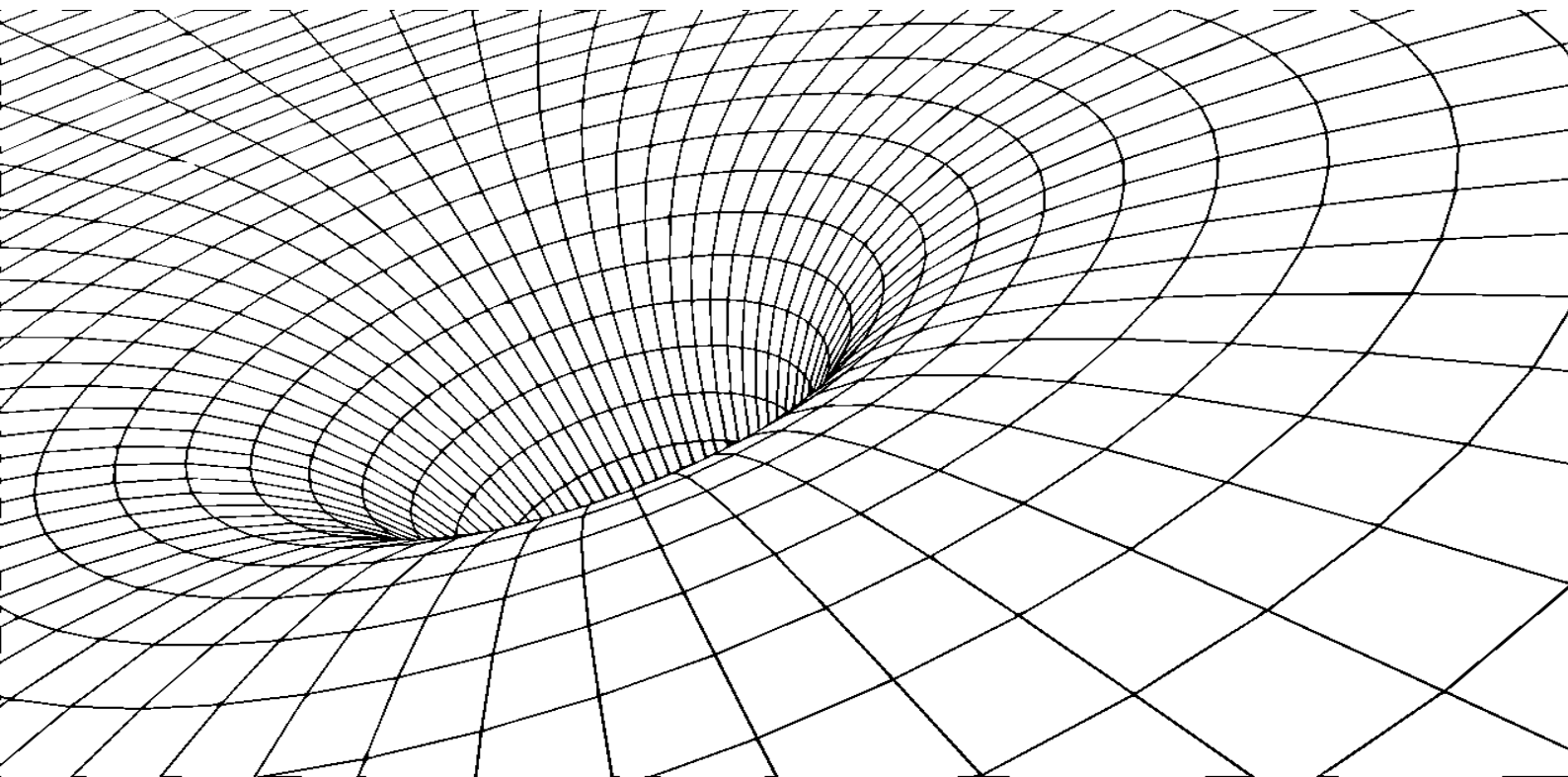


ESTIMATING THE PRIVATE COSTS OF ORBITAL DEBRIS FOR SATELLITE MISSIONS

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This paper estimates the private costs that orbital debris imposes on satellite operators. Specifically, we quantify the increase in mission costs associated with the growing presence of debris in Earth's orbit. The proliferation of orbital debris raises the probability of collisions with operational satellites, which may damage or destroy space assets and compel operators to adopt costly mitigation measures. The resulting increase in collision risk generates a range of additional operational expenses, including higher launch costs, expenditures on collision-avoidance maneuvers, and investments in shielding and debris-tracking capabilities. Orbital debris may also lead to the premature loss of space capital due to destructive collisions. In the baseline year 2025, private costs attributable to debris are estimated at approximately \$166,700 per mission. These costs increase substantially over time, reaching about \$1 million within 50 years, about \$5 million in 75 years, and more than \$50 million in 100 years. (JEL Classification: D24; D62; E21; Q53).

KEYWORDS. Outer space, Orbital debris, Satellites, Collisions, Deorbiting, Shielding, Collision avoidance operations.

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1. INTRODUCTION

Human activities in space, spanning commercial, scientific, and military domains, have increasingly polluted Earth's orbits with large quantities of orbital debris. According to the European Space Agency (ESA) and NASA, as of October 2025 there are approximately 44,700 debris objects larger than 10 cm, around 1.2 million objects between 1 and 10 cm, and more than 140 million fragments between 1 mm and 1 cm orbiting the Earth. While the smallest fragments pose a relatively low risk of catastrophic damage, debris larger than 1 cm can be lethal to operational satellites due to the extremely high velocities involved in orbital collisions. Most debris, around 85%, is concentrated in Low Earth Orbit (LEO), below 2,000 km, with peak densities occurring at altitudes between 700 and 900 km.

NASA defines orbital debris as any human-made object in orbit that no longer serves a useful purpose, including retired satellites, spent rocket upper stages, and fragments of spacecraft. Orbital debris therefore represents a form of space pollution that poses potentially severe risks to the continued use of outer space, as highlighted by the Kessler syndrome (Kessler and Cour-Palais, 1978; Kessler, 1991). Its consequences include the partial or complete destruction of operational satellites, service disruptions, higher tracking and monitoring requirements, and increased operating costs associated with collision-avoidance maneuvers. Even small fragments can cause catastrophic damage because of their high relative velocities and kinetic energy, while larger intact objects, such as derelict satellites and rocket bodies, constitute a further hazard because collisions involving them can generate thousands of additional debris fragments.

The accumulation of orbital debris consequently represents a growing threat to the long-term sustainability of space activities and imposes increasing costs on space operators. However, these costs are not necessarily fully internalized by the firms generating or contributing to the debris stock. Individual operators primarily bear the costs directly associated with protecting their own assets, while the broader consequences of increased orbital congestion and collision risk are distributed across other operators and, ultimately, society. This creates a negative externality that can lead to insufficient incentives for debris mitigation. Although the economic burden remains relatively limited at present, continued growth in the debris population is expected to increase collision risks and operational requirements, making debris-related costs an increasingly significant component of future space missions.

In accounting for the mission costs associated with orbital debris, we distinguish three main categories: (i) increased launch costs, (ii) higher operational costs, and (iii) loss of space assets due to collisions. Increased launch costs arise from two sources: the need for collision-avoidance measures during ascent and the additional payload mass required for shielding. Operational costs include expenditures on tracking and conjunction analysis, execution of collision-avoidance maneuvers, and forgone revenue due to temporary service interruptions during such maneuvers.

The literature has produced several estimates of the costs associated with orbital debris. A number of studies quantify the value of space asset losses from collisions of operational satellites with orbital debris as a percentage of world output (Adilov et al., 2023; Nozawa et al., 2023; Bongers et al., 2025; Bongers and Torres, 2025). Other contributions, such as Locke et al. (2004) and the World Economic Forum (2026), consider additional cost components associated with debris. However, existing estimates either omit important categories of costs or do not rely on a formal model capable of capturing the joint evolution of space activity and orbital debris, particularly how investment decisions by spacefaring firms respond to the increasing costs imposed by debris accumulation. This paper addresses this gap.

This paper contributes to the literature by estimating a comprehensive set of mission costs associated with orbital debris using a dynamic general equilibrium integrated assessment model. The model provides quantitative estimates of these debris-related costs and examines how they evolve as a function of the orbital environment. Because mission costs depend on the global dynamics of the space environment, we explicitly model the trajectories of satellites and other orbital objects, derive collision probabilities, and analyze how debris dynamics interact with mission requirements and operational decisions. To this end, we develop a general equilibrium integrated space-economy model, solved for a competitive decentralized equilibrium using a fixed-point algorithm. In this framework, the debris externality is not internalized by spacefaring agents; however, firms optimally respond to debris-related costs when making investment decisions. The resulting trajectories of launches and spacecraft reflect these optimal choices, with returns to space capital incorporating the full set of mission costs induced by orbital debris.

