

Review

Challenges of Space Debris Detection, Tracking, and Monitoring in Near-Earth Orbit: Overview of Current Status and Mitigation Strategies

Motti Haridim , Assaf Shaked, Niv Cohen and Jacob Gavan

Department of Electrical and Electronics Engineering, Faculty of Engineering, Holon Institute of Technology, Holon 5810201, Israel

* Correspondence: mharidim@hit.ac.il

Abstract

The accumulation of space debris in near-Earth orbit, particularly in Low Earth Orbit (LEO), poses an increasing threat to satellite operations, communication infrastructures, and long-term space sustainability. As modern constellations expand and incorporate advanced satellite technologies, including sensing and wireless communications, artificial intelligence-of-things (AIoT), enabled payloads, and edge computing for on-orbit data processing, the risk profile grows. This paper reviews the current debris environment and existing sensing and monitoring techniques, highlights major collision events and deliberate debris-generating activities, and analyzes the role of both governmental and commercial satellite constellations in exacerbating and mitigating the challenges. Emerging space surveillance and tracking (SST) techniques, leveraging radar, optical sensors, and interferometric SAR for enhanced intelligence, surveillance, and reconnaissance (ISR), are highlighted alongside software-defined networking (SDN) approaches and cloud communication technology that enable coordinated debris-avoidance maneuvers. Key international regulatory frameworks, tracking architectures, and mitigation measures, including alignment with ISO 24113 standards, advanced TT&C capabilities, and evolving active debris removal technologies, are examined. The study emphasizes the necessity of a global, interoperable ecosystem that integrates AI/ML (artificial intelligence and machine learning)-driven situational awareness, secure SATCOM links with AJ/LPI/LPD (anti-jamming/low probability of interception/low probability of detection) characteristics, and collaborative protocols among space agencies, commercial operators, and regulatory bodies to ensure the sustainable use of orbital space for future generations.

Keywords: space debris; space surveillance and tracking; space situational awareness; mega-constellations; space traffic management; active debris removal



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1. Introduction

The accumulation of space debris in near-Earth orbit has emerged as one of the most urgent challenges for the long-term sustainability of space operations, particularly in Low Earth Orbit (LEO), where the rapid deployment of large satellite constellations has dramatically increased orbital congestion [1–3]. Debris objects ranging from spent rocket bodies to centimeter-scale fragments travel at hyper-velocities on the order of several kilometers per second, meaning that even small particles can cause catastrophic damage to operational spacecraft [2,4]. This growing density of objects has intensified concerns

regarding collision cascades consistent with the Kessler Syndrome, in which a single fragmentation event can trigger a self-sustaining chain of further collisions and debris generation [5].

Recent major debris-generating events, such as the 2007 FY-1C anti-satellite test and the 2009 Iridium–Cosmos collision, have demonstrated the long-lasting consequences of fragmentation in heavily populated orbital regimes [6–8]. In parallel, tipping-point analyses suggest that LEO may be approaching critical thresholds beyond which debris growth becomes increasingly difficult to control through mitigation alone [8].

Effective management of this hazard depends on the ability to detect, track, and characterize resident space objects with sufficient accuracy to support operational decision-making. In this context, space surveillance and tracking (SST) systems provide the technical foundation for orbit estimation, catalog maintenance, and conjunction assessment, thereby enabling the broader framework of space situational awareness (SSA) required for coordinated collision avoidance and sustainable traffic management [9,10]. Modern SST increasingly relies on multi-modal sensing architectures, combining ground-based radar and optical telescopes with emerging space-based sensor concepts [9,11], alongside AI/ML-enabled data fusion methods that improve prediction accuracy and reduce response latency in increasingly congested orbital environments [12,13].

At the same time, mitigation of the debris environment requires a clear distinction between prevention-oriented measures and post-event remediation strategies. While debris mitigation policies focus on limiting the generation and persistence of new debris through post-mission disposal practices and international guidelines [14], active debris removal (ADR) targets existing non-maneuverable objects whose breakup would produce long-lived debris clouds [15,16]. ADR missions face substantial engineering challenges because most debris represents a non-cooperative target, often with uncertain geometry, uncontrolled tumbling motion, and no pre-designed interfaces for capture [15,17]. Consequently, removal systems must be designed with extreme reliability to avoid becoming additional debris themselves.

