Saudi Arabia
Centre for
Space Futures

WORLD
ECONOMIC
FORUM

Clear Orbit, Secure Future: A Call to Action on Space Debris

INSIGHT REPORT

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Foreword

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Humanity has never been more interconnected or data-driven than it is today, and space infrastructure sits at the heart of this transformation. Satellites enable global connectivity, power our economies and underpin the digital systems on which we depend every day. They provide communications in disaster zones, deliver tele-education to remote communities, monitor environmental changes, track disruptions in global supply chains, support farmers in managing their crops and keep our navigation and timing systems running. Over the years, we have grown heavily reliant on data coming from or through the satellites orbiting our planet. Yet this infrastructure is under increasing pressure.

The World Economic Forum and the Centre for Space Futures have jointly led several community consultations to assess the escalating risk and economic cost of space debris, particularly the growing collision risk it presents over the coming decade. Through close collaboration with the Saudi Space Agency and LeoLabs to develop an orbital population model, and with Novaspace to produce an economic forecast, this report quantifies the potential economic impact of space debris on the global space economy.

Under the most optimistic assumptions, space debris imposes a significant and growing economic burden on the sector, even while the current estimated impact may appear temporarily manageable. The projected cumulative cost between 2025 and 2035, ranging between $25.8 billion and $42.3 billion, represents a business-as-usual scenario, one that assumes no major debris-generating events occur.

This cost can be viewed as an implicit "tax" on the global space economy, which will only rise in the decades to come. If the ambitions of a rapidly expanding space economy, encompassing commercial space stations, large satellite constellations and global satellites services are to be realized sustainably, urgent progress is needed in regulation, methodologies, international collaboration, technology innovation and investment.

We hope this publication provides the global space community with valuable insights and guidance to address this growing challenge. Ensuring that the benefits of space remain accessible, reliable and sustainable for all is not only a technical imperative but a shared global responsibility. We invite the community to share their perspectives and feedback as we continue to shape collective solutions for a safer, more sustainable orbital environment.

Executive summary

The number of objects in orbit has surged over the past two decades, driven largely by the expansion of commercial space activity.

Today's population of orbital objects includes active satellites, derelict rocket bodies and inactive satellites, alongside millions of smaller debris fragments. With space infrastructure increasingly interwoven with economic growth and daily life, this growth is starting to affect more than ever the collision risk of existing missions, projections of overall debris fields, planned missions and, consequently, investments committed now and in the future.

Since 2024, the collaboration between the World Economic Forum and the Centre for Space Futures has developed novel quantitative models to illustrate the physical and economic dimensions of the debris challenge. The combined analysis projections find that even with improved adherence to debris-mitigation guidelines, orbital stability will continue to deteriorate between 2025 and 2040, leading to increasing operational costs for space operators.

A model showing the population of orbital debris, developed in collaboration with the Saudi Space Agency and LeoLabs, identifies dense debris clusters forming at altitudes of around 775 km, 840 km and 1,000 km, with the highest-risk band facing up to a 29% probability of a major collision by 2032. Even without a major event, debris in these bands poses an immediate threat as smaller collisions and rocket-body explosions accumulate at an expected rate of 40–50 new catalogued fragments each year.

In order to understand the economic implications of these trends, the debris model formed the basis for an economic valuation analysis developed in collaboration with Novaspace. This valuation estimates cumulative losses of between $25.8 billion and $42.3 billion over the next decade under a business-as-usual scenario, assuming no major, cascading collisions. Most projected losses result from service disruptions, avoidance manoeuvres and premature asset degradation, which reduce mission revenues and longevity. Together, these effects represent a sustained drag on the economic efficiency and profitability of the space sector as well as industries heavily reliant on space data, emphasizing the urgency of collective mitigation.

This report underscores that inconsistent implementation of priority actions – such as universal adoption of the five-year post-mission disposal rule, consistent passivation of spacecraft (for example, removing or neutralizing stored energy sources to prevent explosions) at end-of-life and targeted removal of high-risk derelict objects – limits mitigation of space debris risks. Achieving these objectives will require stronger international coordination across regulatory, financial and governance domains. Neutral conveners play an important role in facilitating transparency, policy alignment and exchange of methodologies among governments, industry and multilateral institutions.

By monitoring implementation outcomes and shared lessons learned with the global space community, the Centre aims to inspire transparency, identify effective approaches and accelerate the adoption of responsible orbital practices.

Introduction

To protect the benefits that space infrastructure delivers, the sector must shift towards proactive, cross-sector sustainability strategies.

Once thought to be a distant aspiration, space technologies now form foundational and critical infrastructure underpinning daily life on Earth. Space is no longer limited to the civilian government or military. Across the globe, society depends on space infrastructure for everything from telecommunications and navigation to global finance and national security, with services increasingly delivered through commercial markets. This has generated a vibrant space economy, valued at more than $600 billion in 2023 and projected to reach $1.8 trillion by 2035.[1]

While space enables global benefits, growing dependence also creates a strategic vulnerability. Any disruption to space infrastructure now directly threatens global security, scientific missions and commercial activity, resulting in potentially severe economic consequences.

One of the most immediate and growing threats to space infrastructure is space debris, which includes everything from small fragments of old satellites to entirely defunct rocket bodies abandoned in orbit. Low Earth orbit (LEO) is becoming progressively more congested with these objects. As of September 2025, LeoLabs tracked 25,081 objects, including 12,000 active satellites and various derelicts. This does not include the millions of fragments too small to track but still highly dangerous to spacecraft, which are the result of decades of global space activities. This cluttered orbital environment poses a systemic risk to critical satellite missions.

The rise of commercial space activities over the past 20 years has further intensified the urgency of ensuring sustainable access to, and safe operations in, the space environment. In the past decade, the increase in the number of active objects has been driven by commercial space actors, who have played an active role in ensuring the overall safety of their mission to protect their economic investments. Nevertheless, the risk of collisions continues to rise due to the increasing number of objects in orbit. Even a single debris-related event in a critical orbit may trigger service disruptions, financial claims and reputation damage, with cascading impacts on nearby missions. More contentiously, past anti-satellite testing activities and collisions have provided a level of debris in space that creates ongoing hazards for current commercial activities.

Space debris is therefore not only a technical challenge but also a strategic issue with profound economic, diplomatic and security dimensions.

Despite initiatives to address this matter, progress has been hindered by geopolitical tensions and economic uncertainties. The lack of a unified diplomatic mechanism to address the issue of space debris leaves the global community without a structured way to address shared vulnerabilities and develop collective solutions. This gap highlights the urgent need for international cooperation, policy innovation and economic incentives to ensure the long-term reliability and safety of space activities.

Before actors can identify which solutions are the most appropriate to pursue, they must first share an understanding of how the debris landscape will evolve in the coming decades, what the potential cost to satellite operations may be and what range of solutions may be required to ameliorate the problem. Through technical modelling and economic analysis, this report aims to provide a shared baseline for evaluating debris remediation and mitigation solutions. A high-level overview of this integrated modelling framework, from population projections to economic impact, is illustrated in Appendix A.

Space capabilities are vital to modern life on Earth, and their safe operation is a shared responsibility. Space debris is a growing strategic risk that threatens the reliability of satellite services and the sustainability of all space activities. Without concrete action, both the space sector and the terrestrial economy will have to shoulder the rising costs. Addressing this issue requires a shift in perspective from viewing debris as a technical nuisance to recognizing it as a systemic challenge that demands coordinated global action.

1 Understanding the debris landscape

Without mitigation, the probability of a serious collision occurring by 2032 is potentially 29% in certain altitude zones.

Space debris consists primarily of defunct satellites, abandoned rocket bodies and fragments from past explosions or collisions.

Space debris consists primarily of defunct satellites, abandoned rocket bodies and fragments from past explosions or collisions. While thousands of these objects are tracked, millions of smaller pieces remain untrackable yet capable of inflicting significant damage. For example, debris fragments as small as 5 mm can damage a satellite, while debris larger than 1 cm can terminate a satellite's mission. These non-trackable objects, typically smaller than 10 cm, outnumber catalogued fragments by many orders of magnitude and pose the main debris threat to spacecraft reliability.

Debris populations and risk findings published for the first time in this report rely on an orbital population model developed by the Saudi Space Agency and LeoLabs in collaboration with the Centre for Space Futures. The low Earth orbit (LEO) population model functions as a digital twin of the orbital environment, a simulation that projects how the number and type of objects in orbit will change from 2025 to 2040 and what risks they pose to spacecraft operations. A detailed description of the methodology and assumptions behind this model can be found in Appendix B.

Based on these projections, this report aims to answer an important question: "What is the likelihood that a given satellite will be struck by an object of a certain size within a year?" This is projected by calculating the probability of collision using established statistical methods, applying representative assumptions for object size, mass and motion. This translates the physical population of debris into a clear percentage of risk.