The calibrated model is solved numerically as a nonlinear programming problem over a 125-year simulation horizon.¹ We use the model to quantify the mission costs generated

¹Orbital debris constitutes a long-term challenge for two main reasons. First, debris is generated endogenously through on-orbit activities, including collisions and fragmentation events. Second, the natural decay rate of debris is extremely low at higher altitudes, allowing debris to persist for extended periods.

by orbital debris, accounting for a broad range of cost components, from higher launch costs to expenditures associated with collision-avoidance operations. To do so, we jointly simulate the evolution of the orbital environment and economic activity, generating trajectories for operational satellites, debris populations, and collision risks. Based on the projected accumulation of orbital debris and satellites over time, we estimate the corresponding economic costs imposed on space missions.

In the baseline year 2025, the average mission cost attributable to orbital debris is estimated at approximately \$166,700. These costs increase sharply over time, reaching about \$1 million within 50 years, approximately \$5 million after 75 years, and more than \$50 million after 100 years. During the initial decades, shielding represents the largest component of debris-related mission costs, followed by expenditures on collision-avoidance maneuvers. As space activity expands and orbital congestion intensifies, however, the frequency and complexity of collision-avoidance operations increase rapidly, making them the dominant source of mission costs over the following three decades in the baseline scenario. Over longer time horizons, direct losses from collisions eventually become the largest component of the economic burden imposed by orbital debris.

Aggregating these mission-level costs across all satellite operators, we estimate that the total private costs imposed by orbital debris amount to approximately \$2.15 billion in 2025. In the absence of additional debris mitigation measures, these costs rise to more than \$8 billion by 2050, almost \$500 billion by 2100, and nearly \$8 trillion by 2125. These projections highlight the substantial economic costs that orbital debris can impose over time if effective mitigation measures are not implemented.

The remainder of the paper is organized as follows. Section 2 characterizes the different types of mission costs produced by orbital debris. Section 3 presents a general equilibrium economy-space model for a decentralized economy. Section 4 describes the computational solution approach. Section 5 calibrates the parameters of the model. Section 6 presents the estimation of the mission costs of orbital debris. Finally, Section 7 offers concluding remarks.

2. THE PRIVATE COSTS OF ORBITAL DEBRIS

Orbital debris produces a number of direct and indirect costs on spacefaring actors throughout the duration of the space missions. The literature has produced some initial estimates of such costs, using alternative approaches. Adilov et al. (2023, 2024) estimate the cost of collisions in the range \$83-\$103 million in 2020. Locke et al. (2024) estimate

some of these costs using three alternative models: the NASA's Orbital Debris Engineering Model (ORDEM), the ESA's MASTER model, and the Ecolab model. They estimate a total cost between \$115 million and \$692 million, considering the costs of warnings, maneuvers, and mission-ending collisions.² For satellites in geostationary orbit, the OECD (2020) reports that such costs amount to an estimated 5–10% of the total mission costs, which could be hundreds of millions of dollars.

Lee (2024) and Lee et al. (2024) define the cost of orbital debris as the sum of damages to satellites, including physical losses, collision-avoidance expenditures, and service disruptions, as well as impacts on space stations and effects on Earth. Using a contingent valuation approach, Lee (2024) estimates the loss of satellite value due to orbital debris in South Korea by eliciting households' willingness to pay for mitigation. The study finds an average willingness to pay of \$16.4 per household, which, when aggregated at the national level, corresponds to a total value of approximately \$388.8 million. Expressed as a share of GDP, this willingness to pay represents about 33.9% of the projected losses associated with the country's Earth observation satellites over a 10-year horizon (given a GDP of approximately \$1.713 trillion). The World Economic Forum (2026) estimates the cost of orbital debris for the period 2025-2035, resulting from projected losses from service disruptions, avoidance manoeuvres and premature asset degradation, and collisions, which reduce mission revenues and longevity, with estimates cumulative losses of between \$25.8 billion and \$42.3 billion over the next decade.

We consider the following categories of mission costs induced by orbital debris:

2.1 *Launch collision avoidance costs*

Launch activity implies crossing the orbit with a rocket before inserting the payload into the target orbit. However, during this phase, the rocket has a positive risk of collision with orbital debris and operational satellites crossing its trajectory. This forces the implementation of a pre-launch safety and analysis procedures. This is the so-called Collision on Launch Assessment (COLA). Although this cost would be relative small compared to the cost of a launch, the increasing number of objects in orbit would lead to an expected increasing future COLA costs, including possible delays in launches. This cost should include the cost of tracking and conjunction calculation of orbital objects, the cost of delay of

²However, in the text, they give values between \$66 million to \$1.4 billion.

the launch due to a large enough probability of collision, and higher insurance costs. Although actually the probability of collision of a launch is very low compared to the risk of a launch failure, it is expected to increase in the future as orbits become more congested.

Collision avoidance is a concern during spaceflight launch windows. Typically, a COLA needs to be performed and approved before launching a satellite. A launch window is said to have a COLA blackout period during intervals when the vehicle cannot lift off to ensure its trajectory does not take it too close to another object already in space (Beaver et al., 2015; Faco et al., 2001; Prézeau et al., 2025). COLA involves four steps: 1) Data collection by gathering orbital data (Two Lines Elements: TLEs) for all cataloged objects³; 2) Trajectories prediction with the propagation of the launch vehicle's planned path and the trajectories of potential threats; 3) Risk calculation of the miss distances and probabilities of collision, considering uncertainties; and 4) Decision making for trajectory adjustment or launch delay if the risk exceeds an established threshold.

2.2 *Shielding*

A second cost derived from the presence of orbital debris is related to spacecraft shielding. To protect valuable space assets from collision with orbital debris, spacefaring firms may adopt two main strategies: Spacecraft shielding and the implementation of collision avoidance systems. The first absorbs the impact energy to protect the spacecraft, while the second aims to prevent collisions altogether. Since collisions typically result in a spacecraft fragmenting into a cloud of debris, both strategies also help mitigate debris generation. Nevertheless, both strategies have limitations. Shielding is only effective against small debris fragments, while most debris is too small to be tracked to be avoided, limiting the effectiveness of collision avoidance systems under current technological capabilities.

We identify two types of costs related to spacecraft shielding. The first one is the own cost of the shield, which increases the final manufacturing cost of spacecraft. The second is the extra weight of the spacecraft, which results in an increase in the launch cost.

2.3 *Collisions avoidance operations*

Collision avoidance operations involve a set of procedures and strategies used by satellite operators and space agencies to prevent collisions between spacecraft and space debris

³Two-Line Elements (TLEs) are a standardized orbital data format providing the parameters necessary to propagate the trajectories of Earth-orbiting objects and are the primary data input for collision-on-launch assessments.

or other spacecraft. These operations are crucial for maintaining the safety and longevity of satellites, as well as for minimizing the creation of additional space debris. Every day, hundreds of collision avoidance maneuvers have to be conducted by satellite operators. As an example, only the SpaceX Starlink satellites had to make more than 275 collision avoidance maneuvers every day during 2024.

A key aspect of collision avoidance is the monitoring and tracking of space objects. Various organizations, including the U.S. Space Surveillance Network (SSN), NASA, ESA, and other national space agencies and private firms, track objects in space to predict potential collisions. Orbital debris is tracked using Earth-based radar and optical sensor facilities. The principal orbital tracking system is the United States SSN. These devices can track orbital objects larger than 10 centimeters in size in LEO (larger than 30 cm in GEO), although some tracked objects are smaller than 10 centimeters. These organizations maintain catalogs of all known (tracked) objects in orbit, including active satellites and sufficiently large debris. These entities use models to predict the closest approach between two orbiting objects.

When two objects are predicted to come within a certain distance, it is called a "conjunction event." Conjunction analysis helps determine the risk of collision; Once a potential conjunction is identified, the probability of collision is calculated. Factors such as the size, shape, and relative velocity of the objects are considered. The conjunction assessment helps to decide whether avoidance maneuvers are necessary. If the probability of collision exceeds a certain threshold, the satellite operator may decide to perform an avoidance maneuver. This involves changing the satellite's orbit slightly to avoid the predicted collision trajectory. Collaboration and communication between different space agencies and satellite operators are crucial. They often share tracking data and collision alerts to coordinate avoidance maneuvers, especially in geostationary orbits and other crowded regions. Advanced algorithms and artificial intelligence are increasingly being used to predict and manage conjunction events. Automated systems can provide faster and more accurate collision risk assessments and maneuver planning.

As the number of satellites in orbit grows rapidly due to increased activities in space, collision avoidance has become a critical component of satellite operations. This process comes with significant costs that can be categorized into operational, technical, and opportunity costs. First, collision avoidance maneuvers involve monitoring potential threats, analyzing orbital data, and executing thruster burns to adjust a satellite's trajectory. These activities require highly skilled personnel, advanced tracking technologies, and software systems capable of analyzing large amounts of data to predict conjunctions. Maintaining

such infrastructure and expertise entails ongoing expenses, especially as the volume of orbital objects increases. Second, there is a cost due to fuel expended. Satellites often rely on limited onboard fuel for propulsion. Each avoidance maneuver consumes some of this precious resource, reducing the satellite's operational lifespan. As a result, operators face long-term economic impacts, needing to plan for earlier satellite replacements or mission terminations. Finally, there is an opportunity cost. Collision avoidance maneuvers temporarily disrupt the primary mission of a satellite, such as communications, imaging, or data collection. For commercial satellites, this could translate to revenue losses due to interrupted service. Scientific missions may lose critical data if operations are paused during maneuvers.

