



Understanding and mitigating the impacts of space-related risks

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Introduction

The CRO Forum's core aims include providing insights on emerging and long-term risks through the CRO Forum's Emerging Risk Initiative (ERI), which it has run for over 20 years. Space risk has been in the Major Trends and Emerging Risk radar since 2022.

Both natural and human-induced factors causing space risks pose a concrete threat to modern society and many questions remain for companies and their insurers regarding this rather complex and obscure threat.

This paper seeks to raise awareness on different causes and impacts of space-related risks which can have an impact on both space and terrestrial infrastructures.

Numerous critical infrastructures on Earth, including telecommunications, power grids and financial networks, are highly dependent on space-based assets such as satellites and Global Positioning Systems (GPS). Failures within space infrastructure, whether induced by natural phenomena or human-induced factors, have the potential to cause significant disruptions across these essential terrestrial systems, resulting in substantial economic losses on a large scale.

Cascading effects from a damaged single satellite or space system can propagate across multiple industries, resulting in failures within transportation networks, emergency response systems, supply chains, and other critical sectors. This can create complex, interconnected claims that insurers need to anticipate and manage.

From the (re)insurance industry's view, space risks affect more than just companies that insure space operations. While insurers do not operate space systems directly, they exert significant influence through risk assessment, underwriting practices, and policy conditions and thereby encourage actions to improve resilience among both space infrastructure and terrestrial infrastructure operators which are the most vulnerable to space risks.

This position paper was developed in collaboration with the European Space Agency (ESA). This collaboration facilitated the gathering of valuable insights and technical details in relation to forecasting and monitoring space weather events.



Executive summary

From mobile phones to critical infrastructure, rescue services and beyond, the “worst case scenario” of a severe solar weather event is a very real, and more abstract risk, that few understand. The purpose of this CRO ERI positioning paper is to raise awareness and support preparedness to prevent losses and mitigate risks relating to space.



Causes of space-related risks

Both natural and human-induced risks pose a concrete threat to modern society, and many questions remain for companies and their insurers regarding this rather complex and obscure threat. There are several risks within space that could impact the Earth. This section covers both natural causes, such as gamma ray bursts, as well as human-induced causes, for example satellite congestion among others.



Impacts of space-related risks

This section explores tangible and systemic risks impacting space infrastructure and the services they support on Earth. From physical infrastructure, such as satellites and launchers on Earth, to the services humankind utilises daily, such as communications and navigation, this paper dives into the scale and scope of space-related risks.



Forecasting space-related risks

Forecasting plays a vital role in ensuring safety, reliability, and sustainability of space operations and Earth-based technology and infrastructure that depend on them. This section includes an article by Matthew West and Giuseppe Mandorlo of the European Space Agency (ESA), which discusses the Vigil project, an initiative being developed under ESA's Space Safety Programme to improve space weather forecasting.



Mitigation and adaptation strategies

Mitigation and adaptation strategies to tackle space risks demand a combination of a broad range of interconnected factors. For example, careful spacecraft design, responsible operational practices, active space debris removal development as well as international cooperation to keep space safe and sustainable. This section provides insights into how insurance companies can serve as a strategic tool for mitigating space risks, as well as presents insights on the current regulatory frameworks governing space-related risks.

By raising awareness of space risk related issues and questions, this paper seeks to encourage further dialogue and discussion on insurability as well as to clarify misconceptions through the compilation of relevant information and facts that support industry, (re) insurance companies and societies in their preparedness when facing solar weather phenomena and space debris related risks.

1. Causes of space-related risks

1.1. Natural causes (e.g., space conditions and phenomena, others)

There are a number of risks within space that could impact the Earth. In this section natural causes of space risk will be discussed and these include asteroids and comets, space weather and gamma ray bursts.

1.1.1. Asteroids and comets

Asteroids are rocks which are mainly found in a ring around the Sun between the orbits of Mars and Jupiter called the asteroid belt. A comet differs from an asteroid and instead of being made up of rock is made of ice and dust (NASA 2021). Some asteroids and comets come close to Earth (caused by gravity of nearby planets pushing them towards Earth) and pose a potential risk to Earth (known as Near Earth Objects). 99% of Near-Earth Objects (NEOs) are asteroids and range in size and likelihood of hitting Earth (Table 1) (NASA 2025).

Table 1: Asteroid size and likelihood of hitting Earth (NASA 2025)

Size	Approximate likelihood of an asteroid hitting Earth
10 meters	1 in 10 years
50 meters	1 in 1,000 years
140 meters	1 in 20,000 years
1,000 meters	1 in 700,000 years
10,000 meters	1 in 100 million years

1.1.2. Space weather

Space weather can be described as ‘disturbances of the upper atmosphere and near-Earth space that can disrupt a wide range of technological systems’. In addition, Earth’s own magnetic domain can drive unpredictable events that can cause significant effects both on satellites and on the ground. Space weather follows the solar cycle with the peak number of events occurring every 11 years (Centre for Risk Studies 2016). There are 3 main types of solar activity associated with extreme space weather as shown on the right.

Space weather types

(Centre for Risk Studies 2016, NASA 2022)

- **Solar flares**
Rapid release of radiation from the Sun that travels at the speed of light, takes only 8 minutes to reach Earth and can last from minutes to hours (Figure 2).
- **Coronal Mass Ejections (CMEs)**
Large explosions of charged particles and magnetic fields from the Sun and according to the Centre for Risk studies report 2016 pose the most risk out of the 3 types (1). They take 1 to 3 days to reach Earth.
- **Solar Proton Events (SPEs)**
Large increase in energetic particles sent into space.



Figure 1: Coronal Mass Ejections



Figure 2: Solar Flares

CMEs and Solar flares sometimes occur at the same time and the largest flares are often associated with CMEs (NASA 2022). They are the result of reconnecting of magnetic fields at the Sun in active regions (sunspots) (NASA 2022, NOAA 2025). Both pose a risk to Earth in a number of ways such as disrupting Global Navigation Satellite System (GNSS) and power networks (NASA 2022, UKHSA 2025). The 1859 Carrington event is noted as one of the worst observed space weather events to date which interrupted telegraph communications and is discussed more in chapter 4 (UKHSA 2025). These events are very unlikely, however, an extreme event could cause large-scale impacts according to a European Space Agency 2016 study (ESA 2016). Scientific literature suggests a range of estimates when predicting the likelihood of a Carrington-size event or larger with likelihood ranging from around 1% chance in the next decade to 12% (Morina et al 2019).

Miyake events are rare powerful bursts of solar radiation that occur infrequently but regularly every 400 to 2,400 years with the most powerful event occurring 14,300 years ago (BBC 2024). A large Miyake event was also observed in 774 AD. These events cause blasts 10 times larger than the Carrington event and could damage technology on Earth (BBC 2024).

1.1.3. Gamma ray bursts

Gamma ray bursts are the largest explosions in the universe (more energy than the Sun) either when a star dies or two neutron stars merge. If a Gamma Ray Burst occurred 1,000 light years from Earth, then it would damage the Earth's ozone layer and have a large impact on Earth. However, the chance of this happening is very low with it predicted to occur every 500 million years (RAS 2024).

1.2. Human-induced factors

Humans started to explore space more than 60 years ago, driven by the desire to unveil the unknown, as well as to achieve technological and political supremacy. Throughout this relatively short history of space exploration and exploitation, we have come to acknowledge that space is not an infinite resource, but since satellites need specific orbits to function effectively and these orbits have limited “slots”, they can be depleted and polluted, equally to the resources on the ground, generating externalities that have turned into new sources of risk for activities on Earth.

1.2.1. Space debris

Ever since the beginning of the Space Age there has been more space debris in orbit than operational satellites. According to ESA data from May 2025, since 1957 6,910 rockets have reached outer space placing 21,620 satellites into Earth orbit, of which only 14,240 are still in space and with 11,400 still functioning (ESA, 2025). Space debris is defined as “*all artificial objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional*” and can originate from different sources (Figure 4) (ESA, 2025), mostly from:

- **Mission related objects**, meaning payload and rocket bodies that served a purpose during launch designed to be released when no longer in use, e.g. launch adapters, lens covers or engines;
- **Unintentional fragmentation events**, meaning unintended explosion of satellites and rocket bodies due to fuel remains or reaction with the space environment triggering self-ignition which can disintegrate the object into many fragments, as well as accidental collision between space objects and accidental breakup due to design flaws;
- **Intentional breakup events**, such as anti-satellite tests (ASAT) consisting in satellite interceptions by surface-launched missiles, which have been a major contributor to the increase in space debris in the recent past (Figure 5 - NASA, 2023).