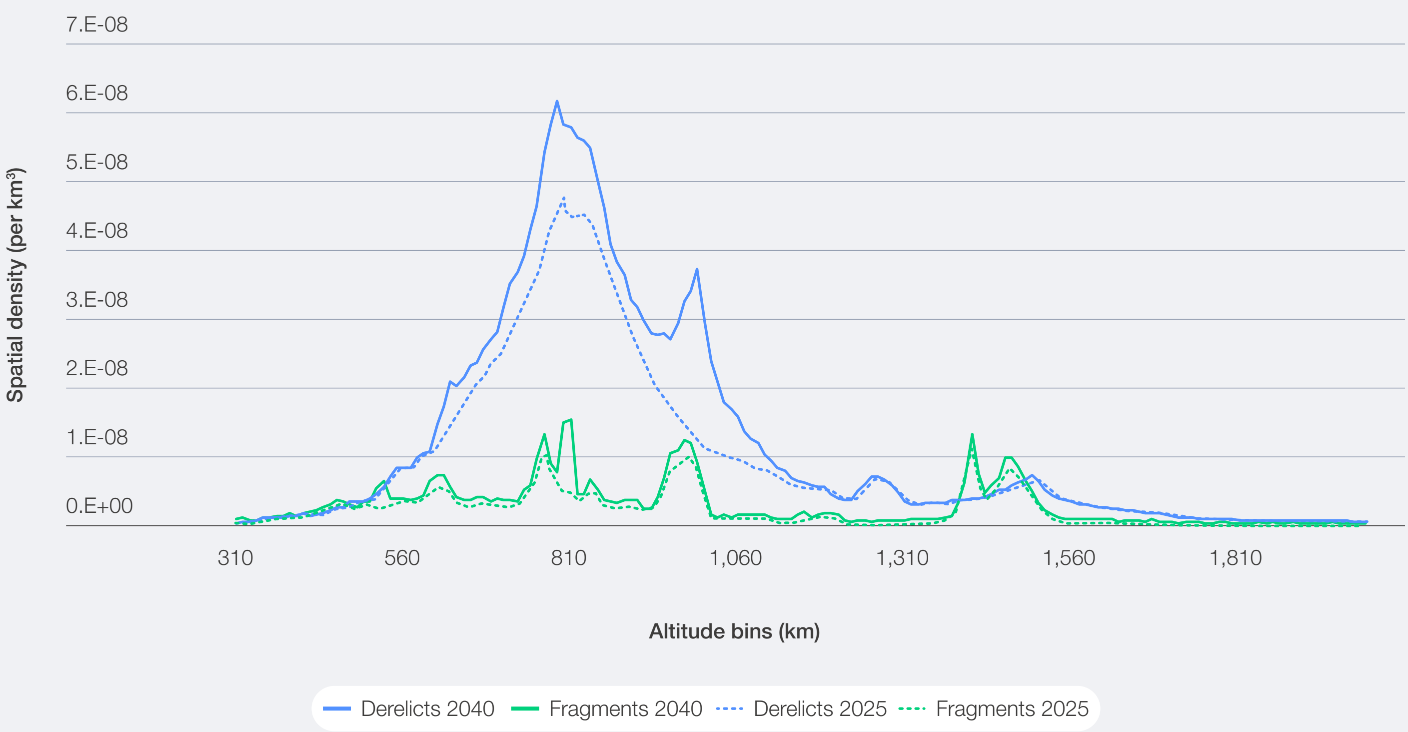
The results reveal that collision risks are not evenly distributed across orbital altitudes. There are three clusters that already represent particularly dangerous altitude zones – around 775 km, 840 km and 1,000 km – where dense collections of heavy derelicts and older fragment clouds overlap. If no further mitigation occurs, the probability of a serious collision in these clusters by 2032 is estimated at 8%, 6% and 29%, respectively.

Below 600 and 700 km, atmospheric drag naturally clears debris, but above that altitude, fragments can persist for centuries. This persistence explains why the 800–1,000 km altitude band has been labelled the "bad neighbourhood" for LEO.

The findings are based on a clear set of foundational assumptions, detailed in Appendix B. These assumptions create a conservative, business-as-usual baseline. For example, the model assumes that satellite operators will become more compliant with disposal guidelines over time and that no active debris removal missions will affect the debris population before 2040. Together, these assumptions define the model's boundaries while illustrating how behavioural and policy choices directly shape both the physical and economic trajectory of space activity.

FIGURE 1 **Debris levels of intact derelicts and fragments (2025–2040), showcasing the peak fragment spike getting worse around 800 km**

Intact derelicts and fragments: 2025 vs. 2040



Source: Saudi Space Agency and LeoLabs

1.1 Understanding the model

Development of the orbital population model started from a full snapshot of the orbital catalogue as of May 2025, encompassing every known object tracked by the US Space Force and mirrored in the LeoLabs catalogue. Each object is classified into one of three categories:

1. Operational satellites → functioning payloads
2. Intact derelicts → inactive satellites and rocket bodies
3. Fragments → pieces of debris produced by explosions or collisions

Using this baseline, the model projects in five-year increments (2025–2030, 2030–2035 and 2035–2040), updating the population in each step by adding newly launched satellites, newly abandoned derelicts based on observed failure trends and newly generated debris from expected fragmentation events.

Each step yields a spatial density map (how many objects exist in each 10 km altitude slice between 300 and 2,000 km) and applies representative assumptions for their size, mass and motion. A typical working satellite is modelled with a 3 m^2 cross-section, an inactive rocket body with 8 m^2 and 1,400 kg mass and debris fragments with 0.04 m^2. Conjunctions and impacts in low Earth orbit occur at roughly 12 km/s, meaning even millimetre-sized fragments can puncture critical spacecraft components.

To mimic real-world behaviour, the model also introduces expected fragmentation events, including rocket-body explosions in 2029, 2033 and 2037, each producing roughly 350 new tracked fragments and thousands of small non-trackable ones. For every catalogued fragment (>10 cm), there are an estimated 90 lethal non-trackable (>1–10 cm) pieces and 250 hazardous non-trackable (5 mm–1 cm) pieces, objects too small to track but capable of terminating or degrading a spacecraft's mission.

1.2 Phases and uncertainties

These uncertainty levels determine the confidence intervals applied to each five-year modelling phase. In practice, they define how widely the model's outputs – such as object counts, collision probabilities and debris growth rates – may vary from baseline scenarios. A ±10% uncertainty reflects relatively reliable inputs, since near-term launch manifests and constellation plans are well documented. By contrast, the ±50% uncertainty reflects the compounding unpredictability of future operator behaviour, market consolidation, regulatory enforcement and unplanned fragmentation events. The wider the uncertainty band, the greater the dispersion of projected debris densities and collision risks that feed into the economic model.

Because operational practices evolve over time, the model does not assume a single, static future. Instead, it projects the risks from 2025 to 2040 in three developmental eras:

TABLE 1 **Confidence intervals applied to each five-year modelling phase**

Phase	Period	Description	Uncertainty
Constellation revolution	2025–2030	Rapid deployment of mega-constellations	±10%
Constellation maturity	2030–2035	Improved reliability, lower failure rates	±20%
Constellation evolution	2035–2040	Mergers, migration to lower orbits	±50%

1.3 Translating population into risk

Even small annual probabilities accumulate to form a notable threat across tens of thousands of spacecraft. For instance, a satellite operating near 805 km in 2035–2040 faces a 1.5% chance of an anomaly and a 0.55% chance of mission-ending impact per year, small individually but substantial collectively.

To translate broad projections into specific risk probabilities for a typical satellite, it is crucial to understand the annual likelihood of an impact for a representative satellite (3 m^2 cross-section) from three different categories of debris, each with a different real-world consequence.

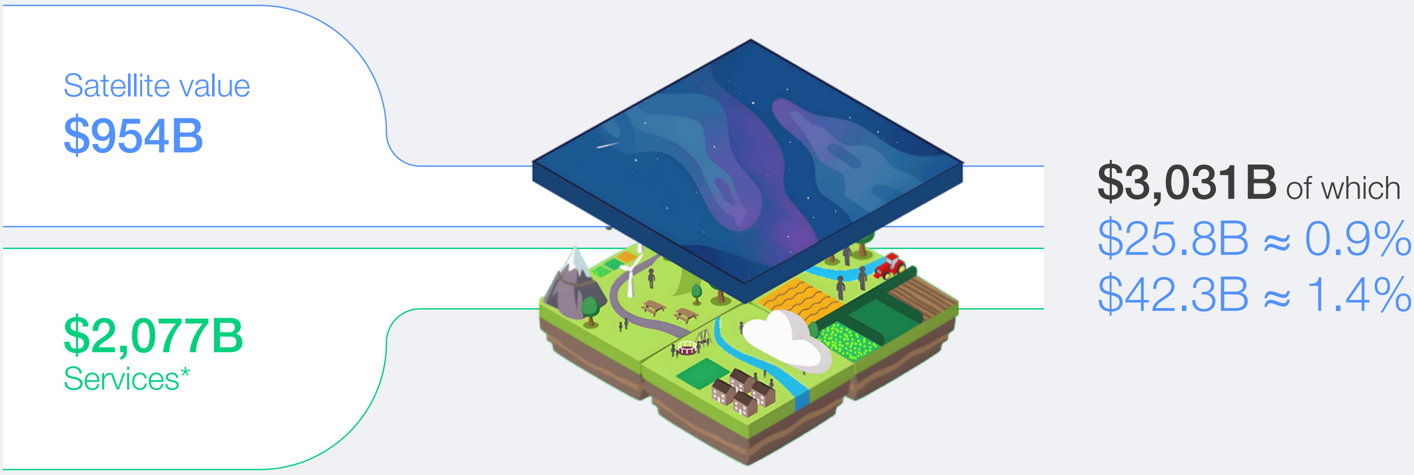
TABLE 2 **Specific risk probabilities for a typical satellite**

Symbol	Description	Likely effect
PC(HNT)	Probability of collision by hazardous non-trackable debris (5 mm–1 cm)	Causes a non-mission-ending anomaly, such as temporary service disruption or partial damage
PC(LNT)	Probability of collision by lethal non-trackable debris (>1–10 cm)	Causes mission-ending damage or total loss of the satellite
PC(Cat)	Probability of close approach with tracked object	Requires an operator to perform a collision-avoidance manoeuvre

2 Economic impact of inaction

Inaction imposes a hidden tax on the space economy, projected to cost $25.8–42.3 billion in a business-as-usual scenario by 2035.

