DEBRIS CLOUD FORMATION ANALYSIS.
SENIOR DESIGN
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PROBLEM STATEMENT

- The accidental collision of the Iridium 33 and Cosmos 2251 satellites in 2009 created one of the largest debris clouds in Low Earth Orbit (LEO), generating more than 1,800 trackable fragments and hundreds of thousands of smaller pieces.
- This event highlighted critical vulnerabilities in space operations, including the lack of proactive collision avoidance measures, the limited ability to track hazardous small debris, and the absence of effective strategies to mitigate long-term debris accumulation.

REAL COLLISION SCENARIO

- **The Collision of Iridium 33 and Cosmos 2251**
- **Date & Location: Feb 10, 2009, at ~790 km altitude**

•Satellites involved:

- **Iridium-33 (U.S., ~560 kg, operational)**
- **Cosmos-2251 (Russia, ~900 kg, non-operational)**
- **First accidental hypervelocity collision between two intact satellites**
- **Velocity: 11.6 km/sec**

OBJECTIVE

Analyze the Iridium 33–Cosmos 2251 collision to understand the scale and behavior of the resulting debris cloud

Quantify debris generation and orbital evolution over time.

Assess the short-term operational impacts on active satellites and crewed missions.

Examine long-term risks of uncontrolled debris growth in LEO.

NASA STANDARD BREAK UP MODEL

- **A data driven model.**
- **Defines the size, area-to-mass ratio, and ejection velocity of each generated fragment. Different size distributions are modeled before explosion events versus collision events**

$$N(L_c) = 0.1(M)^{0.75} L_c^{-1.71}$$

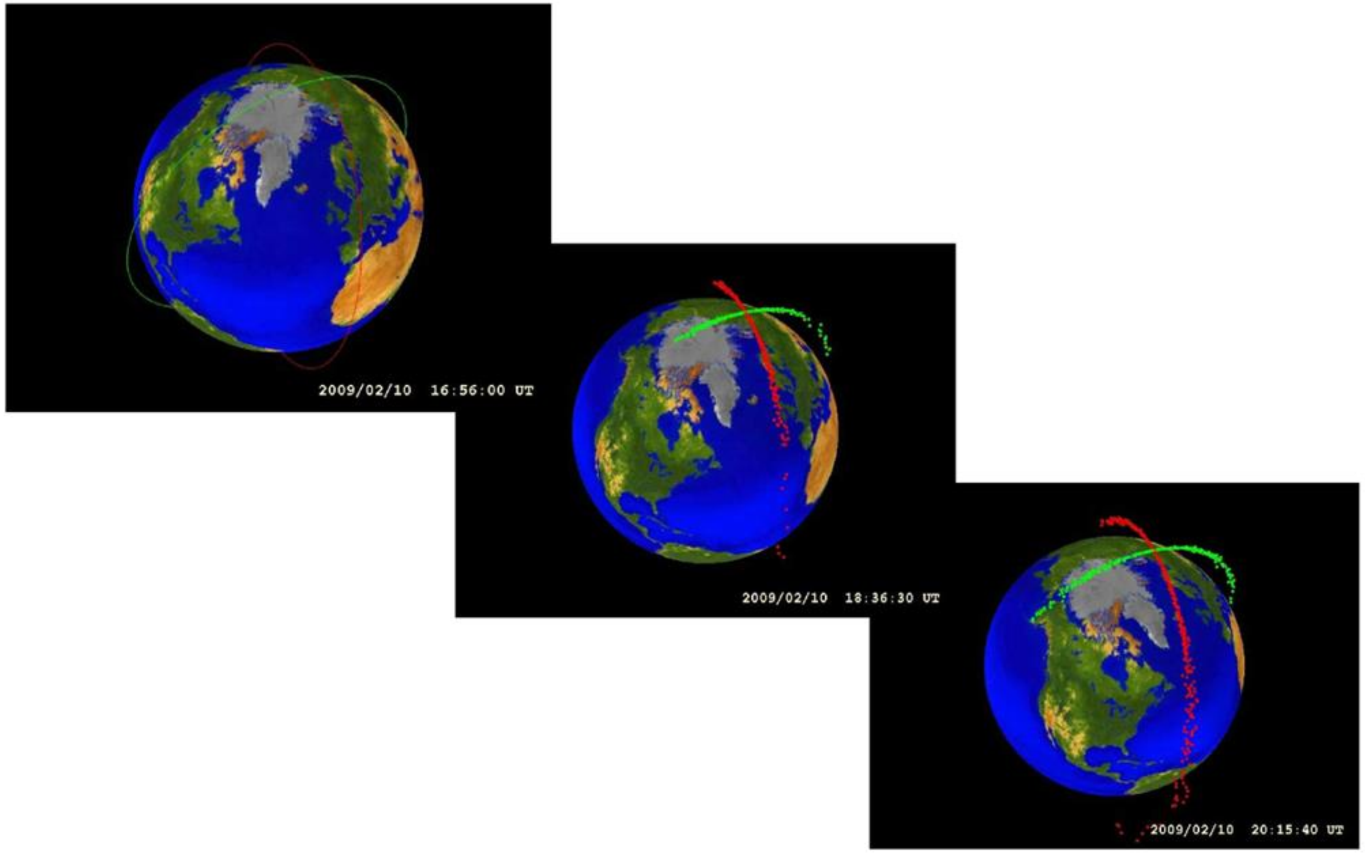
L_c = characteristic length of the fragment (average of the three longest orthogonal dimensions) and M = mass of the satellite.

Calculates:

- **Collision risk**
- **Debris density in different altitudes**
- **Long-term orbital environment evolution.**

