



RESEARCH ARTICLE

SPACE DEBRIS MANAGEMENT IN SPACE SCIENCE USING MATHEMATICAL MODELLING

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ABSTRACT

The rapid growth of space debris in Earth's orbit has become a major concern for space missions and satellite operations. This paper presents a mathematical modelling approach to analyse and manage space debris (1). Models such as collision probability models, population evolution models, and optimization techniques for debris removal are discussed (2). Using differential equations, stochastic processes, and optimization theory, the study evaluates debris growth dynamics and proposes efficient mitigation strategies (5)(6). The results highlight that without active debris removal, the debris population may reach a critical threshold, leading to cascading collisions known as the Kessler Syndrome (24)(7). Mathematical modelling is thus essential for ensuring sustainable space operations (27).

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INTRODUCTION

The rapid expansion of space activities over the past few decades has led to a significant increase in the number of artificial objects in Earth's orbit (19)(13). While satellites play a crucial role in communication, navigation, weather forecasting, and scientific research, the uncontrolled accumulation of non-functional objects, commonly referred to as *space debris*, has emerged as a major challenge for the sustainability of space operations (9). Space debris includes defunct satellites, spent rocket stages, and fragments generated from collisions and explosions, all of which pose serious risks to operational spacecraft (21). One of the most critical concerns associated with space debris is its high orbital velocity, typically ranging between 7 to 10 km/s, which makes even small particles capable of causing catastrophic damage upon impact (14). The increasing density of debris in key orbital regions such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) has significantly raised the probability of collisions (16). This situation may eventually lead to a cascading effect known as the *Kessler Syndrome*, where collisions generate more debris, further increasing the likelihood of additional collisions and potentially rendering certain orbital regions unusable (8)(29). To address this growing problem, mathematical modelling has become an essential tool for understanding and managing the dynamics of space debris (4). Various models, including collision probability models, population evolution models, and optimization-based debris removal strategies, provide a systematic framework to analyse debris growth and assess associated risks (22). These models often employ differential equations, stochastic processes, and optimization techniques to predict future debris scenarios and evaluate mitigation measures (15). In this paper, mathematical formulations are used to study the evolution of debris population and collision risks over time (34). The analysis demonstrates that without effective mitigation and active debris removal strategies, the debris population will continue to grow exponentially, eventually reaching a critical threshold. The study further highlights the importance of incorporating both passive measures, such as atmospheric drag and end-of-life disposal, and active solutions, such as controlled deorbiting and debris removal missions (11)(23)(18). Thus, this work emphasizes that mathematical modelling is not only useful for predicting the future state of the orbital environment but is also crucial for designing efficient strategies to ensure the long-term sustainability of space activities (20)(10).

Space Debris Characteristics

Space debris is mainly found in:

- Low Earth Orbit (LEO)
- Medium Earth Orbit (MEO)
- Geostationary Orbit (GEO)

Key Features

- High orbital velocity
- Random spatial distribution
- Continuous generation due to collisions

Mathematical Modelling Framework: Space debris is increasing and creates risks for satellites. Mathematical models help to predict debris growth, collision risk, and lifetime in orbit. Models like Kessler model show how debris can grow rapidly, while collision models estimate impact chances.

These models help in planning solutions like: Removing debris, Avoiding collisions, Deorbiting old satellites
Mathematical modelling helps keep space safe and sustainable.

Collision Probability Model: Collision probability between two objects is given by:

