather community.

Underpinning infrastructures

One of the key points made by experts is the need to focus on infrastructures that underpin other critical services, with the primary examples being satellites and power grids.

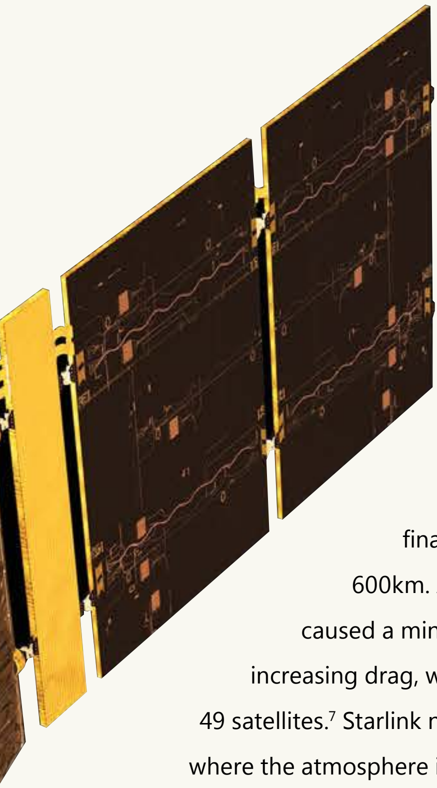
Given our reliance on satellite-based data and services, it's essential to understand the risks satellites face from space weather. One is 'single event effects' caused by ionising radiation damaging onboard electronics. This can be mitigated to an extent by using radiation-tolerant components, shielding and redundancy in the design, but all of these come at a cost.

Another concern is the increased drag caused by solar flares and CMEs temporarily heating Earth's upper atmosphere – something that mainly affects spacecraft in LEO, of which there are now many thousands. Increased drag makes satellites speed up and lose altitude, requiring precious fuel to return them to their operational orbits. Federico Da Dalt, Starion Space Weather Application Scientist, explains: "The planning phases of a satellite mission consider propulsion and fuel consumption as very important factors. Propulsion is fundamental for operations such as spacecraft manoeuvres and orbit raising, which allow the mission

Image © Met Office

“Space weather can affect our ability to accurately track objects in orbit, including debris, which can vary hugely in size.”

Image © Spacecraft: ESA/ATG medialab; Sun: ESA/NASA SOHO to reach its objectives. Failing to consider an increase of solar activity during the planning phases, for example when approaching a period of maximum solar activity, would result in an increase in risks to the operation, such as spacecraft disruptions, unplanned manoeuvres and shortened lifespan. This is particularly important for small satellites in low Earth orbit."



Among the satellites at risk are the thousands of Starlink SmallSats, which operate in LEO and now comprise 65% of all active satellites.[6] In February 2022, 49 Starlink satellites were launched and deployed at an altitude of 210km en route to their final operational altitude of around 600km. A weak CME around that time caused a minor geomagnetic storm, sharply increasing drag, which brought down 38 of the 49 satellites.[7] Starlink now launches to 320km instead, where the atmosphere is thinner, but during a severe geomagnetic storm, satellites at that altitude would still be at risk.

Simon Machin, Meteorologist and Manager of the Met Office Space Weather Programme in the UK, explains the broader problem: "Over the next 5 years, low Earth orbit will become increasingly congested as other mega constellations are launched. If none are affected in any way, that's not a problem. But space weather can affect our ability to accurately track objects in this orbit, including debris, which can vary hugely in size. This is compounded by the fact that increased atmospheric density causes objects to react in different ways depending on their mass, size and shape. In parallel, radar systems can be impacted by space weather, which is an issue because radar is one of the main technologies we use to track satellites. Space weather can also affect communications with satellites at some frequencies, including command and control. Taken together, this reduces confidence in any warnings that are sent to satellite operators."