National Aeronautics and Space Administration

Initial Spread of Debris



TRACK DATA DEBRIS OVER TIME

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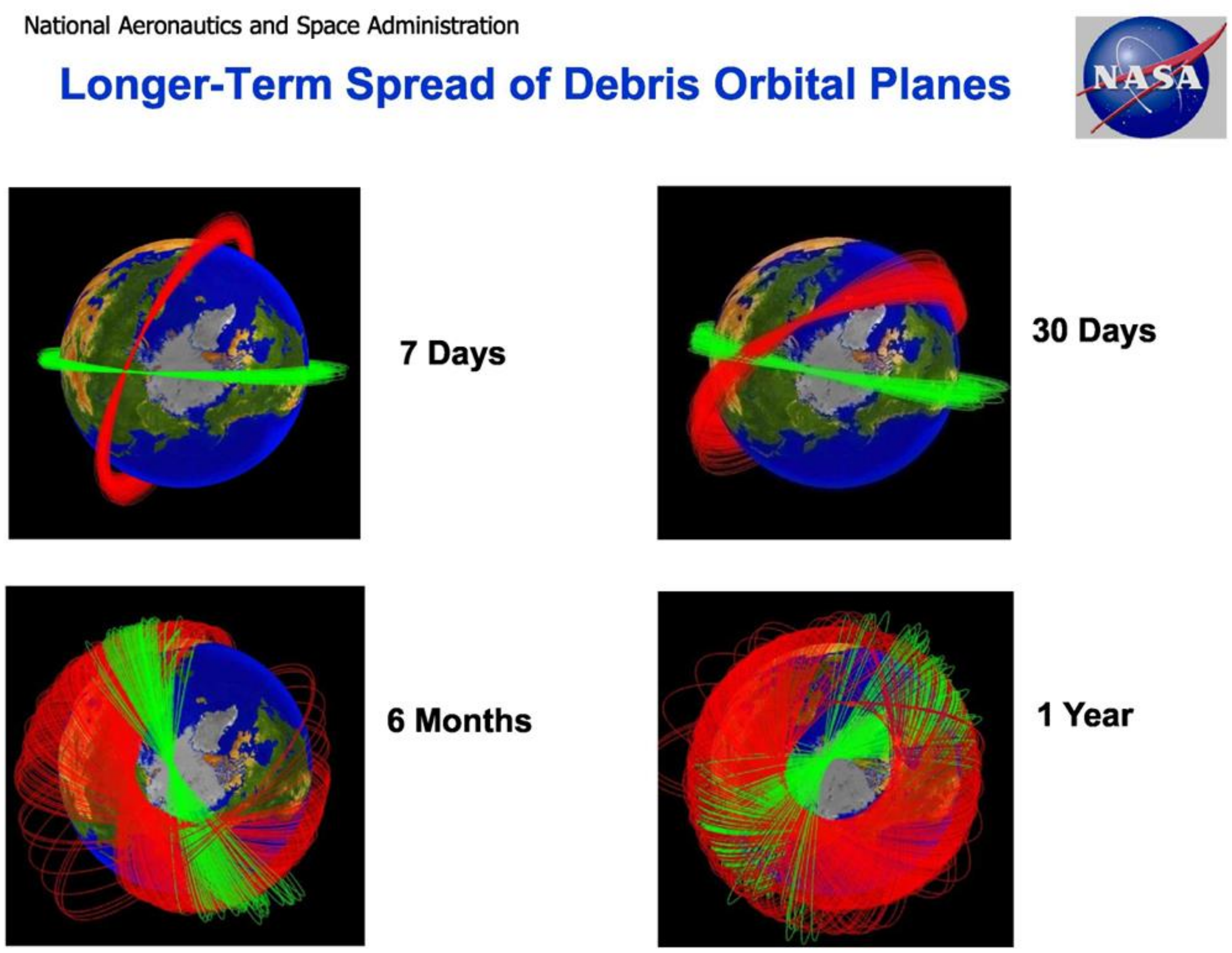
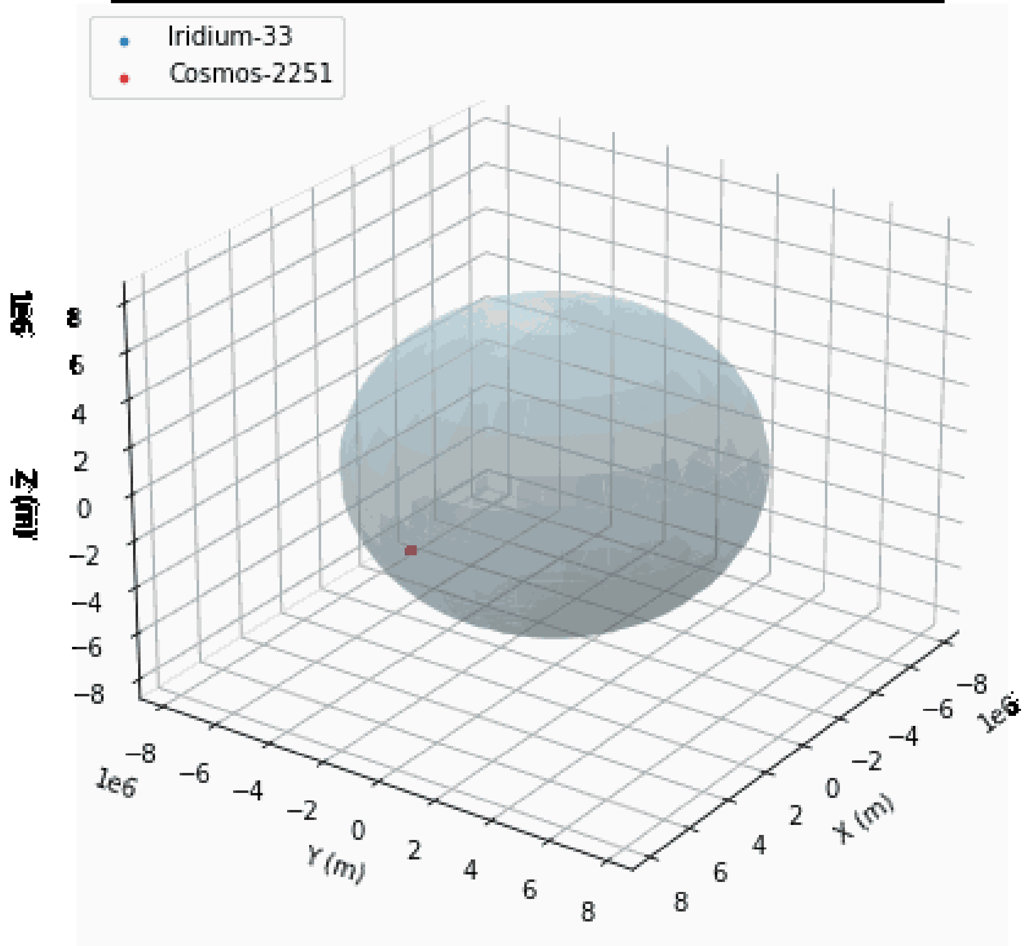