Figure 4: Fragments from events
(ESA's Annual Space Environment Report 2025)

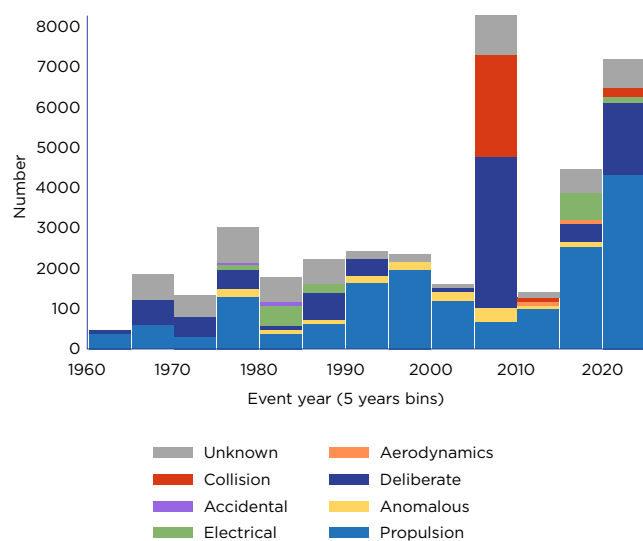
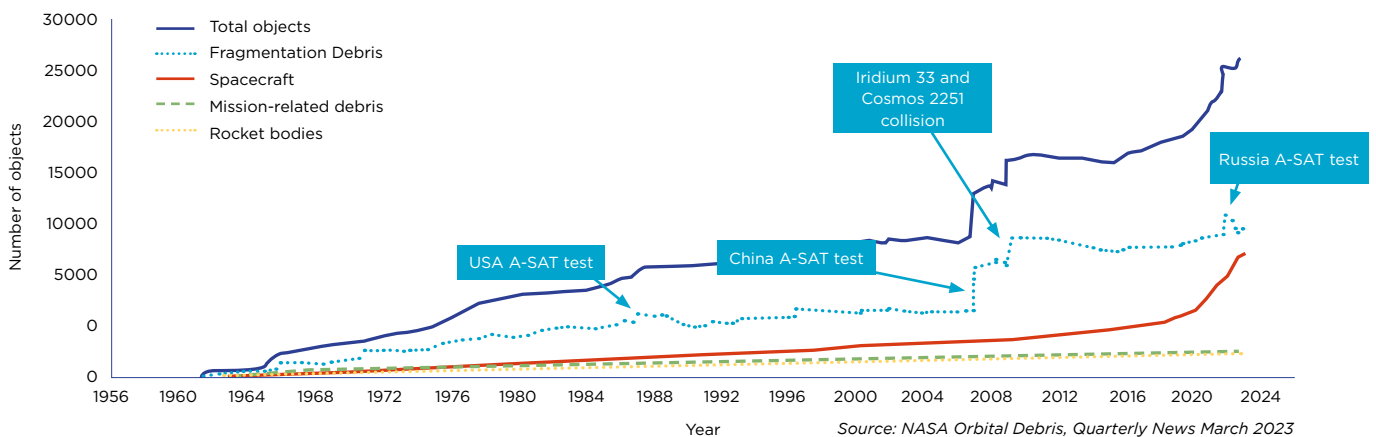
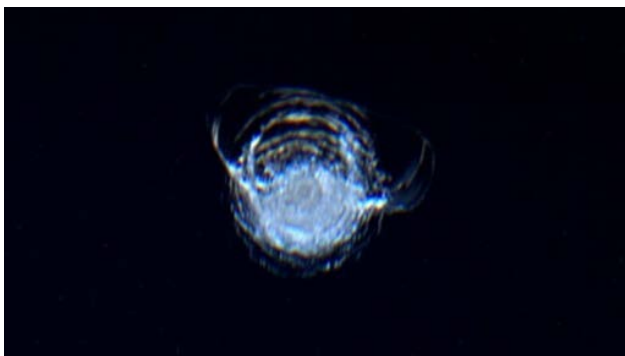


Figure 5: Number of objects in orbit by event - 2023 (NASA)

Space debris, even very small pieces, represents a hazard to spaceflight because, as the number of satellites continues to grow, the pieces of debris, which move very fast reaching speeds of up to 18,000 mph, can collide with active or defunct satellites causing their destruction and creating more debris. An object up to 1 cm in size could disable an instrument or a critical flight system on a satellite (see Figure 6). A chain reaction of collisions, known as the “Kessler Syndrome” could result in the exponential growth of the population of objects, making the LEO region (Low Earth Orbit, up to about a minimum of 1800 km altitude) largely unusable by essential satellites. With improvements in space surveillance sensor capabilities during the last decades, debris pieces larger than 10 cm can be reliably tracked and catalogued by space agencies such as ESA. The International Space Station and the other robotic spacecraft in space are designed to resist collision with small-sized fragments of debris, but when collision risks exceed the levels of tolerance specific collision avoidance manoeuvres are performed (ESA, 2021).

Figure 6: A photo from inside Cupola of the International Space Station showing damage caused by the impact from a tiny piece of space debris, possibly a paint flake or a small metal fragment (ESA Website, 2016)

1.2.2. Satellite congestion

The rapid expansion of commercial satellite networks like Starlink (SpaceX), OneWeb (Eutelsat), and Project Kuiper (Amazon), along with military and scientific satellites from different nations, has raised concerns about space congestion, especially in LEO. Starlink alone has over 6,750 satellites in orbit and aims at reaching 12,000. The number of satellites in space is increasing by 30% each year (UNDP, 2024), posing the problem of long-term sustainability of space activities since congestion means more pollution and more possibility for the Kessler Syndrome to happen. We are also witnessing a race in the procurement of orbital slots by countries and commercial operators, as the number of filings is growing rapidly that could soon outpace the available orbital space (Falle et al, 2023) potentially leading to the “tragedy of the commons”. Moreover, as the competition for the scarce resources on Earth becomes more heated, an increasing number of countries are looking at the opportunities that space offers in terms of economic, energetic, strategic and technological advantages, laying the ground for new geopolitical disputes concerning the control of resources extracted from extraterrestrial sources (Harvard Law Today, 2024).

1.2.3. Militarization of Space

Modern economies are extensively dependent on space data, from satellite TV and radio broadcasts to Earth observation, critical communications and logistics. The increased reliance on satellite technology also exposes them to potential physical, electronic and cybersecurity threats, which can come from nations or state-backed military activities (LSE 2025). The advancement of human technologies has made space the fourth military operational domain, and cyber-space the fifth.

Although in the original treaties space exploration's purpose was for the benefit and the interests of all countries, an increased number of nations are building the capabilities to access satellites for military purposes in order to “prevent an adversary from exploiting space to their advantage”.

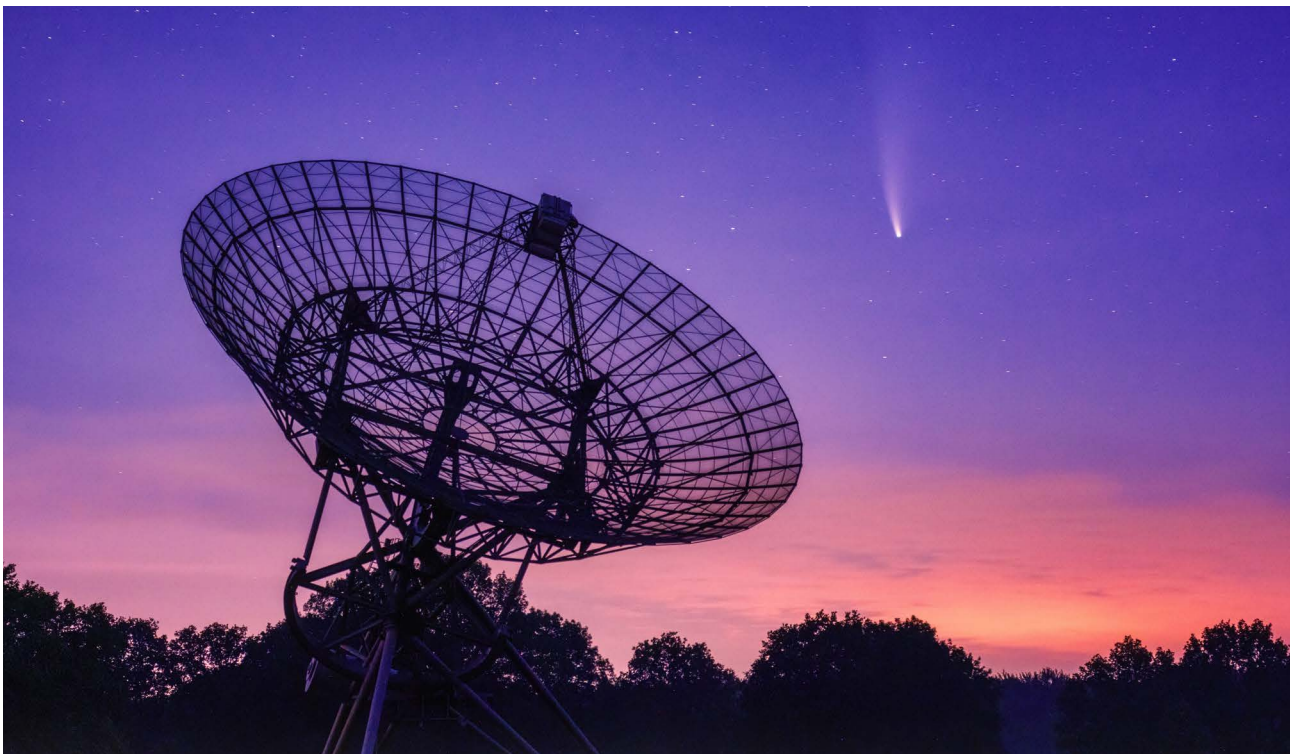
Military threat space capabilities fall into four broad types (Rajagopalan, R. 2019):