Although a growing body of literature addresses individual sensing modalities, removal concepts, and regulatory frameworks [15,17], there remains a need for integrated reviews that critically connect sensing-driven SST performance limitations with the operational trade-offs of mitigation and ADR approaches under the accelerating pressure of mega-constellations [3,18]. In particular, quantitative differences in detection thresholds, coverage, revisit cadence, uncertainty bounds, and practical deployment constraints are often discussed in isolation rather than within a unified sustainability framework [19,20].

Accordingly, this work is structured as a scoping review that maps current technological and operational approaches to space debris monitoring, tracking, mitigation, and removal, while highlighting key capability gaps and research challenges. The paper emphasizes comparative insights across sensing architectures and remediation strategies, as well as the governance mechanisms required for interoperability and compliance with emerging space traffic management frameworks [18,19].

The remainder of this paper is organized as follows. Section 2 summarizes the current debris environment and the physical drivers of collision risk in LEO. Section 3 surveys sensing and SST methodologies, focusing on representative performance characteristics and limitations across radar, optical, and space-based approaches [9,11], and outlines major ADR technology classes and their associated trade-offs [15,20]. Section 4 discusses international standards, regulatory efforts, and coordination requirements for sustainable orbital operations [14,18,19]. Section 5 concludes with actionable future directions toward an integrated, globally cooperative ecosystem for debris prevention, monitoring, and remediation.

2. Physical and Operational Aspects of Debris Accumulation

The accumulation of space debris has transformed near-Earth orbit into an increasingly hazardous operational domain for both satellite services and human spaceflight activities [1,6]. Orbital debris includes defunct satellites, spent rocket stages, fragments from collisions or explosions, and smaller particles such as paint flakes or insulation materials. Although these objects vary widely in size and origin, their shared orbital velocities imply that even small fragments can generate catastrophic impact effects [2,4].

From an operational perspective, this creates a fundamental asymmetry in debris risk management: while large objects are more easily cataloged and tracked, smaller debris—often below current detection thresholds—can still produce mission-ending damage. This persistent gap between detectability and lethality remains one of the central limitations of current mitigation frameworks.

The debris population spans all major orbital regimes, including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) [21]. However, LEO represents the most congested and collision-prone environment due to its high concentration of active satellites, frequent launches, and dense clustering of spacecraft in narrow altitude shells [8]. Importantly, congestion effects are not purely linear: increases in satellite population lead to disproportionate growth in conjunction rates, placing escalating demands on collision avoidance systems and long-term sustainability planning [8].

Orbital velocity decreases with increasing altitude, meaning that satellites and debris in lower Earth orbits travel at significantly higher speeds. Consequently, collisions in LEO involve greater kinetic energies, increasing both the probability and severity of fragmentation events and making this regime the most hazardous with respect to debris generation.

2.1. Major Debris Sources and Fragmentation Events

The present debris environment is strongly shaped by fragmentation events, which act as long-term risk multipliers rather than short-lived anomalies. A defining example occurred in 2009, when the inactive Russian satellite Kosmos 2251 collided with the operational Iridium 33 spacecraft at an altitude of approximately 776 km. This was the first recorded collision between two intact satellites and produced thousands of trackable fragments, substantially contaminating a critical LEO band [6,7,22].

Crucially, such collisions demonstrate that even relatively rare satellite–satellite impacts can dominate the debris environment for decades. Fragment clouds disperse over time across inclinations and altitudes, increasing conjunction risks not only for nearby spacecraft but also for crewed infrastructure such as the International Space Station [7]. Figure 1 highlights the distribution of collision events across LEO altitudes, illustrating how fragmentation introduces persistent orbital contamination.

Beyond accidental events, deliberate military actions further exacerbate debris growth. In 2021, Russia conducted an anti-satellite (ASAT) missile test against Kosmos 1408, generating a large debris cloud in the heavily utilized 300–800 km altitude region [23]. Such events underscore a critical governance challenge: a single intentional action by one actor can externalize long-term collision risk onto the entire global space community, highlighting the limitations of voluntary mitigation measures alone.