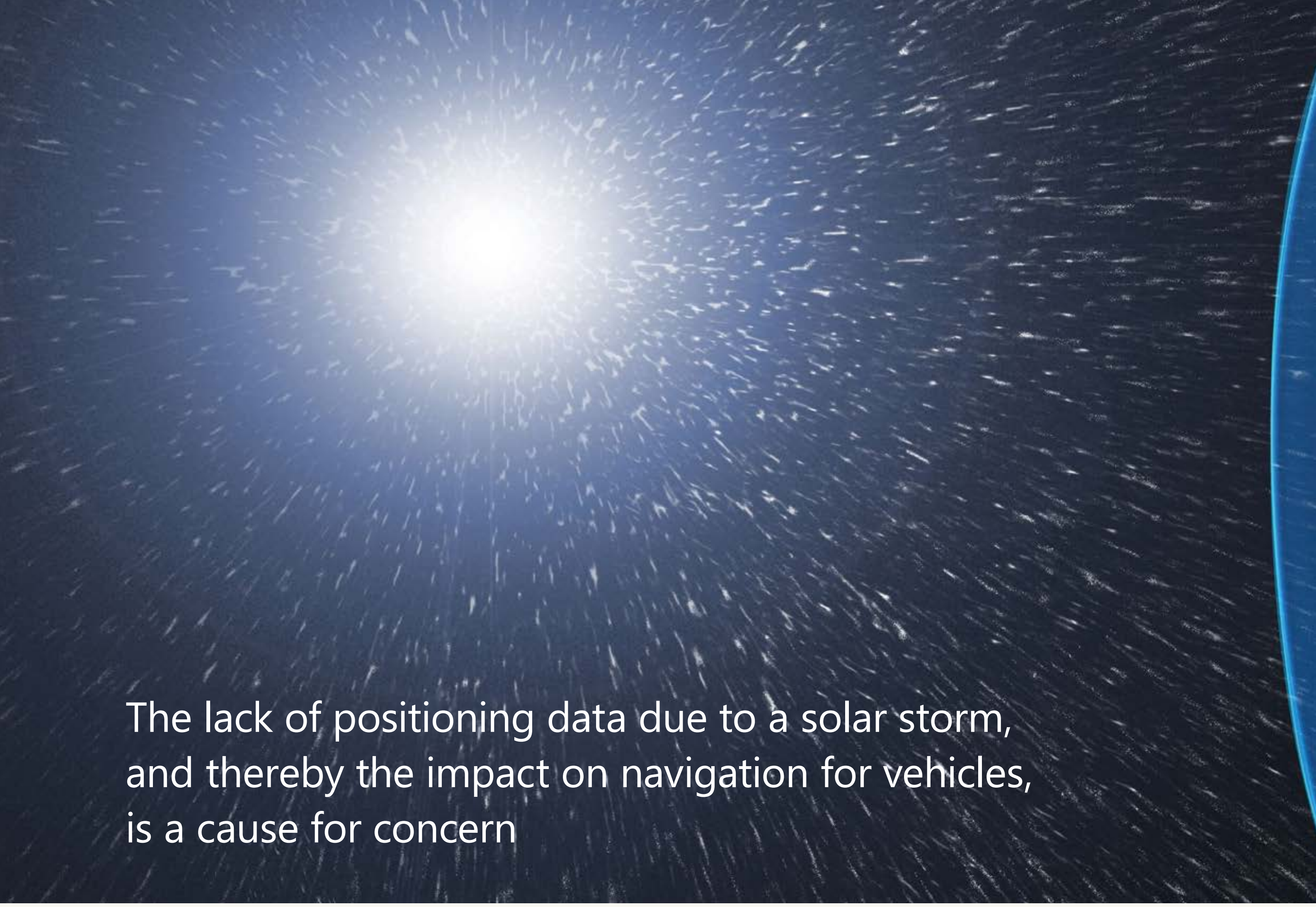
A further concern is the risk presented by multiple satellites all having their positions adjusted simultaneously, without knowledge of how nearby satellites are about to change paths.

Increased drag also increases the risk presented by defunct satellites that can no longer be controlled. Gareth Lawrence, Space Environment Specialist at Starion, describes how serious a problem this is: "It's hard to know exactly where defunct satellites are because they are no longer providing any telemetry and there's not enough radar capacity globally to monitor everything in space more than a fraction of the time. The positions of some old satellites that are thought not to be a risk are only checked very occasionally. But if you suddenly have an extended period of higher atmospheric density due to a space weather event, and therefore greater drag, the orbit of one of those old satellites may fall by tens or even hundreds of metres, so that it's suddenly presenting a new and very serious risk to other satellites."

Why does this matter? "The 2009 collision between an operational American communications satellite and a long-defunct Russian satellite created more than 2,000 new large pieces of space debris that required cataloguing, one of which necessitated a collision avoidance manoeuvre by the International Space Station more than 2 years later in 2011.[8] Since the advent of mega-constellations, the impact of any future collision will be far greater."

Positioning and timing

We rely, directly and indirectly, on satellites for a wide range of services and data, including positioning and



The magnetic field around Earth can be thought of as a huge bubble, protecting us from cosmic radiation and charged particles in solar winds that bombard Earth.

timing from global navigation satellite systems (GNSS). The lack of positioning data due to a solar storm, and thereby the impact on navigation for vehicles on land, at sea and in the air, is an obvious cause for concern. But continuous accurate timing is also vital, being more critical than many realise.

