The Cost of (Un)regulation: Shrinking Earth's Orbits and the Need for Sustainable Space Governance

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Abstract

Outer space is boundless, but usable planetary orbits are limited. This unique aspect of Earth's orbit poses challenges in sustainability and equity, with international regulation proving difficult. By employing a probability based model, this article predicts that unless significant measures are taken, the density of space objects will reach a critical threshold soon, endangering future satellite constellations. Addressing this issue will require not only technological advancements but also a fundamental overhaul of outdated international regulations, which have contributed to the current orbital debris crisis.

Background

Earth's orbits, classified as Areas Beyond National Jurisdiction (ABNJ), are regulated by international treaties, but the evolving complexity of space activities calls for a more flexible legal framework. Recent regulatory shifts, such as the US Executive Order 13914, challenging the notion of outer space as a global commons, present obstacles to equitable resource usage and sustainable growth. Earth's orbits, divided into Lower Earth Orbit (LEO), Medium Earth Orbit (MEO), and geosynchronous orbit (GEO), are under increasing strain due to overcrowding. The number of objects sent to space continues to rise, with thousands of satellites projected for launch, particularly in congested LEO. This proliferation increases the risk of collisions and contributes to space debris, threatening the sustainability of the space environment.

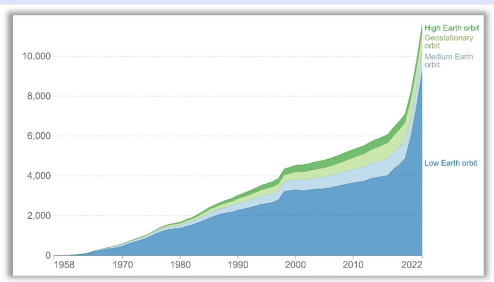

Figure: Space Objects by Orbit (not including space debris).

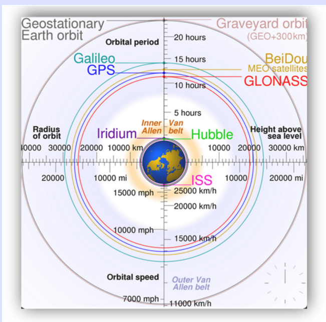

Figure: The Earth's orbits.

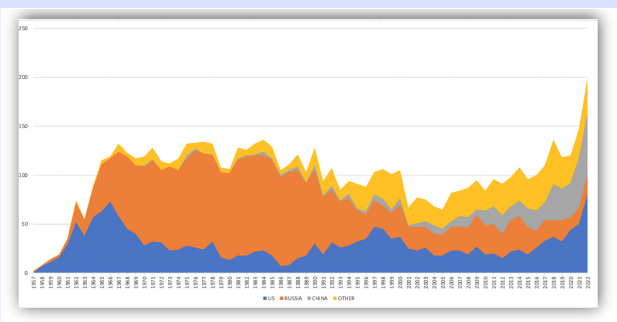

Figure: Annual number of launches by country (1957–2022).

Results

Critical Density

Natural Critical Density: This rate determines how often collision-based fragments re-enter Earth's atmosphere and disintegrate due to. If the debris population remains below this critical density, it diminishes over time, however surpassing it leads to a Kessler Event.
Impact of Collision-based Fragmentation: Annually, 200 to 400 objects re-enter Earth's atmosphere. Implementing Active Debris Removal (ADR) strategies can delay the onset of a Kessler Event.
Timeline for Action: Our model predicts critical density will be reached by 2031 in the base scenario and late-2027 in the high scenario.