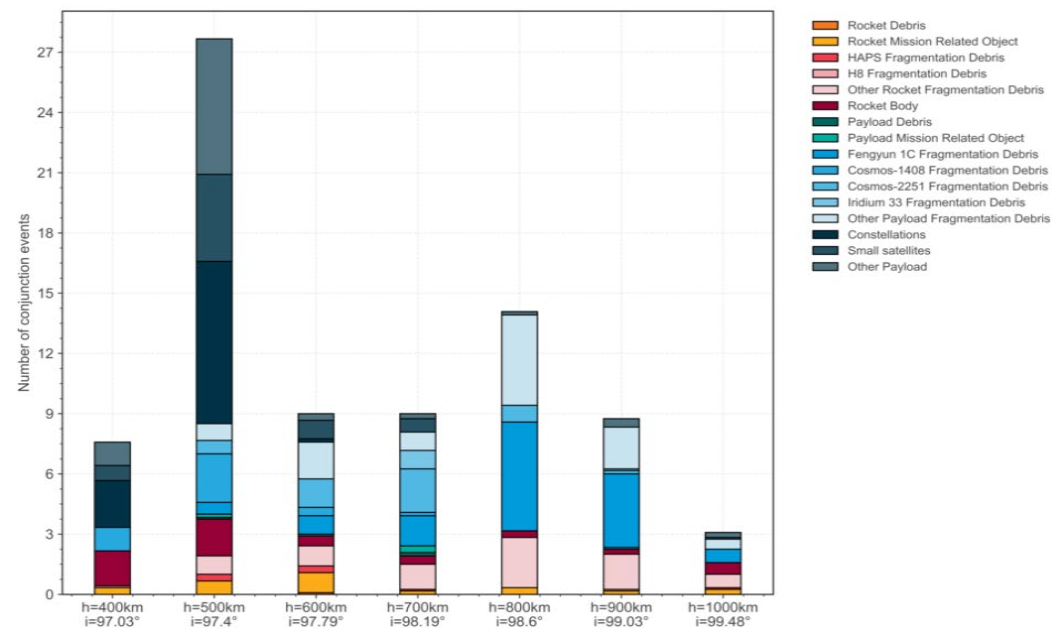


Figure 1. Number of collision events at different altitudes in LEO by contamination type. Adapted from ESA debris environment statistics [4].

2.2. The Challenge of Mega-Constellations and Congestion

In parallel with fragmentation-driven debris growth, the rapid deployment of satellite mega-constellations has introduced a new and continuous driver of orbital congestion. Large commercial systems such as Starlink have placed thousands of satellites into similar orbital shells, intensifying the operational complexity of conjunction assessment and maneuver coordination [3,24].

Unlike historical debris growth, which was dominated by discrete fragmentation events, mega-constellations introduce persistent high-cadence traffic. This increases reliance on automated collision avoidance pipelines and raises concerns regarding inconsistent maneuver practices, coordination failures, and uneven regulatory oversight among operators [15]. As a result, congestion is no longer solely a debris-population problem but increasingly a space traffic management challenge requiring interoperable decision frameworks [18,20].

Figure 2 provides an illustrative example of constellation turnover through atmospheric re-entry events. While controlled re-entry represents a mitigation mechanism, the scale of continuous satellite replacement highlights the operational pressures imposed by large constellation architectures.



Figure 2. Starlink satellites during atmospheric re-entry (2022). Public domain imagery [4].

2.3. Velocity, Energy, and Terrestrial Hazards

The severity of orbital debris risk stems from the hyper-velocity nature of orbital collisions. Relative impact speeds in LEO may reach several kilometers per second, meaning that even centimeter-scale debris can puncture shielding, disable subsystems, or trigger secondary fragmentation cascades [2,4]. This implies that debris mitigation cannot rely exclusively on catalog maintenance but must also address the untracked fragment population through prevention and removal strategies.

Finally, the debris population includes multiple object classes—intact derelict spacecraft, rocket bodies, and fragmentation debris—each requiring distinct mitigation or remediation approaches. Figure 3 summarizes the main categories of space debris currently present in Earth’s orbit, illustrating the diversity of sources and the resulting complexity of debris-control strategies.