The SWIMMR report (mentioned previously) notes both the energy and communications services are dependent on GNSS timing systems, as are many other sectors, such as financial services and transport.[9] As a result, one of the report's priority recommendations is that in the UK: "Government and relevant policymakers ensure a diversity of position, navigation and timing systems for safety-critical applications in CNI [critical national infrastructure]. In particular, it recommends that GNSS should not be solely relied upon by emergency services, maritime port operations, tracking of trains and aircraft operations." It also recommends that "space-based timing services should not be solely relied upon for … electricity network synchronisation and cellular network synchronisation."

GNSS timing only requires a signal from one satellite, so timing is unlikely to be completely disrupted, and alternative timing solutions do exist, such as crystal oscillators and atomic clocks. (National Grid Electricity Transmission – the UK's national grid transmission asset owner – uses centralised atomic clocks as backup timing during GNSS disruptions.) However, given that long-term disruption can't be completely ruled out, and because the same satellites are used for positioning, for which multiple satellites are required, it is important to consider using multiple satellite systems to provide redundancy and resilience. The SWIMMR report, which is UK-specific, recommends development of national-scale backup PNT systems for fixed and mobile systems.

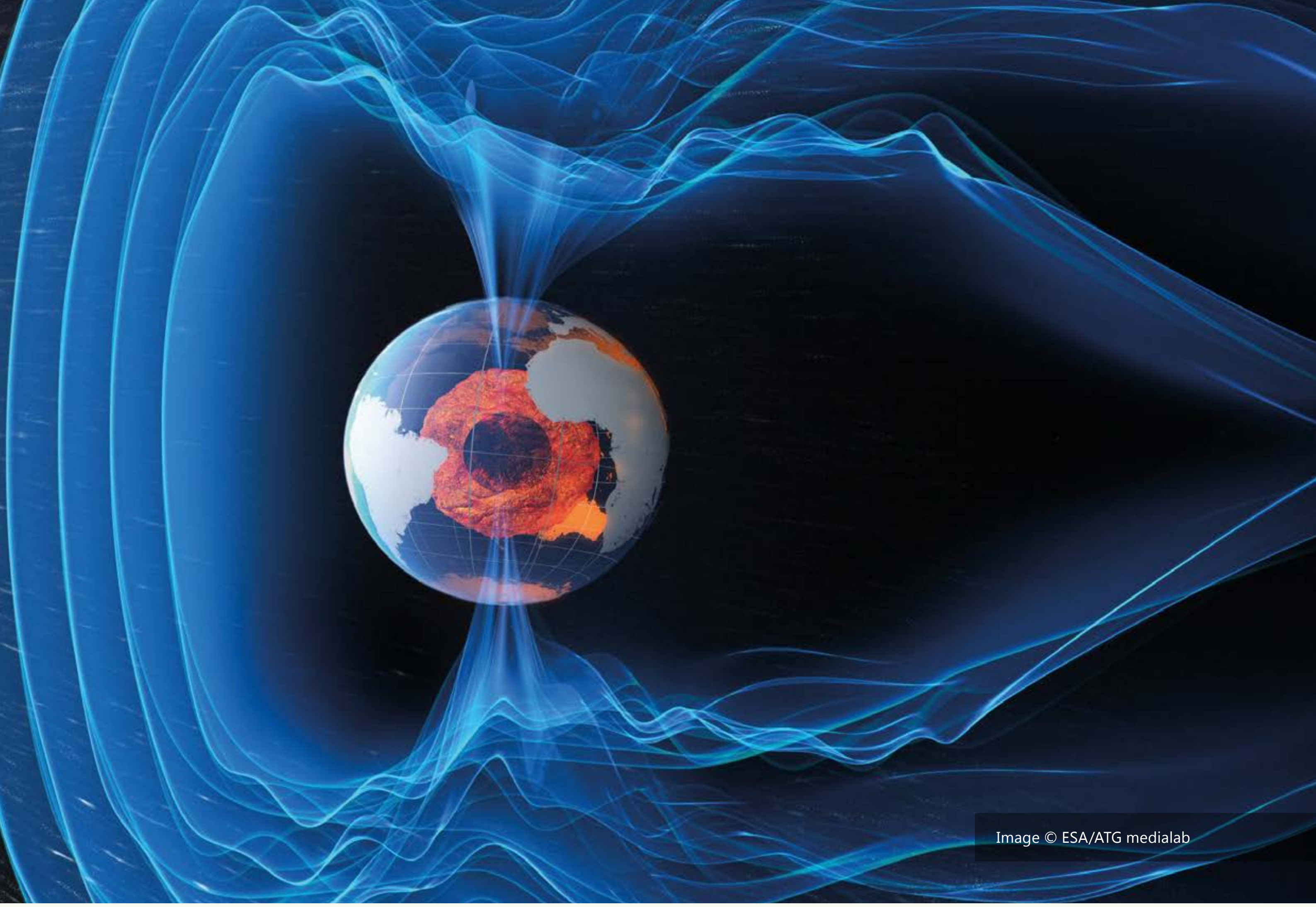


Image © ESA/ATG medialab

Power

Power underpins so many services that it is a primary focus for research into its vulnerabilities and potential mitigations.

Geomagnetic storms can induce powerful direct currents in power lines and other lengthy conductors such as railways and pipelines. These geomagnetically induced currents (GICs) in transmission networks are the most likely impact of space weather on power systems, although there's also the potential for problems caused by single event effects in electronics and dependencies on GNSS and communications systems, which are themselves vulnerable. The interdependencies between the various organisations within the power industry further complicates matters.

Because power is recognised as a vulnerable sector, a lot of related work is going on, both within and for the industry. One project being led by Starion for ESA is EuroGIC, which is focusing on the impact of severe space weather on power grids across Europe, with the aim of enabling electricity grid operators to assess the risk to their transformers and, ultimately, avoid blackouts. EuroGIC will be a web application that will model GICs in power grids, using data from existing geomagnetic sensor networks across Europe and providing information to users in near-real time.