FIGURE 2 | **Cumulative total value of satellites and their services from 2025 to 2035**



Note: *Includes the value of services in low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary Earth orbit (GEO)

Source: Novaspace, 2025

To convert the physical risks of debris identified in the orbital population model into economic costs, the valuation categorizes collision types corresponding to specific economic impacts, detailed in Table 3.

TABLE 3 | **Specific economic impacts of collision types**

Collision type	Physical outcome	Economic impact
HNT (5 mm–1 cm)	Temporary malfunction	Lost service revenue, repair or back-up activation
LNT (>1–10 cm)	Total mission loss	Replacement and launch cost, insurance payout
PC(Cat)	Avoidance manoeuvre	Fuel consumption, shortened lifetime, labour cost

For each collision type, the probability of occurrence as a factor of the estimated financial consequence produces an expected-value range rather than a single figure. When aggregated across all LEO assets between 2025 and 2035, this yields between $25.8 billion and $42.3 billion in expected losses. These losses represent approximately 0.9% to 1.4% of the $3.03 trillion total projected value of the entire global space economy (including LEO, MEO and GEO services) over that same ten-year period (see Figure 2).

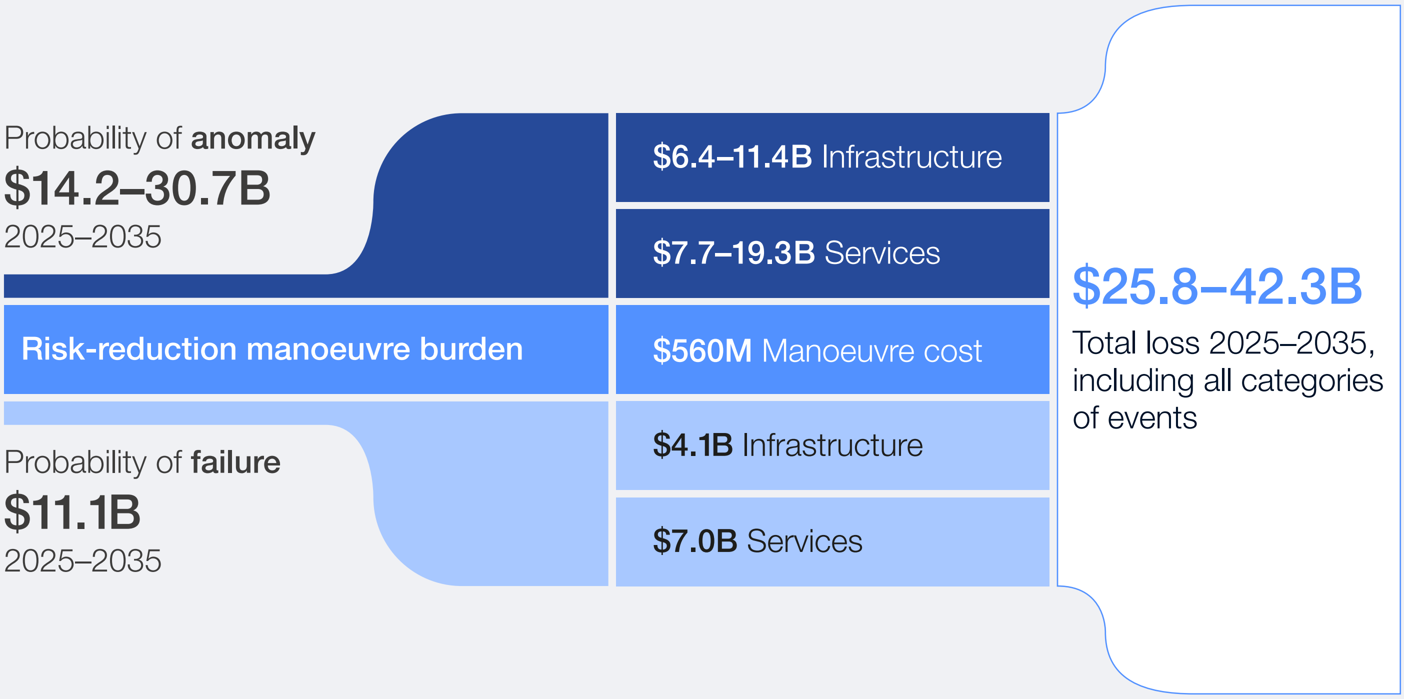
BOX 1 | **Cumulative total value of satellites and their services of 2025–2035**

- Total satellite value (combined manufacturing cost and launch cost) 2025–2035: $954 billion
- Total value of the services rendered by the satellites in orbit 2025–2035: $2,077 billion
- The potential economic loss from orbital debris collisions with satellites is $25.8–42.3 billion, which represents between 0.9% and 1.4% of the total value over the decade

These losses can be broken down into specific areas of impact (see Figure 3):

- $14.7–26.3 billion from service disruptions and degraded performance
- $10.5–15.5 billion from physical asset loss
- $0.56 billion from collision-avoidance manoeuvres

FIGURE 3 **Economic impact of orbital debris collisions over the decade according to different categories of events**



Note: Includes the value of services in low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary Earth orbit (GEO)

Source: Novaspace, 2025

Orbital debris already imposes a measurable economic drag, a hidden cost absorbed by satellite operators, insurers and downstream industries reliant on uninterrupted space services. A detailed description of the economic valuation methodology and assumptions can be found in Appendix C.

Using the orbital population model, together with the market valuation and satellite forecasts, this report presents the first integrated economic assessment quantifying the cumulative operational and service-level impact of orbital debris.

Although the annual risk to any single satellite is low, the cumulative effect across thousands of spacecraft is substantial. Scaled across constellations and years of operation, these small probabilities translate into higher fuel use, lost data, tighter profit margins and stricter insurance terms, even in the absence of major incidents.

The projected cost range represents a business-as-usual baseline. It is critical to note that this is a conservative estimate. A single catastrophic event excluded from the debris population model, such as a large-scale collision in a dense cluster or a deliberate anti-satellite (ASAT) test, could far exceed these estimates and drastically amplify losses.

The figures highlight a persistent and escalating economic burden. Proactive action – through improved mitigation, remediation and coordinated international governance – is essential to prevent these baseline costs from further compounding the systemic constraint on the growth of the space economy.

2.1 Understanding the range

> Because there are far more small, non-trackable fragments in orbit than larger ones, they are the most significant and frequent source of anomalies.

The wide range in this estimate – from $25.8 billion to $42.3 billion – is driven by the high level of uncertainty surrounding the real-world impact of small, non-trackable debris. To understand the variation in this range, further details about the methodology of the economic valuation can be found in Appendix C.

Potential economic losses derive from collision risk across three categories:

1. **Collision with subsequent anomaly**

   The probability of an anomaly caused by hazardous non-trackable debris with objects measuring between 5 mm and 1 cm. The losses are partial, and the service degradation is temporary without causing the destruction of the spacecraft.