- **Kinetic-physical systems** employ direct-ascent anti-satellite missiles or “co-orbital” interceptors to collide with or blast a satellite (or its ground infrastructure), producing permanent, irreversible destruction.
- **Non-kinetic physical methods** use electromagnetic pulses or high-energy directed beams (e.g. lasers, microwaves) to damage or degrade space systems without actual impact (e.g. ASAT weapons)
- **Electronic warfare** exploits radio-frequency energy jamming, spoofing or otherwise corrupting the links between satellites and their users to deny or degrade services temporarily, though without inflicting lasting hardware harm
- **Cyber warfare** targets satellites via malware, network intrusions, and software exploits. Modern satellites’ reliance on digital systems and cloud services increases their vulnerability to attackers including hijacking of controls, data theft, or satellites being disabled with minimal cost and plausible deniability.

Warfare in space presents significant challenges to international security and stability. To address this, the international community has tried to establish a sound basis for developing effective measures to prevent dangerous escalation, implementing regulatory frameworks but with very little effectiveness, as explained in chapter 6.

1.2.4. Non-military cyber threat to satellites

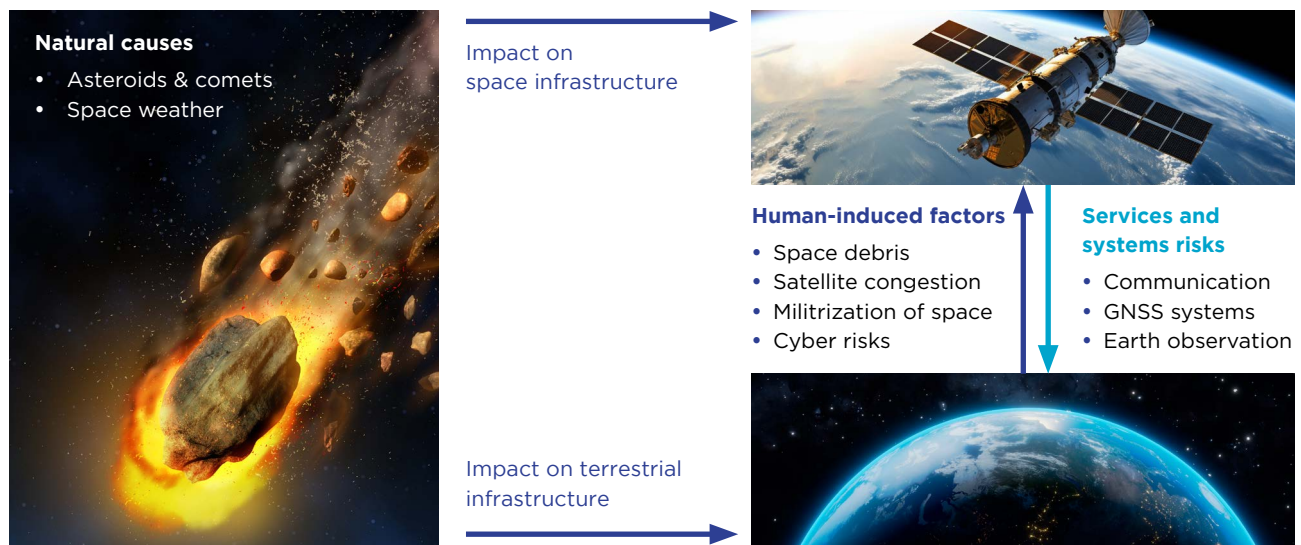
In the previous section it was noted that satellites are at risk from attack through cyber warfare, however there is also a risk to satellites through attack from cyber criminals and hacktivists (Dark Reading 2023). For example, in November 2022 a hacktivist group performed a distributed denial of service attack against the SpaceX Starlink system. In 2023 researchers highlighted the lack of cyber defenses in satellite models. The researchers looked at 17 satellite models and found 3 models didn't have any cyber defenses, 5 were either unsure or didn't know and the remaining 9 did have cyber defenses in place (Dark Reading 2023).



2. Impacts of space-related risks

As space becomes increasingly the subject of (terrestrial) economic and security interests, the number and type of risks associated have multiplied. The transition from a sphere dominated by a few state actors to a complex ecosystem involving private companies, civil and military

operations and broader applications, has expanded the spectrum of risks. This chapter concentrates on tangible and systemic risks impacting space infrastructure and the services they support on our Earth.



To assess these challenges effectively, we distinguish between:

- **Infrastructure risks**, related to the physical infrastructure, such as satellites, launchers, and orbital environment.
- **Services and systems risks**, which affect the services delivered through space assets, including communications, navigation, and Earth observation.

While the first faces threats from launch failures to space debris, the latter is more prone to threats such as cyber-attacks or signal jamming and space weather in both categories (ESPI 2023).

Moreover, these risks are increasingly interconnected. For instance, damage to satellites can disrupt global supply chains, aviation systems or emergency response systems. This interdependence amplifies potential systemic impacts and underscores the crucial role of redundancies for network stability and the importance of keeping an integrated risk management approach in the re(insurance) sector.

2.1. Risks happening in Space: Infrastructure Risks

2.1.1. Impacts on launch infrastructure

Launch services represent one of the most risk-intensive segments of the space value chain. They are the critical gateway from Earth to orbit, but also a significant point of failure. Despite advances in technology and increased launch frequency driven by commercial providers such as Space X, Rocket Lab and Arianespace, launch failures still occur and can lead to total mission loss. According to data from Seradata, the average global launch failure rate remains at 6%, with large variations depending on the type and maturity of launch vehicle (Seradata 2023).

Insurance involvement typically covers satellites during their integration, transport, pre-launch activities, launch, initial operations (usually few weeks/months after launch) and in-orbit operations. These policies are often high-value, accounting for a major share of premiums in the space insurance market – estimated at \$550 to \$600 million in

annual volume globally, though highly cyclical (AXA XL 2023). With the development of small satellites in the new space trend, some innovative covers have emerged that cover with one single insurance policy a satellite from the factory until delivery in space, simplifying the insurance process for the small satellite owners.

The emergence of reusable launch systems like Space X's Falcon 9 and the introduction of rideshare missions raise new insurance questions: Should reused hardware be treated differently in underwriting? Is it possible to insure the re-entry of the launch vehicle and all maintenance activities to guarantee a subsequent launch success? These developments are reshaping actuarial models as they pose new regulatory compliance questions and commercial complexity.

In addition, new heavy launch vehicles are coming with a mass-to-orbit capacity 2-3 times greater than today's reference and a subsequent rise in accumulation of risks when multiple high-value assets are lost in a single incident.

Furthermore, launch sites themselves – such as the Guiana Space Center or Cape Canaveral – are exposed to climate-related risks, cyberattacks and geopolitical tensions. As launch risks are at the intersection of engineering, finance, and geopolitics, they demand increasingly sophisticated assessment frameworks from insurers and reinsurers alike.

CASE STUDY **Vega-C failure**

December 2022

In December 2022, Arianespace's Vega-C rocket failed during its second flight, resulting in the total loss of the Pleiades Neo 5 and 6 satellites – high resolution Earth observation spacecraft developed by Airbus Defence and Space. The failure was attributed to structural issues in the Zefiro¹ 40 motor, which led the launcher to deviate from its trajectory.

This incident not only led to an estimated \$200 million insurance claim for the loss of the two involved Pleiades Neo satellites (Seradata 2022), but also had wider ramifications for European launch reliability, prompting ESA and CNES to initiate a full failure investigation (ESA 2023). For insurers it highlighted the persistent technical and supply chain risks launch systems; as well as the financial exposure involved in high volume satellite missions.

Russia anti-satellite test 2021

In November 2021, Russia conducted an anti-satellite (ASAT) test that destroyed one of its defunct satellites, creating over 1,500 pieces of trackable debris and prompting a temporary relocation of the International Space Station crew to docked capsules. After this event, the UN agreed to ban ASAT in 2022.