2.4 Collisions

The risk of collision with orbital debris implies the possibility of losing a satellite. Damages will depend on the size, mass, and other characteristics of colliding objects. Cost of collision depends on damages. Small debris can cause limited damage, for example, by damaging a solar panel. This can reduce the operational lifespan of the satellite. Larger debris can destroy or disable the satellite. Traditionally, debris are classified in debris larger than 10 cm, debris between 1 cm and 10 cm, and debris between 1 mm and 1 cm. It is assumed that debris larger than 10 cm and intact objects (derelict satellites and rocket bodies) can be avoided with collision avoiding maneuvers, and that any debris fragment larger than 1 cm is lethal.

3. THE SPACE-ECONOMY MODEL

This section describes the structure of the dynamic general equilibrium Integrated Space-Economy model. The model extends the DISE-2024 framework developed by Bongers and Torres (2025) by incorporating a comprehensive set of costs borne by spacefaring agents as a consequence of orbital debris.

The economic component is modeled as an optimal growth framework for the global economy, featuring two types of capital inputs: terrestrial physical capital and space capital (i.e., satellites), with the latter treated as a distinct form of productive capital in the aggregate production function. The model builds on a standard neoclassical dynamic general equilibrium structure and incorporates a negative externality arising from the accumulation of orbital debris. Output is allocated across consumption, investment in terrestrial capital, investment in space capital, and abatement activities. In contrast to

standard environmental economic models, orbital pollution does not directly reduce output through a decline in aggregate productivity. Instead, its economic impact operates through an increased risk of collision and destruction of operational satellites. This reduces the effective stock of space-based capital, thereby lowering production if lost assets are not replaced, or diverting resources from other uses if replacement occurs. More broadly, the externality influences economic growth by affecting investment decisions in both terrestrial and space capital, as well as the future evolution of the capital stock.

The physical component of the model consists of a tractable representation of orbital debris dynamics. Like the economic model, it is global in scope, covering orbital regions from Low Earth Orbit (LEO) to Geostationary Orbit (GEO). In addition to modeling the population of operational satellites, including other spacecraft and two space stations, the framework captures the evolution of orbital debris. The debris population includes objects larger than 1 cm and is divided into three categories: non-deorbited defunct satellites, abandoned rocket upper stages, and fragments. A key feature of the model is that both defunct satellites and rocket bodies can fragment or collide with other objects, generating additional debris and contributing to the growth of the debris stock.

The model includes variables in two dimensions: physical variables and output-measured variables. Physical variables are represented in capital letters, while economic output-measured variables are represented in lowercase letters.

3.1 *The economy model*

The economic part of the model is based on the optimal neoclassical growth model of Ramsey (1928), adapted to account for human activity in space. Time is discrete and extends over an infinite horizon. The model is solved for a decentralized competitive economy where individual agents (i.e., households and firms) make optimal decisions.

3.1.1 Households The economy is populated by a large number of identical households, represented by a single representative household with instantaneous utility $U(\hat{c}_t, N_t)$, defined over per capita consumption $\hat{c}_t$, where N_t is the population. The aggregate consumption, c_t , is defined as $c_t = \hat{c}_t N_t$. The function $U(\hat{c}_t, N_t)$ represents the flow of utility and assumed to reflect overall social welfare. The function $U(\cdot)$ is assumed to be concave and twice continuously differentiable.

The problem to be solved by the stand-in household consists in maximizing the sum of discounted utility,

$$\max_{\{\hat{c}_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t U(\hat{c}_t, N_t) \quad (1)$$

where $\rho > 0$ is the subjective intertemporal preference parameter or the pure rate of social time preference. The discount factor, $0 < \beta < 1$, is defined as $\beta = 1/(1+\rho)$. There is a continuum of identical households, each of whom has preferences that are characterized by the following constant relative risk-aversion (CRRA-type) utility function,

$$U(\hat{c}_t) = \left(\frac{\hat{c}_t^{1-\sigma} - 1}{1-\sigma} \right) \quad (2)$$

where $\sigma \geq 0$ is the relative risk aversion parameter. This household satisfies the following budget constraint:

$$c_t + i_t^k + i_t^s = r_t^k k_t + r_t^s s_t + w_t N_t + \pi_t \quad (3)$$

where i_t^k is investment in physical capital other than satellites (Earth capital), i_t^s is investment in satellites (space capital), which includes all costs associated with placing satellites into orbit, r_t^k is the rental rate of Earth capital, k_t is Earth capital, r_t^s is the rental rate of space capital, s_t is space capital, w_t is the wage, and π_t are profits. All prices are defined in output units and are normalized to one.

Investment in space capital includes three main components: launch cost, the cost of space equipment, and the operational costs imposed by orbital debris,

$$i_t^s = l_t + h_t + d_t \quad (4)$$

where l_t is launch cost, h_t is space equipment cost (i.e., satellites), and d_t are operational overruns due to orbital debris. Inserting a satellite into orbit requires the use of launch vehicle, which is costly. Additionally, spacefaring operations face extra costs due to orbital debris. As a result, not all space investment spending is converted into productive space capital. It is worth noting that the private cost of orbital debris is not limited to operational overruns. Launch costs also incorporate additional expenses arising from the presence of orbital debris, and collision-related losses must be accounted for as well.

3.1.2 Launch cost The launch cost is defined as,

$$l_t = r l_t + col a_t + lsh_t \quad (5)$$

where rl_t is the raw launch cost, $cola_t$ are the collision launch avoidance costs, and lsh_t is the extra launch cost by increasing satellite mass due to shielding.

The raw launch cost is interpreted as an installation cost required to build up the satellite stock, independent of the population of orbital debris. It is modeled as an adjustment cost per unit of investment, reflecting that launch prices are typically charged per kilogram of satellite mass. Formally, the raw launch cost function for satellites is defined as:

$$rl_t = m_t M_t H_t \quad (6)$$

where m_t is the price of launch per kilogram, M_t is the raw mass (in kilograms) of the representative satellite under no orbital debris, and H_t is the number of new operational satellites launched. In the macroeconomic literature, investment adjustment costs are commonly introduced to smooth capital accumulation and replicate observed investment dynamics. These costs capture the notion that adjusting the capital stock is not frictionless, that is, firms cannot install or reallocate capital instantaneously or without incurring costs.

We assume that the price per kilo of launches decreases over time at the rate $g_{m,t} < 0$, where,

$$m_{t+1} = \exp(g_{m,t}) m_t \quad (7)$$

$$g_{m,t} = g_{m,0} (\exp(-\delta_m t)) \quad (8)$$

where $g_{m,0} < 0$ and $\delta_m > 0$ is the decay in the growth rate of raw launch costs.

Second, overall launch cost is increased by the launch collision avoidance procedures $cola_t$. This cost, which depends on the probability of collision with an in-orbit object, is shared by all payloads in the rocket, resulting in a higher price per kilogram of satellite mass. Launch collision avoidance (COLA) is modeled as an endogenous operational effort that reduces the probability of rocket-debris collision at the cost of additional resource expenditure. While COLA mitigates private collision risk in the launch of a rocket, it does not reduce debris accumulation and therefore does not internalize the orbital congestion externality. In reality, COLA includes *i*) tracking, monitoring, and control costs; *ii*) trajectory design constraints at launch; *iii*) delayed or suboptimal launch windows; and *iv*) maneuvering (fuel) costs.

The expected probability of collision of a launched rocket is defined as,

$$plc_t = \psi D_{1,t} - \zeta cola_t \quad (9)$$

where $D_{1,t}$ is the number of tracked debris objects in orbit (derelict satellites, rocket bodies, and fragments larger than 10 cm), ψ is a parameter representing the risk of collision of the launch vehicle, and ζ is a proportional parameter indicating how the probability of launch collision is reducing depending on COLA spending. The first term in the right side is the probability of collision for a rocket launch if no action is taken, whereas the second term in the right side represents the reduction in the probability of collision as a function of the launch collision avoidance effort. The number of tracked objects includes operational satellites, derelict satellites, rocket bodies, and fragments larger than 10 cm.

We assume that COLA is implemented such as the expected probability of collision of the rocket, based on tracked objects, is zero, and hence, the total cost of COLA is given by,

$$cola_t = \frac{\psi}{\zeta} D_{1,t} L_t \quad (10)$$

where L_t is the number of launches.

Third, the final launch cost is also affected by the increasing mass of satellites with shields. This cost is defined as,

$$lsh_t = m_t E_t H_t \quad (11)$$

where E_t is the additional mass, in kilograms, of the shield.

Summing up, the total launch cost, is given by,

$$l_t = m_t (M_t + E_t) H_t + \frac{\psi}{\zeta} D_{1,t} L_t \quad (12)$$

which includes both the raw launch cost and the additional launch cost due to orbital debris.