2. **Collision with subsequent failure**

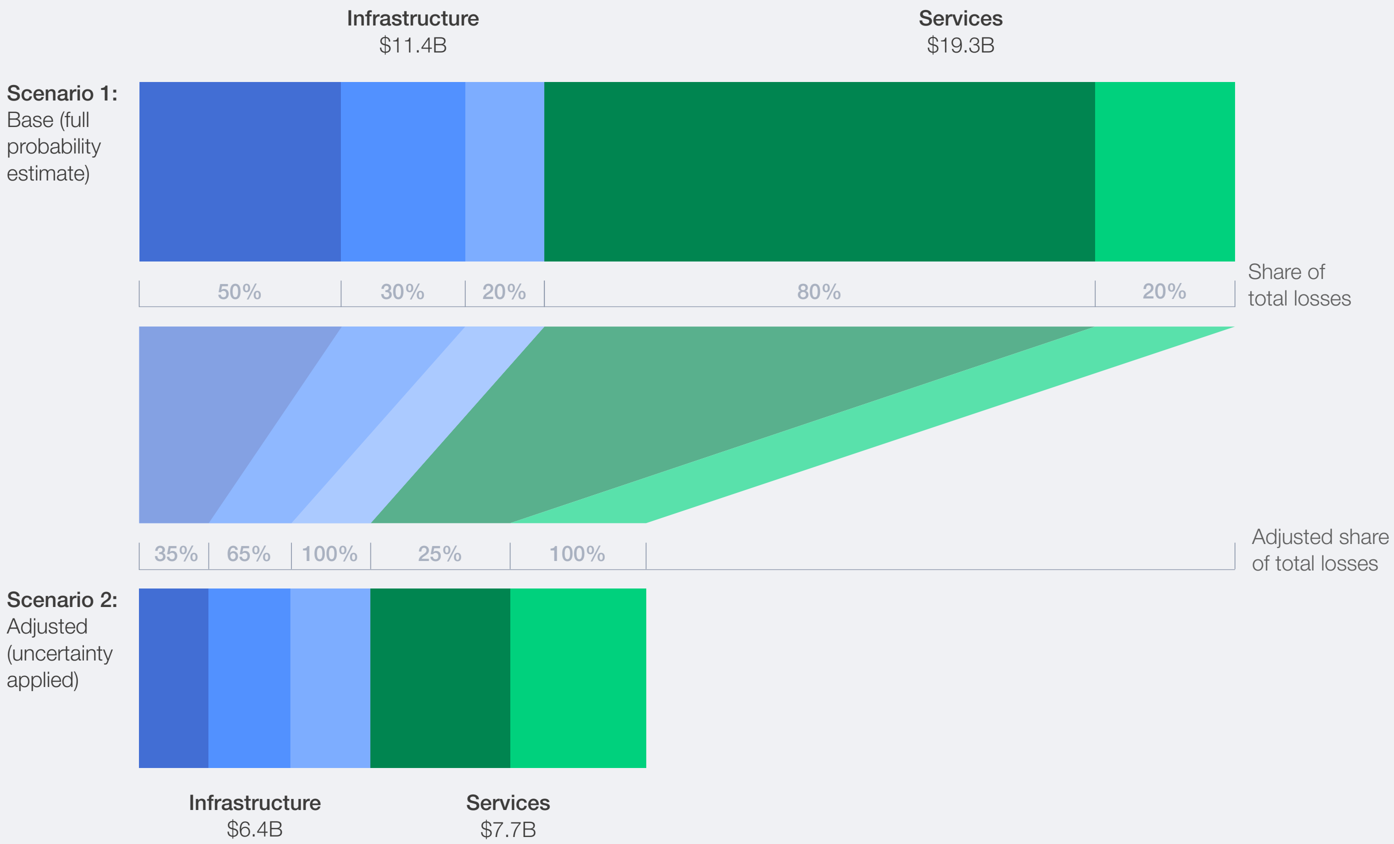
   The probability of failure caused by lethal non-trackable debris, defined as objects between 1 cm and 10 cm in size.

3. **Collisions avoided through preventive manoeuvres**

   The probability of collision with catalogued objects, i.e. debris that can be reliably tracked and considered for collision prevention.

Because there are far more small, non-trackable fragments in orbit than larger ones, they are the most significant and frequent source of anomalies. This means that Category 1 is the most significant and uncertain element of the total cost.

FIGURE 4 | **Two scenarios to represent the uncertainty in anomaly events (2025–2035)**



Source: Novaspace, 2025

> **While most anomalies may be minor, a small fraction can cause lasting damage that shortens a satellite's lifespan.**

The effects of these anomalies are not uniform. While most may be minor, a small fraction can cause lasting damage that shortens a satellite's lifespan.[2] The effects of anomalies are also non-linear. The way operators respond to anomalies, such as the time and resources spent on diagnosing or mitigating issues, adds further economic costs that are difficult to capture.

To account for the impact of Category 1 uncertainty, the valuation uses distinct approaches to create two scenarios.

In scenario 1, the economic estimation model applies a deterministic expected-value approach, using the annual probability of collision derived from the orbital population model. This represents the upper-range estimate of projected losses of approximately $30.7 billion (see Figure 3), based on the annual value of anomaly events derived from the collision probability model. Even at this level, the estimated impact equals only about 1.4% of the space industry's projected $3.03 trillion in cumulative infrastructure and services value over the next decade, and it treats the model's probabilities as the best reflection of current knowledge.

In scenario 2, the valuation supplements the deterministic approach with an uncertainty-aware scenario that provides a range of possible outcomes rather than a single figure. While the valuation cannot fully capture the severity of anomalies due to its expected-value design, it allows for adjustments to the expected value to better reflect the variance in outcomes of an anomaly event. When incorporating uncertainty adjustments, it is assumed that most anomalies have limited effects, such as minor malfunctions or temporary service interruption. Applying this uncertainty factor to both infrastructure and services yields an estimated impact of $14.2 billion.

BOX 2

Economic impact of orbital debris collisions over the decade

- Total impact in 2025–2035, including all types of events: $25.8–42.3 billion
- Probability of an anomaly (2025–2035): $14.2–30.7 billion, of which $6.4–11.4 billion is due to infrastructure damage and $7.7–19.3 billion is from service disruption
- Probability of a failure (2025–2035): $11.1 billion, of which $4.1 billion is due to infrastructure damage and $7.0 billion is from service disruption
- Risk-reduction manoeuvre burden (2025–2035): $560 million

Source: Novaspace, 2025

The differences between these two scenarios highlight the need for continued research and greater industry input to refine anomaly modelling, particularly in differentiating between minor failures, system-level anomalies and collisions with catalogued objects where uncertainties are narrower.

The uncertainties surrounding anomaly events create a significant gap between expected values and possible real-world outcomes. Greater clarity from industry and academia would help policy-makers adapt rule-making to areas with the highest potential damages and recognize where impacts may be minimal. Areas where more insight is particularly needed include:

1. **Magnitude of damage:** How hazardous non-trackable debris affects spacecraft lifespan or causes physical damage
2. **Service disruption:** Whether or how often services are interrupted following an anomaly event, and the duration of such interruptions
3. **Operator response:** The length of time and amount of resources operators dedicate to assessing and mitigating the effects of impacts with hazardous debris
4. **Mission type differences:** How these factors vary between single-satellite missions and large constellations

2.2 Possible futures for debris costs

“ If current mitigation and coordination norms remain unchanged, the orbital environment will steadily become increasingly costly, hazardous and unpredictable to operate in.

If current mitigation and coordination norms remain unchanged, the orbital environment will steadily become increasingly costly, hazardous and unpredictable to operate in. Collisions and fragmentations are statistical certainties over long-term horizons and are increasingly likely in the near term within specific, densely populated orbital bands.

Fast satellite growth, dense clustering around altitudes of 500–600 km and persistent debris reservoirs between 850 km and 1,000 km increase the frequency of close approaches and manoeuvring demands, especially for spacecraft with limited or no ability to manoeuvre. Experts estimate that only six fragmentation events created circa 50% of the current fragment population in LEO.[3]

For crewed platforms in LEO, each new fragmentation event adds debris that drifts downwards through their operating corridor. This forces expensive avoidance manoeuvres and raises residual risks from smaller, non-trackable debris. Without stronger measures, such as post-mission passivation of spacecraft, shorter disposal timelines and targeted removal of high-risk derelicts, the probability of damaging encounters will increase. In response, operators are adopting more conservative mission designs that require greater fuel reserves and additional shielding, both of which increase mass and cost while reducing operational efficiency and lifetime.

Operationally, a status quo future could mean:

- Operators will be forced to perform more frequent avoidance manoeuvres, shrinking mission margins and consuming fuel needed for primary operations.
- Satellites will suffer from higher anomaly rates caused by non-trackable fragments, leading to more frequent service disruptions.
- Missions will face growing design penalties, as satellites will require more shielding and propellant, reducing their performance and efficiency.
- New entrants will face elevated risks when launching into already congested orbital shells.
- As loss probabilities rise, insurance premiums will surge, coverage will narrow and parts of the orbital environment may become effectively uninsurable, further discouraging investment and innovation.

2.3 Understanding the impact of debris

The report's data estimates suggest that service interruptions could cost up to $26.3 billion, compared to $15.5 billion in infrastructure damages.

The socioeconomic risks of orbital congestion extend beyond the direct costs quantified in this report. Analysis from the Organisation for Economic Co-operation and Development[4] highlights the broader value at stake:

Value at risk: An estimated $191 billion in global economic activity in 2024 depends on satellite services, with the bulk of the value concentrated in orbits in the congested 500–600 km orbital band.

Benefits at stake: Satellite-enabled services generate major public benefits. Weather forecasting avoids about $1.4 billion in costs annually, while air-quality monitoring satellites could save thousands of lives each year.