For (re)insurers, this incident illustrates the growing exposure to debris-related risks that are difficult to price. Moreover, this event also demonstrates how geopolitical actions generate systemic uninsurable scenarios with potentially cascading impacts for the sector.

Source:
ESA/ID&Sense/
ONIRIXEL



2.1.2. Impacts of space debris in infrastructure in Space and on Earth

Space debris are uncontrolled, human made objects orbiting Earth and represent one of the fastest, growing risks to space infrastructure. 35,000 objects have been tracked, however, the actual number of space debris objects large enough to cause catastrophic damage is estimated to be already over one million and growing, indicating the increasing likelihood for collision with operational satellites (ESA 2024).

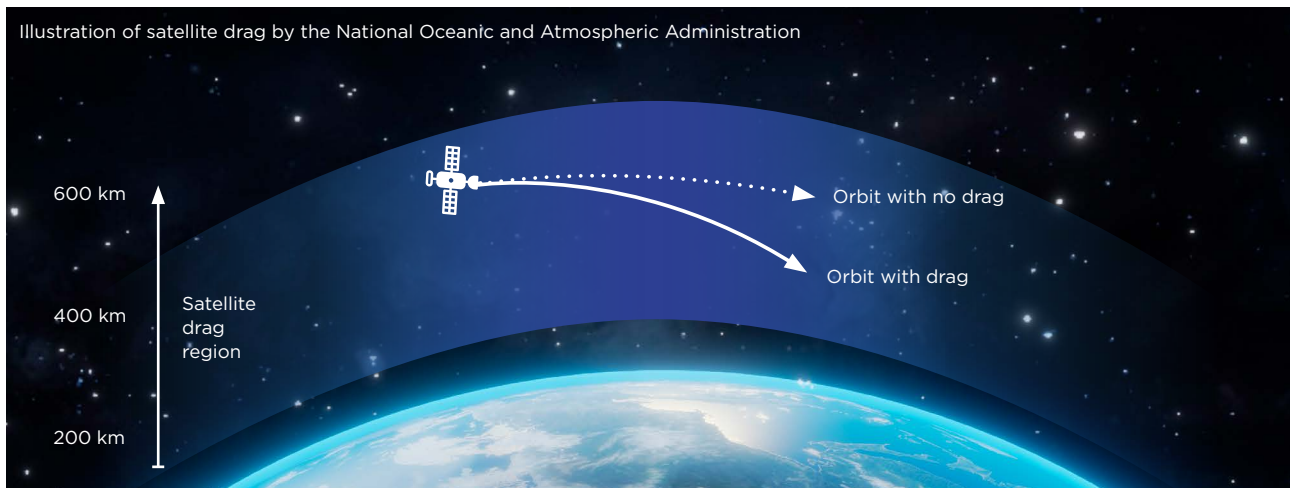
This risk is amplified by the proliferation of low-cost CubeSats² and mega-constellations such as Starlink, OneWeb and Amazon's project Kuiper, which introduce thousands of small satellites on into LEO, increasing orbital congestion. While CubeSats often lack propulsion systems, they can still generate significant debris in the event of fragmentation, especially given the deployment in large numbers with limited post-mission disposal compliance.

Space debris poses both physical and systemic risks. The primary concern is damage or destruction of insured satellites caused by collision with untracked or defunct objects, which may trigger satellite loss claims and increase the collision risk on other satellites operated in the same orbit.

A cascading event scenario with orbit pollution will be a complex claim on the liability side and may highlight the risk of generic failure on a given orbit if several satellites are impacted.

¹ It's a power propulsion engine used for the VEGA launcher.

² CubeSats are small cube shaped satellites that allow for lower costs and quicker development.



2.1.3. Impacts of space weather on satellite drag

Satellite drag refers to the aerodynamic force that opposes the motion of a satellite as it travels through the upper part of Earth's atmosphere (see illustration). The atmospheric density causing the drag decreases with increasing altitude. As the satellite moves at high speeds, it collides with atmospheric particles, creating a force that opposes its motion. Drag affects all satellites below approximately 600 km altitude and is the largest source of error in modelling satellite's force.

However, the design and deployment of satellite constellations can influence drag. For example, satellites placed in higher altitudes with minimal atmospheric interference may experience less drag, while others in lower altitude orbit may face increased drag due to higher atmospheric density.

As the number of objects in space increases and AI tools boost reliance on satellite imagery for underwriting and prevention, drag emerges as a significant risk.

It causes satellites to **lose altitude and malfunction** and, if the on-board propulsion system has not been designed to compensate for such effects, can lead to **orbit decay and loss of the mission**. For instance, in 2022, a so-called "Terminator Event" occurred around the same time as a Starlink launch and prevented 40 satellites from reaching their intended orbits, which ended up burning in the atmosphere. This incident resulted in a \$100 million economic damage. Despite its name, the event was a minor space weather storm.

2.2. Terrestrial risks: services and systems risks

2.2.1. Impacts for radio and satellite communications

Satellite and radio communication services are a critical pillar of space-enabled services and systems, supporting everything from broadband internet and television to emergency communications and remote sensing on Earth. However, as reliance on satellite-based infrastructure deepens, these systems face mounting risks from both space-based and terrestrial threats.

The International Telecommunications Union (ITU) has repeatedly raised concerns about the deliberate misuse of frequencies and inadequate coordination across orbital slots, which can degrade service quality and create legal ambiguity in liability attribution. Signal jamming and spoofing, deliberate or accidental, pose a growing operational and security risk. In addition, one of the most pressing concerns is cybersecurity. Satellite ground systems and signal links have become attractive targets for state and non-state actors, particularly in the context of geopolitical crisis. Geopolitical tensions further exacerbate vulnerabilities in satellite communications, exposing satellite operators to strategic targeting – a recent example (expanded in the case study box) is the Viasat cyberattack in February 2022, which disrupted satellite broadband services across Ukraine and Europe during the early hours of Russia's invasion.

Space weather events such as solar flares and coronal mass ejections, further compound these vulnerabilities. Such phenomena can damage satellite electronics, interfere with signal propagation, and lead to temporary or permanent outage of communications infrastructure.

Lastly, component failures in commercial satellites, especially fast-tracked or low-cost CubeSat deployments, have led to shortened mission lifespans and higher failure rates.

Given this constellation of threats, space enabled communication services represent a complex risk environment as they are at the intersection of natural hazards, geopolitical tensions, technical reliability, and regulatory gaps.

For the (re)insurance sector, interruptions in radio and satellite communications can negatively impact their ability to operate, and that of their clients. They can also trigger potential data unavailability for example for satellite-based processes, such as satellite imagery to monitor wildfire conditions and help to prevent wildfire events.

2.2.2. Impacts for Global Navigation Satellite Systems (GNSS)

GNSS/GPS can be impacted in a number of ways by space risk (cyberattacks, space debris and weather) that can have significant impacts on Earth-based services and systems (LSE 2025, GPSWorld 2021, UKHSA 2025). If there is no GNSS/ GPS, then transport would slow down as it is used for navigation (Quartz 2017).

For example, it's used in the maritime sector to navigate and locate ships at sea (UK Government 2023). The slowing down of transport networks would not only impact individuals but also impact supply chains.

GPS systems play a pivotal role in geopolitical conflicts, since the first "space war": during Operation Desert Storm in 1991 where U.S led coalition forces relied heavily on GPS for navigation, communication, and weapon guidance, which were crucial in the challenging desert terrain of Kuwait and Iraq (Scientific American 2016). In today's context of rising geopolitical tensions disrupting GPS/GNSS remains a key tactic in conflict (ICRC 2025).

If GNSS/GPS went down, then there could be impacts to financial services since stock exchanges rely on GNSS/GPS to time transactions (Quartz 2017). In addition, there could be impacts to power grids which rely on GNSS/GPS for timekeeping (Quartz 2017). Agriculture is also dependent on GNSS/GPS and is used in precision farming (UK Government 2023). If the UK lost access to GNSS/GPS for 7 days then it's estimated that the economic cost would be £7,644 million according to a UK government report in 2023 (UK Government 2023).

CASE STUDY Viasat attack 2022

In February 2022, just hours before Russia's invasion of Ukraine, a cyberattack targeted Viasat's KA-SAT satellite network, disrupting internet service across Ukraine and parts of Europe. The attack, attributed to Russian military intelligence (GRU), disabled tens of thousands of ground-based modems.

The disruption affected not only Ukrainian military and government communications, but also civilian infrastructure – including wind farms in Germany. This incident marked one of the first major uses of space-based assets in hybrid warfare, highlighting satellite networks as critical geopolitical targets.

For (re) insurers, the Viasat case underscores emerging risks in space-based communication systems, particularly the cascading impacts of cyberattacks across sectors and borders, raising questions around attribution, liability, and coverage scope.