SIMULATION 3D

90 min after collision



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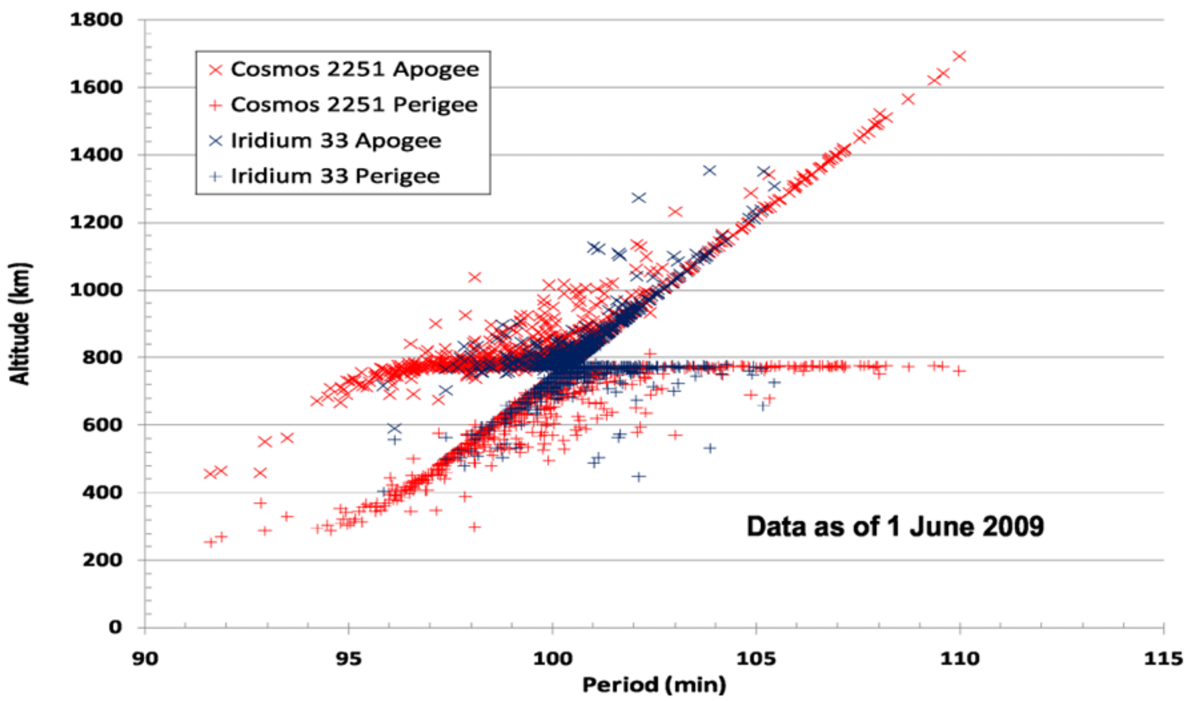
Composite Debris Tracked by US Space Surveillance Network

- **Cosmos 2251 debris (red) are more numerous and spread across a greater altitude regime than that of Iridium 33 (blue)**



TRACK DATA DEBRIS OVER TIME

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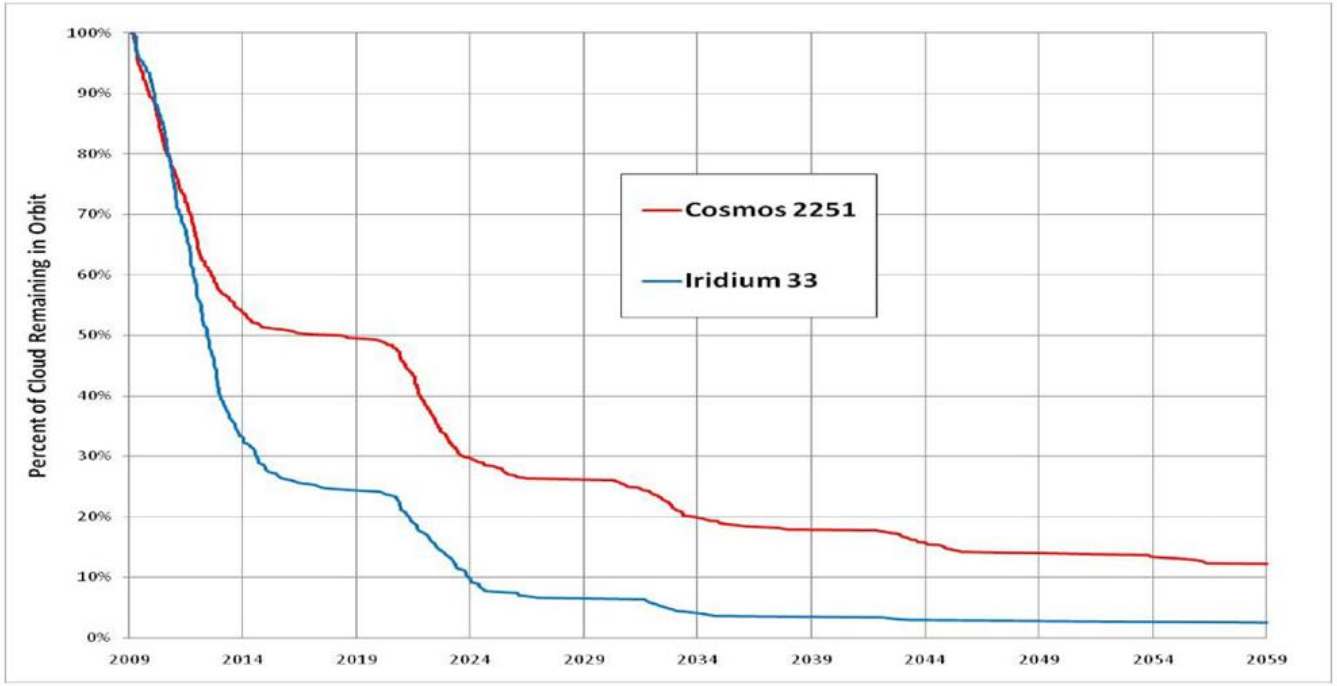
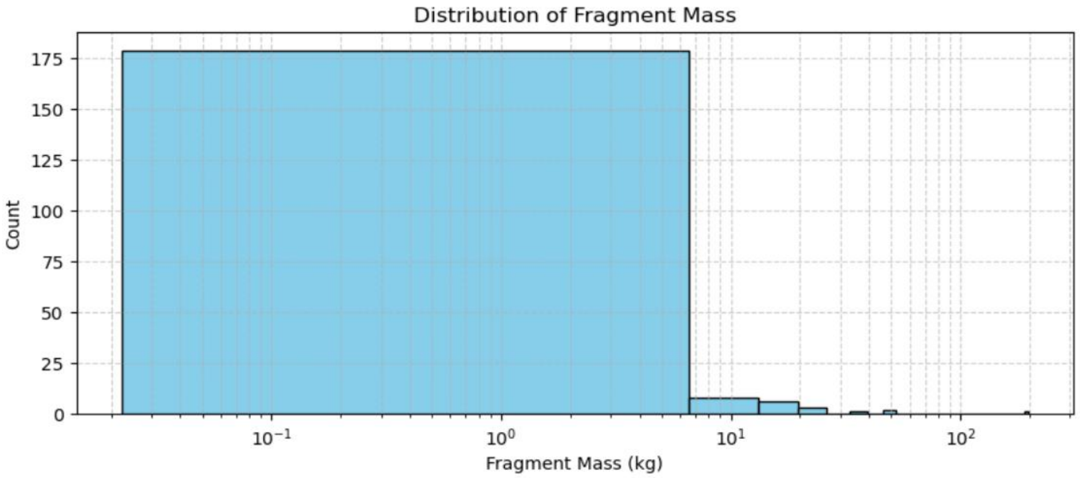
National Aeronautics and Space Administration