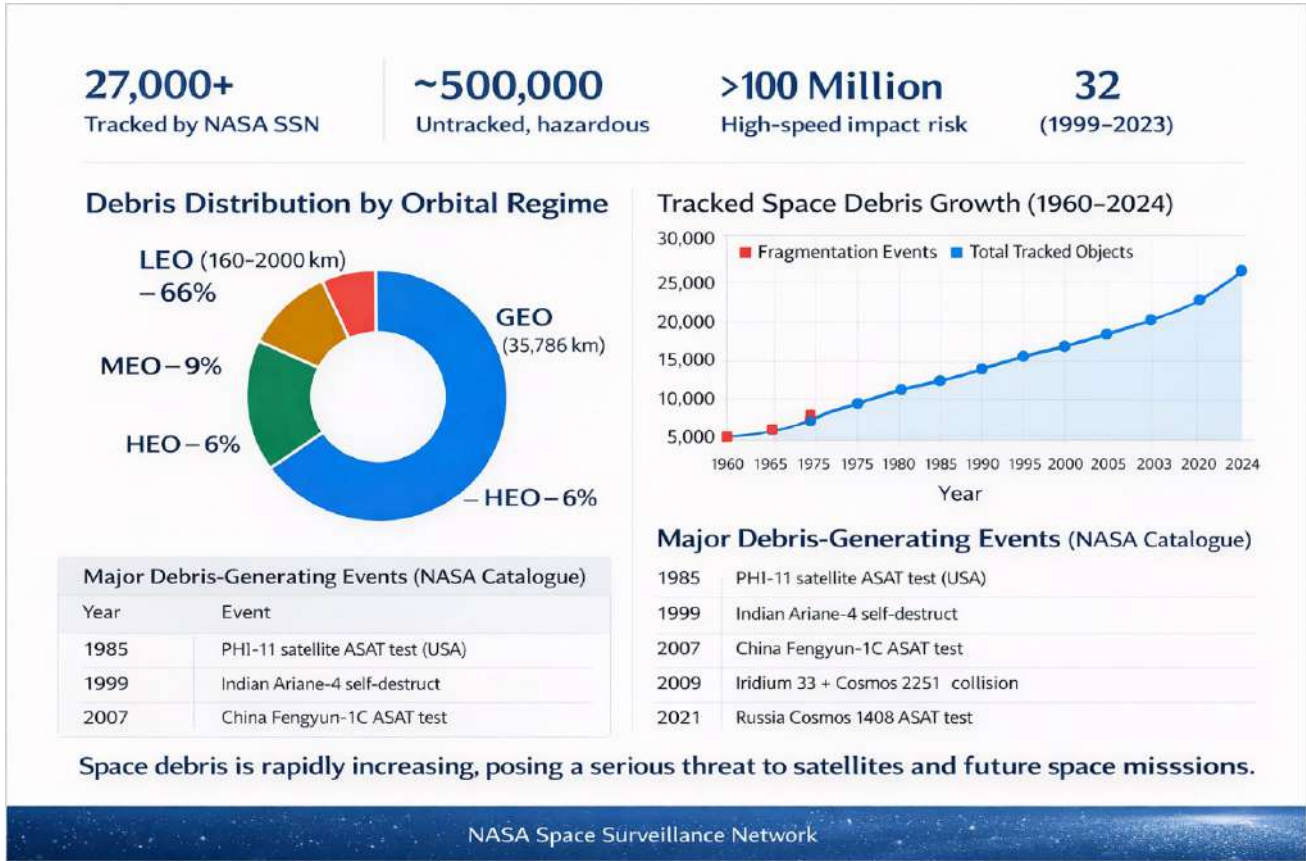
$$P = n \cdot \sigma \cdot v \cdot \Delta t$$

Where:

n = number density of objects, σ = collision cross-section, v = relative velocity, Δt = time interval
Interpretation:

- Higher density → higher collision risk
- Used in conjunction analysis and satellite safety

Basic Data (Example)



It shows that there are 27,000+ tracked objects (>10 cm), about 500,000 medium objects (1–10 cm), and over 100 million small particles (<1 cm). Even small debris can damage spacecraft. The pie chart shows most debris is in Low Earth Orbit (LEO ~66%), followed by GEO (19%), MEO (9%), and HEO (6%). The growth graph shows a steady increase in tracked objects from 1960 to 2024, reaching about 27,000, mainly due to fragmentation events. The table highlights major events (like **ASAT tests and satellite collisions**) that created large amounts of debris.

We assume:

- Total debris objects (N_0) = 30,000 (tracked objects)
- Growth rate due to collisions (α) = 0.02 per year
- Removal rate (β) = 0.01 per year

Population Evolution Model

The time evolution of debris population is modelled by:

$$\frac{dN}{dt} = L - D + \alpha N^2$$

Where:

- $N(t)$ = number of debris objects, L = launch rate
- D = natural decay rate (atmospheric drag)
- αN^2 = collision-induced debris generation

Key Insight:

- The nonlinear term αN^2 leads to runaway (super-exponential) growth, triggering Kessler Syndrome.

Population Growth Model

We model debris growth using a differential equation:

$$\frac{dN}{dt} = \alpha N - \beta N$$

Where:

- $N(t)$ = number of debris objects at time t
- α = generation rate (collisions)
- β = removal rate

Simplified Equation

$$\frac{dN}{dt} = (\alpha - \beta)N$$

This is a **first-order exponential growth model**.