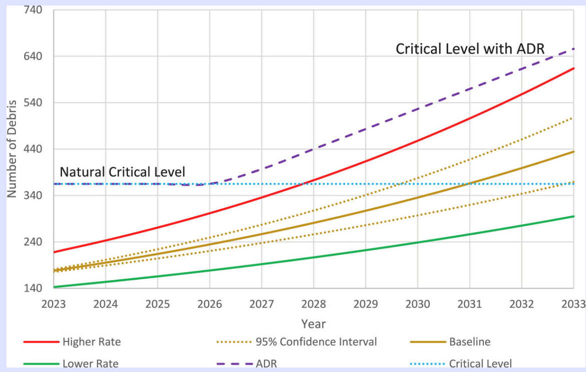

Figure: Active collision-based fragmentation removal with re-entry (LEO)

Active Debris Removal (ADR)

ADR Policy Implementation: Assuming all future space activities won't cease, a robust ADR policy is essential to manage congestion. For instance, to achieve 10k objects in space within a decade, starting ADR in January 2026, we'd need to remove 3500 debris in 2026, increasing by 30% annually.
Debris Removal Targets: Cumulatively, approximately 61k debris would need removal in the next decade to meet sustainability goals. Fig. 9 illustrates the required reduction speed for debris to reach 10k within a decade through ADR implementation from 2026.

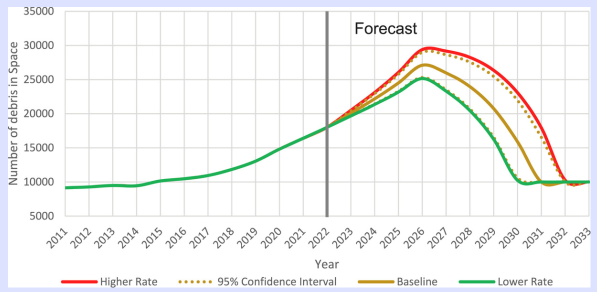

Figure: ADR removal visualisation.

Cost-savings per debris de-orbited

Cost-Benefit Analysis: Conducted a cost benefit estimate for debris removal.
Annual Total Cost: The annual total cost from debris impact is estimated to grow from $35M in 2023, to $66M by 2033. (total cost of replacing a satellite in LEO x mean annual collision rate)
Debris in LEO: Estimated number of debris in LEO at 12.5k in 2023, rising to 23.2k in 2033.
Cost-Savings Analysis: By dividing the annual total cost by the number of debris in LEO, we calculated a cost-saving per unit of debris de-orbited, of $2,6574 in 2023, falling to $2350 by 2033.

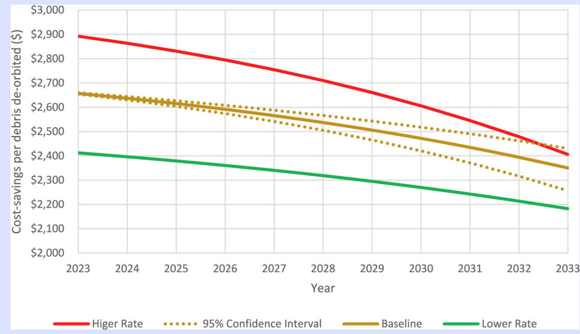

Figure: Cost-savings per derbis object de-orbited.

Methodology

Research Design: a quantitative research design grounded in probabilistic economic theory to project the potential number of objects in orbit
Variables and Measures: trackable objects in space, debris generated by collisions, and satellites launched
Data collection: Commercial revenue of global space economy (Space Foundation), history of number of trackable objects (European Space Agency)
Growth Rate Estimation: Used an OLS regression to estimate the growth rate of trackable objects and additional satellites. The growth rate of collision debris is calculated based on the mean number of collisions per year, which is a function of the number of trackable objects.
Collision Debris Estimation: As the total number of objects increases, the probability of collisions rises, leading to the creation of additional debris. We used a Poisson distribution to calculate the additional number of debris generated by predicted collisions, assuming at least one collision per year.

Conclusion

- **Importance of the Space Sector:** With a growing valuation and increasing private sector involvement, satellites play a crucial role in the space sector.
- **Urgency for Active Debris Removal**: Our model predicts a high probability of a Kessler Event within a decade without active mitigation measures. Urgent action is needed to address debris remediation, highlighting the importance of further research in this area.
- **Outdate legal frameworks:** Additionally, outdated legal frameworks hinder progress in achieving sustainable usage of Earth's orbits, emphasizing the need for internationally agreed-upon space governance.