Rising collision-avoidance activity, shortened spacecraft lifetimes and recurring service interruptions translate these physical risks into sector-level economic consequences:

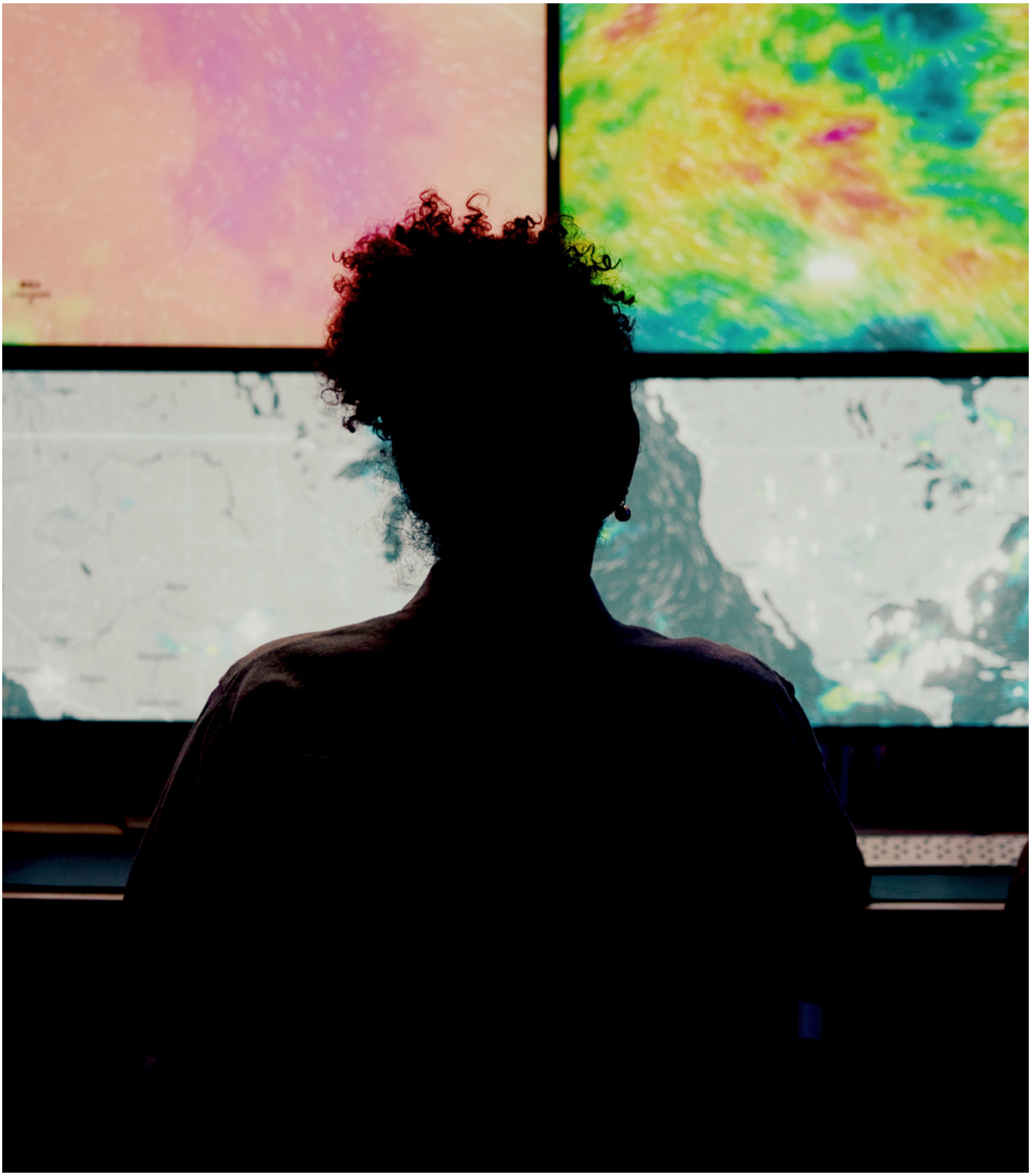
Telecommunications: Degraded signal quality and downtime leads to corrective mechanisms, service credits and customer churn.

Earth observation: Data discontinuity weakens for scientific and safety applications and for commercial services such as insurance, supply-chain monitoring and carbon accounting.

The report's data estimates suggest that service interruptions could cost up to $26.3 billion, compared to $15.5 billion in infrastructure damages, showing that the primary burden lies in lost service value rather than hardware replacement. However, the indirect consequences – including degraded connectivity, less accurate navigation signals and reduced availability of Earth observation data – could have far greater and wider-ranging economic and societal impacts than the direct cost alone.

3 Forging a path forward

A pragmatic shift from voluntary guidelines to binding rules, new economic incentives and diplomacy focused on building trust can mitigate debris-related risk.



Addressing the challenge of space debris demands a coordinated, multidimensional approach that links technological innovation, economic incentives, legal and policy reform and international diplomacy. The roots of today's debris problem lie in the operational behaviours and design practices of the past six decades. Managing its consequences, however, requires more than improving compliance among current actors; it calls for significant advances in spacecraft design and end-of-life technologies, new market mechanisms that reward responsible operations, modernized governance frameworks and stronger global cooperation.

3.1 Technology

Technological innovation sits at the core of any sustainable debris strategy. The near-term priority is to reduce the creation of new debris through smarter design, automated collision avoidance and reliable post-mission disposal. In the longer term, progress depends on remediation capabilities that can actively remove or neutralize existing objects. Together, mitigation and remediation (see Table 4 for more detail) define the technological pathway to a safer and more stable orbital environment.

TABLE 4 **Mitigation and remediation serve different needs**

Aspect	Mitigation	Remediation
Purpose	Preventing new debris	Removing existing debris
Timing	Before or during mission	After debris is already in orbit
Cost and complexity	Lower	Higher (tech-intensive, costly)
Policy role	Compliance-driven	Incentive-driven or publicly funded

Most technology solutions from prevention to monitoring, active debris removal (ADR) or in-orbit servicing are still technically immature, highly costly and, for now, not commercially viable.

Significant challenges continue to impede the large-scale implementation of these technologies. The sector still faces obstacles that hinder widespread adoption and operationalization. Most technology solutions from prevention to monitoring, active debris removal (ADR) or in-orbit servicing are still technically immature, highly costly and, for now, not commercially viable. The absence of sustainable business models and committed anchor customers further limits private investment and delays deployment. While industrial actors often advocate for such missions, few have succeeded in creating consistent demand beyond a single partial in-orbit demonstration and/or validation mission because of the lack of scalability and integration into operational frameworks. The transition from proof of concept to routine service remains challenging. Appendix C provides an overview of the main challenges and cost-related considerations per technology type.

The commercially driven services related to LEO satellite constellations have intensified the need for reliable conjunction analysis and collision avoidance planning, as frequent manoeuvres directly affect fuel budgets and satellite lifetimes. This has spurred a growing market for space situational awareness (SSA) services, although challenges persist in interoperability (e.g. lack of standardized interfaces for telemetry and manoeuvre data), high infrastructure costs and fragmented governance. Solutions, such as autonomous collision-avoidance systems and AI-enhanced SSA analytics, are beginning to play a critical role in operational safety and mission efficiency.

However, these systems cannot prevent debris-on-debris collisions, nor protect against impacts from small, non-trackable debris affecting active satellites.[5] In the longer term, technologies such as ADR, in-orbit servicing and recycling capabilities will be essential to achieving a sustainable orbital environment. Global actors are increasingly accelerating investments into these technologies. For example, China's current five-year roadmap[6] focuses heavily on testing new technologies for space mission extension vehicles, innovative space propulsion and "space debris cleaning" capabilities.

These technologies still face major technical challenges. Important limitations include restricted artificial intelligence (AI) autonomy, lack of durable radiation-hardened onboard computing and processing[7] and the absence of common docking interfaces.[8] Meanwhile, in-orbit recycling and manufacturing further require breakthroughs in material separation, contamination control and system compatibility across diverse spacecraft designs. Overcoming these obstacles will be critical to scaling next-generation debris removal and servicing missions.

A clear business case is needed for generating returns, alongside coordinated public procurement frameworks that can de-risk these early deployment challenges.

Despite ongoing innovation, the debris-mitigation and remediation sector remains constrained by immature technologies, limited market readiness and insufficient policy and procurement frameworks. The wave of private-sector entrants and commercialization since the 2010s, sometimes referred to as "new space", has yet to translate into scalable investment or sustained demand for debris-related capabilities, leaving public programmes as the primary source of funding.

The challenge is largely circular: without proven and affordable technologies, customers hesitate to commit; without anchor customers or long-term contracts, investors remain cautious; and, without funding, costs stay high and progress slows. A clear business case is needed for generating returns, alongside coordinated public procurement frameworks that can de-risk these early deployment challenges.

3.2 Economy

As is frequently the case, a significant part of the overall challenge is economic. For decades, it has been the standard approach to simply leave old rocket bodies and satellites in orbit due to the high cost of removal and lack of clear financial incentives to deorbit them. The most cost-efficient approach currently is to avoid the debris that can be seen, while accepting the damage from smaller objects that cannot. The overall collision risk is deemed low enough by most actors to not warrant more expensive types of intervention or changes in regimes and behaviour. Lack of alignment in the sector means that no single actor wants to take first steps due to the risk of becoming uncompetitive.