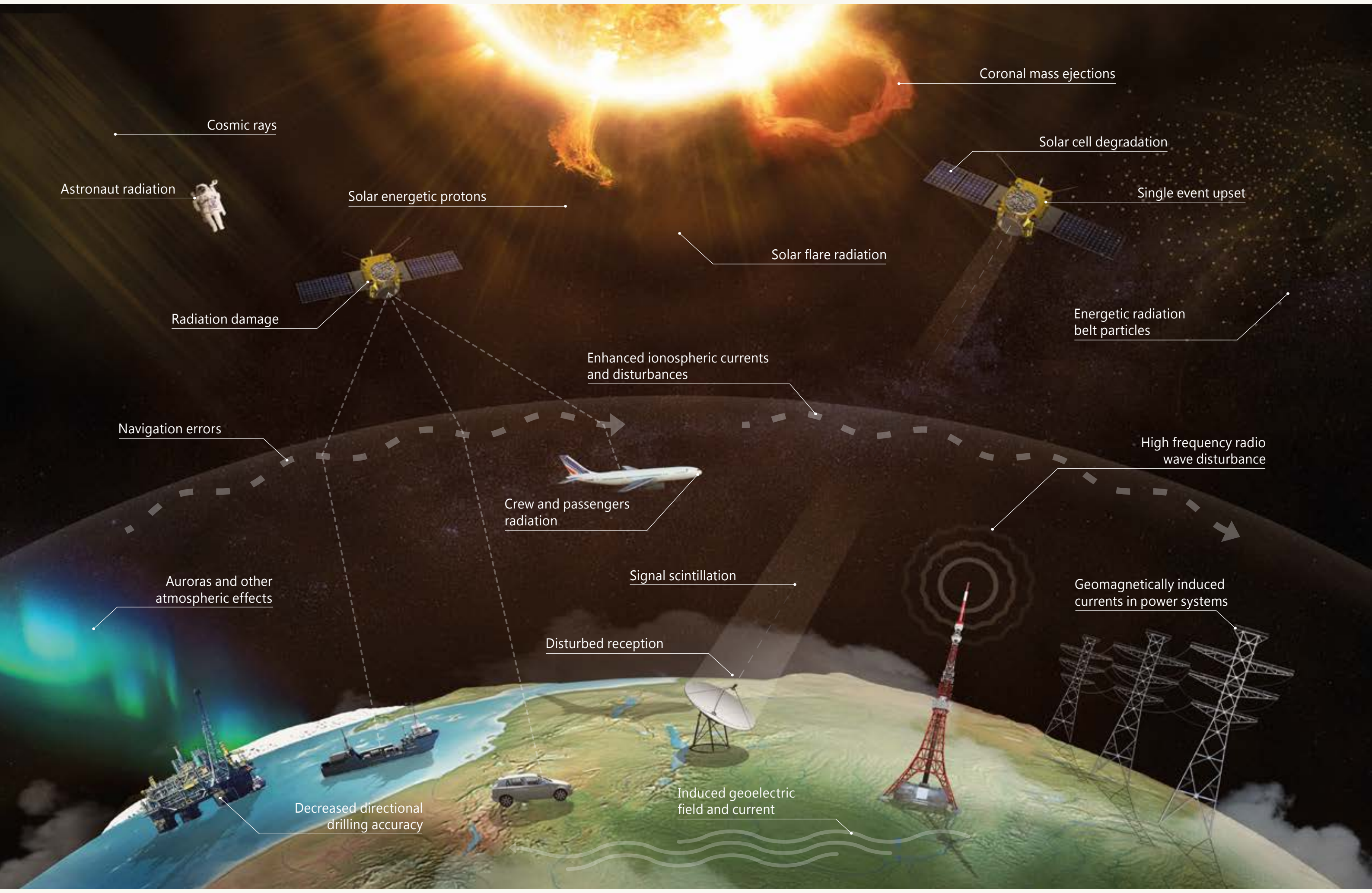
Emerging technologies

Any consideration of the effects of space weather needs to include emerging technologies. One notable example is autonomous vehicles, which are poised to revolutionise transportation. Safety is vital for such vehicles, whether they are on public roads, such as self-driving cars, on private land (for example agricultural vehicles), or in the air or at sea.

In the Starion-led Space Weather Autonomous Vehicle Effects (SWAVE) project, experts are helping ESA understand the risk that space weather may pose to this emerging industry, and the support that could be offered to mitigate the risks. The focus has been on the vast array of technologies autonomous vehicles employ to navigate, communicate and make split-second decisions. Although the space weather impacts on these technologies individually – GPS receivers and radar systems, cellular networks and onboard computers – are known, it's important to understand the effects their disruption would have on the autonomous transport systems that depend on them.

ESA's Alexi Glover says: "In addition to our pre-operational service provision, the Space Safety Programme supports a number of targeted, high priority development activities and feasibility studies. Developments such as EuroGIC address key needs identified by end-users and provide an opportunity for the development of targeted applications and products, with users directly involved in the definition and testing phases of the project. Other example areas of development include GNSS performance indicators providing end-users with information on how they may be affected by space weather conditions and radiation belt nowcasting and forecasting, which targets the needs of operators of spacecraft in Earth orbit.

"Feasibility studies such as the SWAVE project address newly emerging potential user domains where requirements for space weather information and use