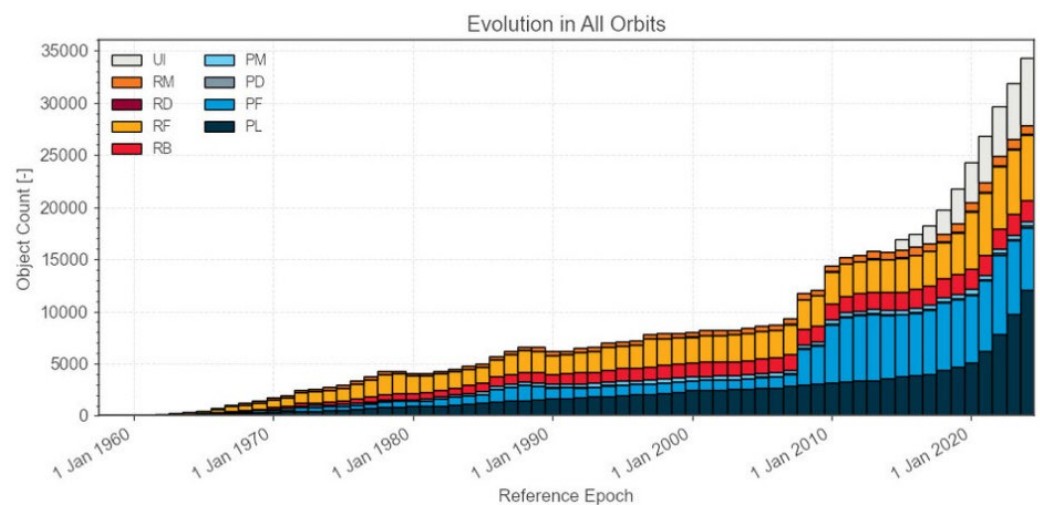


Figure 3. Types of space debris currently present in Earth’s orbit (2023). Courtesy of ESA.

An illustrative example of an orbital debris fragment is shown in Figure 4, highlighting the heterogeneous geometry and unstructured nature of debris objects that contribute to the severity of hyper-velocity impact risks.



Figure 4. Example of an orbital debris fragment. Courtesy of ESA debris environment reporting [4].

Overall, the combined effects of fragmentation events, mega-constellation congestion, and hyper-velocity impact physics underscore the urgent need for coordinated global action. Sustainable orbital operations will require high-fidelity SST capabilities, enforceable mitigation compliance, and scalable ADR solutions to reduce long-term collision risk in LEO and beyond [1,16].

3. Approaches to Debris Mitigation

Technological innovation is central to addressing the space debris challenge, as mitigation requires both preventive operational practices and high-fidelity monitoring capabilities. In practice, debris-control strategies rely on two complementary pillars: (i) improving Space Surveillance and Tracking (SST) to support timely collision avoidance, and (ii) developing scalable mitigation and Active Debris Removal (ADR) technologies for long-term sustainability [1,16].

3.1. Enhanced Space Surveillance and Tracking (SST)

Effective debris mitigation depends fundamentally on the ability to detect and maintain accurate orbital knowledge of resident space objects. SST provides the technical basis for persistent cataloging and orbit determination, thereby enabling the broader operational framework of Space Situational Awareness (SSA), which supports conjunction assessment and coordinated collision avoidance [9,10].

Current SST architectures rely primarily on ground-based radar and optical networks, each offering distinct performance trade-offs. Radar systems provide robust all-weather detection and are particularly effective for monitoring objects in LEO, but their sensitivity decreases rapidly for smaller fragments, leaving much of the sub-10 cm debris population untracked [2,4,9]. Optical telescopes, by contrast, can achieve high angular accuracy and are valuable for tracking higher-altitude objects, yet their performance is constrained by illumination conditions, weather, and limited revisit cadence [11].

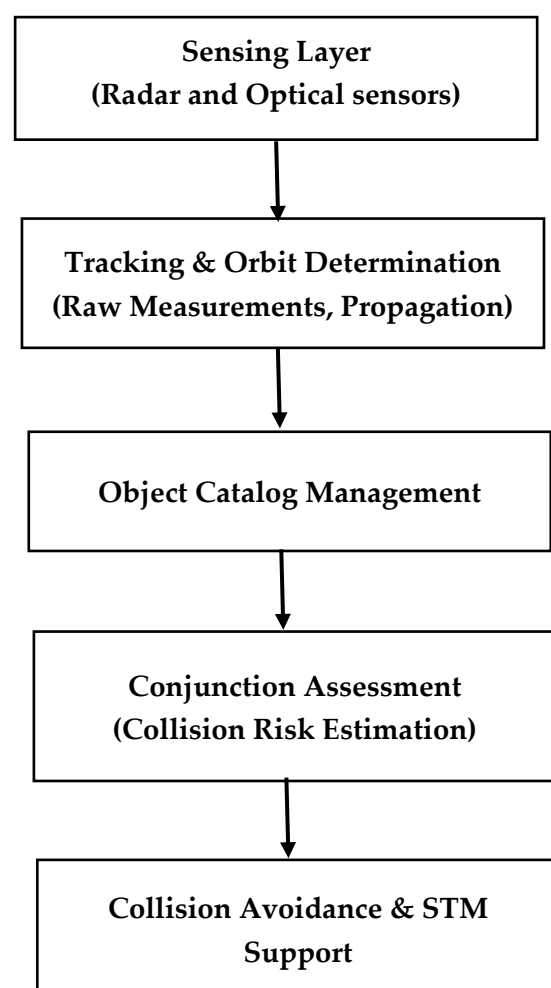
Table 1 provides a structured comparison of representative SST sensing modalities, highlighting their operational characteristics in terms of detectable object size, coverage, revisit cadence, uncertainty, and key limitations. The comparison illustrates that while individual sensing approaches offer complementary strengths, no single modality is sufficient on its own. Integrated, data-fused SST architectures combining radar, optical sensing, and AI/ML-based processing are therefore essential to reduce prediction uncertainty and to support scalable collision avoidance and space traffic management under mega-constellation conditions.