3.1.3 Operational Debris costs Next, we define the orbital debris costs, excluding those already included in the rocket launch cost. The operational debris cost, d_t is defined as,

$$d_t = cao_t + shs_t \quad (13)$$

where cao_t is the cost of collision avoidance operations, and shs_t is the manufacturing cost of shielding. The cost of satellite losses resulting from collisions is treated as an investment loss and is incorporated directly into the law of motion governing the satellite stock.

The collision avoidance operations cost is a function of the number of objects in orbit. This is becoming a critical functionality of new vintages of satellites that reduces the effective probability of collision with orbital debris and other operational satellites. It is assumed that the expected collision probability is zero for tracked objects, but positive

for non-tracked fragments. To simplify, we assume that the CAO cost is a function proportional to the number of tracked objects in orbit. That is, the cost per tracked object is constant. We follow Beaver et al. (2015) who argue that the probability of collision is roughly proportional to on-orbit object density.

First, we define the warning and the collision avoidance maneuver costs as the unitary cost times the number of warning and CAO. The warning cost is defined as,

$$war_t = \pi_{war} n_{war,t} \quad (14)$$

where π_{war} is the cost per warning and $n_{war,t}$ is the number of warnings, given by,

$$n_{war,t} = \beta_{war} D_{1,t} S_t \quad (15)$$

where β_{war} is a proportional parameter representing the risk of conjunction, and S_t is the number of satellites.

Similarly, the collision avoidance maneuver cost is defined as,

$$man_t = \pi_{man} n_{man,t} \quad (16)$$

where π_{man} is the cost per maneuver, and $n_{man,t}$ is the number of maneuvers given by,

$$n_{man,t} = \beta_{man} D_{1,t} S_t \quad (17)$$

and where β_{man} is a proportional parameter representing the risk of conjunction below the threshold.

Finally, during collision avoiding maneuvers services produced by the satellite can be disrupted, provoking an additional cost. This cost is computed as

$$dis_t = \pi_{dis} n_{man,t} \quad (18)$$

where π_{dis} is the imputed cost of services disruption or redundancy.

Hence, the CAO cost is defined as,

$$cao_t = war_t + man_t + dis_t \quad (19)$$

excluding the cost of the reduction in the satellite lifetime due to extra fuel consumption over the estimated fuel reserve for collision avoidance maneuvers. This last cost is included in the law of motion of the stock of operational satellites.

Second, whereas CAO reduces the probability of collision, shielding reduces the probability of destruction in case of collision. It is assumed that, by construction, all satellites

have a natural shield against fragments debris lower than 1 mm. This type of protection is known as the “Whipple shield”. Whipple shield (proposed by Whipple, 1947) consists of several layers of materials around critical parts of spacecraft designed to absorb the energy of hypervelocity impact of micrometeoroids or orbital debris. This protection is effective for debris smaller than 2 cm (Locke et al., 2024). We define the shielding cost in the manufacturing of satellites as,

$$shs_t = \pi_{shs} E_t H_t \quad (20)$$

where π_{shs} is the manufacturing cost of the shield per kilogram.

Summing up, the operational debris cost, excluding launch and collision cost, is given by,

$$d_t = (\pi_{war} \beta_{war} + (\pi_{man} + \pi_{dis}) \beta_{man}) D_{1,t} S_t + \pi_{shs} E_t H_t \quad (21)$$

3.1.4 The technology We assume that all firms have access to the same technology; therefore, the analysis is conducted using a representative firm and a representative aggregate production function. Output, y_t is assumed to be a function of aggregate productivity, the stock of physical capital on the Earth, k_t , the stock of satellites, s_t , and labor, N_t . It is assumed that the production function is of Cobb-Douglas type, exhibiting constant returns to scale, where labor equals population,

$$y_t = a_t k_t^{\alpha_1} s_t^{\alpha_2} N_t^{1-\alpha_1-\alpha_2} \quad (22)$$

where $0 < \alpha_1, \alpha_2 < 1$, $\alpha_1 + \alpha_2 < 1$, and where a_t is the Total Factor Productivity (TFP), representing Hicks-neutral technological change. Labor is assumed to be equal to population, and therefore, the growth rate of labor is equal to the population growth rate.

The representative firm maximizes profits by choosing the appropriate levels of capital and satellites given population dynamics. Profits are defined as,

$$\pi_t = y_t - r_t^k k_t - r_t^s s_t - w_t N_t \quad (23)$$

The accumulation of physical capital other than satellites follows the standard capital accumulation equation:

$$k_{t+1} = (1 - \delta_k) k_t + i_t^k \quad (24)$$

where $0 < \delta_k < 1$ is the capital depreciation rate.

The stock of satellites, measured in final output units as an equipment asset, is denoted by s_t , and is given by the following process,

$$s_{t+1} = (1 - \Lambda_t)[(1 - \delta_s - \varepsilon_s)s_t + q_t h_t] \quad (25)$$

where $0 < \delta_s < 1$ is the physical depreciation rate for satellites depending on the expected lifespan, ε_s is a parameter representing the probability of breakup due to design failure, and Λ_t represents the loss of satellites assets due to collisions (damage from space pollution). This accumulation process establishes the link between the space environment and the accumulation of space capital. Damage results in the destruction of satellites, the reduction of space capital stock used in production, and the reduction of the final output if the loss asset are not replaced.

The stock of satellites law of motion incorporates an investment-specific technological change (ISTC), denoted by q_t , (see Greenwood et al., 1997). For simplicity, it is assumed that ISTC occurs only in the space sector.

3.1.5 Total mission overrun due to orbital debris Based on the calculations presented above, we are now in a position to provide an estimate of the total additional costs incurred by a mission as a result of the presence of space debris. The total mission overrun, tmo_t , is given by,

$$\begin{aligned} tmo_t = m_t E_t H_t + \frac{\psi}{\zeta} D_{1,t} L_t + (\pi_{war} \beta_{war} + (\pi_{man} + \pi_{dis}) \beta_{man}) D_{1,t} S_t \\ + \pi_{shs} E_t H_t + \Lambda_t [(1 - \delta_s - \varepsilon_s) s_t + q_t h_t] \end{aligned} \quad (26)$$

3.1.6 Exogenous growth sources The model incorporates three exogenous sources of growth: aggregate neutral technological change, investment-specific technological change for satellites, and aggregate labor growth. The growth rates of technological change and population are not a constant; rather, similar to climate change AIMs, they are assumed to decline over time. Aggregate productivity technological progress is characterized as,

$$a_{t+1} = \exp(g_{a,t}) a_t \quad (27)$$

where $g_{a,t}$ is the growth rate of TFP defined as,

$$g_{a,t} = g_{a,0} \exp(-\delta_a t) \quad (28)$$

where δ_a is the decay rate in the TFP growth rate.

We assume a similar specification for the satellite investment-specific technological progress,

$$q_{t+1} = \exp(g_{q,t})q_t \quad (29)$$

where $g_{q,t}$ is the growth rate of ISTC defined as,

$$g_{q,t} = g_{q,0} \exp(-\delta_q t) \quad (30)$$

where δ_q is the decay rate in ISTC for satellites.

Finally, we define the dynamics of the population, N_t . Population represents another source of growth, as labor is assumed to equal population. Following the specification by Hassell (1975), population dynamics are defined as,

$$N_{t+1} = N_t \left(\frac{N^*}{N_t} \right)^\zeta \quad (31)$$

where N^* is the asymptotic population at the end of the simulation period and ζ is a population growth parameter.

3.1.7 Economic to physical variables mapping To obtain a numerical solution of the model it is necessary to use different units of some variables. First, some variables need to be measured in monetary units, but simultaneously they need also be measured in physical units. A typical example is satellites. Satellites is an input in the aggregate production function and a result of the accumulation of investment in space capital. On the other hand, the number of satellites is the relevant variable for computing damages in the form of operational satellites destroyed by collision. Second, in the space model, the dynamics for debris is a function of physical variables such as the number of launches, which is also related to the resources spent in launches. In order to ensure that the model's parameters are calibrated correctly and that economic and physical variables are integrated properly, a mapping between the two environments must be established.

A first mapping is assumed between the investment in satellites and the number of new satellites inserted into orbit, H_t ,

$$H_t = \mu(i_t^s - l_t - d_t) = \mu h_t \quad (32)$$

where the parameter μ the conversion parameter that transforms "economic" values into "physical" values and where the number of new satellites is proportional to investment in space capital net of installation and debris-related operational costs.⁴

⁴The parameter μ reflect the (inverse) price of a satellite. The number of new satellites, H_t is measured in units, whereas the value of new satellites, h_t is measured in trillion international 2025 dollars.

The second step in creating this mapping involves connecting the stock of satellites as a capital asset, s_t , expressed in output units, with the number of satellites, S_t , is given by,

$$S_t = \mu \frac{s_t}{q_t} \quad (33)$$

Notice that satellite's ISTC affects the productivity value of the asset but not the quantity of assets. ISTC is considered embodied technological progress in new vintages of satellites. The higher the value of q_t , the larger the number of new satellites produced per unit of investment. In practice, a positive trend in q_t reflects embodied technological change in spacecraft reflecting a decreasing trend in manufacturing costs of satellites.