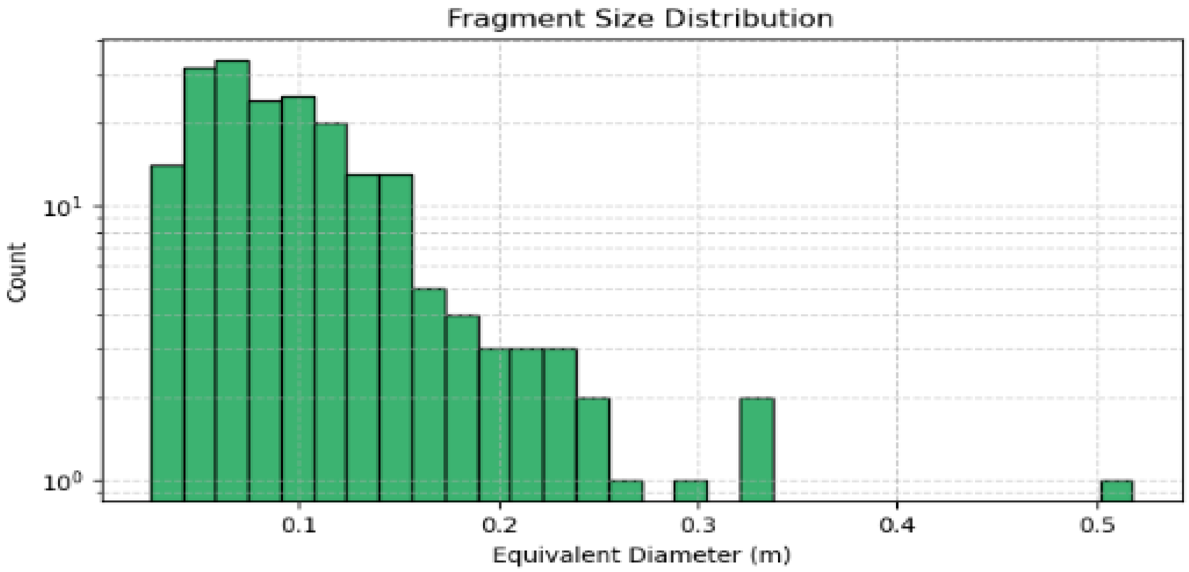
Projected Debris Orbital Lifetimes

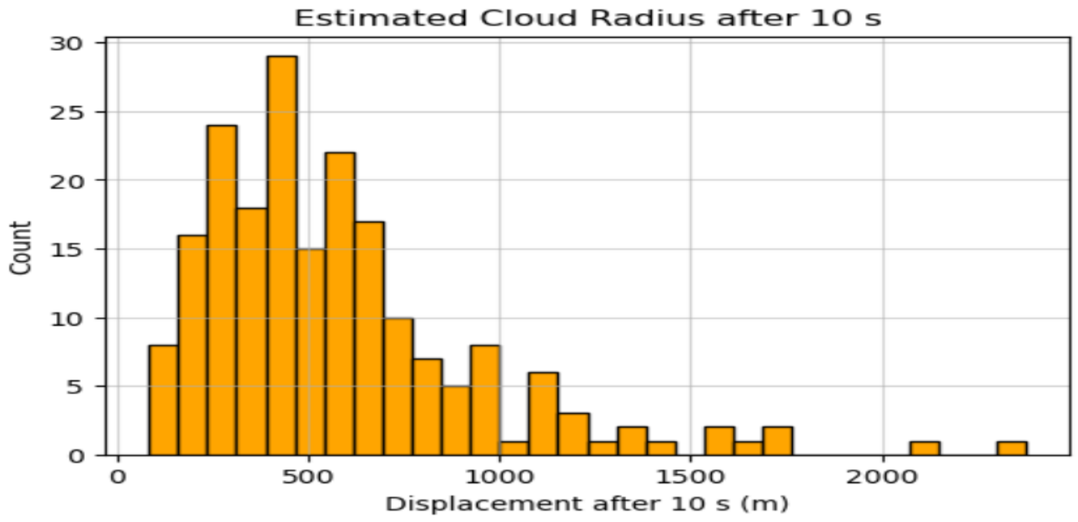
- **Cosmos 2251 debris exhibit normal decay characteristics.**
- **A substantial portion of Iridium 33 was made of light-weight composite materials, yielding shorter orbital lifetimes for its debris.**