Numerous sectors can be affected by space weather, especially near the Earth's poles, including space-based telecommunications and navigation services. Image © ESA/Science Office cases for the data may need further elaboration. These studies provide an opportunity to analyse in detail the potential impacts and also to engage with the user community to understand their needs."

Weather forecasts

There have been great advances in capabilities and knowledge in the last couple of years, but how far away are we from a true space weather forecasting system?

"The expertise required and the thematics are huge in comparison to terrestrial weather forecasting," says Starion's Federico Da Dalt. "The weather system is 'closed', whereas space weather is open and very complicated. You might see an active spot on the Sun, but nothing tells you when that might 'go off', what type it will be, whether it will head in our direction, its velocity and how it will interact with Earth. I think we are quite far off any kind of reliable forecasting system. That said, we are working towards this with the launch of satellites such as Vigil and increasing ground-based instrumentation, and eventually AI may help here too, but it is very, very complicated to solve."

Gareth Lawrence from Starion adds: "Terrestrial weather forecasters are very lucky that they don't have to consider magnetic fields in their models. The Sun releases most of its built-up magnetic energy through the solar wind, which is constantly flowing at different speeds. The solar flares and coronal mass ejections only happen now and again when there's a build-up in a particular area and it moves beyond the point of stability. The hope is that Solar Orbiter and NASA's Parker Solar Probe mission will provide at least initial data to be able to parameterise and describe these events. But the question is whether we will ever be able to predict with real confidence that a flare of a certain magnitude will originate in a particular region in the next 24 hours. There's a huge amount of active research going on and some really clever people working on it, but it's a very tricky problem."

