

A Physics-Based Monte Carlo Framework for Space Debris Cascade Risk and Insurance Pricing

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Abstract

The commercial space insurance market was worth about \$1.2 billion in 2025. It prices satellite risk using historical launch failure rates. But no actuarial model accounts for cascade risk, where one collision generates debris that triggers more collisions, producing correlated losses across a portfolio. I build a coupled physics-actuarial framework to address this. For the physics piece, I wrote Monte Carlo code that tracks debris cascades in Low Earth Orbit (LEO). Collision rates come straight from orbital mechanics, not fitted parameters. On the pricing side, I used Value at Risk (VaR), Conditional VaR (CVaR), and Extreme Value Theory (EVT) to convert loss distributions into premiums. I set the simulation at 800 km and ran it for 50 years. Debris went from 36,500 to roughly 1.51 million objects. The premiums I get are *16.5 times higher* than what historical-loss pricing would give, \$2,058 million against \$125 million per year for 500 satellites. That \$1,933 million gap is a systemic insolvency risk for the global space insurance market. It also undermines long-term sustainability of outer space activities. I anchor the model to three real collision events and break down premiums following the Solvency II framework. I also talk about what this means for the UN Space 2030 Agenda and argue that risk-adjusted pricing could serve as an economic instrument for orbital sustainability.

Keywords: space debris, Kessler Syndrome, satellite insurance, Monte Carlo simulation, cascade risk, Solvency II, Extreme Value Theory, orbital sustainability, space traffic management, UN Space 2030 Agenda

1. Introduction

1.1 The Unpriced Risk to Orbital Sustainability

The space debris environment in Low Earth Orbit (LEO) has changed. It is no longer a background condition. It is an active operating cost. Tracking networks currently count over 36,500 objects larger than 10 cm in Earth orbit. On top of that, there are roughly 1 million objects between 1-10 cm and 130 million smaller fragments, according to the ESA Space Environment Report (2025). The World Economic Forum put a price tag on this: \$25.8-\$42.3 billion in debris-related costs for LEO assets between 2025 and 2035, assuming nothing changes. That kind of trajectory does not square with the long-term sustainability goals in the UN Space 2030 Agenda or the IADC Space Debris Mitigation Guidelines.

And yet the \$1.2 billion space insurance market still prices risk the old way, using historical loss data. Mostly launch failure rates and single-asset collision probabilities. *Nobody is modeling the chance that*

one debris event sets off a cascade, generating correlated claims across a whole portfolio at once. That gap creates a moral hazard. Operators flying in congested shells pay premiums that have nothing to do with the systemic risk they impose on everyone else in orbit.

1.2 Prior Work and Gap

Freeman et al. (2021) came closest. They built an actuarial modifier for On-Orbit Servicing (OOS) satellite insurance, folding debris mitigation into premiums, but only for direct collision risk. Cascade dynamics, the chain-reaction scenario Kessler (1978) laid out, were not part of their model. Liou and Johnson (2008) ran numerical simulations that showed LEO satellite populations are unstable. They did not take the step of linking those results to insurance pricing. To my knowledge, nobody has coupled first-principles collision physics with actuarial risk metrics to produce regulatory-compliant insurance premiums.

1.3 Contribution

My framework does six things. It couples collision physics with actuarial science so debris growth is driven by actual collision rates, not free parameters. Collision events are drawn from a Poisson distribution, with fragment yields from the NASA Standard Breakup Model. DS and DD collision yields are kept separate to prevent finite-time singularities. Portfolio-level correlated risk is quantified using Gaussian Copula methods. Extreme Value Theory handles tail risk estimation. The model is calibrated against three documented collision events. I also discuss the framework's relevance to international space governance and propose risk-adjusted pricing as an economic instrument for orbital sustainability.

2. Methodology

2.1 Physical Layer: Collision-Driven Debris Dynamics

I model a representative LEO shell at altitude $h = 800$ km with thickness $dh = 200$ km (700-900 km). The shell volume works out to $V = 1.29 \times 10^{11} \text{ km}^3$. I picked this altitude because it has the most defunct satellites and is where most mega-constellations operate. Drag at 800 km is weak enough that debris can stick around for decades, sometimes centuries.

2.1.1 Collision Rate

For collision rates between debris and satellites, I use the Kessler-Flournoy formula:

$$R_{ds} = N_d \cdot N_s \cdot \sigma \cdot v_{rel} \cdot T / V (1)$$

Debris-debris collisions drive the cascade. The rate R_{dd} is proportional to $N_d(N_d-1)$, which means it scales with N_d^2 . Double the debris, you quadruple the collision rate. This quadratic feedback is the mathematical root of the cascade. At current population levels ($N_d = 36,500$, $N_s = 8,000$), I compute about 7 debris-satellite and 16 debris-debris collisions per year.