NASA BREAK UP MODEL RESULTS





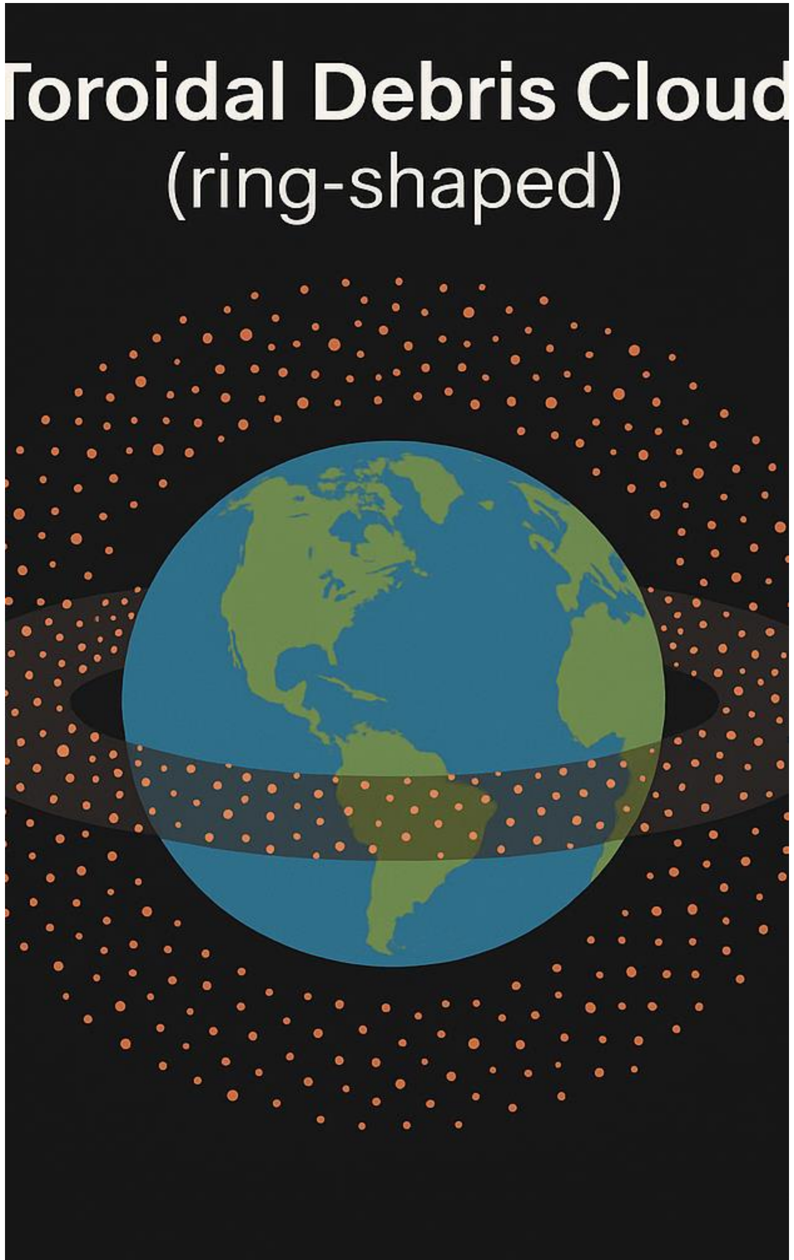


Max expansion radius after 10s: 2376.1 m
Mean expansion radius after 10s: 578.1 m

RESULTS

- Cumulative size: 0.7–0.9
- Cumulative mass: 0.2–0.3
- Mean A/M(decay): 0.20 m^2/kg
- Mean KE (J): 1.4×10^4 joules
- Total KE (J): 2.0×10^7 joules

All values are consistent with what NASA predicts for this type of collision.



ANALYSIS

- **Altitude range after breakup: 720–860 km (≈ 140 km cloud thickness).**
- **Cloud becomes toroidal within ~6 months.**
- **Matches NASA observations and validates the breakup model**

ESA BREAKUP MODEL

- The **ESA Breakup Model** is part of the **MASTER** system developed by the European Space Agency system.
  It's a **data-based model** that simulates how satellites break apart during **collisions or explosions**.

. Estimates:

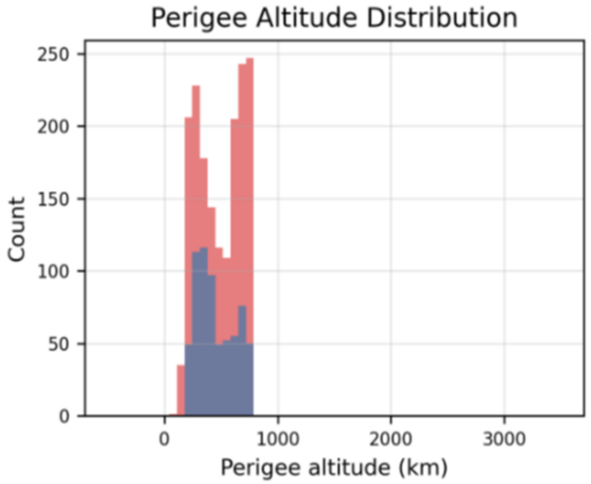
- How many fragments are created
- The size and mass of each fragment
- How fast (ΔV) and in what direction the pieces move
- How the debris cloud spreads around Earth

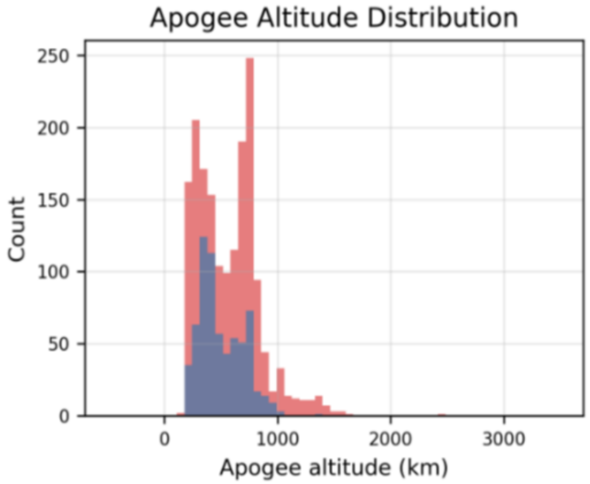
ESA INPUT PARAMETERS

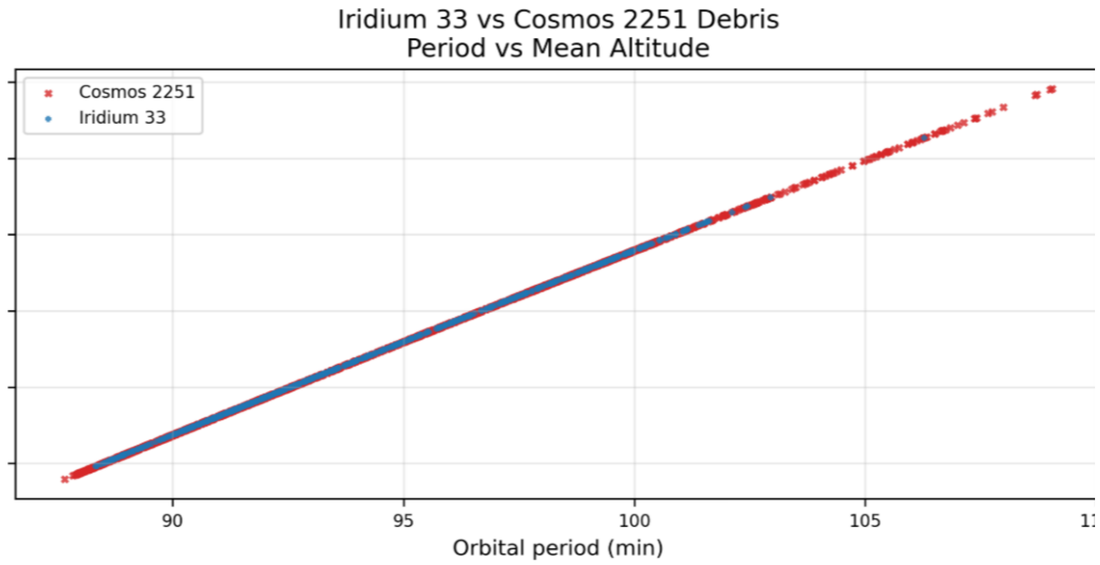
Parameter	Description	Typical Range / Formula
(L_c)	**Characteristic size (m)**	**0.01–0.35 m**
A/M	**Area-to-Mass ratio (m^2/kg)**	**0.005–0.2**
ΔV	**Ejection speed (m/s)**	**10–200**
ΔVx, ΔVy, ΔVz	**Direction components**	**Random isotropic unit vector**
a, e, i	**Orbital elements after collision**	**Computed from ΔV & orbital mechanics**