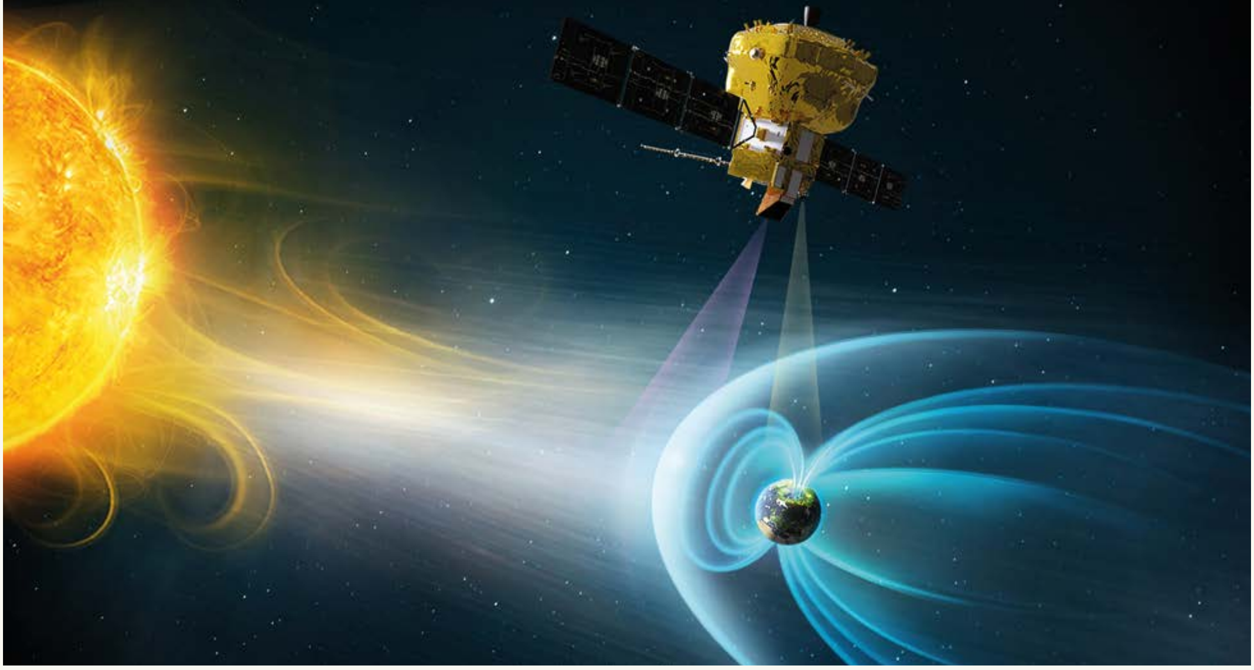
ESA's Solar Orbiter. Image © ESA/ATG medialab

Ultimately, says the Met Office's Simon Machin, "A 'sun-to-mud' forecasting system – one that can forecast all elements of space weather including flares and radiation and geomagnetic storms – is, I think, many years away: maybe 50 years away. But we are constantly improving what we can do in all respects. Our scientific understanding is improving and so is our ability to monitor and, to a limited degree, predict what will happen in response to any space weather event. But if we're to be able to provide a sun-to-mud forecast, we really need to fully understand the dynamics of the Sun and that is a long way off."

Take action now

Despite the Gannon Storm and other subsequent powerful solar events, there have not (at the time of writing) been any major impacts on space or ground infrastructures during this solar cycle. Nevertheless, now is not the time to be complacent or to wait for others to act.

"There's an onus on all organisations to understand their own risks," says Simon Machin. "In the UK, the Government's strategy requires each government department to understand the risk to the sectors they oversee, but it is still down to each organisation to decide if it is a priority and take pre-emptive action. Some sectors, such as energy, have put a lot of time and effort into understanding the risk, but I'm sure there are others that could be affected by space weather but have taken little or no interest so far.



ESA's Smile mission will reveal how Earth's magnetic field reacts to streams of particles and bursts of energy from the Sun. Image © ESA

"Ultimately, if something happens, it's important to understand why your system is malfunctioning or degraded. There are numerous drivers that could be the cause: it could be space weather, but it could instead be an engineering or electrical fault, or even a cyberattack. Your responses to each of these might be different. If it's a space weather event there would be specific things you would do to mitigate the effects and manage the situation that would be different from responding to a cyberattack, for example. Also, you will want to know who to contact to understand how long it might last and what the implications might be."

There is now more information available in terms of space weather monitoring and modelling capabilities than ever before from national organisations such as the UK's Met Office, which provides a 24/7/365 active service, and international agencies including ESA.

ESA's Alexi Glover summarises: "The ESA Space Weather Service Network ensures the continued pre-operational provision of the space weather services through a network consisting of more than 50 different entities including academic groups, institutes and industry. Here the teams collaborate in order to provide pre-operational services to end-users supported by a helpdesk located at the Space Pole in Brussels. New products and applications resulting from targeted developments are continuously integrated into the services and the close interaction with service users enables both provision of timely and reliable space weather information, along with improved awareness of user needs and understanding of the potential impacts of space weather on our critical infrastructures."