Source: ENISA Threat Landscape 2022

CASE STUDY Example of when GNSS/GPS has gone down

Signal jamming

The Russia/Ukraine conflict has seen GPS jamming events such as one in March 2024 when a UK Royal Air Force plane had its GPS jammed (BBC 2024). During the conflict constant disruption led to Finnair suspending flights to Tatu, Estonia because this airport relies solely on GPS for navigation (BBC 2024). Larger airports don't rely on GPS alone and hence might not be so impacted, but this case study highlights that GPS signal jamming can cause disruption.

Solar storm May 23rd, 1967

In 1967 a powerful solar flare caused radio and radar communication disturbances in the UK and USA (NOAA 2023). This occurred during the Cold War and caused the US air force to ready themselves as they initially thought that this was linked to a Soviet attack rather than space weather event (NOAA 2023).

2.2.3. Impacts on Earth Observation data

Earth Observation (EO) technologies have become indispensable tools for the insurance industry, offering enhanced capabilities in monitoring and mitigating risks associated with natural disasters and climate change but also for monitoring crop-conditions in near real-time, improving risk modelling and response. By providing high-resolution, near real-time data, EO enables insurers to assess exposures accurately, streamline claims processing, and develop innovative products like parametric insurance models. These models, for example, use EO data as triggers, allowing for faster payouts and reduced administrative costs (Swiss Re 2025). However, this growing reliance on commercial EO providers introduces strategic vulnerabilities. European insurers often depend on such providers for high-resolution and frequently updated imagery, which Copernicus satellites do not always offer due to their medium-resolution design. This dependency can pose risks in terms of data continuity, cost escalation, or access restrictions in times of geopolitical tension or regulatory divergence. Ensuring strategic autonomy in EO capabilities is therefore crucial – not only through public infrastructure like Copernicus but also from the insurance perspective, to diversify the data providers.

2.2.4. Naturally caused space risk impacts on Earth

Impact of space weather on power outages

Space weather also causes large ionospheric currents that induce geomagnetically induced currents (GICs) in all long conductors at ground. These GICs can affect terrestrial electric and electronic systems that could result in huge impacts on Earth. Of particular concern are extreme scenarios of large-scale and longstanding power outages which have knock on impacts to multiple sectors from manufacturing to healthcare, as illustrated in the 2016 Helios solar storm scenario conducted by the Centre for Risk Studies. There would be far-reaching impacts across society from issues with communication and transportation to disruption to infrastructure such as water and waste systems.

Power outages could cause huge economic losses, industries such as manufacturing would slow down/stop and the impacts ultimately could reduce a country's GDP.

For extreme space weather scenarios and in combination with major physical damage to the power supply infrastructure, power outages could have significant implications for business interruption insurance, but also for personal lines insurance policyholders. The impact on insurers depends on outage duration and the length of policy waiting periods as illustrated in the CRO Forum publication on critical infrastructures.

CASE STUDIES of Solar storm impacts on Earth

Carrington event

On May 23rd, 1859, a space weather event caused powerful surges in the telegram network which prevented messages being sent and caused small fires at telegram offices (NOAA 2023).

Halloween solar storms 2003

In October 2003 geomagnetic storms caused disturbances to GPS in particular in Northern Europe including power outages in Southern Sweden (Bruyninx 2004, NASA 2003). A study by Xue et al. (2023) estimates that if a severe geomagnetic event comparable to the 2003 Halloween Storm occurred in a more modern context, e.g. 2019, the economic impact on aviation alone could include communication blackouts costing between €0.21 million and €2.20 million per day, plus a satellite navigation failure cost of around €2.43 million (AGU 2023).

1989 Quebec event

The 1989 geomagnetic storm caused a 90 second power outage and a consequent collapse of the power grid in Quebec. It not only damaged power grid equipment that cost 6.5 million USD, and 6 million customers remained without power for 9 hours in Canada (Centre for Risk Studies 2016). It also impacted customers in New Jersey USA (Centre for Risk Studies 2016).

Other space risk impacts on Earth

Asteroids

Asteroids have the potential to impact Earth however as noted in Chapter 1 the likelihood of an asteroid hitting Earth is small. Table 2 notes the impact of different sized asteroids.

Depending on the size of the asteroids the impact to the economy/insurance industry could vary with the largest sized asteroid causing the most impact. The larger asteroids would impact many and particularly impact commercial and personal line property insurance policies. The low likelihood of an event occurring highlights that the space risk concerns should be focused on other natural events such as space weather.

Table 2: Asteroid size and impact on Earth (NASA 2025)

Size	Approximate Likelihood of an Asteroid hitting Earth	Impact on Earth
10 meters	1 in 10 years	Sonic boom and fireball
50 meters	1 in 1,000 years	Localised impact that might not create a crater
140 meters	1 in 20,000 years	Depending on impact location could cause deaths across built up areas.
1,000 meters	1 in 700,000 years	Create a 10-kilometer crater which could cause a global disaster
10,000 meters	1 in 100 million years	Create a 100-kilometer crater which could cause mass extinction



3. Forecasting space-related risks

Space risk forecasting plays a vital role in ensuring safety, reliability, and sustainability of space operations and Earth-based technology and infrastructure that depend on them. As reliance on space-based systems grows across scientific, commercial and defence sectors, the ability to anticipate and mitigate potential hazards in the space environment becomes increasingly critical.

3.1. Space debris

Forecasting space debris is crucial for preventing collisions that can damage satellites or create more debris. Strategies to forecast space debris typically combine tracking, modelling, simulation and data sharing. A few examples of these strategies can be broadly categorized as follows:

3.1.1. Ground-based tracking systems

Ground-based sensors, particularly radar and optical telescopes, constitute the foundational tools for detecting and tracking orbital debris.

- Radar systems are especially effective in monitoring objects in LEO. High-frequency phased-array radars can detect debris as small as 10cm.
- Optical telescopes, both passive and active, are primarily used for tracking objects in higher altitudes such as geostationary orbit (GEO), where radar sensitivity decreases.

Key systems include the United States Space Surveillance Network (SSN) and the ESA's Space Debris telescope.

3.1.2. Orbital dynamics and propagation models

Physics-based propagation models are used to forecast the future positions of space debris based on current orbital parameters. These models incorporate perturbative effects such as atmospheric drag, solar radiation pressure, Earth's gravitational anomalies, and third-party influences. The largest uncertainty to the orbit dynamics comes from space weather, as large ionospheric currents heat the atmosphere causing it to unpredictably expand resulting in increases of friction on satellites and debris objects.

3.1.3. Conjunction assessment and collision avoidance

Conjunction analysis involves calculating the probability of close approaches between active spacecraft and catalogued debris objects. When a high-risk conjunction is identified, satellite operators may execute collision avoidance manoeuvres. Organization such as the European Union Space Surveillance and Tracking (EU SST) provides conjunction warnings and risk assessments based in real-time tracking data.

3.2. Cyber threats

Forecasting cyber threats in space requires an interdisciplinary approach combining cyber threat intelligence, rigorous vulnerability assessment and collaborative information sharing. Given the high stakes of space operations, ranging from national security to commercial services, advanced forecasting capabilities are indispensable for proactive defence. Some examples of these capabilities are as follows.

3.2.1. Threat intelligence and information sharing

The organised gathering and analysis of cyber threat intelligence (CTI) from various sources – including government agencies, private cybersecurity firms, and international space organizations – provides a basis for forecasting possible cyber threats. This process includes monitoring Indicators of Compromise (IoCs) and identifying new threat trends. Engaging in collaborative networks such as the Space Information Sharing and Analysis Center (Space ISAC) helps ensure that relevant threat information is shared quickly and understood in the context of space operations.

3.2.2. Vulnerability and attack surface analysis

Thorough mapping and description of key space system components – including satellite hardware and software, ground stations, and communication networks – helps identify possible vulnerabilities. Using risk modelling approaches designed for space systems allows for a structured analysis of potential attack methods and adversary techniques.



Furthermore, conducting simulated attacks or red team exercises offers practical understanding of system weaknesses, which supports the development of effective defence measures.

3.2.3. Supply chain risk management

Cyber threats may also originate from hardware or software suppliers. Implementing stringent verification processes, provenance tracking technologies such as blockchain, and audits of component origins mitigates risks of counterfeit or compromised elements that could serve as vectors for cyber intrusion. Strengthening supply chain security requires the enforcement of stricter controls throughout the entire supply chain lifecycle.

3.3. Challenges in forecasting & preparedness on space weather

Forecasting is always based on model, be it a physics-based models like the terrestrial weather circulation models, or empirical models. Observations always concern the current time and the past, but their extrapolations into the future must always be accompanied by some model with which the projections are made. In space weather, there are two categories of models that are developed. The first considers the launch and arrival of the solar events like CMEs, and the second concerns modelling their impacts in the near-Earth space and at ground.