Figure 5 illustrates the functional pipeline of a modern SST architecture, from raw sensing measurements obtained by radar and optical sensors through tracking and orbit determination, object catalog maintenance, and conjunction assessment. This pipeline forms the technical basis for collision avoidance and space traffic management (STM) support. The diagram emphasizes that effective debris risk mitigation relies not only on sensing performance, but also on robust processing, decision-support, and coordinated data flows capable of scaling to the increasing conjunction rates associated with mega-constellation deployments [9,10,12].

These limitations imply a critical operational gap: the most hazardous debris population often lies below routine tracking thresholds, creating an asymmetry between detectability and collision lethality. As orbital traffic increases, particularly under the deployment of mega-constellations, the resulting growth in conjunction rates places escalating demands on automated processing, maneuver coordination, and uncertainty reduction within SST pipelines [13,21].

Table 1. Comparative overview of representative Space Surveillance and Tracking (SST) sensing modalities and their operational characteristics.

Key Limitations	Typical Uncertainty	Revisit Cadence	Coverage	Typical Detectable Object Size	Sensing Modality
Limited sensitivity to small debris; high cost; frequency allocation	Moderate (range & velocity accurate, angular less precise)	High (minutes–hours)	Regional/global networks	~5–10 cm (LEO)	Ground-based radar
Daylight/weather dependence; poor performance for small LEO debris	High angular accuracy, limited range accuracy	Medium–low (hours–days)	Wide-field but weather/illumination dependent	~10–50 cm (LEO), larger in GEO	Ground-based optical telescopes
Limited field of view; cost; deployment complexity	Improved geometry, reduced atmospheric effects	Medium	Global, geometry-dependent	~5–10 cm (LEO)	Space-based optical sensors
Infrastructure complexity; coordination requirements	Improved cross-section estimation	High	Local–regional	<5 cm (select regimes)	Multi-static/networked radar
Dependent on data quality, interoperability, standardization, and governance	Reduced prediction uncertainty (relative to single-sensor approaches)	High (sensor-driven)	System-level (network-dependent)	Depends on contributing sensors	Data-fused SST (Radar + Optical + AI/ML)

**Figure 5.** Functional pipeline of a modern Space Surveillance and Tracking (SST) architecture supporting collision avoidance and space traffic management.

Recent advances increasingly incorporate AI/ML-based data fusion into SSA workflows, improving object classification, anomaly detection, and orbit prediction in dense traffic environments [12,13]. However, AI/ML does not eliminate the fundamental constraints of sensing physics, and its effectiveness remains dependent on data quality, sensor

coverage, and standardized data-sharing across operators. Consequently, the transition toward sustainable space traffic management requires not only improved sensing technologies, but also compatible coordination frameworks and governance mechanisms capable of enabling automated, high-cadence collision avoidance across large satellite constellations operating simultaneously in congested orbital regimes [18,25].

3.2. Mitigation Policies and Post-Mission Disposal Practices

While enhanced SST capabilities are essential for near-term collision avoidance, long-term sustainability cannot rely on tracking alone. Debris mitigation fundamentally requires preventive measures that reduce the creation of new debris and limit the orbital lifetime of spacecraft after end-of-life [1,14]. International guidelines emphasize that operators must incorporate post-mission disposal planning into spacecraft design, including controlled re-entry for LEO missions or relocation to disposal orbits for GEO assets [14].

However, mitigation is not equivalent to removal. Mitigation measures primarily aim to prevent future debris growth, yet they cannot directly reduce the existing population of large derelict objects already in orbit. This distinction is critical because even full compliance with mitigation guidelines may be insufficient to stabilize the debris environment if fragmentation events continue to occur or if traffic volumes increase faster than disposal rates [8].