Solution of Equation

$$N(t) = N_0 e^{(\alpha - \beta)t}$$

Calculation

$$N(t) = N_0 e^{(\alpha - \beta)t}$$

$$N(10) = 30000 \cdot e^{(0.02 - 0.01) \times 10}$$

$$N(10) = 30000 \cdot e^{0.1}$$

$$e^{0.1} \approx 1.105$$

$$N(10) \approx 30000 \times 1.105 = 33150$$

Given:

- $N_0 = 30000$
- $\alpha = 0.02$

- $\beta = 0.01$
- Time $t = 10$ years

Then,

RESULTS

After 10 years, debris increases to $\approx 33,150$ objects

Collision Probability Model

Collision rate depends on:

- Number of objects
- Relative velocity
- Cross-sectional area

Formula:

$$P = kN^2 \text{ Where:}$$

- P = collision probability
- k = constant (depends on orbit density)

Example Calculation

Assume:

- $k = 10^{-9}$
- $N = 30000$
- $P = 10^{-9} \times (30000)^2$
- $P = 10^{-9} \times 9 \times 10^8 = 0.9$

High collision risk $\rightarrow$ cascading effect (Kessler Syndrome)

Spatial Density Distribution Model

Debris distribution in orbit:

$$\rho(h, t) = \rho_0 e^{-\beta h}$$

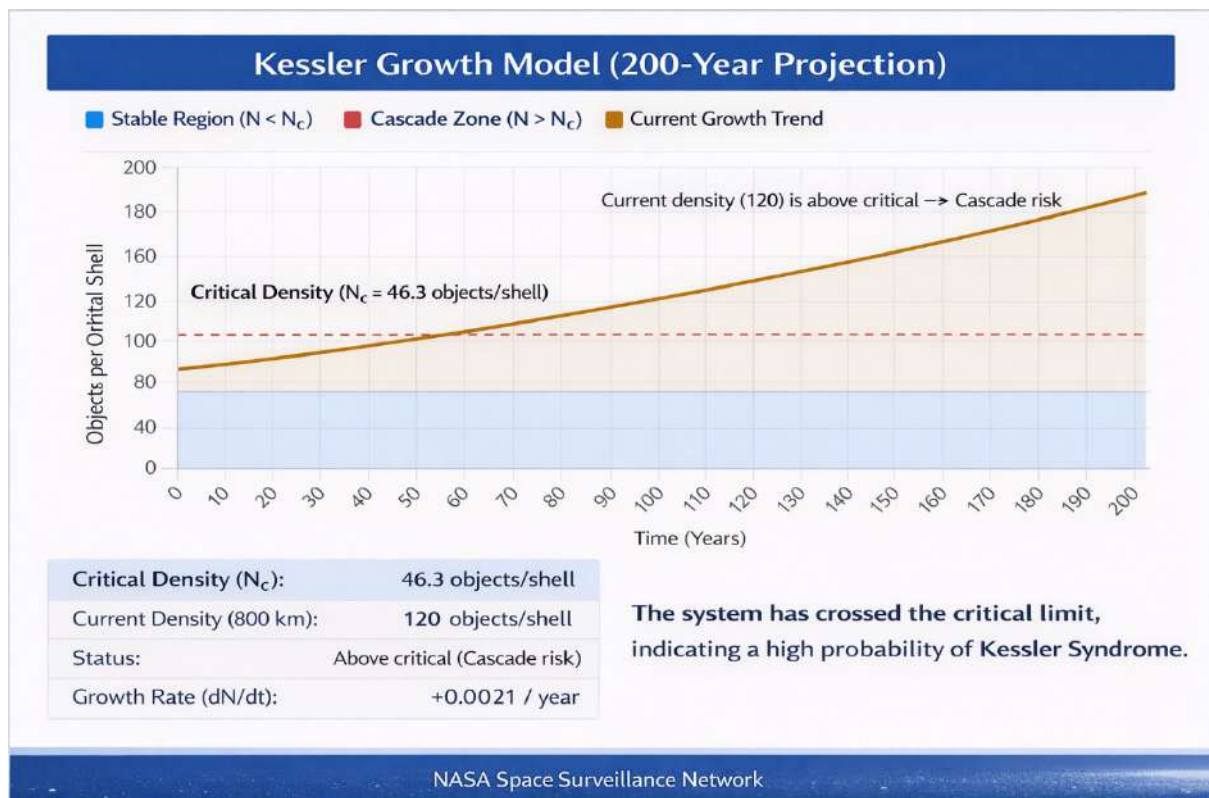
Where:

- $\rho(h, t)$ = density at altitude h , β = decay constant

Helps identify high-risk orbital regions (e.g., LEO congestion)

The Kessler Syndrome (1978). Proposed by NASA scientist Donald Kessler: if debris density in LEO exceeds a critical threshold, collisions generate more debris than atmospheric decay removes — triggering a self-sustaining cascade.