The risk of collisions with and between large derelict objects has been low enough not to warrant investment in removing these; the cost of adjusting one's trajectory is relatively insignificant – $560 million for all actors in LEO over the coming 10 years per this report's findings.

While immediate focus on policy alignment and data sharing may lead to the greatest gains, new economic models are essential to fund technological solutions and encourage sustainable activities. Some of the most relevant approaches could include:

1. **Insurance:** Currently, most space insurance covers launch and in-orbit operations, primarily protecting the asset itself and third-party liability, but it is increasingly under strain as a sub-sector.[9] Reimagining it in new ways to help address orbital sustainability beyond operations, however, could generate new resources to deal with debris, although facing additional practical challenges. Insurance models typically rely on historical data to assess risk and set premiums, which limits their ability to predict risk of potential space debris related losses. The sector also primarily covers launch and initial operations, with limited coverage for

“ As technology solutions mature and the cost of inaction becomes more widely understood, opposition to such financial frameworks may diminish.

the entire lifespan of a satellite and no universal mandate for operators to carry insurance covering debris removal. Lastly, government assets, which comprise the majority of debris objects, are often self-insured or uninsured.

Despite these limitations, insurance could play a targeted role in incentivizing future commercial responsibility. For example, regulators could require new insurance products that cover end-of-life disposal, theoretically creating a funding pool for remediation missions if a satellite fails. While this would require a mechanism for translating payouts into debris remediation, it could create market-based incentives to adopt new technologies, such as ADR-compatible docking plates, in exchange for lower premiums. Such a system may include models such as a tiered insurance approach, offering lower rates for operators who follow all guidelines, or a captive mutual model where third-party liability coverage is shared among operators, contingent on all parties meeting strict sustainability standards. While not a complete solution, a reimagined framework could serve as an economic lever to align commercial incentives with long-term orbital safety.

2. **Performance or surety bonds:** A similar market-based mechanism, performance bonds would require an operator to set aside funds that are only returned upon successful completion of their end-of-life disposal plan. This creates a direct financial incentive for compliance and provides a source of funding for remediation if obligations are not met.[10]

3. **Economic instruments:** Other mechanisms – such as taxes, corrective mechanisms, credits and subsidies – could be used in combination to influence actor behaviour. These instruments typically require a mature regulatory structure and a high degree of international alignment to prevent the creation of competitive disadvantages for any single nation’s industry and due to the physical nature of space where the actions of one actor can potentially impact all other space assets.

4. **Public–private funding models**: A public–private partnership (PPP) could be seen as a more inclusive way to direct financial resources in dealing not only with specific debris linked to a given actor but also with the broader debris population, including pieces that exist today and are not attributable. Powerful precedents for this type of hybrid governance exist in the maritime and climate sectors. For example, the International Oil Pollution Compensation Funds, established under the International Maritime Organization, provide a liability and compensation regime for oil tanker spills. This system is funded through mandatory contributions from companies that receive oil by sea, based on a “polluter pays” principle. This approach successfully internalizes the negative externalities of the industry and ensures that a mechanism is in place for compensation and clean-up, offering a proven pathway for how the space sector might manage debris. While complex, such an approach could be considered an alternative to previous types of instruments and a preferred method by the private sector.

All these economic solutions require regulatory advances to implement. As technology solutions mature and the cost of inaction becomes more widely understood, opposition to such financial frameworks may diminish.

3.3 Law and policy

The process for implementing space sustainability legislation and policy can often be hindered by the economic trade-offs created for domestic industry, a lack of regulatory capacity in some nations and national security considerations in others. However, addressing foundational obstacles in space law and policy will be crucial to supporting technological and economic efforts in mitigating and remediating space debris. A robust international consensus on methodologies already exists, built upon key international efforts.[11,12,13,14]

The most effective path forward is for nations to build on this shared baseline by implementing guidelines into binding domestic law and maintaining international consistency for commercial operators. Implementing guidelines can be driven through several national-level tools, including licensing conditions, procurement standards for government contracts and market access rules that apply standards equally to all operators wishing to serve a country's market. For example, China requires all domestic operators to submit a dedicated debris mitigation plan that covers passivation and disposal as a mandatory prerequisite for obtaining a launch permit.[15] Furthermore, there is a need for commonly accepted, practical and objective standards that can fill the gaps in binding law and be more easily adopted by emerging space nations that may lack extensive regulatory capacity.

The push for accelerated post-mission disposal is a clear example in debris mitigation, supporting the Long-Term Sustainability Guidelines (LTS Guidelines)[16] for either controlled deorbiting or the removal of space objects into a controlled orbit following the termination of their operations. The United States' Federal Communications Commission has shifted from a 25-year to a five-year deorbit rule for commercial low Earth orbit satellites licensed in the US. Canada's government is in consultations to adopt a similar rule, while the proposed EU Space Act is also expected to set a legal obligation for a five-year maximum orbital lifetime, in line with the European Space Agency's (ESA) Zero Debris approach. Similarly, India has announced its debris-free space missions initiative,[17] aiming for zero debris generation by 2030 and requiring a post-mission orbital lifetime of less than five years for all governmental and non-governmental missions. To make implementation plans that are flexible to differing commercial capabilities, countries can focus on requiring technology-neutral, performance-based, accelerated post-mission disposal plans as a condition for national licensing.

Additional LTS Guidelines can also be integrated into national legislation, such as requiring updated contact information and information sharing on space objects and orbital events. Mandating the sharing of such information through centralized, government-led platforms, direct operator-to-operator exchanges, as many satellite operators already practise, or neutral third-party platforms, would support global efforts for space traffic coordination. The US government's TraCSS programme[18] provides a civil-led service for operators and the European Union's EUSST service[19] is a government-supported consortium that also provides collision avoidance alerts free of charge to global operators, demonstrating a parallel approach to providing SSA as a public good. However, a standardized system for data sharing at the international level will likely still be necessary.

On debris remediation, the Outer Space Treaty[20] creates legal uncertainty for ADR missions. Article VIII states that the state of registry retains jurisdiction and control over its space objects, while Articles VI and VII outline state responsibility for national and private space activities and liability for damage caused by their space objects. This ambiguity means that a commercial company that attempts an ADR mission, even with consent, could be held liable for any new debris generated, discouraging the investment needed to accelerate technologies essential for removing identified high-threat derelict objects.

A scalable solution requires a clear legal framework for the transfer of responsibility, liability and operational control, supporting the market certainty needed to overcome the cycle of technology development waiting for regulatory clarity. This could begin with bilateral or multilateral "safe harbour" agreements for specific authorized missions, such as the one underpinning ESA's ClearSpace-1 mission.[21] Furthermore, such a legal framework could introduce a viable financial model for liability, as standard insurance markets may not yet be equipped to cover such high-stakes missions alone.

Solutions will also require the political will to implement them. In the US, non-partisan legislation, such as the US ORBITS Act,[22] has stalled, but other nations have successfully moved forward in debris legislation. For example, Japan has taken concrete action to establish domestic frameworks for debris remediation and is currently developing international regulations and legal frameworks for active debris removal. In this sense, law, regulation and policy are closely interconnected with economic and technology solutions while creating economic incentives may help encourage political progress.

3.4 Diplomacy

> Diplomatic efforts to address debris must harness commercial innovation and market opportunity while ensuring that the process aligns with long-term orbital sustainability.

Strategic mistrust and a lack of consistent data sharing are the most significant diplomatic barriers to addressing space debris. These multilateral dynamics create operational uncertainty that directly increases the risk of exceeding the $42.3 billion in potential economic losses. The friction between space powers is primarily rooted in the dual-use nature of debris-remediation technologies, as the capability needed to remove debris could also be used to tamper with an active satellite. While these tensions are most pronounced between the major debris-generating nations, they impact the entire global space community.

This operational mistrust is a symptom of the deeper issue of trust between dominant space actors who host the majority of space-based systems delivering global benefits as well as the technologies capable of causing significant debris-generating events. Seemingly reasonable proposals from either side face challenges in moving forward due to opposition from the other. Building a common baseline of communication and trust is crucial, beginning with international approaches to transparent data sharing and space traffic management. A federated international model for data sharing should be an immediate priority. While technically feasible, its primary diplomatic hurdle will be establishing a neutral governance framework that answers critical questions of funding, oversight and standard-setting. This model must address more than just technical data exchange, as a contact list is insufficient without established trust and a willingness to respond. It would also need to prioritize interoperability between sovereign space situational awareness systems and address operational burdens caused by conflicting sources and isolated data.

Breaking the diplomatic deadlock among the largest debris-generating states is a practical necessity for all space actors, as the escalating debris threat directly endangers critical sovereign assets. This reality creates an opening for third-party states to serve as critical intermediaries or lead regional sustainability efforts. At the same time, commercial constellation operators create opportunities as well as new challenges in these efforts. While commercial operators' direct financial stake in orbital stability makes them natural leaders in developing operational methodologies, market competition may encourage risk-taking behaviours or resistance to adopting costly sustainability measures. Diplomatic efforts to address debris, therefore, must harness commercial innovation and market opportunity while ensuring that the process aligns with long-term orbital sustainability.

