Orbital Debris Responsibility and Mandatory Removal Readiness: A Legal-Technical Framework for State Attribution, an International Removal Fund, and Hosted Collector Modules

Final submission-ready paper for ODI Debris attachment

Prepared by: Vehicle Systems Lab research initiative

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Note: This paper is a policy and research proposal. It distinguishes existing treaty obligations from proposed new obligations and should be read as a framework for review, simulation, legal analysis, and further technical validation.

Abstract

Orbital debris is no longer a narrow technical inconvenience; it is a cumulative transboundary risk affecting the orbital environment, critical terrestrial services, crewed spaceflight, commercial missions, scientific access, and long-term sustainability of outer space. Existing international space law establishes State responsibility for national space activities, launching-State liability for damage, jurisdiction and control over registered objects, and the duty to authorize and continuously supervise national activities. However, current law does not yet provide a complete operational mechanism for assigning annual remediation costs or for requiring every new mission to contribute directly to debris removal readiness. This paper proposes a legal-technical framework for ODI Debris consideration: (i) a forensic attribution method to associate catalogued debris and fragmentation events with launching States and authorizing jurisdictions; (ii) a proportional contribution formula based on attributable mass, number of catalogued debris objects, and fragmentation events; (iii) an International Orbital Debris Removal Fund to finance remediation and collector-module deployment; and (iv) a staged licensing requirement for hosted collector modules or equivalent removal-ready payloads on future orbital missions. The proposal is modeled by analogy to environmental pollution regimes while recognizing the specific legal constraints of outer space, including registration, ownership, consent, safety, national security, and non-appropriation. The objective is not to claim that current treaties already impose this exact funding or module requirement, but to provide a functional, auditable and implementable pathway for converting general responsibility principles into measurable stewardship obligations.

Keywords: orbital debris; space law; State responsibility; active debris removal; COPUOS; Liability Convention; environmental analogy; remediation fund; hosted payload; ODI Debris

Executive Summary

This paper proposes a practical framework for turning the global concern over orbital debris into a measurable responsibility and remediation system. The central claim is straightforward: the orbital environment functions as a shared operational ecosystem, and the States and operators whose activities have generated debris should contribute proportionally to its cleanup and future protection.

The framework has four pillars. First, debris attribution should be based on open and auditable data: object catalogues, international designators, launch records, fragmentation databases, and licensing or registration information. Second, annual financial responsibility should be calculated through a transparent formula that combines attributable debris mass, object count, and fragmentation events. Third, a dedicated international fund should finance removal missions, insurance, technical standards, and the deployment of hosted collector modules. Fourth, future orbital launch authorizations should progressively require missions to carry, host, fund, or otherwise enable removal-ready modules, unless a justified exemption applies.

The proposal is intentionally conservative in legal terms. It does not assume that a private operator may freely capture any object in orbit. Instead, it recommends a consent-based or pre-authorized removal protocol, a registry of eligible debris, and clear allocation of liability for collector-module integration and operations. This makes the proposal more defensible before regulators, auditors, space agencies, insurers, and international organizations.

Key Deliverables for ODI Debris

Deliverable	Purpose	Audit status
Legal framework	Defines State responsibility, launching-State liability, registration constraints, and the need for a new remediation instrument.	Ready for legal review; treaty citations included.
Attribution methodology	Defines Mi, Ni, Ei and a proportional contribution formula for annual State shares.	Ready for simulation and data validation.
Removal fund proposal	Creates an International Orbital Debris Removal Fund to finance cleanup and modules.	Policy-ready; requires institutional sponsor.
Hosted collector module model	Requires or incentivizes future missions to integrate a removal-readiness payload or equivalent contribution.	Concept-ready; requires engineering feasibility study.
Implementation roadmap	Provides staged adoption: voluntary pilot, licensing condition, treaty/soft-law adoption.	Ready for ODI Debris discussion.

1. Introduction: Orbital Debris as a Shared Environmental Risk

The orbital environment is a finite and increasingly congested operational domain. Objects launched into Earth orbit do not disappear when their missions end. Defunct satellites, spent rocket bodies, mission-related objects, and fragments from explosions or collisions may remain in orbit for years, decades, or centuries depending on altitude and area-to-mass ratio. Even small fragments can create severe risk because orbital velocities are extremely high.