ESA RESULTS GRAPH

- Cosmos 2251 was **larger and older**, so it shattered into more pieces.
- Iridium 33 had **a stronger structure**, fewer fragments.
- Iridium 33 (blue) → **higher inclination**, **tighter cluster**
- Cosmos 2251 (red) → **greater altitude spread**, **more eccentric**

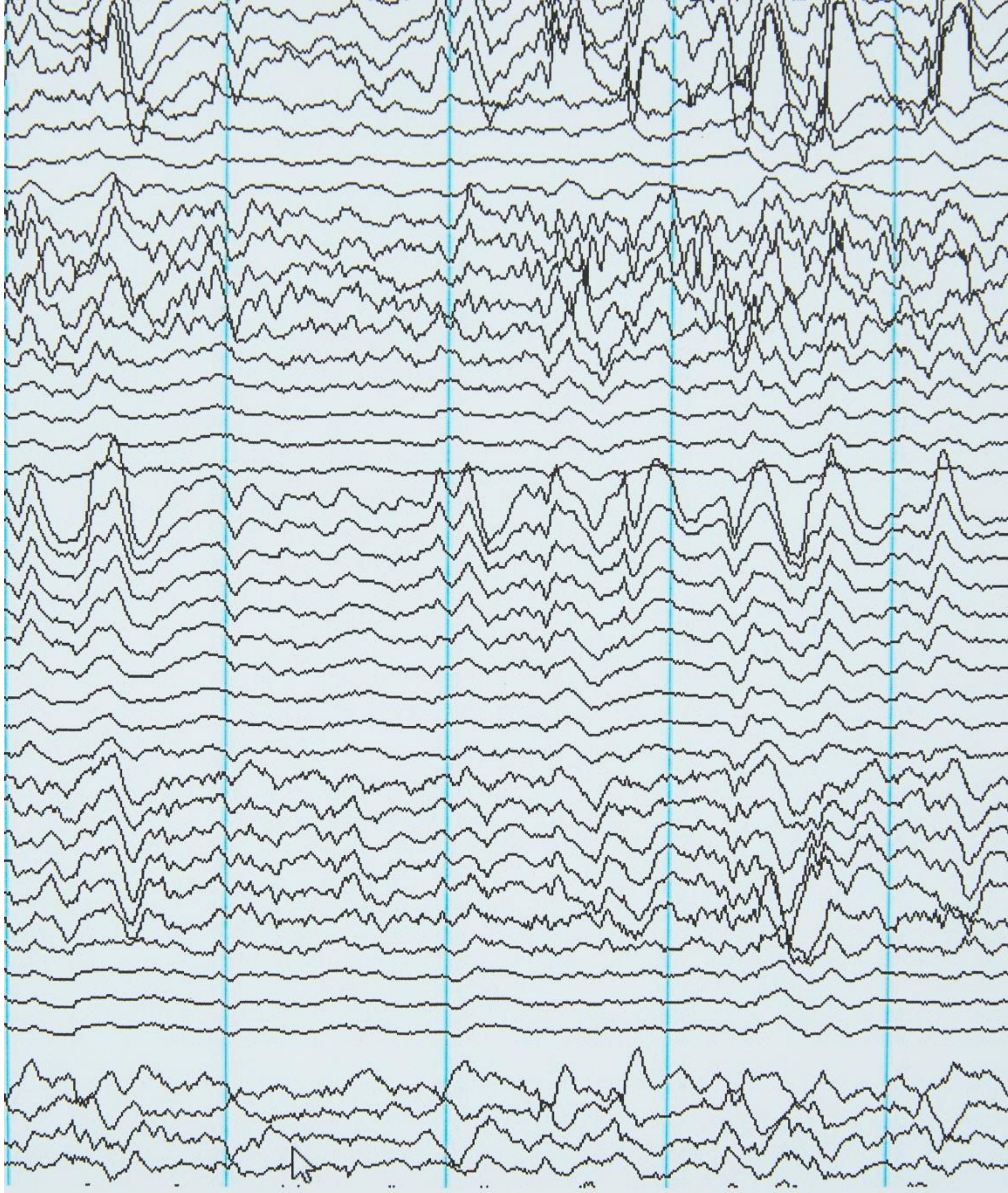






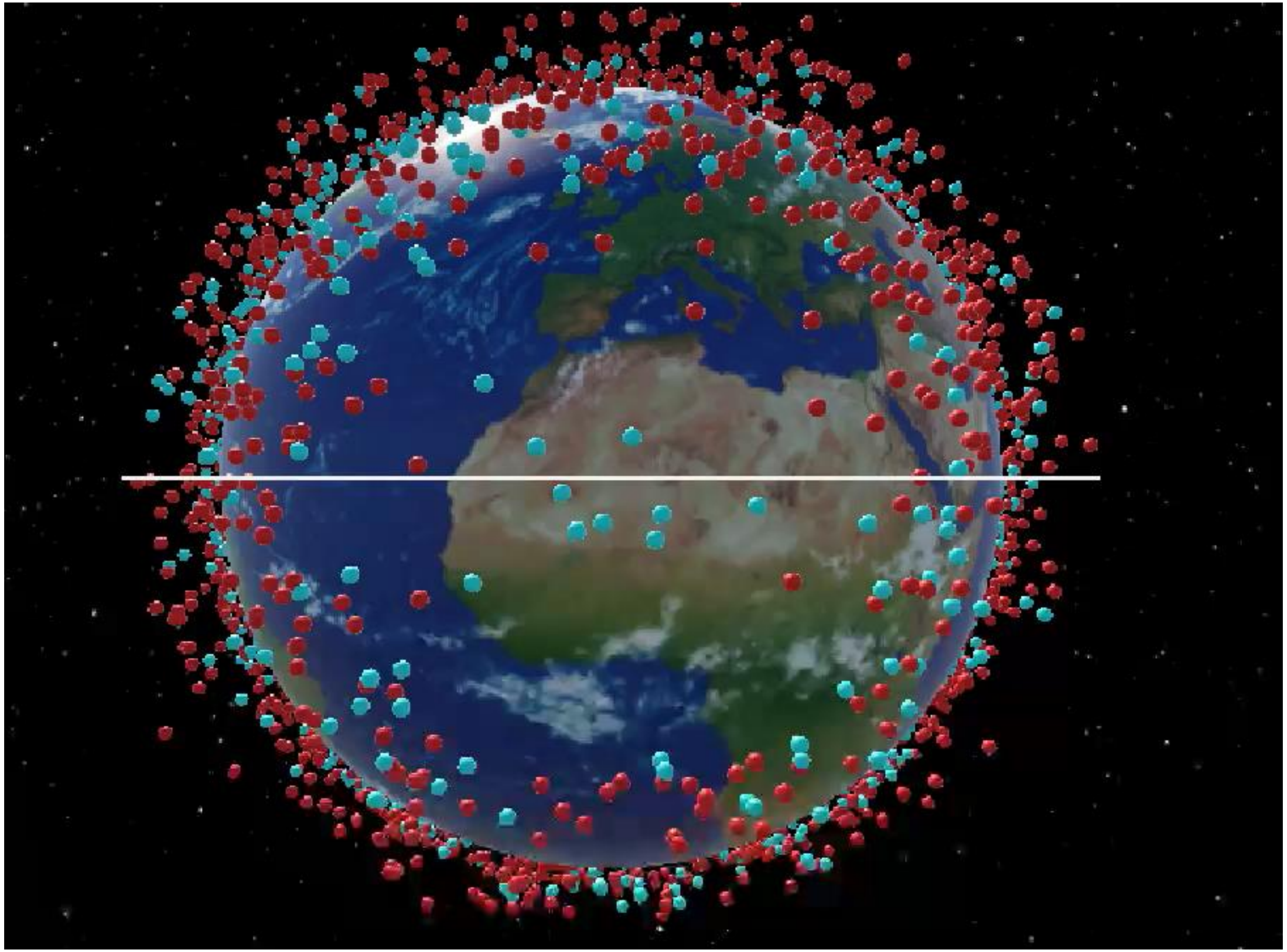
ESA BREAK UP MODEL OUTPUT

- Cumulative size: 0.752
- Cumulative mass: 0.251
- Mean A/M (m^2/kg): 0.2–0.3 m^2/kg
- Mean β(ballistic coefficient): 13.9 kg/m^2
- Mean KE (J): 1.3×10^4 joules
- Total KE (J): 2.3×10^7 joules
- Mean cloud radius after 10s: 950.503m