By substituting the above mappings into the restriction (25), we can derive the accumulation process for the number of satellites. Therefore, the stock of operational satellites, measured by the numbers of a representative satellites can be expressed as,

$$S_{t+1} = (1 - \Lambda_t)[(1 - \delta_s - \varepsilon_s)S_t + H_t] \quad (34)$$

Satellites are equipment assets placed in orbit. Each period, the amount $\delta_s S_t$ of satellites becomes non-operational. Satellites that are no longer useful and remain in orbit turn into space debris if not removed.

3.1.8 Rockets launches The number of satellites inserted into orbit, H_t , is assumed to be a proportion η of the number of launches, L_t :

$$H_t = \eta L_t \quad (35)$$

where the parameter η can be interpreted as the number of satellites deployed per launch. Taking advantage of expression (35), and from the mapping between investment in satellites and the number of new satellites inserted into orbit (expression 32), we can obtain the relationship between investment in satellites net of installation costs, and the number of launches, given by,

$$L_t = \frac{\mu}{\eta} h_t \quad (36)$$

3.2 The space model

Next, we describe the physical space model. This part of the model includes three main functions: the damage function, the emission (debris generation) function, and the law of motion of the stock of debris. Any human-made object that is not functional and is orbiting around Earth is considered space junk, which moves at high speeds and has the

potential to collide with and destroy other objects. We distinguish three types of orbital debris: Derelict satellites, rocket bodies, and fragments.

3.2.1 The stock of pollution Pollution in Earth's orbit takes the form of orbital debris. The stock of orbital debris includes any non-operative, human-created object in orbit, that is, it excludes functioning satellites and other spacecraft. We measure orbital debris by counting the number of objects. The stock of debris, $D_{i,t}$ can be defined as:

$$D_{i,t} = W_t + Z_t + F_{i,t} \quad \text{for } i = 1, 2, 3 \quad (37)$$

where W_t is the stock of derelict satellites abandoned in orbit, Z_t is the number of final-stage rocket bodies, and $F_{i,t}$ are fragments larger than size i , where $i = 1$ are fragments larger than 10 cm, $i = 2$ are fragments larger than 1 cm, and $i = 3$ are debris fragments larger than 1 mm. The key distinction is that fragments are dead debris, where both derelict satellites and rocket bodies can breakup generating a large number of fragments.

3.2.2 Damages Human activities in outer space produce pollution in the form of orbital debris, which travels at high speeds (on average of 36,000 km/h, or approximately 10 kilometer per second in LEO). This debris can collide with operational satellites and other spacecraft, leading to the loss of valuable space assets. While it is true that some uncontrolled, large mass debris in low orbit can re-enter the Earth's atmosphere and potentially cause harm to life or property, the probability of such an event is very low. Additionally, they can pollute the atmosphere.

The number of satellites destroyed each period due to collision with debris is modeled as a function of both the stock of debris and the number of operational satellites,⁵

$$\Lambda_t = (1 - v_{w,t})\theta W_t + (1 - v_{z,t})\theta Z_t + (1 - v_{f,t})\theta F_{2,t} \quad (38)$$

where $\theta > 0$ is a parameter representing the collision probability per unit of debris, $v_{w,t}$ represents the collision avoidance capability of satellites against derelict satellites, $v_{z,t}$ is collision avoidance against rocket bodies, and $v_{f,t}$ is collision avoidance against fragments. The parameter θ captures factors such as cross-section, relative velocity, orbital

⁵This specification follows the standard Lotka-Volterra approach for modeling interactions between two populations based on a mass-action principle. Under this framework, the frequency of interactions is proportional to the product of the population sizes. The intuition is straightforward: as the number of objects increases, so does the likelihood of random encounters between them. For interactions involving objects of the same type, the collision rate is proportional to one-half of the squared population size, which prevents double-counting of collision pairs. This adjustment is offset by the fact that each collision generates debris from both colliding objects, resulting in a corresponding doubling of debris production.

overlap, etc. The probability of collision can be reduced through the use collision avoidance systems, which rely on tracking data and maneuver capabilities to prevent high-risk encounters.

The number of operational satellites destroyed by collision, X_t , is defined as,

$$X_t = \theta[(1 - v_{w,t})W_t + (1 - v_{z,t})Z_t + (1 - v_{f,t})F_{2,t}][(1 - \delta_s - \varepsilon_s)S_t + H_t] \quad (39)$$

3.2.3 Debris generation Debris comes from different sources: launches (including derelict final-stage rockets and fuel deposit bodies), derelict satellites not removed from orbit, accidental explosions and breakups, collisions, and intentional debris creation through military activities, such as destroying a satellite using an anti-satellite missile. The integrated model identifies the following five sources of orbital debris: The first source of debris is Mission-Related Objects (MROs), which are directly linked to the number of launches. We represent this debris generation process as ωL_t , where ω denotes the number of debris items created per launch at the time of launch. This type of debris is classified as *fragments* and includes protective fairings, covers, adapters, bolts, cables, and similar components.

The second source of debris arises from the final stages of launch vehicles, which often remain in orbit after payload insertion. These rocket bodies are large objects that pose a significant risk of breakup. We assume the number of rocket bodies produced per launch is given by φL_t , where $0 < \varphi < 1$ represents the fraction of launches that generate this type of debris. This fraction is strictly less than one to account for the use of reusable launch vehicles. Rocket bodies accumulate over time in a stock of large debris objects in orbit.

The third source of debris consists of derelict satellites, W_t , which are end-of-life satellites that are no longer operational (typically due to fuel depletion) and are not de-orbited but instead abandoned in orbit. In each period, the number of end-of-life satellites is $\delta_s S_t$, and a fraction χ of these are abandoned in orbit.

The fourth source of debris is fragmentation events resulting from the explosion or breakup of both derelict satellites and rocket bodies. These events can be unintentional or deliberate. Unintentional fragmentation debris originates from the breakup of operational satellites, rocket bodies, or engines. The main cause of in-orbit explosions is residual fuel remaining in the tanks of upper-stage rockets and satellites. The harsh space environment accelerates the deterioration of spacecraft components, which can lead to leaks that mix fuel components and trigger accidental explosions. Batteries may also explode. Once a rocket stage or satellite is left in orbit, residual fuel in tanks or fuel lines can eventually cause structural failure. The harsh conditions of outer space can gradually damage the mechanical integrity of both external and internal parts, leading to leaks and/or mixing

of fuel components, which may self-ignite. Such explosions destroy the source object and scatter its mass into numerous fragments with varying sizes and velocities. Additionally, intentional spacecraft interceptions using surface-launched missiles have become a major source of debris in recent years.

Finally, the last source of debris is fragmentation caused by collisions between objects. The model accounts for collisions between operational satellites and debris, as well as collisions involving derelict satellites, rocket bodies, and fragments. Taking these sources of debris generation into account, we next define the law of motion for the three types of debris.

3.2.4 Derelict satellites The law of motion of derelict satellites is given by,

$$W_{t+1} = (1 - \delta_w - \varepsilon_w)W_t - \theta(D_{2,t} + (1 - v_{w,t})S_t)W_t + \chi\delta_s S_t \quad (40)$$

where δ_w is the natural decay rate of derelict satellites, and ε_w is the fraction of derelict satellites that explode in each period. The natural decay rate of debris varies significantly with altitude. At low altitudes, this ratio is very high, leading to a short lifespan for debris. However, as altitude increases, the natural decay rate declines exponentially. At high altitudes, it approaches zero. In the case of explosions, the number of debris fragments generated is $\phi_w \varepsilon_w W_t$, where ϕ_w is the number of fragments per exploding derelict satellite.

3.2.5 Rocket bodies Second, the stock of body rockets can be defined as

$$Z_{t+1} = (1 - \delta_z - \varepsilon_z)Z_t - \theta(D_{2,t} + (1 - v_{z,t})S_t)Z_t + \phi L_t \quad (41)$$

where δ_z is the natural decay rate of body rockets bodies, and ε_z is the fraction of body rockets that breakup each period. The number of debris fragments produced by the breakup of a large rocket body is given by $\phi_z \varepsilon_z Z_t$.

3.2.6 Fragments The third type of debris considered are fragments. The stock of fragments increases due to the following sources: debris from launches (mission-related objects), breakups of derelict satellites and body rockets, collisions between debris and operational satellites, and intentional military anti-satellite tests. We consider only collisions between operational satellites with debris; collision between debris themselves are not considered. Formally, the law of motion of fragments is given by,

$$\begin{aligned} F_{2,t+1} = & (1 - \delta_f)F_{2,t} + (1 + \Gamma)\omega L_t + (1 + \Gamma)\gamma_s X_t + (1 + \Gamma)\phi_w \varepsilon_w W_t + (1 + \Gamma)\phi_z \varepsilon_z Z_t \\ & + (1 + \Gamma)\phi_w \varepsilon_s S_t + (1 + \Gamma)\gamma_w \theta D_{2,t} W_t + (1 + \Gamma)\gamma_z \theta D_{2,t} Z_t \end{aligned} \quad (42)$$

where δ_f is the natural decay of fragments, γ_s is the number of tracked debris fragments created by a collision that destroys an operational satellite, and ω is the number of tracked fragments produced per launch. We exclude the possibility that operational satellites can breakup due to design failure. The number of tracked fragments produced by the collisions of derelict satellites with other debris is denoted by γ_w , and γ_z represents the number of tracked fragments produced by the collision of rocket bodies with other debris. The parameter Γ is a scaling factor that converts the number of fragments larger than 10 cm into fragments larger than 1 cm.