This paper treats orbital debris as a form of environmental contamination affecting a shared ecosystem. The analogy is not perfect: outer space is governed by a specific legal regime, and space objects remain subject to jurisdiction, control, and ownership rules. Nevertheless, the analogy is useful because debris produces cumulative risk, imposes costs on future users, and can harm actors that did not create the original hazard.

The proposed framework seeks to move beyond generic appeals to sustainability. It asks whether responsibility can be made measurable, whether annual cleanup financing can be assigned proportionally, and whether future missions can be required to carry or host standardized removal-ready modules. The answer proposed here is yes, provided the mechanism is built with clear data, consent rules, liability allocation, and technical safety constraints.

2. Existing Legal Basis and Its Limits

The Outer Space Treaty establishes that States bear international responsibility for national activities in outer space, including activities conducted by non-governmental entities, and that such activities require authorization and continuing supervision by the appropriate State. This provides a foundation for licensing-based obligations imposed on private operators.

The Liability Convention clarifies that a launching State is absolutely liable for damage caused by its space object on the surface of the Earth or to aircraft in flight, and liable on a fault basis for damage caused elsewhere than on the surface of the Earth. This is essential, but it is primarily a damage-compensation instrument, not a complete preventive cleanup funding mechanism.

The Registration Convention and Article VIII of the Outer Space Treaty create a further constraint: the State of registry retains jurisdiction and control over its registered object, and ownership is not affected merely because the object is in outer space or returns to Earth. Therefore, any active debris removal regime must address consent, pre-authorization, eligible-object registries, and liability for removal operations.

The COPUOS Space Debris Mitigation Guidelines and the IADC mitigation framework provide important technical and policy guidance, including limits on debris released during normal operations, avoidance of on-orbit breakups, post-mission disposal, and prevention of collisions. Yet these guidelines do not by themselves establish a binding global fund or a mandatory collector-module requirement. The present paper therefore proposes a new operational layer built on existing principles.

3. Core Proposal

The proposal consists of a measurable responsibility mechanism and an operational remediation requirement. The responsibility mechanism identifies attributable debris and calculates annual State contribution shares. The operational requirement progressively obliges new orbital missions to carry, host, fund, or otherwise enable debris-removal readiness through collector modules or equivalent mechanisms.

The proposed mechanism should be introduced in stages. Phase I would be voluntary and pilot-based, using ODI Debris simulations, open datasets, and participating operators. Phase II would be implemented through national licensing conditions and insurance incentives. Phase III would be formalized through a COPUOS-endorsed instrument, model law, protocol, or multilateral agreement.

4. Forensic Attribution Methodology

A defensible debris-responsibility model requires a transparent attribution method. The proposed method uses object catalogues, international designators, launch records, fragmentation databases, and registration or licensing information. Each object or event should be linked, where possible, to a launching State, State of registry, operator, object type, mission event, and fragmentation cause.

The methodology distinguishes three metrics. Mi is the attributable mass of debris associated with State i. Ni is the number of catalogued debris objects associated with State i. Ei is the number of attributable fragmentation events associated with State i, including explosions, collisions, deliberate destructive events, or other events recognized by the chosen fragmentation database.

These metrics are not identical. A State may have fewer objects but higher mass, or many small fragments but lower mass. A deliberate fragmentation event may justify a distinct event-based weighting. Combining Mi, Ni, and Ei helps avoid a one-dimensional responsibility model.

5. Contribution Formula

The annual contribution share Qi for State i is proposed as a weighted sum of its attributable mass share, object-count share, and fragmentation-event share:

Qi = alpha * (Mi / sum Mj) + beta * (Ni / sum Nj) + gamma * (Ei / sum Ej)

For an initial policy simulation, alpha = 0.50, beta = 0.35, and gamma = 0.15 are recommended. These coefficients can be adjusted by treaty, policy process, or ODI Debris simulation. The mass component recognizes environmental burden, the count component recognizes collision probability and tracking burden, and the event component recognizes conduct that created debris clouds or systemic risk.