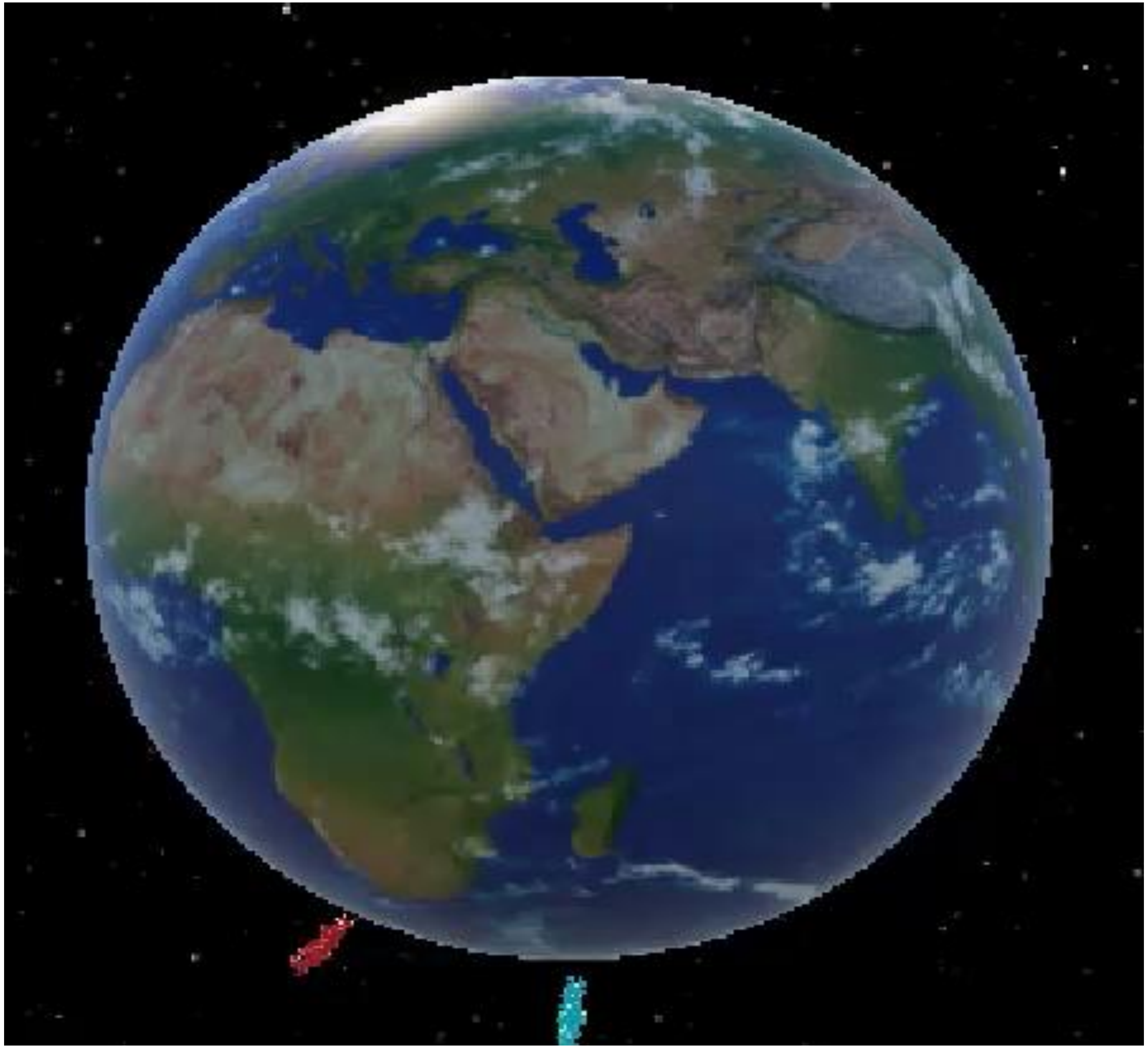
ESA & NASA BREAKOUT MODEL TABLE

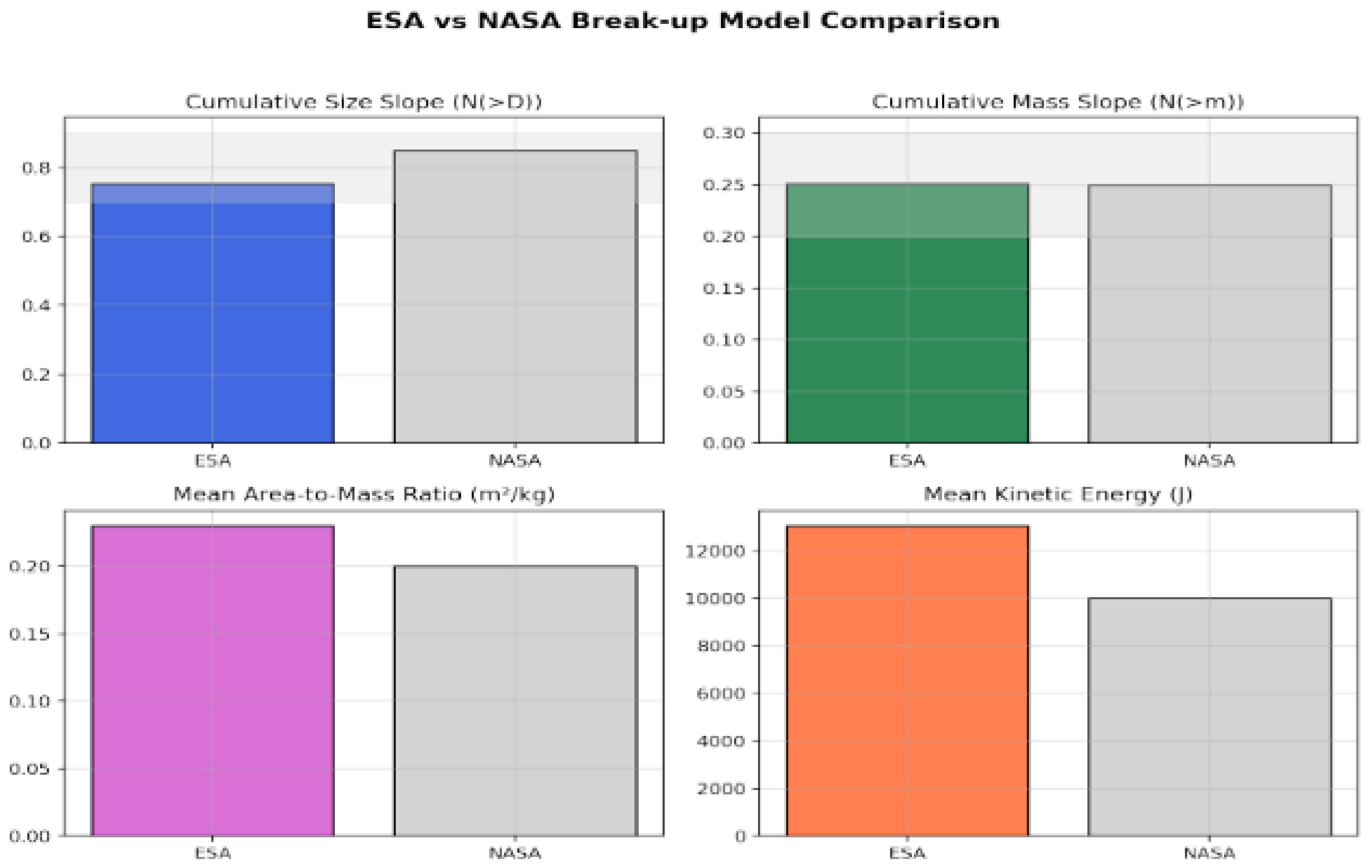
Category	NASA SBM	ESA MASTER
Purpose	Predicts debris from collisions/explosions	Models full space debris environment, including breakups
Model Type	Empirical power-law fragmentation	Semi-empirical + physics-based fragmentation & propagation
Inputs	Impact energy, mass, velocity	Stored energy, materials, structure, failure mode
Outputs	Fragment count, size, mass, ΔV	Fragment properties + orbital evolution + density maps
Size Law	Power-law (−1.6 exponent)	ESA-specific calibrated fragmentation laws
ΔV Model	Empirical $\Delta V \propto m^{-0.6}$	Multi-regime directional velocity model
Strengths	Fast, simple, widely used (NASA standard)	More detailed, includes propagation and environment modeling
Limitations	Less detailed physics; no orbital propagation	More complex; requires MASTER/DRAMA suite



UNITY DEBRIS SIMULATION

UNITY COLLISION SIMULATION





COMPARISON TABLES

ESA VS NASA BREAK-UP MODEL ANALYSIS REPORT

1.Size Distribution Slope ESA slope ≈ 0.75, matching NASA's typical 0.7–0.9. This validates realistic fragment size distributions consistent with known hypervelocity breakups.

2.Mass Distribution Slope ESA slope ≈ 0.25, identical to NASA break up model expectations (0.2–0.3). This indicates correct fragment mass decay.

3.Area-to-Mass Ratio (A/M) ESA mean A/M ≈ 0.23 m^2/kg, slightly higher than NASA's typical 0.20 m^2/kg, implying stronger drag and faster orbital decay for ESA fragments.

ESA VS NASA BREAK-UP MODEL ANALYSIS REPORT

4.Kinetic Energy Behavior
ESA mean kinetic energy ≈ 1.3×10^4 J and
NASA mean ≈ 2.35×10^7 J.
It matches NASA hypervelocity impact physics. Energy–mass coupling is linear on log–log scale, confirming correct physical scaling.

5.Cloud Radius ESA expansion radius ≈ 950 m after 10 seconds, consistent with expected outcomes from high-energy collisions such as Iridium–Cosmos.