Now is therefore the time to maximise resilience to the impacts of space weather. After all, even when we have a comprehensive, timely forecasting system, it will not prevent those impacts – it will only give us more time to prepare to react to the Sun's outbursts.

Resources and sources

ESA SWE Service Portal: swe.ssa.esa.int

Met Office Space Weather: weather.metoffice.gov.uk/specialist-forecasts/space-weather

Sources: stariongroup.eu/os34-sources

"There's an onus on all organisations to understand their own risks from space weather, decide if it is a priority and take pre-emptive action."

The Gannon Storm of May 2024

From 10 to 13 May 2024, a series of powerful solar events occurred that had a wide range of impacts on and around Earth. Collectively known as the Gannon Storm, after space physicist Jennifer Gannon, or the Mother's Day Storm, it gained widespread public attention when aurora caused by the storm were visible much further from the magnetic poles than usual in both hemispheres.

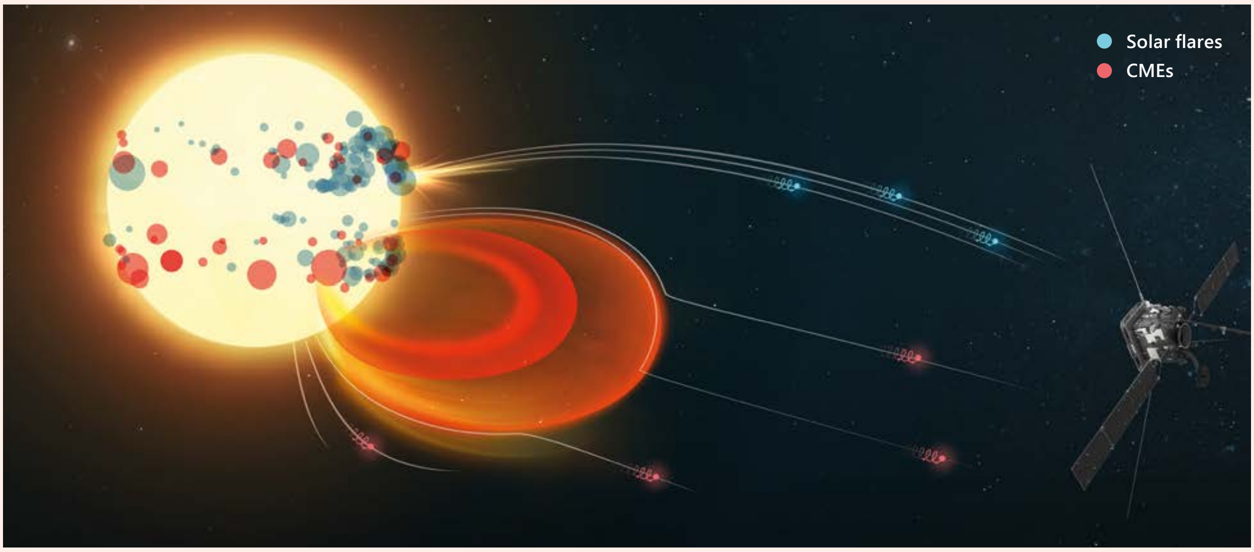
Beyond the pretty aurora, other effects of the storm were less welcome:

- The increase in the density of a layer of the ionosphere caused by the storm affected ground-based and two-way radio communications, primarily on the HF band but also on the VHF and UHF bands.[10]
- The GOES-16 geostationary weather satellite, which provides a view over the Americas, stopped transmitting any data for nearly 2 hours, with a further loss of transmission for 11 minutes soon afterwards.[11]
- There were reports of degraded service from Starlink's satellites, but these ultimately remained operational.[12]
- The European Geostationary Navigation Overlay Service (EGNOS), which augments the GPS satellite navigation service to provide more accurate positioning data, was degraded, with no service for a period of time.[13]
- Flight trackers showed that airlines rerouted planes to lower latitudes because solar storms can cause spikes in cosmic radiation near the poles, which is best avoided by crew and passengers.[14]
- Some farmers in the USA experienced problems with the GPS guidance systems, including precision farming functionality, on older model John Deere tractors.[15] Some veered off course or stopped working, forcing those farmers to suspend planting operations, resulting in average financial losses of about US$17,000 per farm.[16]
- Disruption to GPS signals was reported to have affected some aerial drones.[17]

The storm also served to illustrate that some critical infrastructures were prepared to act on receipt of storm warnings. In New Zealand, for example, Transpower issued several 'grid emergency notices' due to geomagnetically induced current events and removed some transmission lines and circuit breakers from service.[18] In the USA, AT&T and T-Mobile both issued statements saying they were prepared to respond to any service disruption, as did power companies in Canada, where a solar storm in 1989 caused a 9-hour power outage.