2.1.2 Fragment Generation

The *asymmetric fragment yield* between collision types is calibrated to the NASA Standard Breakup Model:

Collision Type	Distribution	Median	Physical Rationale
Debris-Satellite (DS)	LogNormal(5.5, 0.8)	~245	Large satellite breakup
Debris-Debris (DD)	LogNormal(1.1, 0.5)	~3	Small fragment impact

Without this distinction, the N^2 scaling of DD rates combined with high yields (~ 245) produces a finite-time singularity. Debris populations diverge to unphysical values in short times. The asymmetry reflects the energy differential: a fragment striking an intact satellite releases orders of magnitude more energy than two small fragments colliding.

2.1.3 Stochastic Time-Stepping

I model collisions as a Poisson process. I broke time into 0.1-year steps, about 36.5 days each. Within each step, I draw DS and DD collision counts, generate fragments from log-normal distributions, apply orbital decay ($\lambda = 0.005/\text{year}$ with 10% stochastic noise), and update the population. *There are no free parameters.* Debris growth is entirely determined by collision physics. Each Monte Carlo path uses a distinct random seed for reproducibility.

2.2 Economic Layer: From Debris to Insurance Premiums

Getting from debris population to financial loss takes four steps. First, I compute per-satellite annual hit probability $p_{\text{hit}} = N_d \cdot \sigma \cdot v \cdot T / V$. Second, I calculate per-policy expected loss $= p_{\text{hit}} \cdot V_{\text{sat}}$ (\$50M average). Third, I aggregate across 500 insured satellites with Gaussian Copula correlation ($\rho = 0.3$). Fourth, I pull out VaR, CVaR, and EVT risk metrics from 1,000 Monte Carlo paths.

2.2.1 Solvency II Premium Decomposition

$$P = E[L] + \lambda_R \cdot (CVaR_{95} - E[L]) + r \cdot (VaR_{99} - E[L]) + \lambda_E \cdot E[L] \quad (2)$$

where $\lambda_R = 1.5$ (risk loading multiplier), $r = 0.04$ (discount rate), $\lambda_E = 0.15$ (expense loading). This decomposition follows the European Solvency II Directive (2009/138/EC), the international benchmark for insurance capital adequacy.

2.3 Calibration Against Observed Events

Event	Date	Fragments (>10cm)	Mass
Fengyun-1C (ASAT test)	2007-01-11	~3,500	880 kg
Iridium 33 x Cosmos 2251	2009-02-10	~2,300	1,510 kg
Kosmos 1408 (ASAT test)	2021-11-15	~1,500	2,200 kg

These three events collectively created over 7,300 trackable fragments and anchor the fragment yield distributions. Both ASAT tests (Fengyun-1C, Kosmos 1408) and the accidental collision (Iridium-Cosmos) are represented, ensuring the model captures both intentional and unintentional debris generation mechanisms.

2.4 Validation Against Current Observations

Metric	Model Value	Observed/Market Data	Source
Tracked debris (>10cm), 2025	36,500	36,500	[11]
Global insurance market, 2025	-	\$1.2B	[10]
Historical premium rate	0.5%	0.5%	[5]
Fengyun-1C fragments	~3,500	~3,500	[4]
Iridium-Cosmos fragments	~2,300	~2,300	[4]
Kosmos 1408 fragments	~1,500	~1,500	[4]

Cascade-adjusted premium	\$2,058M/year	Not yet priced	Model prediction
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The model's initial conditions align with current observational data from the ESA Space Environment Report 2025 [11]. The calibration events match IADC records and NASA fragmentation data [4]. The cascade-adjusted premium of \$2,058M/year represents the model's prediction of what insurance pricing should reflect if cascade risk were properly accounted for, compared to the current \$125M/year historical baseline based on industry practice [5].

3. Results

3.1 Debris Projection

Parameter	Value
Monte Carlo paths	1,000
Time horizon	50 years (2025-2075)
Time step	0.1 year (36.5 days)
Initial debris (>10 cm)	36,500
Active satellites in shell	8,000
Insured portfolio	500 satellites at \$50M each
Final debris (mean)	1,509,425
Final debris (median)	1,429,504
Final debris (95th pctlile)	2,236,440

Debris grows 41x over 50 years under business-as-usual conditions. The 95th percentile path reaches 2.24 million objects, representing a 61x increase.

3.2 Actuarial Risk Metrics

Metric	Definition	Value
Expected Loss (EL)	Mean annual portfolio loss	\$921.4M
VaR (95%)	95th pctlile worst-year loss	\$1,365M
CVaR (95%) / ES	Avg loss beyond VaR(95%)	\$1,565M
VaR (99%)	99th pctlile worst-year loss	\$1,721M
CVaR (99%) / ES	Avg loss beyond VaR(99%)	\$1,854M
EVT VaR (95%)	Generalized Pareto estimate	\$1,803M
EVT shape (xi)	Tail heaviness indicator	-0.032

3.3 Premium Decomposition

Component	Formula	Amount
Expected Loss (EL)	Mean annual loss	\$921.4M

Risk Loading	1.5 x (CVaR95 - EL)	\$966.0M
Capital Charge	4% x (VaR99 - EL)	\$32.0M
Expense Loading	15% x EL	\$138.2M
TOTAL PREMIUM		\$2,058M / year
Per-policy premium	Total / 500 policies	\$4,115,098 / year
Historical premium	0.5% x \$50M x 500	\$125.0M / year
CASCADE FACTOR	Cascade / Historical	16.5x

3.4 Key Findings

1. Debris grows 41x over 50 years (36,500 to 1.51M). The driver is super-exponential N^2 feedback in debris-debris collision rates. Liou and Johnson (2008) found the same thing: LEO is already unstable at current population levels.