Recent governance initiatives, including the United Nations Guidelines for the Long-Term Sustainability of Outer Space Activities, highlight the need for coordinated norms, transparency, and compliance mechanisms across both governmental and commercial actors [19,20]. In parallel, emerging space traffic management frameworks increasingly recognize that mitigation must be coupled with operational interoperability, automated conjunction assessment, and shared responsibility for collision avoidance in congested orbital shells [18,22]. Thus, mitigation policies represent a necessary foundation, but not a complete solution, for debris sustainability under mega-constellation growth [3].

3.3. Active Debris Removal (ADR): Technology Classes and Trade-Offs

Because mitigation alone cannot eliminate the legacy debris population, Active Debris Removal (ADR) is increasingly viewed as a necessary complement, particularly for large non-maneuverable objects whose breakup would generate extensive fragment clouds [15,16]. ADR targets represent some of the most challenging engineering problems in modern space operations: they are typically non-cooperative, may be tumbling unpredictably, and lack standardized capture interfaces, making proximity operations inherently risky [15,17].

Current ADR approaches can be broadly categorized into contact-based and non-contact concepts, each with distinct operational trade-offs.

Table 2 provides a comparative summary of representative debris mitigation and remediation approaches. The table contrasts preventive measures, such as post-mission disposal and collision avoidance, with active debris removal concepts, highlighting their respective target object classes, levels of operational maturity, and key trade-offs. The comparison illustrates that while mitigation strategies are generally mature and effective in limiting future debris growth, they cannot address the existing population of large non-maneuverable objects. Conversely, active removal approaches offer the potential for long-term stabilization of the debris environment but remain constrained by technical complexity, cost, and unresolved legal and governance challenges.

Table 2. Comparison of debris mitigation and remediation approaches.

Key Limitations	Key Advantages	Operational Maturity	Target Object Class	Approach
Does not reduce existing debris population; relies on compliance	Prevents long-term debris growth; low operational risk	High (widely implemented)	Operational satellites at end-of-life	Post-mission disposal (controlled re-entry / graveyard orbit)
Increases fuel consumption; coordination complexity under congestion	Immediate risk reduction; relies on existing SST	High	Maneuverable operational spacecraft	Collision avoidance maneuvers
Ineffective for legacy objects already in orbit	Reduces fragmentation risk; embedded at design stage	High–medium	Spacecraft and launch vehicle stages	Design-for-demise/passivation
High technical risk; cost; legal and liability challenges	Direct debris mass reduction; long-term stability benefit	Low–medium (demonstrators)	Large non-cooperative derelicts	Active Debris Removal (contact-based)
Limited effectiveness; power and governance constraints	Avoids physical capture; reduced collision risk	Low (conceptual/experimental)	Small to medium debris	Active Debris Removal (non-contact)

3.3.1. Contact-Based Capture Methods

Contact-based approaches include robotic manipulators, nets, harpoons, and docking or grappling mechanisms. These methods offer the advantage of direct control over the target once captured, enabling controlled deorbiting or relocation. However, they also carry significant risks of collision, fragmentation, or mission failure during the capture phase, particularly when interacting with rotating or structurally degraded debris [15].

Robotic capture systems have attracted increasing attention due to their versatility for on-orbit servicing and debris removal, but they require high-precision guidance, navigation, and control, as well as complex autonomous manipulation capabilities [26]. As a result, while contact-based ADR is technologically feasible, its scalability and cost-effectiveness remain open challenges. Commercial initiatives, such as those pursued by Astroscale, illustrate the practical translation of contact-based ADR concepts into demonstrator missions focused on capturing and deorbiting large defunct satellites [27].

3.3.2. Non-Contact Momentum Exchange and Directed Energy

Non-contact concepts seek to avoid the hazards of physical interaction by applying momentum exchange remotely. Laser-based debris remediation, for example, has been proposed as a method to induce small velocity changes through ablation or photon pressure, potentially enabling gradual orbital decay for smaller debris objects [28]. Such techniques reduce the risk of direct collision, but they face substantial practical constraints, including atmospheric distortion for ground-based systems, high pointing accuracy requirements, and dual-use governance concerns [29,30].

More broadly, non-contact approaches may offer improved operational safety, yet their effectiveness is often limited to specific debris size ranges and requires sustained energy delivery over multiple engagements [31]. To clarify the underlying physical interaction governing non-contact plume-based active debris removal approaches, Figure 6 provides a conceptual schematic of the chaser–plume–target relationship.