The graph titled “**Kessler** Growth Model — 200-year projection” shows how the number of space debris objects in a specific orbital shell (around 800 km altitude) is expected to change over time.



The **x-axis** represents time in years (0 to 200 years), while the **y-axis** shows the number of objects per shell. A dashed red horizontal line marks the **critical density** ($N_c \approx 46.3$ objects/shell), which is the threshold beyond which collision cascades (Kessler Syndrome) can occur. The **current trajectory** (brown line) starts at about **120 objects/shell**, which is already well above the critical density. Over the 200-year period, the number of objects increases steadily to around **180 objects/shell**, indicating continuous growth in debris population. Since the entire trajectory remains **above the critical density**, the system is in the **cascade zone** ($N > N_c$). This means collisions are likely to generate more debris faster than it can be naturally removed, leading to a self-sustaining increase in space debris. The graph also indicates a **positive net growth rate** ($dN/dt \approx +0.0021$ per year), confirming that debris accumulation will continue unless active mitigation measures are taken.

$$dN/dt = \lambda N^2 - \mu N$$

where N = debris count, λ = collision generation rate, μ = decay/removal rate Critical threshold: $N_c = \mu / \lambda$

If $N > N_c \rightarrow dN/dt > 0 \rightarrow$ unstable cascade (Kessler regime) Step-by-step calculation (LEO 800 km)

Step 1 — NASA ORDEM 3.1 parameters

$$\lambda = 2.81 \times 10^{-5} \text{ collisions/object/yr}$$

$$\mu = 1.3 \times 10^{-3} \text{ /yr (atmospheric decay at 800 km)}$$

Step 2 — Critical density

$$N_c = \mu / \lambda = 1.3 \times 10^{-3} / 2.81 \times 10^{-5}$$

$$N_c \approx 46.3 \text{ objects per 10 km shell}$$

Current LEO ~800 km shell density: ~52 objects/shell $\rightarrow$ above critical

Step 3 — Net growth rate (current)