3.3.1. Awareness and monitoring

Ongoing, worldwide surveillance is essential. Operational observation networks comprise:

- **Spaceborne assets:** The Solar Dynamics Observatory (SDO) and the Solar and Heliospheric Observatory (SOHO) offer multi-wavelength photography of the solar disk, while GOES satellites give real-time observations of X-ray flux and proton flux (NOAA, 2025). However, Earth-based observations cannot detect active zones on the solar far side. The ESA Vigil mission, scheduled for launch in 2031 at the Sun–Earth Lagrange L5 point, will rectify this oversight, facilitating the earlier identification of Earth-directed coronal mass ejections (CMEs) (ESA, 2016).
- **Ground-based magnetometer networks:** The World Data Center for Geomagnetism (Kyoto) consolidates global magnetometer data, generating indices (Dst, SYM-H) that indicate the commencement of storms. Enhancing this network augments spatial coverage and expedites storm classification.

Precise situational awareness constitutes the primary defense against space weather phenomena. The capacity to predict and react to solar disruptions is significantly hindered without ongoing, worldwide monitoring. Monitoring assets – both spaceborne and terrestrial – provides critical data for predictive models and situational dashboards. Enhancing observational coverage,

particularly from off-Sun-Earth-line perspectives (e.g., Lagrange L5), directly results in prolonged lead periods for storm forecasting. For insurers, prolonged lead time enhances confidence in probabilistic models and diminishes uncertainty in loss projections, therefore refining risk assessment.

3.3.2. Forecasting of solar eruption arrival times

Notwithstanding sophisticated observations, forecasting remains fundamentally probabilistic:

- **Statistical and empirical methodologies:** Chapman et al. (2020) revealed that the phase of the solar cycle influences the occurrence and intensity of extremes. Incorporating cycle-phase factors into extreme-value models can enhance storm-probability forecasts which reveal the likelihoods of certain event sizes for example that a Carrington event statistical likelihood is roughly once per 100 years, and a Miyake event roughly once per 1000 years.
- **Physics-Based MHD modeling:** WSA-Enlil and analogous magnetohydrodynamic (MHD) models describe coronal mass ejection (CME) propagation from its solar origin to 1 astronomical unit (AU). The integration of real-time solar-wind data from DSCOVR and ACE is crucial for minimizing arrival-time discrepancies to within ± 6 hours (Kappenman et al., 2000; Eastwood et al., 2017).
- **Machine learning methodologies,** specifically Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), applied to full-disk magnetograms and historical solar-wind time series enhance short-term predictions of flares and Coronal Mass Ejections (CMEs) (Platts et al., 2022; Bobra & Couvidat, 2015). Although impressive, these models necessitate ongoing retraining to accommodate changing solar dynamics. Further, they do not give insights about the space weather impacts at orbit or on ground.

Statistical and empirical models yield rapid, computationally efficient estimations of storm probability but frequently neglect to account for tail-risk extremes. Physics-based magnetohydrodynamic models recreate the physical propagation of coronal mass ejections, providing more accurate storm-arrival features. Machine learning models can detect nuanced precursors in extensive datasets that traditional methods overlook. Collectively, these forecasting layers diminish uncertainty regarding the time and amount of storm impacts.

3.3.3. Redundant systems for critical ground infrastructure

Effective preparedness necessitates resilient infrastructure and redundancy.

- **Fortified power grids:** The implementation of series capacitors and geomagnetically induced current blockers at susceptible substations alleviates transformer saturation during storms (Oughton et al., 2019). Utilities must uphold guidelines for the swift isolation of essential transformers when geomagnetic indices surpass established criteria.
- **Backup GNSS receivers:** Services reliant on GNSS (telecommunications, emergency response, aviation) must utilise multi-constellation receivers (GPS + GLONASS + Galileo) and inertial navigation alternatives to maintain continuity during ionospheric scintillation that impairs positioning (UK Government, 2023; GPSWorld, 2021).
- **Satellite operations centers:** Command and control (C2) uplinks must provide redundant capabilities in HF, VHF, and S-band frequencies. If solar radio noise interferes with one band, an alternative uplink must be accessible (NOAA SWPC rules).

No prognosis, regardless of its accuracy, can avert damage if essential systems lack physical or operational resilience. Geomagnetically induced currents (GICs) can compromise transformers within minutes of storm initiation; in the absence of hardware mitigation, losses are unavoidable. Redundant GNSS and communication lines guarantee the uninterrupted provision of critical services, especially pertinent for aviation and financial networks reliant on accurate time. For insurers underwriting energy, telecommunications, and satellite portfolios, comprehending the degree of infrastructure fortification influences both insurance conditions and pricing. Redundancy measures function as mitigating elements in risk models, potentially diminishing capital charges linked to anticipated losses.

3.3.4. Advances in space physics, and space science

Solar cycle modeling and extreme climatology

Chapman et al. (2020) assessed the influence of solar-cycle modulation on extreme-storm probabilities, demonstrating that storms with $Dst^3 < -300$ nT⁴ peak during solar maximum. Their research, based on extreme-value theory, highlights the non-stationary characteristics of geomagnetic risks.

³ Disturbance storm time

⁴ Nanotesla

Identifying the non-stationary nature of solar cycles is essential for long-term financial planning. Traditional models that presume stationarity underestimate tail risks during periods of solar maximum. Through the implementation of cycle-phase modulation, insurers can modify reserve factors and reinsurance techniques in preparation for intervals with increased risks of extreme storms, thus establishing a more resilient financial buffer against infrequent, high-impact occurrences.

High-Resolution magnetospheric observations

Multi-satellite missions – THEMIS, MMS, Van Allen Probes – elucidate storm – time magnetospheric dynamics with unparalleled spatial and temporal resolutions. Kilpua et al. (2017) examine the amplification of geomagnetic responses by CME sheath regions. Information from these missions informs empirical models of geoelectric fields and geomagnetically induced current forecasts (Thomson et al., 2011). The impacts of solar eruptions within the near-Earth space are not quantitatively known, and this is an active research field requiring infrastructure and supercomputing facilities.

High-resolution observations facilitate the refinement of terrestrial hazard models. The characteristics of CME sheaths frequently determine the maximum intensity of ground effects; comprehending sheath structure aids in forecasting abrupt GIC surges.

For insurers underwriting extensive, geographically diverse portfolios, this fidelity results in enhanced exposure mapping – differentiating areas of probable transformer stress from those less impacted.

Improved CME/Flare source-region identification

- **EUV and X-ray imagery:** The instruments on SDO/AIA and Hinode facilitate the detection of magnetic precursors to solar flares through EUV and X-ray imagery. Machine learning algorithms applied to these datasets detect emerging active regions with increased flare potential (Platts et al., 2022).
- **Spectropolarimetric observations:** Spectropolarimetric observations of sunspot magnetic free energy contribute to ensemble-forecast models that evaluate the probability of coronal mass ejection initiation (Riley, 2012).

Timely recognition of high-risk active areas on the Sun's surface can prolong warning intervals beyond the capabilities of CME detection alone. Improved lead times directly enhance risk-management operations by offering a prolonged planning horizon. However, the impacts of the eruptions can still be unpredictable even if the arrival time was accurately known. Consequently, insurers can enhance short-term loss-estimation models by allocating reserve buffers in the days preceding a forecasted extreme event, rather than solely responding to ground indicators.



Early warnings from Space: How Vigil will transform space weather forecasting

By Matthew West and Giuseppe Mandorlo from ESA

Today, space weather monitoring is largely conducted from Earth-orbiting, or near Earth satellites, directly between the Sun and Earth. These platforms provide vital data, but they only detect solar activity once it's already heading toward us – limiting warning times and reducing preparedness.

Vigil changes this. From its position at L5, it will have a side-on view of the Sun, allowing it accurately to track any solar flares or coronal mass ejections (CMEs) along the Sun-Earth line. These “Earth-directed CMEs” are the most geoeffective, meaning they're the most likely to trigger geomagnetic storms on Earth. From L5, Vigil will see these eruptions from the side as they expand – capturing their speed, width, and trajectory far earlier than current systems allow, which in turn greatly improves the predicted impact time/location.

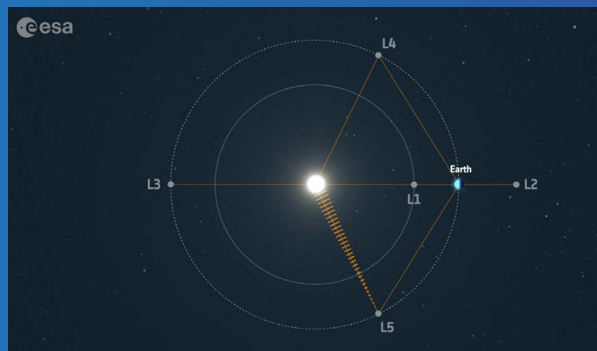


Figure 1. The Lagrange points in the Sun-Earth system. Lagrange points are positions in space where the combined gravitational forces of the Sun and Earth create regions of equilibrium, allowing spacecraft to maintain a stable orbit with minimal fuel. Shown here are the five Lagrange points: L1, L2, L3, L4, and L5. ESA's Vigil mission is being developed for L5 – located to the side of the Sun-Earth line – where it will observe solar regions before they rotate into Earth view and monitor eruptions traveling along the Sun-Earth line, the most geoeffective direction for space weather. *Image: ESA – Vigil.*

In addition, Vigil will see active regions – areas on the solar surface capable of producing flares and coronal mass ejections (CMEs) – 4-5 days before they rotate into direct view from Earth. This adds valuable lead time for alerts and operational planning. Critically, Vigil will be able to watch how these regions evolve, identifying signs of increased complexity or magnetic instability that precede major eruptions.