Emerging space nations are also critical stakeholders in these trust-building efforts. However, the high technical bar for advanced debris mitigation can sideline nations with developing space programmes. To ensure broad compliance, established space powers can actively support capacity-building through technology-sharing and financial partnerships. Emphasizing technology-neutral, performance-based standards is also key, as it allows all nations to contribute to sustainability objectives. The immediate priority should be building a common baseline for trust and communication around debris mitigation. In a rapidly changing space environment, a step-by-step approach will be more likely to keep up with the pace of change.

Conclusion

A safer and more sustainable space environment is essential for all stakeholders, from established space powers and large corporations to emerging nations and start-ups. This insight report's economic analysis illustrates that the cost of maintaining the status quo already carries material cost: up to **$42.3 billion** in cumulative expected losses in 2025–2035, driven primarily by service disruptions and operational inefficiencies. The projections reflect a business-as-usual scenario informed by historical data, in which no major debris-generating events are expected under present operating patterns. A deviation from this trend – for example, a large-scale collision or fragmentation event – would drive losses far beyond current estimates.

The path forward depends on a shared commitment among all space actors to ensure the long-term sustainability of the orbital environment. Operators should increase transparency in manoeuvre planning and adhere to effective methods for post-mission disposal. Launch providers should commit to controlled re-entries and end the practice of abandoning upper stages in congested orbits. Regulators, in turn, need to embed international best practices in domestic law through licensing conditions and encouraging financial incentives that reward sustainable behaviour, where feasible and appropriate.

Ultimately, this report defines a clear decision point for the global space sector: continue with a business-as-usual approach that imposes a debris-caused tax on the entire space economy and dependent sectors or invest now in a more sustainable framework for how space actors manage and operate within Earth's orbital environment. Choosing the latter offers an opportunity to shift from a reactive posture to a proactive strategy that combines preventative measures, economic incentives and international collaboration to ensure that humanity continues to benefit from space infrastructure for generations to come.

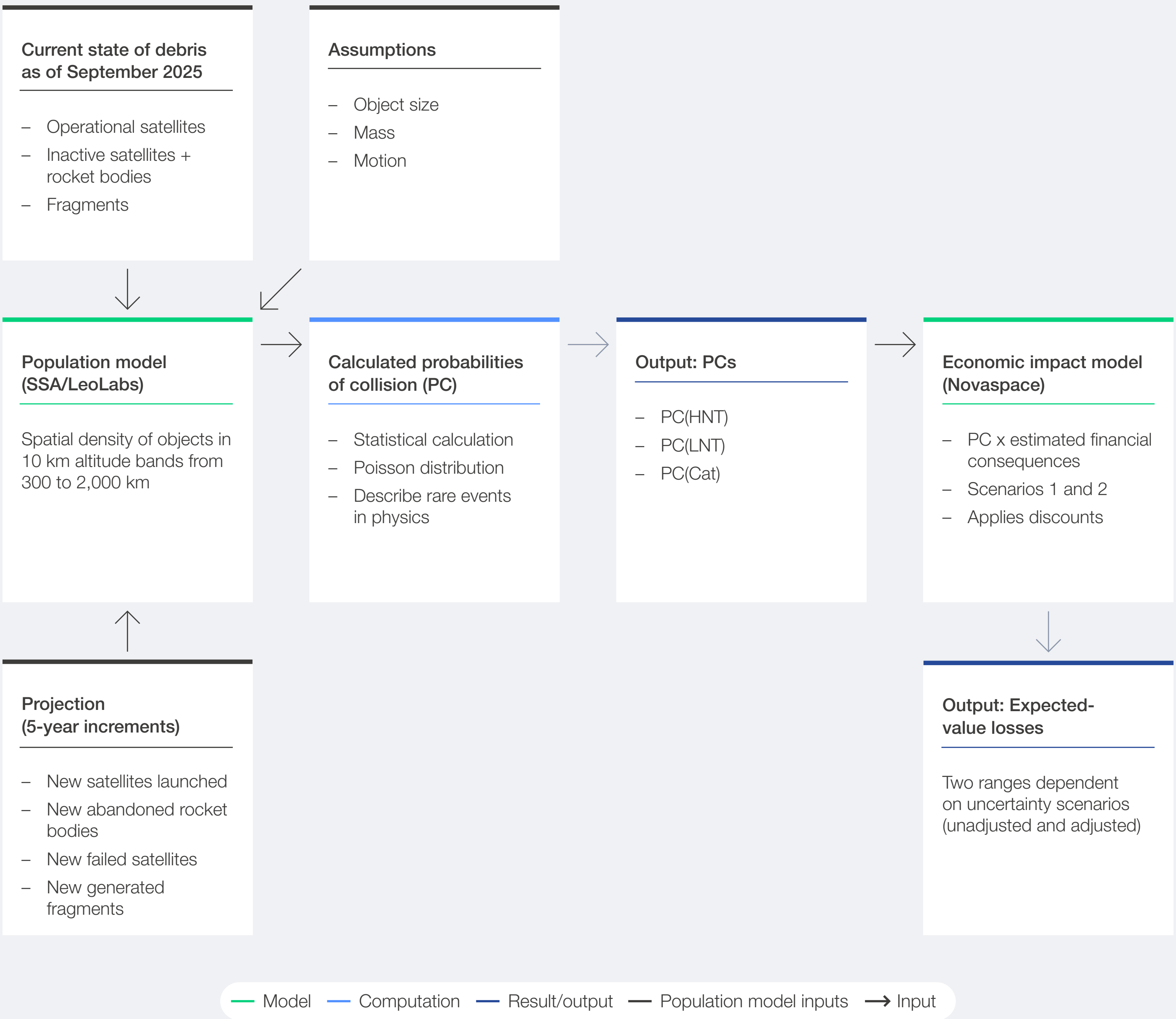
Appendix A

Modelling framework – from orbital population to economic impact

To effectively map the evolution of the orbital debris environment and its economic impacts for the space sector, this report incorporates analysis from multiple studies conducted in collaboration with the Saudi Space Agency, LeoLabs and Novaspace. These analyses build on one another to provide an evidence-based estimate of the economic impact of orbital debris. The orbital population model simulates the growth of operational satellites, derelicts and fragments in LEO (2025–2040). Its collision probability outputs feed into the economic valuation, which quantifies the resulting cost burden to the global space economy.

Figure 5 illustrates the inputs and process that were used to reach the final analyses. Further details on the methodologies for the orbital population model and economic valuations can be found in appendices B and C.

FIGURE 5 **Mapping orbital debris environment and economic impacts**



Source: Centre for Space Futures, 2025

Appendix B

Orbital debris projections – assumptions and methodology

B1 Mathematical formulation (orbital population model)

The orbital population model developed in collaboration with the Saudi Space Agency and LeoLabs estimates the likelihood and rate of orbital collision using the Poisson probability distribution[23] and kinetic-theory analogy,[24] where orbiting objects behave like particles in random motion.

Single-target collision probability:

The basic Poisson form for the probability that a single satellite is struck by another object within a given interval of time is:

$$PC = 1 - e^{-(A_C V_R SPD\ T)}$$

Eqn.1

Where:

PC: probability of collision for one target

AC: collision cross-section

VR: relative velocity

SPD: spatial density = $\frac{N}{Vol}$ (objects per km^3)

N: number of objects

V: volume of orbital shell

This equation is applied separately to three debris-size classes used throughout the model:

PC(HNT): 5 mm–1 cm (hazardous non-trackable)

PC(LNT): >1–10 cm (lethal non-trackable)

PC(Cat): >10 cm (catalogued/trackable)

Cluster collision rate:

To estimate the combined probability of collisions within a dense region of derelicts ("clusters"), the cumulative collision rate (CR) is used:

$$CR = \left(\frac{N^2}{2}\right)\left(\frac{A_C V_R T}{Vol}\right)$$

Eqn.2

Where:

CR: Poisson-derived collision rate for the cluster

T: time interval, typically one year but in units of seconds (3.1536E7 sec)

The ½ term in Eqn. 2 ensures that the potential encounters within a cluster are not double-counted.

Time to first collision

To estimate when the first collision is expected, the model applies a gamma distribution,[25] which relates the collision rate (CR) to a chosen confidence level:

$$\Gamma = -ln(1 - C)\left(\frac{1}{CR}\right)$$

Eqn.3

Where:

Γ: number of years until the first collision event

C: confidence interval

And the probability that a collision occurs within Γ years is:

$$C = 1 - e^{-CR\,\Gamma}$$

Eqn.4

This equation is consistent with the Poisson probability distribution for rare events.

These calculations were applied to three identified clusters in LEO around altitudes of 775 km, 840 km and 1,000 km, where dense constellations of derelicts and fragment clouds persist. The resulting probabilities of a first major collision by c. 2032 are 8%, 6% and 29% respectively. To represent additional long-term debris generation, the model also includes rocket-body explosions in 2029, 2033 and 2037, consistent with historical recurrence rates.