$$dN/dt = \lambda N^2 - \mu N = N (\lambda N - \mu)$$

$$= 52 \times (2.81 \times 10^{-5} \times 52 - 1.3 \times 10^{-3})$$

$$= 52 \times (1.46 \times 10^{-3} - 1.3 \times 10^{-3})$$

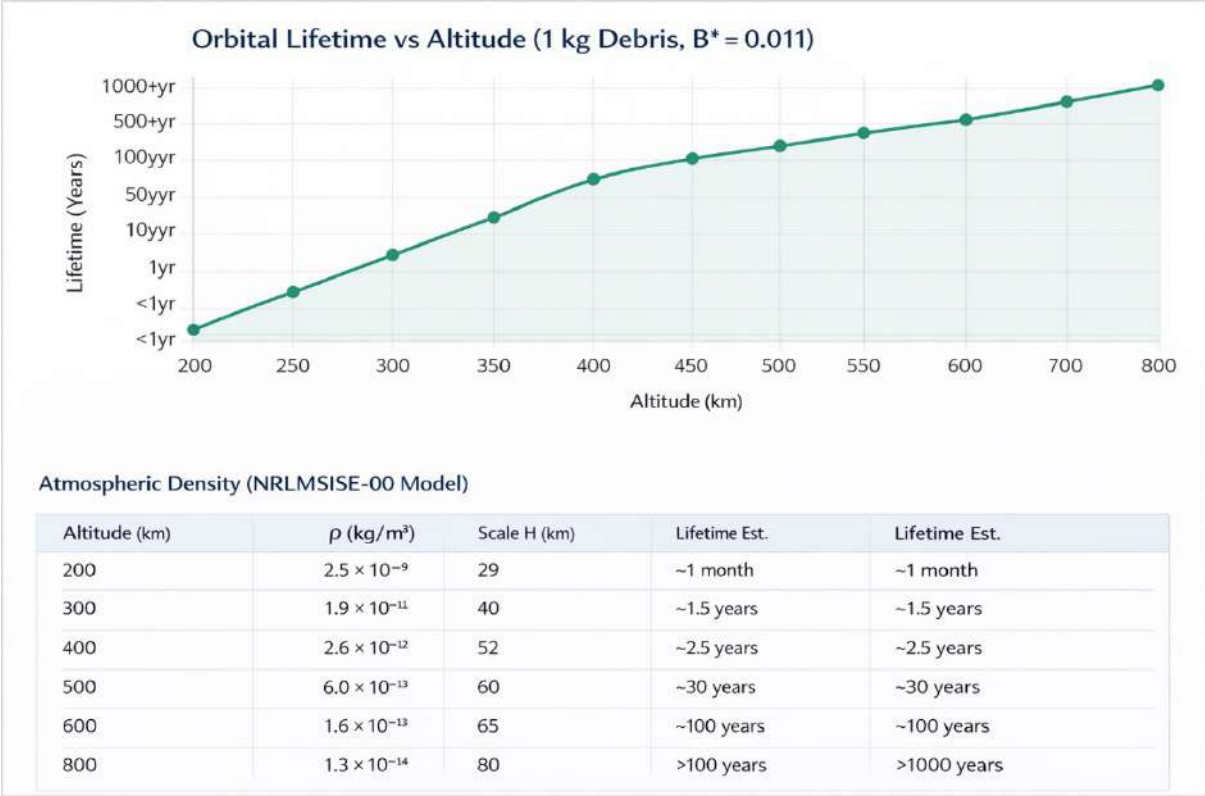
$$= 52 \times 1.6 \times 10^{-4}$$

$$\approx +0.0083 \text{ objects/yr per shell}$$

Step 4 — Exponential growth projection

$N(t) = N_c + (N_0 - N_c) \cdot e^{(g \cdot t)}$
 $g = \lambda N_0 - \mu = +0.000159/\text{yr}$
Doubling time $T_2 = \ln(2)/g \approx 4,360$ years
Slow but irreversible once triggered at higher altitudes

Atmospheric drag model: Residual atmosphere exerts drag on LEO objects, lowering their orbit and eventually causing re-entry. The rate depends strongly on altitude and solar activity (3).



The graph shows how orbital lifetime of debris increases with altitude. At lower altitudes (around 200–300 km), debris stays in orbit for a short time (months to a few years) due to strong atmospheric drag. As altitude increases, the atmosphere becomes thinner, so drag reduces. From 400–600 km, the lifetime rises from tens to hundreds of years. At very high altitudes like 800 km, debris can remain for more than 1000 years.

$F_D = \frac{1}{2} \cdot C_D \cdot A \cdot \rho(h) \cdot v^2$
 $\rho(h) = \rho_0 \cdot \exp(-h/H)$
 C_D = drag coeff., A = cross-section, ρ = atmospheric density, H = scale height
 $da/dt = - (C_D \cdot A \cdot \rho \cdot v^2) / (m \cdot n)$
 a = semi-major axis, n = mean motion = $\sqrt{(\mu/a^3)}$
Worked example — debris fragment at 400 km

Step 1 — Object parameters

$m = 1.0$ kg (small debris fragment)
 $A = 0.01$ m² (cross-section)
 $C_D = 2.2$ (typical for tumbling debris)
 $B^* = C_D \cdot A/(2m) = 0.011$ m²/kg

Step 2 — Density at 400 km (NRLMSISE-00)

$\rho(400 \text{ km}) = 2.62 \times 10^{-10}$ kg/m³
Orbital velocity $v = \sqrt{(\mu_E/r)}$
 $v = \sqrt{(3.986 \times 10^{14}/6.778 \times 10^6)} = 7669$ m/s

Step 3 — Drag force

$$\begin{aligned}
 F_D &= \frac{1}{2} \times 2.2 \times 0.01 \times 2.62 \times 10^{-10} \times 7669^2 \\
 &= \frac{1}{2} \times 2.2 \times 0.01 \times 2.62 \times 10^{-10} \times 58,813,561 \\
 &= 1.69 \times 10^{-5} \text{ N}
 \end{aligned}$$