Qi is not a judicial finding of wrongdoing. It is a remediation-share metric. This distinction is critical: the fund is designed as a preventive and restorative stewardship mechanism, not solely as a litigation-based damages system.

6. International Orbital Debris Removal Fund

The International Orbital Debris Removal Fund would finance active debris removal, collector modules, deorbit assistance, verification systems, insurance pools, and research into safer removal technologies. Contributions would be calculated annually using Qi and a total annual remediation budget C.

The annual contribution of State i would be: Contribution_i = Qi * C. The value of C should be determined through technical assessment of removal targets, collision risk reduction, mission availability, insurance requirements, and administrative costs. ODI Debris simulations could test scenarios such as USD 250 million, USD 1 billion, and USD 2 billion annual fund sizes.

The fund should not merely subsidize technology. It should buy measurable risk reduction. Each funded mission should identify target classes, expected debris mass removed or risk reduced, safety constraints, reentry plan, liability coverage, and verification procedure.

7. Hosted Collector Modules and Removal-Readiness Payloads

The original operational idea underlying this proposal is that future missions should not only avoid creating new debris; they should also help remove legacy debris. This can be implemented through a standardized hosted collector module, a removal-readiness payload, or an equivalent funded contribution.

A hosted collector module would be integrated into a launch vehicle or spacecraft as a secondary system. Once deployed in an approved orbital region, it could perform limited debris collection, target stabilization, inspection, tagging, drag augmentation, or controlled deorbit assistance. For safety and legal reasons, the first generation should target pre-authorized debris, inert objects, mission-related objects, or objects listed in an eligible debris registry.

The module concept should be technology-neutral. It may include nets, drag sails, magnetic capture for ferromagnetic components, robotic arms, inflatable capture systems, electrostatic concepts, or swarms of small assistant units. However, magnetic micro-collection should be treated as an experimental pathway rather than an immediate legal mandate because many debris objects are not magnetically recoverable and small-fragment capture at orbital velocities creates significant tracking and safety challenges.

The obligation should therefore be expressed as a performance requirement rather than a single hardware design: each licensed orbital mission must either host an approved removal-readiness module, contribute equivalent transport capacity, finance a module through the fund, or receive a justified exemption where integration would be unsafe or disproportionate.

8. Consent, Ownership, and Security Safeguards

The most legally sensitive issue is consent. Under the current space law framework, debris is not necessarily ownerless. A defunct satellite or fragment may still be associated with a State of registry, and intervention without authorization could raise jurisdiction, control, ownership, security, or liability concerns.

This paper therefore recommends a consent-based architecture. States and operators should be encouraged or required to pre-register eligible debris for remediation. A removal mission should operate only against objects included in an eligible-object registry, objects integrated into the same mission architecture, objects whose State of registry has granted consent, or objects covered by a future multilateral pre-consent protocol.

Security concerns must also be addressed. A collector module capable of approaching or manipulating objects could be perceived as a dual-use technology. The proposed regime should include transparency measures, mission notification, inspection standards, operational geofencing, telemetry disclosure to an authorized body, and restrictions on proximity operations involving sensitive objects.

9. Liability Allocation and Insurance

A collector-module system creates new risk. It may malfunction, collide with an object, create fragments, fail to deorbit, or cause damage during reentry. The regime must allocate liability before deployment.

A practical allocation model is as follows. The launch operator is responsible for mechanical and electrical integration when the module is hosted on its mission. The module operator is responsible for removal operations after deployment. The authorizing State retains responsibility for authorization and continuing supervision. The fund finances insurance or indemnity coverage for approved removal missions, subject to compliance with safety standards.

No module should be deployed without a mission-specific risk assessment, collision-avoidance plan, end-of-life plan, disposal pathway, and third-party liability coverage. A failed cleanup mission that creates more debris would undermine the legitimacy of the entire framework.

10. Implementation Roadmap for ODI Debris

ODI Debris can implement this proposal through a staged program. First, create a simulation package that calculates Mi, Ni, Ei, and Qi using open data and documented assumptions. Second, generate a pilot list of high-value removal targets or eligible debris classes. Third, model alternative fund sizes and contribution shares. Fourth, develop a hosted-module standard with mass, interface, power, telemetry, safety, and disposal requirements. Fifth, publish a legal appendix distinguishing current law from proposed obligations.