Another key advantage comes from the structure of the solar wind, the continuous stream of charged particles flowing out from the Sun. Due to the Sun's rotation, this wind follows a spiral pattern – the Parker spiral – as it moves through the solar system. Vigil, sitting “upstream” of Earth in this spiral, will encounter solar wind structures and embedded magnetic fields several hours before they reach Earth, providing a crucial early sample of the conditions heading our way.

By combining early imagery of solar eruptions with in-situ measurements of the incoming solar wind, Vigil will vastly improve our ability to forecast not just when an event might arrive – but also how severe its impact may be.



Figure 2. The future ESA Vigil mission will provide a first-of-its-kind capability: monitoring the Sun to provide constant, near real-time data on potentially hazardous solar activity. *Image: ESA/A. Baker – Vigil.*

European mission for global resilience

Vigil is being developed under ESA's Space Safety Programme, with contributions from leading European institutions and international partners. It will carry instruments to image the Sun, monitor solar eruptions, and directly sample the solar wind and magnetic field conditions in space. Together, these tools will form the backbone of a next-generation space weather early warning system, helping protect infrastructure on Earth and in orbit.

As our reliance on satellites, spacecraft, and global communications grows, so does our exposure to space weather risks. Vigil marks a major step in addressing these challenges – offering earlier warnings, better preparedness, and greater resilience.

4. Mitigation and adaptation strategies

4.1. Strategies for mitigating space debris risks

Space debris mitigation is a combination of careful spacecraft design, responsible operational practices, active space debris removal development and international cooperation to keep space safe and sustainable.

A key principle in mitigating space debris and minimizing fragmentation risk is post-mission disposal. Satellites should be designed to move to a safe disposal orbit or deorbit once their mission ends. This involves limiting the time a satellite remains in orbit after the end of its mission, ensuring its residual orbital lifetime is kept as short as possible – ideally not exceeding 25 years for the LEO region.

Space debris is systematically monitored to mitigate the risk of collisions and to preserve the orbital environment. When a potential collision risk is identified, satellite operators may execute orbital adjustments to reposition their spacecraft's location and avoid debris. For crewed missions, manoeuvres or temporary evacuation can be planned if needed.

Active space debris removal is a rapidly developing field focusing on physically removing existing debris from orbit to reduce collision risks and keep space sustainable. It refers to technologies and methods designed to capture, deorbit, or otherwise eliminate space debris objects in orbit. One example of one of the current space debris removal actions is the ClearSpace-1 mission which is a debris removal mission scheduled for the second half of 2026 led by ESA.

4.1.1. International guidelines and policies

The increasing accumulation of space debris and the Kessler syndrome risk highlight the need for action to ensure continued use of the space environment. There is a growing consensus across the space sector that stricter global space debris mitigation practices are essential to keep space activities viable.

There are currently no globally accepted rules or regulations to ensure that on-orbit space activities are conducted in a safe and sustainable manner.

However international cooperation has been ongoing for years for example to set principles for responsible behaviour in space and to develop guidelines to control space debris. The framework to control space debris is still evolving and largely based on international cooperation rather than strict enforceable regulations.

One example of international cooperation to manage space debris is the Inter-Agency Space Debris Coordination Committee (IADC). IADC is a voluntary, non-binding international forum of space agencies for the worldwide coordination of activities related to the issues of man-made and natural debris in space. As of now, the IADC includes 13 space agencies such as ESA and NASA. One of the initiatives of the IADC is to recommend space debris mitigation guidelines on limiting debris, including minimizing debris released during normal operations, post-mission disposal and prevention of on-orbit collisions.

Space Agencies have also implemented their own space debris mitigation programs. According to the ESA Space Environment Report 2025, ESA has set itself the goal to significantly limit the production of debris in Earth and lunar orbits of all future missions, programmes and activities by 2030 through its Zero Debris Approach.

In addition to the international framework to manage space debris there are also national regulations related to space activities and space debris including how satellites are launched, operated and disposed of to reduce the risk of space debris.

4.2. Cybersecurity in space

Mitigating cyber threats in space is increasingly critical as the reliance on satellites and space-based infrastructure expands across commercial, scientific and defence sectors. Ensuring the cybersecurity of these assets requires a comprehensive, multi-layered approach that spans the entire lifecycle of space systems from design and development to operations and decommissioning.

Cybersecurity in space requires integrating secure design principles early in the development of



spacecraft and ground systems. This includes secure software engineering, tamper-resistant hardware, and thorough security testing to reduce vulnerabilities.

Access control is equally critical, employing measures such as multi-factor authentication and encryption to protect data transmission between space assets and ground infrastructure. Due to the long lifespan of satellites, the ability to update software remotely and patch vulnerabilities is critical. Continuous monitoring and incident response plans further enhance system protection.

System resilience is improved through redundancy and fault-tolerant design, ensuring mission continuity during cyber events. Additionally, securing the supply chain through trusted sourcing and strict vetting reduces risks of compromised components.

International cooperation is fundamental, as cybersecurity in space is a shared responsibility. Global collaboration in threat intelligence, standards development, and joint initiatives strengthens collective defences.

There is no binding international regulation for space cybersecurity but there is a national regulatory framework such as the EU Cybersecurity Act and NIS2 Directive which apply to satellite operators and critical space infrastructure. The NIS2 Directive mandates that European Union Member States adopt national cybersecurity strategies, implement risk management measures, and enhance cooperation among authorities. The directive covers sectors such as energy, transport, finance and digital infrastructure. However, as a directive it must be implemented through national laws which have been delayed in several Member States.

4.3. Space weather

4.3.1. Risk mitigation in Space

Given the unique and multifaceted nature of risks associated with space activities, it is essential to explore a range of mitigation strategies that can help manage and reduce potential exposures. Here are the various measures which can be envisaged to mitigate the risks, starting with risk mitigation in Space, and with additional information accessible through the cited references.

Spacecraft hardening

- **Electrostatic discharge protection:** Multilayer insulation and conductive shielding prevent surface-charge buildup, minimizing single-event upsets (Boteler, 2001).
- **Radiation-resistant electronics:** Error-correcting code memory (ECC) and triple modular redundancy (TMR) in crucial subsystems guard against SEUs (Riley, 2012).

Operational protocols

- **Orbit adjustment:** LEO satellites may adjust perigee during projected peak solar activity to reduce drag and radiation exposure. Geostationary spacecraft can enter safe modes to limit power demand when CME-induced charging is near (ESA, 2016).
- **Redundant Command & Control (C2):** Dual uplinks in distinct frequency bands ensure that, if one channel fails due to solar radio noise, an alternate way exists. Operators should pre-stage critical orders during forecasts of elevated activity.

Hardening spacecraft and adopting operational safeguards are crucial because in-orbit failures can result in total-loss claims that surpass average hull values. In addition risks are mitigated in space by significant design margins and redundancies at all levels. Effective mitigation in space immediately reduces the frequency and severity of satellite insurance claims.

4.3.2. Risk mitigation on Earth

While it is essential to focus on the mitigation of risks specific to space operations, it is equally important to consider the terrestrial dimension of space-related activities. Here are the various measures which can be envisaged to mitigate the risks on Earth, with further details available in the referenced sources.

Electric grid resilience

- **GIC Blockers & series capacitors:** Installation at transformer neutrals prevents quasi-DC currents from saturating cores. Series capacitors in transmission lines limit quasi-DC penetration (Oughton et al., 2019).
- **Adaptive operations:** Grid operators should have storm protocols triggered by Dst and Kp thresholds, including load reduction and islanding of substations when indices cross critical values.

GNSS & communication networks

- **Augmentation systems:** Ground-based augmentation (GBAS) corrects ionospheric delays in real time, maintaining positioning accuracy for aviation and surveying (Thomson et al., 2011; UK Government, 2023).
- **Redundant timing sources:** Terrestrial atomic clocks (e.g., hydrogen masers) provide backup timing for critical telecom and financial networks, ensuring continuity if GNSS signals degrade.