ESA VS NASA BREAK-UP MODEL ANALYSIS REPORT

Key Graph Interpretations

ESA aligns with NASA slopes, slightly higher A/M.

The 3D Fragment Cloud Shows realistic triangular mass–velocity–A/M distribution.

- Energy–Mass Coupling – Demonstrates physically correct scaling across fragment masses

RESULT

Cosmos-2251 debris is more chaotic and spreads across a much wider range of altitudes.

Iridium-33 debris remains more compact, forming a tighter orbital band.

This difference results from **different pre-impact orbits** and **fragment ΔVelocity distributions**.

The combined debris field becomes a **large, asymmetric cloud** that intersects across multiple altitude layers.

LONG-TERM RISKS OF UNCONTROLLED DEBRIS GROWTH IN LEO.

- Uncontrolled debris growth in LEO poses serious and compounding risks to satellites, astronauts, national security, and the global economy. As more satellites launch each year like Starlink, Kuiper, and OneWeb the long-term risks become more severe.
- Examples of risk are loss of global communication for any in-service satellite after collision with debris or other satellite.
- Increase the risk for aerospace collision during missions on the LEO by any agency.
- Geopolitical tension between countries after collision.
- In general, the space pollution or saturation of fragments.

DEBRIS CLEANING ACTION PLAN

ESA (European Space Agency) is the first organization on signing a contract with a private company for space debris cleaning .

Contract value is $100M with a private company name Clear Space SA.

Primary goal is to remove out of service satellites and debris from the LEO orbit to avoid collision.

Clear Space provide service for satellite inspections, life extension ,refilling , disposal and repairs.

NEXT STEPS FOR PROJECT

- Microsoft Hololens will be utilized as a visualization tool to appreciate the results virtually of the collision debris

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