4. DECENTRALIZED SOLUTION APPROACH

Modeling a decentralized (market) economy requires explicitly representing both firms and households as decision-makers who respond to private costs and benefits, without internalizing the environmental damage they cause. This setup must also include a market structure where emissions function as a negative externality. The key insight is that, in a decentralized economy, the social cost of environmental damage is not automatically internalized. Instead, it influences the optimal behavior of private agents as they adapt their optimal decisions to changes in the environment. This creates a feedback loop: private decisions affect the environment, and environmental degradation, in turn, shapes future economic outcomes. The consequence is that the model cannot be converted directly to a non-linear programming problem, where social welfare is maximized subject to both economic and environmental restrictions.

For computing the decentralized solution, we follow the fixed-point solution approach by Bongers and Torres (2025). The core idea of that approach builds on the fixed-point iteration method proposed by Krusell and Smith (2024) in the context of climate change. In their framework, the competitive equilibrium is computed by iterating on agents' expectations about aggregate environmental and economic variables. Specifically, they begin with an initial guess for the trajectory of global temperature and the sequence of interregional transfers (e.g., carbon tax revenues). Given these, they solve the Bellman equation backward in time to derive time-dependent policy functions (decision rules) for households and firms. These policy functions are then used to simulate the economy forward, generating updated paths for aggregate capital, consumption, emissions, and temperature. The iteration continues until the guessed and simulated trajectories converge, forming a fixed point that is consistent with a decentralized equilibrium in which agents do not internalize externalities.

In this paper, we adopt a conceptually similar approach to that of Krusell and Smith (2024) but adapt it to the context of orbital environmental externalities following Bongers and Torres (2025), using a nonlinear programming (NLP) formulation instead of dynamic programming. Rather than computing policy functions, we solve a finite-horizon dynamic optimization problem directly at each iteration using numerical optimization tools. The model solution represents a decentralized economy in which agents maximize utility and profits based on private returns, taking the trajectory of orbital debris and associated damages as exogenous.

Briefly, the fixed-point pseudo-algorithm is the following. First, the algorithm starts with an initial guess for the time paths of the externality, specifically, the trajectory of orbital debris $\{W_t, Z_t, F_t\}$, and the associated damages $\{\Lambda_t\}$ over a finite horizon $t = 0, 1, 2, \dots, T$. Second, given the externality paths $\{W_t, Z_t, F_t, \Lambda_t\}_{t=0}^T$, solve the decentralized economic model of previous section as a nonlinear programming problem. Third, using the optimal trajectories of economic activity computed in previous step (e.g., satellite launches), compute the resulting updated path of debris and damage using the debris accumulation equations and the damage function (collision probabilities, emissions, fragmentation dynamics, and natural decay processes). Finally, the algorithm compares the updated debris and damage trajectories to the previous iteration. This iterative process continues until convergence is achieved, yielding a self-consistent equilibrium trajectory in which the economic decisions are optimal given the assumed externality, and the externality evolves endogenously based on those decisions.

5. DATA AND CALIBRATION

The model economy is intended to represent the global economy, also reflecting the global commons nature of outer space. That is, outer space is treated as a shared resource affected by the actions of all spacefaring nations and firms. Economic variables refer to the world economy. Space variables represent all Earth's orbits. Initial data corresponds to the year 2025. For a detailed description of the initial data and calibration of economic, space, and debris cost parameters see the online appendix.

6. ESTIMATION OF PRIVATE COST OF ORBITAL DEBRIS

To obtain numerical simulation, the model is reformulated as a non-linear programming (NLP) problem. The simulation covers the period 2025 to 2150, providing a 125-years time

horizon with annual frequency. The model is implemented and solved with the CONOPT algorithm in GAMS.

Figure 1 illustrates the trajectories of operational satellites, launches, newly deployed satellites, and satellites destroyed through collisions with orbital debris. These dynamics correspond to a *laissez-faire* scenario in which no mandatory mitigation policies are in place. The results reveal a tipping point in the stock of operational satellites around the year 2130. Up to that point, the number of satellites increases steadily, reaching a peak of approximately 150,000, after which it begins to decline. This threshold arises from the growing probability of collisions driven by the accumulation of orbital debris, eventually reaching a level at which satellite destruction reduces the returns on investment in space capital. Over the entire horizon, both launches and the number of newly inserted satellites continue to rise. However, these increases are not solely aimed at expanding the stock of operational satellites, but also at replacing those lost due to debris-related collisions. The bottom-right panel shows the number of satellites destroyed by collisions, which grows exponentially over the simulation horizon as orbital debris accumulates.

Figure 2 presents the trajectories of orbital debris. We identify tipping points in the evolution of intact objects, namely derelict satellites and rocket bodies. Their number increases until approximately 2125, after which it begins to decline. This pattern reflects the expansion of space activity, which initially leads to the accumulation of abandoned satellites and rocket bodies. However, as the overall stock of orbital debris grows, the frequency of collisions involving these intact objects also rises. Once debris accumulation becomes sufficiently large, collisions exceed the rate at which new derelict satellites and rocket bodies are added to orbit. This shift accelerates the generation of debris fragments, further compounding the problem. The bottom-left panel illustrates the accumulation of debris fragments: initially driven by launch activity and fragmentation events, but increasingly dominated by collision-generated debris over time. Finally, the bottom-right panel shows the probability of collision, which begins to rise sharply after 2100 and reaches nearly 20% by the end of the simulation horizon.

Figure 3 depicts the trajectories of total mission costs imposed by orbital debris, excluding the costs associated with the destruction of space assets. The magnitudes of these cost components differ substantially. In all cases, costs increase over time, driven by both the growing stock of orbital debris and the rising number of missions. Collision avoidance (COLA) costs and additional launch costs due to increased shielding mass reach approximately 5 and 4 billion dollars, respectively, by the end of the simulation horizon. The additional manufacturing cost of spacecraft shielding exceeds 10 billion dollars over the

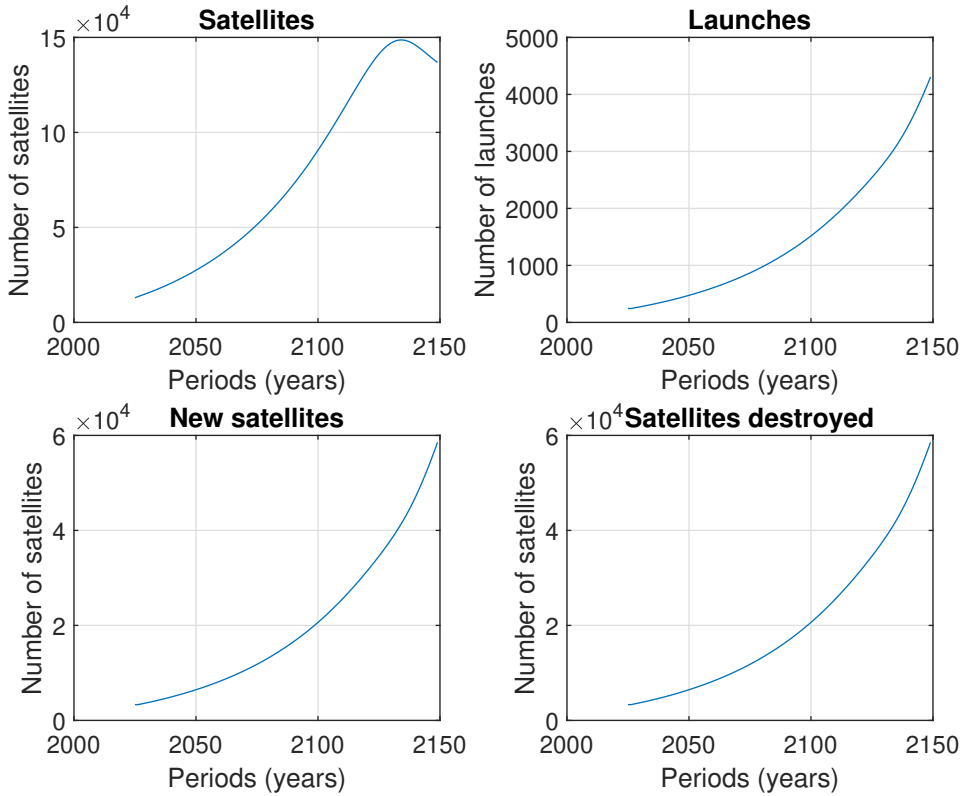


FIGURE 1. BaU optimal trajectories for operational satellites, launches, new satellites, and satellites destroyed by collisions.

same period. Nevertheless, the most significant cost component is associated with collision avoidance operations. While shielding-related costs depend primarily on the number of missions, both COLA costs and collision avoidance costs are also influenced by the level of orbital debris. In particular, collision avoidance costs, being the dominant component, rise sharply once the debris population becomes sufficiently large.