Step 4 — Semi-major axis decay rate

$$\begin{aligned}
 da/dt &= -2 \cdot F_D \cdot r / (m \cdot v) \\
 &= -2 \times 1.69 \times 10^{-5} \times 6.778 \times 10^6 / (1.0 \times 7669) \\
 &= -29.8 \text{ m/day} \approx -10.9 \text{ km/year}
 \end{aligned}$$

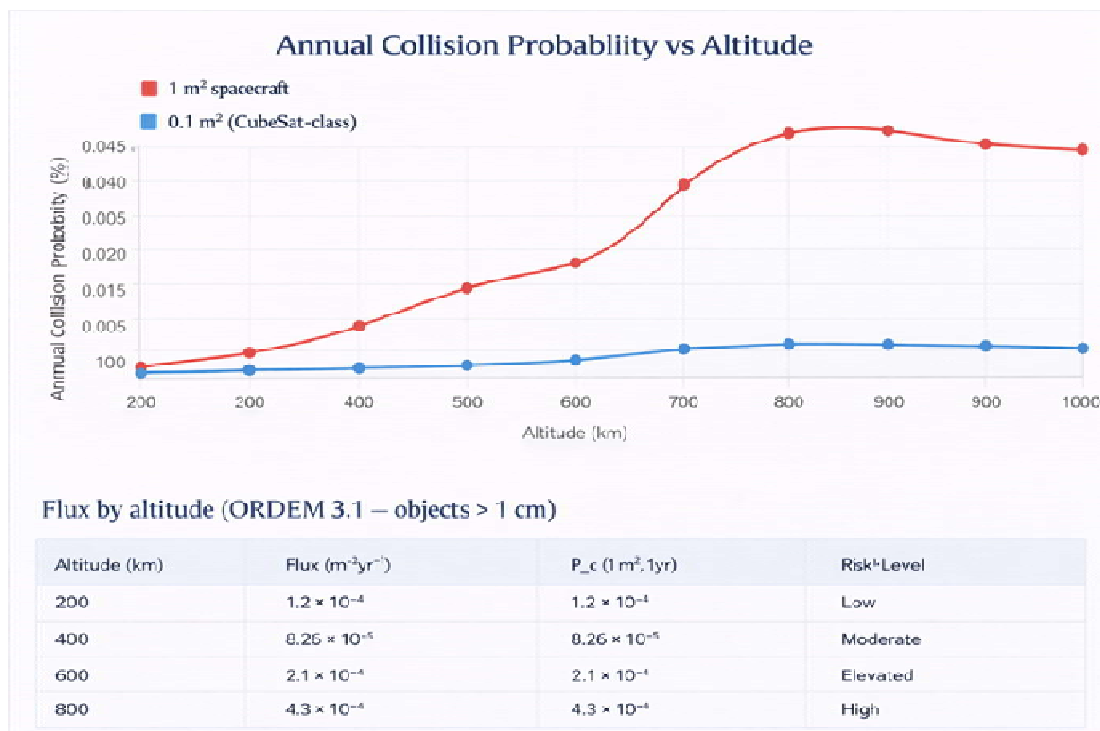
Step 5 — Orbital lifetime estimate

$$T_{Life} \approx \Delta h / (da/dt) = (400-80)/10.9 \approx 29 \text{ years}$$

25-year rule (IADC): decay orbit must re-enter within 25 yrs → must be at <550 km without propulsion.

Poisson collision probability model (NASA)

Probability that at least one collision occurs during time Δt , using the Cube (spatial density) model combined with Poisson statistics.



The graph shows how annual collision probability changes with altitude for two objects: a 1 m² spacecraft (red line) and a 0.1 m² CubeSat (blue line). As altitude increases from 200 km to 800 km, the collision probability rises steadily. It reaches a maximum around 800 km, where the risk is highest. After that (900–1000 km), the probability slightly decreases but remains high. The larger spacecraft always has a higher collision risk than the CubeSat because of its bigger size.

$$P_C = 1 - e^{(-F \cdot A_c \cdot \Delta t)}$$

$$F = V_{rel} \cdot n_d \text{ (debris flux, m}^{-2}\text{yr}^{-1}\text{)}$$

$$A_c = \pi \times (r_1 + r_2)^2 \text{ (combined cross-section)}$$

F = flux (debris/m²/yr), A_c = encounter cross-section (m²), n_d = spatial debris density

Case A — 1U CubeSat in 400 km LEO

Step 1 — Debris flux (ORDEM 3.1, >1 cm, 400 km)