Looking at the Sun

The more data we gather about the Sun, the closer we get to understanding it. "Data from scientific missions such as ESA's Solar Orbiter and NASA's Parker Solar Probe, which are flying close to the Sun in different orbits, are giving us new insights into the Sun's dynamics," says Simon Machin, Meteorologist and Manager of the Met Office Space Weather Programme. "Solar Orbiter, for example, has recently started providing imagery and measurements of the Sun's poles for the first time. All of this data will inform the development of our modelling, which in turn will help us improve our forecasts."



Solar Orbiter traces energetic electrons to different types of sources on the Sun. Image © ESA & NASA/Solar Orbiter/STIX & EPD

"Over the last 18 months, through the UK's SWIMMR programme, we've got a range of new modelling capabilities," says Simon Machin. "One enables us to provide short-term forecasting of atmospheric ionising radiation for airlines. Another provides a risk assessment of the potential impact on the UK's power grid at a substation level. One more, developed by the British Antarctic Survey, provides a model of the Earth's radiation belts to help us understand the real-time environment satellites are operating in and any changes driven by space weather that might lead to single event upsets.

"These models have limited forecasting capability but they help people understand what's happening now and in the short term, the severity, and what the duration is likely to be. But for now, we can't give much notice of events because we don't have the sensing capability in place in space to give us adequate warning."

Understanding more about the Sun and space weather is a target for a number of national and international space agencies. ESA missions have been studying the Sun for 35 years, with the joint ESA–NASA SOHO mission still operational following its launch in 1995, giving insights into the Sun's structure, interior, surface and atmosphere, and the solar wind. Another joint mission, led by ESA, is Solar Orbiter, which is studying the Sun from an incredibly close vantage point, while

NASA's Parker Solar Probe became the first spacecraft to fly through the corona – the Sun's upper atmosphere – in 2021.

Meanwhile, in November 2024, scientists reported the first significant result from Aditya-L1, the first solar observation mission launched by the Indian Space Research Organisation, when one of the instruments captured data that helped scientists estimate the precise time a CME began.

Some solar missions are constellations, such as ESA's four-satellite Cluster mission, which studied the solar wind and the Sun's magnetosphere until it ended in September 2024. In March 2025, NASA launched four small satellites that make up the PUNCH (Polarimeter to Unify the Corona and Heliosphere) mission, which will study how the Sun's outer atmosphere becomes the solar wind.

Solar missions don't have to be big to produce useful results. ESA has SmallSat and nanosatellite missions planned as part of its Space Safety Programme, including a mission to study Earth's aurora. Studying the aurora indirectly enables the observation of solar wind variations and the impact of CMEs, so this will support nowcasting and forecasting. The mission will start with a single satellite demonstrator (Aurora-D), to be followed by a constellation of four to six SmallSats. In November 2024, ESA signed a contract for the Agency's first space weather nanosatellite mission, Swing (Space Weather Ionosphere Nanosat Generation), that will monitor the ionosphere.

Other planned launches include China's Solar Polar Orbit Observatory, scheduled for 2029, and ESA's Vigil, due to launch in 2031. The latter will be the first mission to observe the Sun from the fifth Lagrange point (L5) – this gravitationally stable position provides a view of potentially dangerous solar activity before that side of the Sun rotates to face Earth. Before either of these head into space, the National Oceanic and Atmospheric Administration (NOAA, part of the US Department of Commerce) will launch its Space Weather Follow On – Lagrange 1 (SWFO-L1) mission this year as part of its wider SWFO programme. SWFO-L1 will, as its name suggests, observe the Sun from another gravitationally stable Lagrange point.

Finally, there are also instruments hosted on other spacecraft that monitor aspects of the Sun's activities and the solar wind.

The data from all these missions improves the ability of organisations such as ESA, the Met Office in the UK and NOAA in the USA to provide actionable information to organisations that may be affected. In addition, since some of these missions were conceived, artificial intelligence (AI) and machine learning capabilities have progressed considerably. For example, ESA is now looking at how AI will be used for post-processing data from the Vigil mission, which was originally proposed in 2018.

The Met Office's Simon Machin says: "I think AI could help us with flare forecasting in particular, which is something we're not otherwise able to do in any realistic way. Currently, we can provide a probabilistic forecast of solar flares. But as they're associated with changing local magnetic fields around active areas of the Sun, I think AI could help us to recognise the specific changes that will lead to solar flares erupting."