B2 Core modelling assumptions

The model relies on a defined set of simplifying assumptions summarized in Table 5, where each parameter's technical basis and potential influence on results are outlined for transparency.

TABLE 5 **Simplified core modelling assumptions**

Parameter	Assumption	Source/basis	Implication/sensitivity
Satellite cross-section	3 m^2	SSA/LeoLabs baseline for operational payloads	Simplified geometry; deviations in real dimensions will proportionally alter the collision probabilities
Rocket-body cross-section and mass	8 m^2 and 1,400 kg	Historical mean for SL-8 and similar rocket bodies	Larger derelicts dominate collision energy and debris-generation risk
Fragment area	0.04 m^2	Derived from LeoLabs catalogue statistics	Influences detection thresholds and debris-count estimates
Relative velocity	12 km/s	Standard LEO average	Approximation; orbital-inclination variations slightly adjust outcomes
Fragment ratio	90 lethal plus 250 hazardous per catalogued object	NASA MASTER 8[26]	If underestimated, total cost is conservative
Constellation plans	All major systems proceed per International Telecommunication Union (ITU) filings	ITU filings	Cancellations or delay would lower congestion
Launch upper-stage abandonment rates	50% rocket-body abandonment 2025–2030; 0% rocket-body abandonment 2030–2040 due to lower altitude targets (~500–650 km, where atmospheric drag plays a role)	Based on 10-year average mid-LEO launches	Operator discipline strongly affects outcomes
Satellite failure rate	0.5% declining to 0.25% from 2030–2040	Observed performance of large constellations	Operator discipline strongly affects outcomes
Rocket-body explosions	2029, 2033 and 2037	Historical recurrence rate	More explosions will increase collision probabilities
Atmospheric drag	Removes debris < 600–700 km	Empirical decay threshold	Solar activity variations can temporarily enhance decay
No active debris removal	ADR effects excluded before 2040	Pending business case	Including ADR could reduce modelled losses

B3 Modelled clusters and event probabilities

These clusters were defined as long-lived derelict aggregations with elevated collision potential. Each is modelled as a high-risk debris source zone.

TABLE 6 **Modelled clusters and event probabilities**

Cluster altitude (km)	Collision rate (CR)	Probability of first collision by 2032
775	0.00184	8%
840	0.00136	6%
1,000	0.00743	29%

Representative results from the model are shown below to illustrate how modelled collision probabilities vary first by altitude (spatial variation) and then over time at the most debris-dense altitude (around 805 km). These cases were selected because they represent the two main dimensions of debris-risk growth captured by the orbital population model.

TABLE 7 **Variations on modelled collision probabilities**

Modelling phase	Altitude (km)	PC(HNT)	PC(LNT)	Interpretation
2025–2030	515	0.1%	0.04%	Low-risk region, rapid re-entry zone
2025–2030	805	1.3%	0.047%	High-risk "bad neighbourhood"
2035–2040	805	1.5%	0.55%	Persistent accumulation; risk slightly higher

Note: Values show annual probabilities for a 3 m^2 satellite. The first two rows compare altitudes within the same phase, while the last row shows temporal evolution at the highest-risk altitude (805 km)

Appendix C

Economic analysis – assumptions and methodology

The probabilities obtained from the orbital population model detailed in Appendix B were used in combination with Novaspace's proprietary satellite database to determine the economic value of the forecast orbital collisions through a deterministic valuation. When combining the data for the economic valuation, several assumptions were made:

1. The **value of the infrastructure** is derived from Novaspace's proprietary database, which provides historical, current and forecast data on the total number of satellites launched and to be launched. For each of these satellites, the valuation assigns a manufacturing cost and a launch cost, which **together form the value of the infrastructure** in any given year within the time frame of interest.

2. A **discount rate of 4%** is applied to the manufacturing and launch value of the satellites over the years of their lifespan, with the exception of mega-constellations, to which a discount rate of 6% is applied. The five mega-constellations are: Starlink, Kuiper, Starshield, Guowang and Qianfan. LEO mega-constellations are designed for fast replacement cycles (e.g. five to seven years) to keep performance and spectrum efficiency high. That implies faster economic depreciation and higher obsolescence risk than, say, a 12–15-year GEO satellite. A higher discount rate is a reasonable shorthand for that accelerated economic ageing.

3. The **cost of a risk-reduction manoeuvre** is determined according to a 2023 NASA study,[27] differentiated according to the operator type (commercial, government, academic or defence).

4. The **cost of a risk-reduction manoeuvre** for constellations is considered to be zero, as this cost is assumed to be absorbed in the infrastructure cost of the asset. This is supported by the same NASA study, which found that commercial operators have largely automated their analysis and response to debris interactions.

5. The **threshold for a manoeuvre** is assumed to be 1.00E-04 throughout the decade.

6. The **value of services** is derived from Novaspace's proprietary database, which provides yearly estimates of the total service revenues generated by satellites across different applications. For this analysis, the relevant applications are Earth observation, telecommunications, satellite navigation, space security and space logistics.

To estimate the costs associated with satellite anomalies, the valuation incorporates a set of discounting assumptions that consider the severity and operational impact of those events. These assumptions are different for infrastructure-related and service-related consequences, accounting for the likelihood of benign, moderate and severe anomalies as well as the structural resilience offered by satellite constellations in LEO. The following reports the discounting rationale applied to each category.

For infrastructure:

- 50% of the expected value is heavily discounted to represent that **most anomaly events** are benign, with only 35% of its value retained in the decadal sum.
- Of the remaining 50%, 30% is moderately discounted, with 65% of its value retained. This indicates that **some anomaly events may temporarily disrupt satellite operations** before recovery.
- The final 20% is left undiscounted, meaning its full expected value is carried forward, representing the limited number of anomaly occurrences able to **cause lasting damage**, shortening a satellite's lifespan or diminishing its functionality to provide services in a given period.

For services:

Given that the satellites studied are in LEO and predominantly part of constellations, where redundancy reduces the risk of service disruption, the discounts are steeper:

– 80% of the expected value is discounted, with only 25% of its value retained. This large portion of the expected value is meant to represent the predominance of constellations in the model and their redundancy.

– The remaining 20% is not discounted and is fully counted in the decadal sum, representing the single satellite missions that are more likely to be heavily affected by an anomaly event in terms of service delivery.

BOX 3 **Two scenarios to represent the uncertainty in anomaly events (2025–2035) (see Figure 4)**

Scenario 1	Scenario 2
Reflects unadjusted expected losses, $11.4 billion for infrastructure and $19.3 billion for services, based on the full probability value from the orbital population model	Applies uncertainty-adjustment factors to represent limited-impact anomalies; the adjustments retain a portion of Scenario 1's losses by severity tier, resulting in reduced totals of $6.4 billion for infrastructure and $7.7 billion for services.

Source: Novaspace, 2025

Appendix D

Technology portfolio for space debris

Space debris-related technologies can be grouped into a diversified portfolio based on their type of intervention: monitoring, prevention, mitigation and remediation. Each cluster faces technical challenges and cost drivers, as summarized in Table 8.

TABLE 8 **Technology portfolio for space debris matters**

Technological clusters	Description	Key challenge	Cost-driven matters
Monitoring	**Detection, tracking and characterization of debris objects**	**Accuracy, global coverage data sharing**	**Infrastructure set-up, maintenance**
Ground-based	Radar, telescopes and laser systems	Weather interference, range limitation and detection threshold	Moderate (depending on sensor type)
Space-based	Sensors using optical or infrared payloads	High cost and power limits in space	Very high (launch and operations)
Mitigating	**Prevention of new debris through safer design, operations and traffic coordination**	**Low compliance and fragmented space traffic management**	**Development and coordination platform costs**
Design-for-demise and passivation	Deorbit systems (sails, tethers) and neutralization of residual energy	Mass and reliability trade-offs	Medium (added design and integration cost)
Collision avoidance systems	Data-driven SSA platforms and AI-based conjunction analysis	Fragmented data standards and lack of shared space traffic management layer	Low to medium (depends on AI sophistication)
Autonomous manoeuvring systems	Onboard systems enabling real-time avoidance	Limited processing power, autonomy and onboard AI	Medium-high (integration cost per spacecraft)
Remediating	**Removal or neutralization of existing debris and derelict objects**	**Technical complexity and cost of operations**	**High capital expenditure and mission-specific operating expenses**
Active debris removal (ADR)	Dedicated satellites or servicers capturing and removing objects	Docking precision, object tumbling, legal uncertainty	Very high (per-mission development and launch)
On-orbit servicing and refuelling	Extending satellite life and minimizing failures in orbit	Modular design and interoperability	High R&D and mission-specific
Recycling and in-orbit manufacturing	Repurposing materials from defunct satellites for new builds	Material separation, contamination controls, standardization	High upfront investment, uncertain return on investment (ROI)
Enabling infrastructure	Technologies supporting remediation logistics, e.g. in-orbit tugs, printers and storage depots	System compatibility across varied spacecraft architectures	Cross-mission standardization cost

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