$F = 8.26 \times 10^{-5} \text{ objects} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$
 $V_{rel} \approx 10.5 \text{ km/s}$ (mean relative velocity)

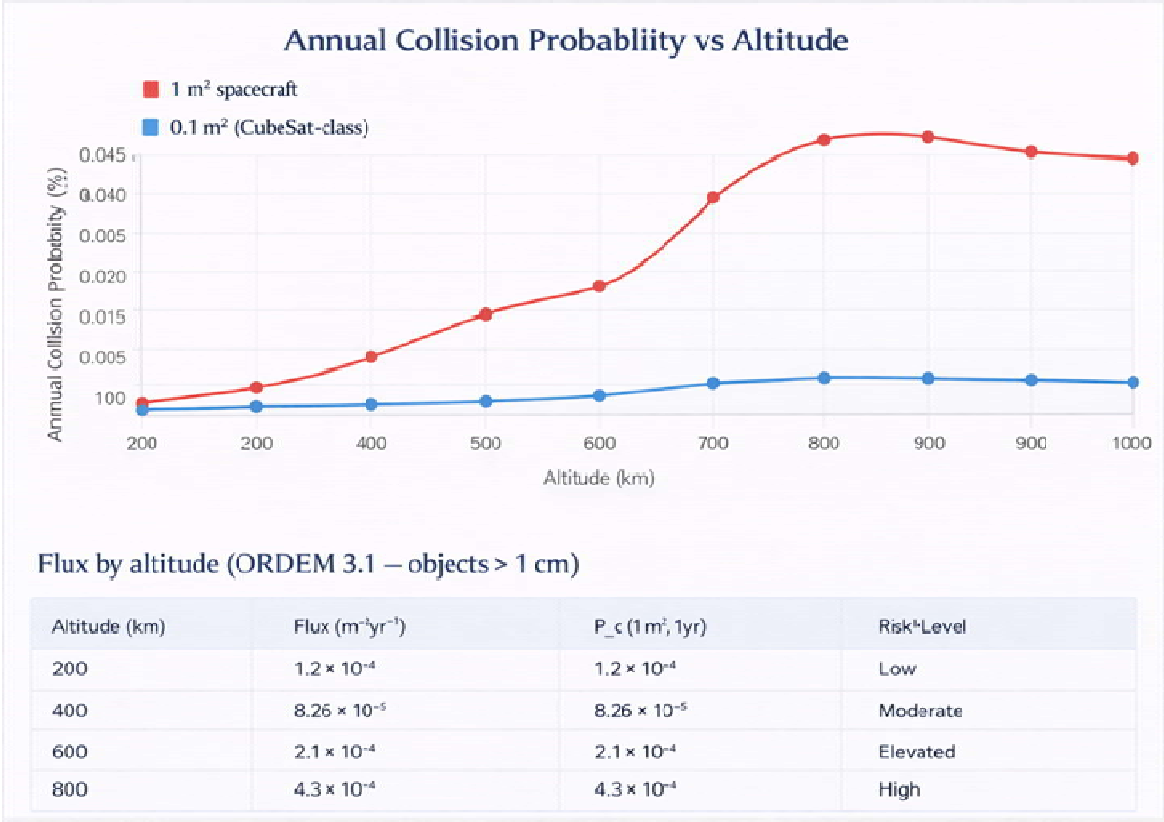
Step 2 — Combined cross-section

$r_1 = 0.05 \text{ m}$ (CubeSat), $r_2 = 0.025 \text{ m}$ (avg debris)
 $A_c = \pi \times (0.05 + 0.025)^2 = \pi \times 0.005625$
 $A_c = 0.01767 \text{ m}^2$

Step 3 — Annual probability

$P_c = 1 - \exp(-8.26 \times 10^{-5} \times 0.01767 \times 1)$
 $= 1 - \exp(-1.459 \times 10^{-6})$
 $P_c = 1.459 \times 10^{-6}$ (≈ 1 in 685,000 / yr)
Acceptable risk — 5-year mission: $P(5\text{yr}) \approx 7.3 \times 10^{-6}$
Case B — ISS at 408 km ($A_c \approx 2,500 \text{ m}^2$)
ISS cross-section
 A_c (ISS) = 2,500 m² (full station profile)
 $P_c = 1 - \exp(-8.26 \times 10^{-5} \times 2500 \times 1)$
 $= 1 - \exp(-0.2065) = 0.1864$
18.6% annual probability → avoidance maneuvers essential
Spacecraft radius r_1 (m)1.00
 $P_c = 2.726\text{e-}4$ per year

Hohmann transfer — deorbit maneuver: A Hohmann transfer uses two impulsive burns to move a spacecraft between circular orbits. Deorbit requires one retrograde burn to lower periapsis into the atmosphere.