As illustrated in Figure 6, the chaser spacecraft does not exert direct mechanical force on the target, but instead defines the relative geometry and propulsion conditions under which the plume-mediated interaction occurs. The physical influence on the debris object arises from the pressure and force generated by the plume, leading to changes in the target's orbital and attitude dynamics.

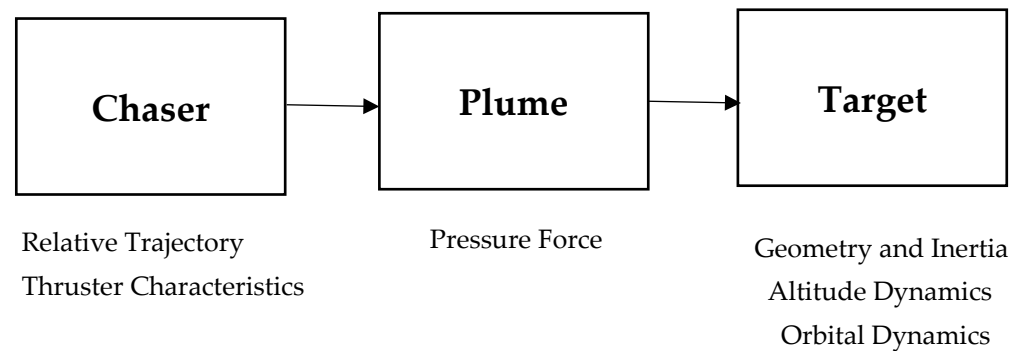


Figure 6. Schematic illustrating a non-contact plume-based debris mitigation concept. The diagram highlights the role of the chaser spacecraft in determining the relative trajectory and thruster characteristics, the resulting plume-induced pressure and force fields, and the corresponding translational and rotational response of a non-cooperative debris target.

3.3.3. Strategic and Operational Limitations

Across all ADR concepts, a central unresolved question is prioritization: removing a small number of high-mass derelict objects may provide greater long-term stability benefits than attempting to target numerous small fragments [15,16]. Furthermore, ADR cannot be treated purely as a technical challenge. Legal accountability, cost-sharing, and international authorization remain major barriers to implementation, particularly given that debris ownership and liability persist even after spacecraft end-of-life [29,32].

Consequently, ADR must be evaluated not only in terms of technological feasibility, but also in terms of operational scalability, governance, and integration with broader space traffic management frameworks [19,21]. Sustainable debris remediation will likely require a combined strategy: rigorous mitigation compliance, selective removal of high-risk legacy objects, and interoperable SST-driven coordination to prevent future cascading instability [1,21].

4. The Role of International Cooperation

The space debris challenge is inherently global: orbital regimes, particularly in LEO, constitute a shared operational environment in which actions by one actor can impose long-term collision risks on all others. Consequently, sustainability cannot be ensured through isolated national policies or unilateral technical solutions alone, but requires coordinated international governance frameworks [18,21].

International efforts have produced widely recognized guidelines for debris mitigation and long-term sustainability. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) has established the Guidelines for the Long-Term Sustainability of Outer Space Activities, which emphasize transparency, responsible behavior, and the reduction in debris-generating practices [18]. In parallel, the Inter-Agency Space Debris Coordination Committee (IADC) provides technical mitigation guidelines that have become foundational references for post-mission disposal and debris prevention practices worldwide [33]. While these frameworks represent essential normative baselines, their largely voluntary nature limits their enforceability under rapidly expanding commercial activity.

A key emerging priority is the development of interoperable Space Traffic Management (STM) architectures that can support consistent conjunction assessment, coordinated maneuvering, and standardized data-sharing across operators. Recent technical analyses highlight that effective STM requires integration of high-fidelity SST capabilities with governance mechanisms that clarify responsibility boundaries, operational procedures, and information exchange protocols [19,32]. Without such interoperability, the growth

of mega-constellations risks producing fragmented regulatory environments in which collision avoidance practices remain inconsistent across jurisdictions [3,21].

Legal and institutional challenges remain substantial. The 1967 Outer Space Treaty establishes state responsibility for national space activities and obligates states to avoid harmful contamination of the space environment. However, the treaty lacks operational enforcement mechanisms, leaving compliance dependent on national implementation and voluntary coordination [34]. Legal scholarship has therefore emphasized that debris remediation and active measures can function as sustainability tools only if supported by clearer enabling frameworks and accountability structures [32]. Proposals for binding international agreements, including concepts analogous to a “Space Debris Convention,” argue that mandatory reporting, tracking obligations, and coordinated removal responsibilities may ultimately be required to stabilize the orbital environment [29].