Figure 4 presents the trajectories of the total private costs associated with orbital debris, decomposed into three main components: additional launch costs, operational costs, and collision-related costs. Over the next 50 years, these costs increase at a moderate pace. However, as orbital debris accumulates and the number of operational satellites continues to grow, total private costs rise sharply. By the end of the simulation horizon, they exceed 60 trillion dollars, with the majority driven by the destruction of operational satellites due to collisions.

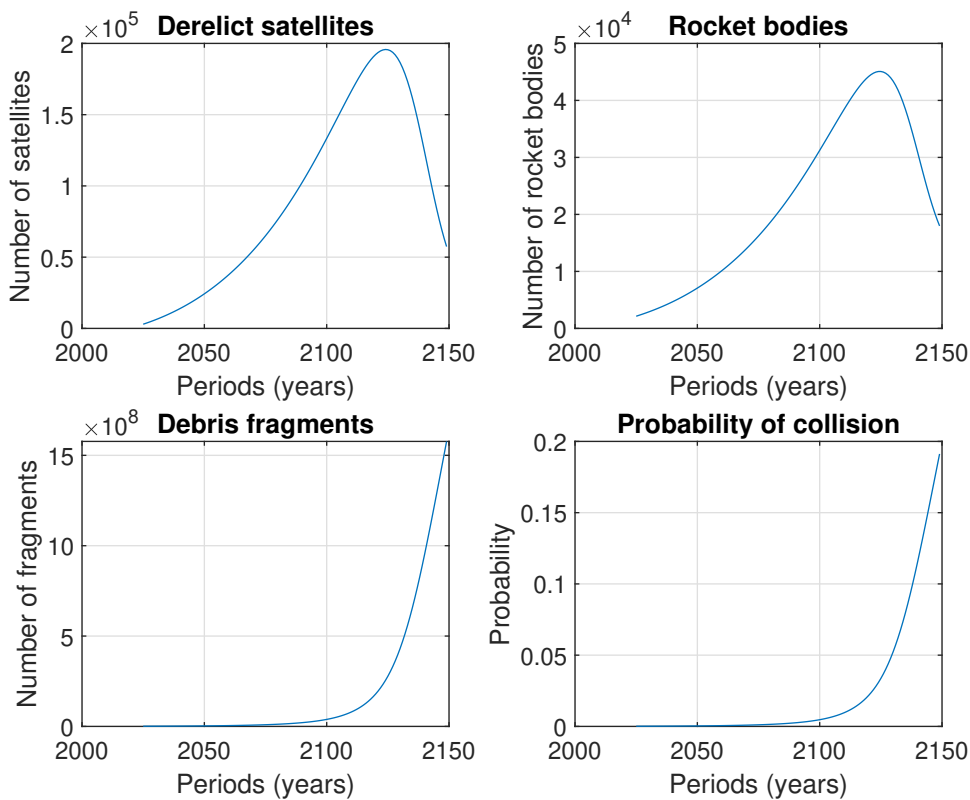


FIGURE 2. Orbital debris trajectories and the probability of collision.

Finally, Figure 5 shows the percentage share of each cost component in total debris-related costs. Initially, shielding-related costs account for the largest share, followed by collision avoidance costs, while COLA costs are the least significant. However, over time, the relative importance of shielding costs declines, whereas both collision avoidance and collision-related costs increase. By around 2060, collision costs converge to the level of collision avoidance costs, and together their combined share rises steadily, reaching approximately 90% of total costs by the end of the simulation horizon.

Table 1 reports the estimated private cost of orbital debris per mission, expressed in thousands of constant 2025 U.S. dollars. The per-mission cost of launch collision avoidance (COLA) is estimated at approximately \$5,800 in the baseline year, increasing to about \$14,600 after 100 years. Despite the projected growth in orbital debris and the continued expansion of satellite operations, COLA costs remain relatively modest throughout the

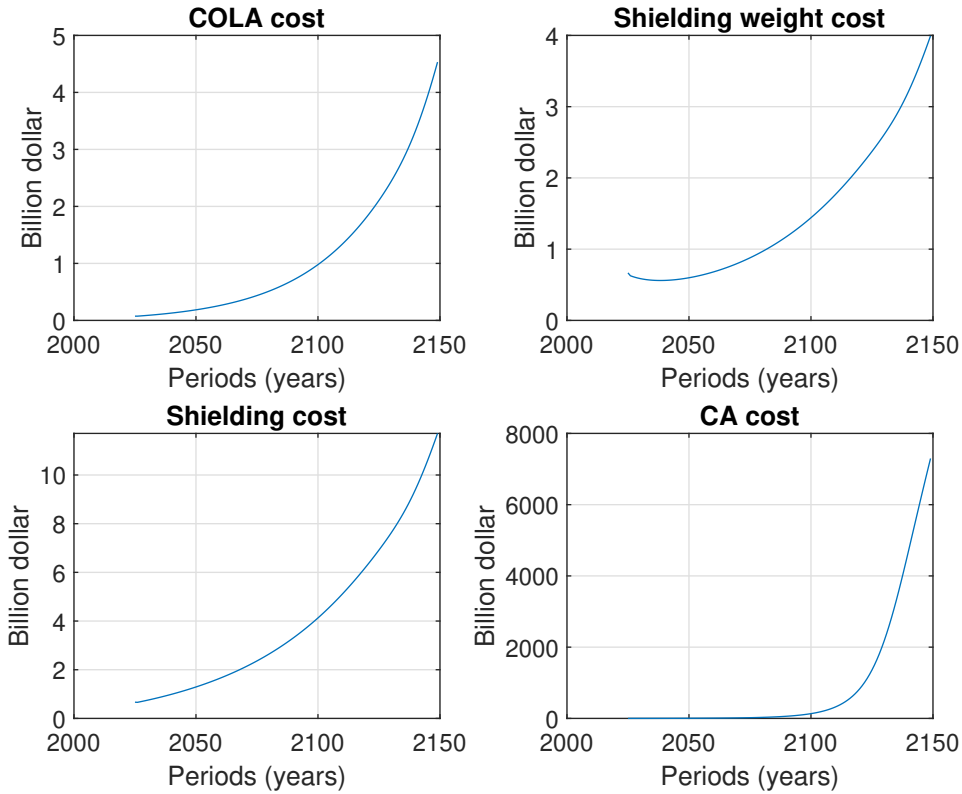


FIGURE 3. Costs of orbital debris: Cola cost, extra-launch cost due to shielding, manufacturing shielding cost, and collision avoidance costs.

simulation horizon. The per-mission cost of spacecraft shielding is estimated at approximately \$103,400 in 2025. Over time, this cost declines to between \$60,000 and \$70,000 per mission, reflecting the projected reduction in launch costs per kilogram as launch technologies improve.

The largest increases in mission costs arise from collision-avoidance operations (CAO) and satellite losses due to collisions. The average cost of CAO is estimated at approximately \$40,900 per mission in 2025. As orbital congestion intensifies, however, this cost rises dramatically, reaching about \$1.4 million per mission by 2100 and approximately \$8.8 million by 2125. Likewise, the expected cost of satellite losses from collisions is relatively modest in the baseline year, at around \$16,600 per mission, but increases rapidly thereafter, approaching \$1 million by 2075, exceeding \$5 million by 2100, and surpassing \$50 million by 2125.