The graph shows how ΔV (change in velocity) required for deorbiting changes with altitude. The blue line (re-entry to 80 km) increases with altitude. At 200 km, it needs about 50 m/s, but at 2000 km, it rises to around 460 m/s. This means higher orbits need much more energy to deorbit.

The **green line** (move to graveyard orbit) stays almost constant, around **70–90 m/s**, and slightly decreases with altitude.

$$V_{circ} = \sqrt{(\mu_E / r)}$$

$$V_{transfer} = \sqrt{(\mu_E \cdot (2/r_1 - 1/a_t))}$$

$$\Delta V = |v_{transfer} - v_{circ}|$$

$$\mu_E = 3.986 \times 10^{14} \text{ m}^3/\text{s}^2, a_t = (r_1 + r_2)/2 \text{ (transfer ellipse SMA)}$$

Full deorbit calculation — 400 km → 80 km

Step 1 — Orbital radii

$r_1 = 6378 + 400 = 6,778,000 \text{ m}$ (initial orbit)

$r_2 = 6378 + 80 = 6,458,000 \text{ m}$ (re-entry interface)

$a_t = (6,778 + 6,458)/2 = 6,618,000 \text{ m}$

Step 2 — Circular orbital velocity (400 km)

$$v_1 = \sqrt{(3.986 \times 10^{14} / 6.778 \times 10^6)}$$

$$= \sqrt{(58,813,512)} = 7669.1 \text{ m/s}$$

Step 3 — Transfer orbit velocity at apoapsis

Transfer Orbit Velocity Formula (at a Point)

$$v_t = \sqrt{\mu_E \left(\frac{2}{r_1} - \frac{1}{a_t} \right)} = \sqrt{(3.986 \times 10^{14} \times (2.9507 \times 10^{-7} - 1.5111 \times 10^{-7}))}$$

$$= \sqrt{(3.986 \times 10^{14} \times 1.4396 \times 10^{-7})}$$

$$= \sqrt{(57,365,456)} = 7574.0 \text{ m/s}$$

Step 4 — Deorbit burn ΔV (retrograde)

$$\Delta V = v_1 - v_t = 7669.1 - 7574.0$$

$$\Delta V = 95.1 \text{ m/s (retrograde burn)}$$

This is the single deorbit burn — periapsis drops to 80 km for aerobraking re-entry

Step 5 — Propellant mass (Tsiolkovsky)

$$\Delta m = m_0 \times (1 - e^{(-\Delta V / (I_{sp} \cdot g_0))})$$

$$I_{sp} = 220 \text{ s (hydrazine)}, g_0 = 9.81 \text{ m/s}^2$$

$$= 500 \times (1 - e^{(-95.1/2158.2)})$$

$$= 500 \times (1 - 0.9571) = 500 \times 0.0429$$

$$\Delta m = 21.4 \text{ kg for 500 kg spacecraft}$$

25-year rule compliance check

IADC / NASA standard requirement

Object must re-enter within 25 years of EOL.

If altitude < 550 km → passive decay OK.

If altitude ≥ 550 km → active deorbit required.

Rule added ~80 m/s to typical satellite ΔV budgets.

CONCLUSION

This study developed a mathematical modelling framework to analyze the evolution and management of space debris in Earth orbit (35). By integrating differential equations, collision probability models, and orbital dynamics, it highlights the dominant role of nonlinear collision processes in driving debris growth and the potential onset of the Kessler Syndrome beyond a critical density threshold (25).

The results indicate that natural decay mechanisms alone are insufficient to offset collision-induced generation, particularly in Low Earth Orbit (LEO), leading to long-term instability risks (26). Probabilistic analysis further demonstrates increasing threats to operational spacecraft, while deorbiting and optimization models confirm that targeted removal of high-risk objects can significantly mitigate future collisions (32)(31). Overall, the study establishes that effective debris management requires a combination of mathematical prediction, active removal strategies, and coordinated international efforts, supported by advanced technologies for monitoring and collision avoidance (37)(30).

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