A strong ODI Debris submission should include three layers: the public-facing paper, an internal audit report, and a technical ZIP containing code, input templates, assumptions, and reproducibility notes. The public paper should be concise and defensible; the technical archive should carry the simulation and data-processing details.

11. Model Policy Clauses

Clause 1: Each participating State shall maintain a national licensing condition requiring orbital missions under its jurisdiction to demonstrate debris-removal readiness, which may be satisfied by hosting an approved collector module, contributing transport capacity, funding a module through the international fund, or obtaining a safety-based exemption.

Clause 2: An International Orbital Debris Removal Fund shall be established to finance active debris removal, module development, insurance, verification, and registry administration. Annual State contributions shall be calculated using an agreed formula based on attributable debris mass, catalogued object count, and fragmentation events.

Clause 3: No removal operation shall target a space object or fragment unless the object is listed in an eligible debris registry, the relevant State of registry has granted consent, the object belongs to the same mission architecture, or a multilateral pre-consent protocol applies.

Clause 4: Collector modules and removal operations shall comply with technical standards for collision avoidance, passivation, command security, end-of-life disposal, casualty-risk limits, and transparent telemetry reporting to the designated oversight body.

Clause 5: Liability shall be allocated among the integrating operator, module operator, authorizing State, and fund according to their respective control over integration, deployment, and operational decisions. Mandatory insurance shall be required for approved missions.

12. Technical Simulation Package

The accompanying technical simulation package should compute country-level contribution shares using a reproducible pipeline. The recommended inputs are: Space-Track or equivalent catalog data for object identity and country association; ESA, NASA, or other recognized fragmentation datasets for events; national registration data where available; and a documented mapping table for operator-to-State attribution.

The output should include a CSV with State, Mi, Ni, Ei, Mi_share, Ni_share, Ei_share, and Qi. The package should also include a README, requirements file, data template, and a run metadata file recording execution date, source versions, assumptions, and hashes of input files. This makes the analysis auditable and suitable for later expert review.

13. Limitations

This proposal has important limits. First, public catalogues may be incomplete or uncertain, especially for small fragments and classified objects. Second, mass values may be missing or estimated. Third, country attribution may be complicated by multinational launches, foreign launch services, private operators, and historical geopolitical changes. Fourth, not all debris is technically removable with current tools. Fifth, a mandatory module requirement could increase launch mass, cost, and complexity if poorly designed.

These limits do not invalidate the proposal. They show why the mechanism should begin as a simulation and pilot framework, then mature into licensing standards and, eventually, an international instrument.

14. Conclusion

Orbital debris is a cumulative environmental and operational risk. Current international law provides essential principles of State responsibility, launching-State liability, registration, jurisdiction, and supervision, but it does not yet create a full annual cleanup-financing system or a universal mission-level removal-readiness requirement.

This paper proposes a bridge between principle and implementation. By combining forensic attribution, proportional funding, eligible-debris consent protocols, and hosted collector modules, the international community can move from mitigation alone toward measurable remediation. The ODI Debris framework is well suited to test this model through simulation, policy review, and technical demonstration.

The core ethical principle is simple: access to orbit must come with responsibility for preserving orbit. Future missions should not merely pass through a polluted environment; they should become part of a coordinated architecture to repair it.

Appendix A: Formula Summary

Metric	Meaning
Mi	Attributable mass of debris associated with State i
Ni	Number of catalogued debris objects associated with State i
Ei	Number of attributable fragmentation events associated with State i
Qi	Annual contribution share of State i

Recommended initial simulation formula:

$$Q_i = 0.50(M_i / \Sigma M_j) + 0.35(N_i / \Sigma N_j) + 0.15(E_i / \Sigma E_j)$$

Appendix B: Proposed Submission Package

1. This paper as the public-facing ODI Debris attachment.

2. Internal audit report for research use and expert validation.

3. Technical ZIP containing simulation code, dataset templates, README, requirements, and metadata.

4. Future optional annex: engineering concept note for collector-module interface standards.

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