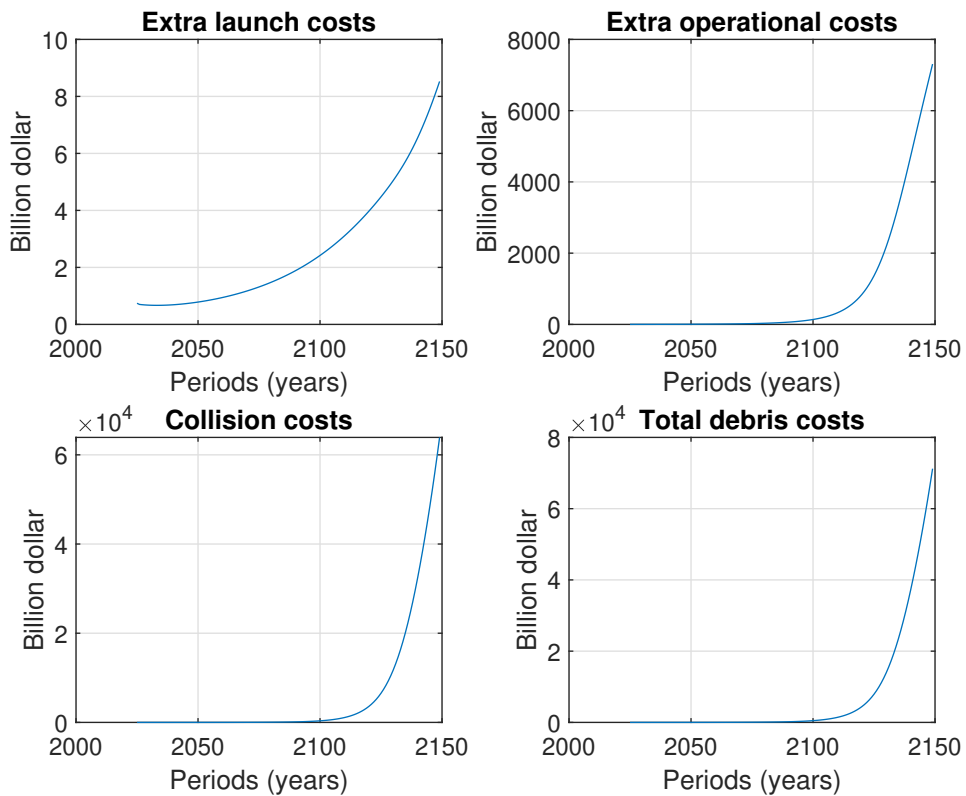


FIGURE 4. Costs associated to orbital debris

Overall, the total mission cost attributable to orbital debris is estimated at approximately \$166,700 in 2025. During the following 25 years, this cost increases moderately to about \$283,100 per mission. Thereafter, mission costs accelerate sharply as orbital debris accumulates and collision risks increase, reaching approximately \$1 million by 2075, \$5 million by 2100, and more than \$50 million per mission by 2125.

TABLE 1. Cost of orbital debris per mission (Thousand 2025 dollar)

Year	COLA	SHIELD	CAO	Collision	Total
2025	5.8	103.4	40.9	16.6	166.7
2050	6.7	69.3	123.4	83.6	283.1
2075	8.4	63.1	379.3	502.4	953.2
2100	10.7	61.5	1,391.5	3,590.0	5,053.5
2125	14.6	65.2	8,840.6	41,592.0	50,503.0

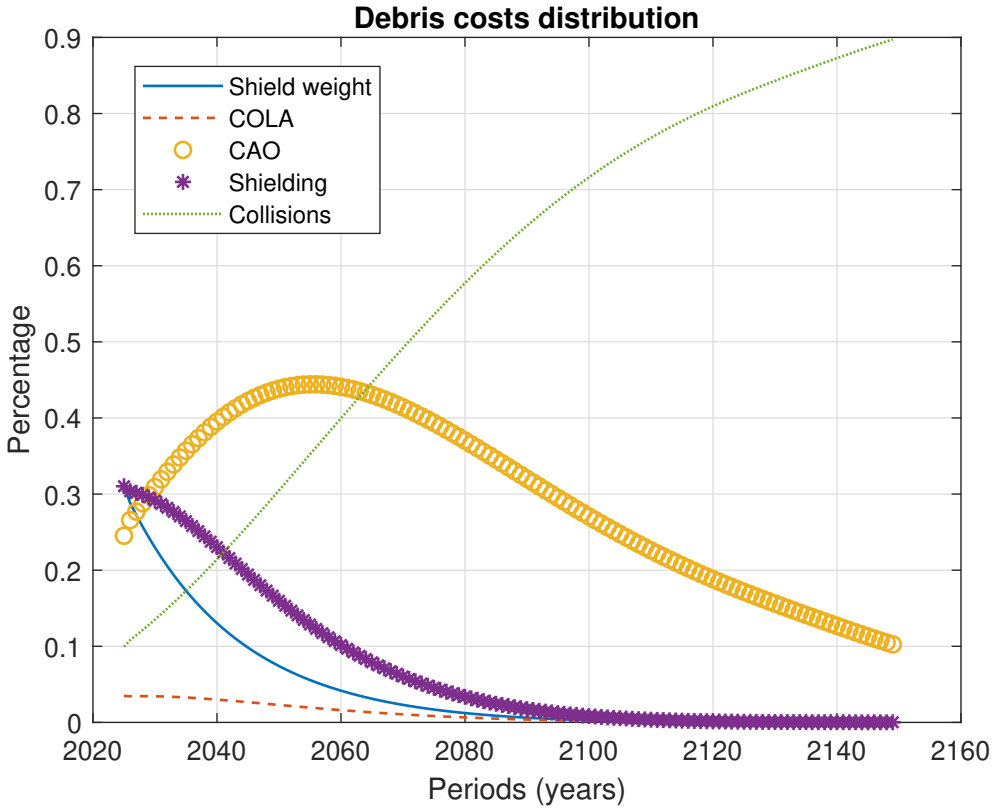


FIGURE 5. Orbital debris cost distribution

Table 2 reports the estimated private costs associated with orbital debris for selected years, expressed in constant 2025 million U.S. dollars. Total launch collision-avoidance (COLA) costs are estimated at approximately \$74.7 million in 2025, rising to more than \$2 billion after 100 years. Shielding costs amount to about \$1.3 billion in the baseline year and increase to approximately \$9.2 billion over the same period. Collision-avoidance operation costs follow a much steeper trajectory, increasing from approximately \$527 million in 2025 to more than \$1.3 trillion by 2125. Likewise, the expected costs associated with satellite collisions rise from about \$200 million in the baseline year to more than \$6.5 trillion after 100 years.

Overall, the total private costs imposed by orbital debris are estimated at approximately \$2.15 billion for the global satellite industry in 2025, with shielding and collision-avoidance operations accounting for the largest share of these costs. In the absence of additional debris mitigation measures, total private costs are projected to increase to more than \$8 billion by 2050, approximately \$52 billion by 2075, and nearly \$500 billion by

2100. Over a 100-year horizon, the total economic burden borne by spacefaring operators is projected to approach \$8 trillion, reflecting the rapid escalation of orbital congestion and collision risks under the baseline scenario.

TABLE 2. Total mission cost of orbital debris (Million 2025 dollar)

Year	COLA	SHIELD	CAO	Collision	Total
2025	74.7	1,334.3	527.3	213.7	2,150.0
2050	185.8	1,890.1	3,543.9	2,463.7	8,083.5
2075	436.2	3,240.3	20,447.0	27,831.0	51,954.5
2100	978.9	5,569.2	134,000.0	354,700.0	495,250.1
2125	2,106.1	9,288.6	1,359,300.0	6,549,400.0	7,920,114.7

7. CONCLUSIONS

Orbital debris has emerged as one of the principal challenges to the long-term sustainability of space activities. Although the direct consequences of debris accumulation have been widely recognized, the economic costs imposed on space missions have received comparatively less attention and are often only partially quantified. This paper contributes to the literature by providing a comprehensive estimate of the private mission costs generated by orbital debris within a dynamic general equilibrium integrated assessment model that jointly captures the evolution of the orbital environment and economic activity.

The analysis demonstrates that debris-related mission costs increase substantially over time as orbital congestion intensifies. While shielding and other launch-related costs constitute the largest component of mission costs in the near term, expenditures on collision-avoidance operations become increasingly important as the orbital environment deteriorates. Over longer horizons, direct losses from collisions eventually dominate the overall economic burden. These changing cost structures highlight that the economic impacts of orbital debris evolve together with the space environment and therefore cannot be adequately assessed using static or short-term analyses.

The model also shows that the aggregate private costs imposed by orbital debris rise rapidly over time in the absence of additional mitigation measures. Although these costs remain relatively modest under current orbital conditions, they increase by several orders of magnitude over the course of the century as the stock of debris and the number

of operational satellites continue to grow. These findings suggest that the economic consequences of orbital debris may become a significant constraint on the expansion of the space economy if current trends persist.

More broadly, the results illustrate the importance of incorporating mission costs into integrated economic models of the orbital environment. Because firms respond optimally to debris-induced costs when making investment decisions, changes in the orbital environment affect not only collision risks but also launch decisions, satellite deployment, and the long-run evolution of space capital. Ignoring these feedback mechanisms is likely to underestimate the economic consequences of orbital debris and may lead to misleading assessments of future space activity.

Several limitations should be acknowledged. The estimates presented in this paper depend on assumptions regarding debris generation processes, collision probabilities, technological progress, future growth in space activity, and the calibration of mission cost components. In addition, the analysis focuses on private mission costs and does not quantify the broader social value of space services, strategic considerations, or the welfare losses associated with disruptions to communications, navigation, Earth observation, and scientific activities. Consequently, the estimated costs should be interpreted as a lower bound on the overall economic burden generated by orbital debris.

Future research could extend the framework in several directions. An important next step is to evaluate the effectiveness and cost-effectiveness of alternative debris mitigation and remediation policies, including post-mission disposal, active debris removal, collision-avoidance technologies, and international regulatory instruments. Extending the model to account for uncertainty, heterogeneous satellite operators, and endogenous technological innovation would also provide a richer characterization of the long-run interaction between economic development and the sustainability of the orbital environment. Such extensions would contribute to the design of efficient policies capable of preserving the benefits of space activities while limiting the economic damages associated with orbital debris.

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