2. Historical pricing underestimates risk by 16.5x. The cascade-adjusted premium (\$2,058M) exceeds historical pricing (\$125M) by \$1,933M per year. That gap is an unfunded liability in the global space insurance market.

3. Tail risk is substantial. CVaR(95%) (\$1,565M) exceeds expected loss (\$921M) by 70%. When I fit a generalized Pareto distribution to the tail, the EVT VaR(95%) comes in at \$1,803M, which is 32% above the empirical VaR(95%) of \$1,365M. Extreme cascade scenarios produce losses that the Monte Carlo sample by itself would not capture.

4. Risk loading dominates the premium. The CVaR-based risk loading (\$966M) exceeds the expected loss (\$921M). This reflects the heavy-tailed nature of cascade losses, a direct consequence of the quadratic feedback mechanism.

5. EVT confirms bounded but heavy tail. The GPD shape parameter $\xi = -0.032$ indicates a Type III (bounded) tail. But the large gap between empirical and EVT VaR estimates shows that extreme events remain non-negligible.

4. Discussion

4.1 Systemic Risk to the Insurance Market

The \$1,933M annual gap between traditional and cascade-adjusted pricing is a *systemic insolvency risk*. When debris density is high, all satellites face elevated risk at the same time. Claims would be correlated across the entire portfolio. A major cascade event at current premium levels could exceed insurer reserves and propagate losses to reinsurers, potentially destabilizing the global space insurance market. This risk is real. Fengyun-1C in 2007, Iridium-Cosmos in 2009, Kosmos 1408 in 2021. Three events, each creating thousands of trackable fragments, all within the last 18 years.

4.2 Implications for International Space Governance

Right now, the UN Space 2030 Agenda and IADC guidelines set norms for sustainable space operations. But there is no enforcement behind them. This framework proposes an *economic instrument* to go along with regulatory approaches: risk-adjusted insurance pricing that internalizes the externality of debris

generation.

Under cascade-aware pricing, operators who place satellites in less congested shells or invest in end-of-life deorbiting would get lower premiums. This gives operators a market-based incentive for sustainability without requiring direct regulation. Operators who contribute to orbital congestion would face premiums that reflect the systemic risk they impose on all space users.

4.3 Policy Recommendations

1. Insurance regulators (e.g., EIOPA, NAIC) should require space insurers to disclose whether cascade risk is incorporated into pricing models.
2. The IADC and UNCOPUOS should commission independent studies on the macroeconomic implications of underpriced cascade risk.
3. Space agencies should explore premium differentiation as a condition for launch licensing -- satellites in congested shells pay higher insurance, which in funds debris mitigation.
4. Reinsurance markets should develop cascade-risk-specific instruments (e.g., catastrophe bonds tied to debris density thresholds) to transfer systemic risk off insurer balance sheets.

4.4 Limitations

Several limitations warrant discussion. First, the single-shell approximation (800 km only) does not capture the full 3D orbital environment with inclination and eccentricity distributions. Second, fragment physics are simplified -- the log-normal yield is calibrated to three events, whereas real fragmentation depends on collision energy, angle, and material properties. Third, the model does not include active debris removal. Fourth, the satellite population is static -- mega-constellation deployments and end-of-life deorbiting are not dynamically modeled. Fifth, there is no cross-altitude debris migration.

4.5 Future Work

Future research directions include: (1) multi-shell model with cross-altitude migration; (2) NORAD TLE data integration for empirical debris tracking; (3) dynamic constellation deployment modeling; (4) ADR scenario analysis and premium reduction quantification; (5) reinsurance layer pricing (excess-of-loss, stop-loss, catastrophe bonds); (6) Sobol global sensitivity analysis to identify the most impactful parameters.

5. Conclusion

This framework shows that incorporating physics-based cascade dynamics into insurance pricing reveals *16.5x underpricing* of LEO satellite risk. The main innovation is replacing ad-hoc cascade parameters with first-principles collision physics. Debris growth is driven by actual collision rates, with fragment yields calibrated to real events and asymmetric treatment of debris-satellite versus debris-debris collisions.

The \$1,933M annual pricing gap is a systemic risk to the global space insurance market, but it is also an opportunity. Risk-adjusted pricing can work as an economic instrument for orbital sustainability, going along with the regulatory framework of the UN Space 2030 Agenda. By aligning private insurance costs with systemic debris risk, this framework gives us a market-based pathway toward long-term sustainability of outer space activities.

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Data and Code Availability: The framework methodology is released under CC BY 4.0. Source code (Python package *cascade_risk*), configuration files, and simulation output data are available from the author upon request.

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