Industrial control systems & critical facilities

- **Shielding & grounding:** SCADA centers should employ enhanced galvanic isolation, optimized grounding grids, and surge arrestors to reduce vulnerability to induced currents (Boteler, 2001).
- **Business continuity planning:** Organizations must conduct tabletop exercises simulating extreme space weather. Exercises should define manual bypass procedures, alternate communication protocols, and pre-positioned spare components.

Earth-based mitigation measures effectively decouple critical infrastructure from immediate storm effects. GIC blockers and grid protocols

can prevent catastrophic transformer failures that could lead to multi-day blackouts with business interruptions in various industries, and potentially also significant losses to the insurance industry. GNSS redundancy maintains critical services – air traffic control, emergency response communications – that, if compromised, would incur large contingent liability and business interruption claims. Demonstrable preparedness at industrial control centers mitigates legal and reputational risk by proving that failures are not due to negligence.

4.4. Regulatory mitigation efforts

The risks outlined earlier are exacerbated by the fact that space regulation, developed within the UN system by the COPUOS (Committee on the Peaceful Uses of Outer Space), remains fragmented, vague and largely reliant on voluntary compliance. The “New Space Economy” is characterized by a growing importance of the private sector, yet the current regulatory system is anchored to international treaties stipulated in the 1960s and 1970s during a bipolar world order where the main spacefaring nations were the United States and the Soviet Union. As a result, it struggles to adequately address today’s complex challenges. This is the case with the 1972 Liability Convention, a key treaty under the United Nations Office for Outer Space Affairs (UNOOSA) which aims to hold launching states internationally liable for damage caused by their space objects both on Earth and in space and ensure compensation for third-party damage. The Convention only allows state-to-state claims, meaning it only accounts for states being liable for space-related damage, and not private actors, therefore not reflecting the commercialized and privatized nature of today’s space industry. Moreover, it does not consider the fact that private actors often operate across borders, hence not establishing which state bears liability in such arrangements. It also fails to account for situations where a space object is hacked or hijacked, potentially holding innocent states liable for damage they didn’t cause and on top of that, there is no enforcement mechanism to ensure compliance other than mutual willingness or diplomatic pressure. For private companies there is no global body with enforcement power that ensures companies meet international standards when sending objects into outer space, but the international legal framework relies on national authorities to license and supervise private actors.

In response to the regulatory gaps at the international level, some countries have taken initiative to respond with national regulations, which

often reflect interpretations of general principles that serve their own interests and domestic priorities, once again highlighting the difficulty of managing global issues through national or regional solutions, therefore weakening the ability to collectively address cross-border risks.

In recent years, however, the international community has made important commitments to address the growing risks deriving from space activities. The adoption of the UN Long-Term Sustainability Guidelines in 2019, together with initiatives such as ESA's "Zero Debris" commitment, reflect a stronger focus on debris mitigation and responsible end-of-life disposal. The International Telecommunication Union continues to refine its regulatory framework to manage orbital crowding and spectrum use, particularly needed in the era of mega-constellations, while on the security front the UN General Assembly approved in 2022 a resolution that bans destructive anti-satellite tests in order to avoid the militarization of space. While these measures are not yet sufficient to solve the challenges ahead, they represent a growing commitment to develop shared norms and cooperative governance of space.

4.5. Insurance as a strategic tool for mitigating space risks

As commercial satellite launches and satellite investments started to grow, so did the demand for comprehensive risk coverage. By the turn of the century, the space insurance market had developed into a specialized global industry capable of underwriting large, complex risks such as multi-satellite constellations and crewed missions.

The global space economy is projected to grow from \$630 billion in 2023 to \$1.8 trillion by 2035. The change that is enabling the rapid growth is access to space, which was previously controlled by large countries or big organisations like the ESA. The opening of the launch market changed the situation, and now many launches are arranged by brokers who seek a slot on a rocket for a fee. Another big change is the use of more cost-efficient off-the-shelf technology, which is making space more affordable for small and medium-sized companies.

Many of today's satellites are small, low-cost and often operating in large constellations. These smaller satellites mainly dominate LEO. First party Property Insurance is not legally required for satellites in orbit, whereas third-party liability insurance can be required in certain countries.



The large majority of the satellites in LEO are not insured for first-party losses. Mainly operators of small CubeSats and small, short-duration imaging satellites choose to self-insure, accepting the risks themselves to avoid premium expenses.

A significantly smaller share of satellites is in Geostationary Orbit (GEO) and of these, commercial satellites are insured. Medium Earth Orbit (MEO) is known as the orbit for navigation satellites managed by governments, which are mainly insured for their launch but often do not have the in-orbit coverage.

While the space insurance market demonstrates significant growth potential, it continues to face challenges primarily due to the high-risk nature of space operations and the limited pool of (re)insurers with the expertise and capacity to underwrite these risks. Furthermore, the high cost of space insurance premiums can pose a barrier for smaller companies.

At the same time, the integration of new technologies and business models in the space industry presents opportunities for innovation in space insurance. The development of small satellites and mega-constellations is generating increased demand for new tailored insurance products.



4.5.1. Mitigating exposure, improving resilience

From the perspective of the (re)insurance industry, space-related risks are not confined solely to entities involved in underwriting space insurance. It is not very common for traditional (re)insurance policies (property, casualty) to explicitly exclude space risks like space weather events from coverage. Instead, their coverage depends on how broadly or narrowly the terms are written especially regarding covered perils, exclusions and definitions like ‘natural disasters’. For example, in the event of an extreme space weather event in combination with large-scale physical damage to power supply infrastructure, the potential losses from power outages – affecting electricity companies, power consumers, and consequently (re)insurance companies through casualty and business interruption payouts – can be significant.

Insurance companies play a pivotal role in the mitigation of space-related risks that pose potential threats to critical terrestrial infrastructure, including communications, navigation, finance, and energy systems. While insurers do not operate space systems directly, they exert significant influence through risk assessment, underwriting practices, and policy conditions, thereby encouraging the adoption of robust risk management strategies among satellite operators and critical terrestrial infrastructure operators. Especially for the electricity transmission network and its key assets ongoing work is needed to implement mitigation measures and response plans, including deploying temporary power generators and short-term portable replacement transformers.

Key mitigation activities include the establishment of rigorous underwriting standards aligned with best international practices, such as those issued by IADC and ESA. Insurers can require comprehensive pre-launch risk assessments focusing on design

and testing to evaluate satellite resilience against hazards, such as space weather, orbital debris, and cyber threats.

Furthermore, insurance providers may incentivize the implementation of advanced security and redundancy measures by offering favorable terms or premium reductions. Insurers can also introduce price loadings in case such advanced security standards have not been matched. This includes promoting the use of encrypted communications, autonomous failover capabilities, and participation in space traffic management systems.

In the context of cybersecurity, insurance providers increasingly require compliance with standardized protocols, including secure data transmission, authenticated access to ground control systems, continuous threat monitoring, and comprehensive incident response strategies. A related example of operational vulnerability is the potential failure of a GPS satellite, which could significantly impact critical sectors such as banking (transaction timestamping), aviation and maritime navigation, and telecommunications (network synchronization). To address such risks, insurers may include in their coverage conditions the implementation of alternative positioning technologies, redundant ground infrastructure, and multi-constellation GNSS receivers to strengthen system resilience. With regard to cyber insurance, these policies typically exclude the exposure from satellites through an infrastructure exclusion.

Additionally, insurance companies often engage in reinsurance and risk pooling arrangements to distribute exposure and collaborate with governmental agencies and infrastructure operators to model the systemic impact of satellite failures on Earth-based services. Through scenario modeling and risk analytics, insurers contribute to enhanced preparedness and resilience against cascading disruptions originating in the space domain.

Outlook

As we consider the complexities of space risks, the future holds promising advancements in both technology and research. These advancements are expected to further improve our understanding and management of space-related challenges.

Innovative new technologies such as artificial intelligence, machine learning, and advanced robotics are anticipated to play an important role in enhancing our capabilities to identify and forecast, monitor, and mitigate space risks. Furthermore, ongoing research in materials science and propulsion systems is likely to yield innovative solutions that will bolster our resilience against the harsh conditions of space.

The outlook for the (re)insurance industry regarding space risks is growing and increasingly important. As space activities expand the risks connected to these activities also rise. The insurance sector is expected to continue playing a key role in helping

manage risks associated with space activities, encouraging safer practices and increased resilience both in orbit and on Earth, and supporting the sustainable growth of the space economy.

Additionally, continued progress is expected in the areas of risk mitigation and adaptation. The development of more robust and adaptive systems will be crucial in safeguarding space missions and assets. Enhanced international collaboration will remain paramount, as well as the need for comprehensive regulatory frameworks, which will be instrumental in addressing the multifaceted nature of space risks. By fostering a proactive approach to risk management, industry, society and governments alike can ensure the sustainability and safety of ambitious and challenging ventures in the future. Through better preparedness, increased resilience and dedicated loss prevention, companies can continue to mitigate space risks and secure their operations on Earth and in Space.



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