Public–private coordination is also becoming increasingly important, as commercial operators now constitute a dominant presence in LEO. Initiatives supporting global SSA coordination emphasize the need for data-sharing partnerships, standardized interfaces, and cooperative risk mitigation between governmental catalog providers and private tracking companies [25]. However, such cooperation raises unresolved questions regarding data ownership, liability, and the balance between transparency and commercial sensitivity.

Finally, the rapid proliferation of small satellites and CubeSats introduces additional regulatory complexity. Their limited maneuverability, short mission lifetimes, and high deployment cadence challenge both tracking infrastructures and disposal compliance, increasing the probability of uncontrolled persistence in congested orbital shells [35]. Addressing these challenges will require harmonized technical standards, enforceable mitigation requirements, and coordinated STM practices that scale with the increasing pace of orbital activity [18,19].

Overall, international cooperation remains a central prerequisite for debris sustainability. While existing guidelines provide an essential foundation, the accelerating pressures of mega-constellations and traffic growth suggest that stronger interoperability mechanisms, accountability structures, and coordinated STM implementation will be necessary to ensure the long-term safety and accessibility of near-Earth space [3,19].

In summary, while existing international guidelines provide an essential normative foundation, the accelerating growth of mega-constellations suggests that voluntary coordination alone will be insufficient. Sustainable orbital operations will require interoperable STM architectures, enforceable mitigation compliance, and shared data-exchange mechanisms that can scale with increasing traffic density in LEO [3,19,21].

5. Emerging Challenges and Future Directions

The space debris environment is entering a new phase in which emerging operational and governance challenges are amplifying collision risk beyond historical fragmentation-driven growth. While mitigation guidelines and improved SST capabilities provide an essential foundation, the accelerating pace of launches, the rise of mega-constellations, and the proliferation of small satellites introduce nonlinear congestion effects that require proactive intervention [3,8,21,36].

Mega-constellations such as Starlink, OneWeb, Kuiper, and other national initiatives are deploying thousands of satellites in narrow LEO shells to enable global connectivity [21,31]. Although these systems deliver significant economic value, they substantially increase conjunction rates and operational complexity, requiring unprecedented levels of real-time coordination among operators [3,18]. Under such conditions, even small inconsistencies in maneuver practices or disposal compliance can propagate system-level instability consistent with cascading collision scenarios [5,8].

The rapid growth of CubeSats and other small spacecraft further complicates sustainability. Many such platforms lack propulsion or autonomous maneuvering capability, limiting their ability to respond to conjunction warnings and increasing the probability of uncontrolled persistence in orbit [35]. This trend exposes a critical gap: current SST infrastructures remain constrained in their ability to reliably detect and track debris below approximately 10 cm, despite the fact that such fragments remain fully capable of producing catastrophic impacts [2,4,9].

Figure 7 illustrates the small physical scale of CubeSats, which contributes to high deployment rates and poses challenges for tracking, collision avoidance, and end-of-life disposal in congested LEO environments.

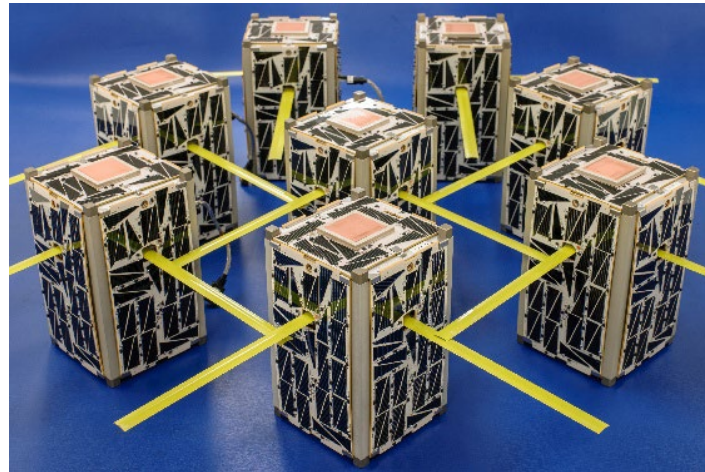


Figure 7. CubeSats in the size of a palm of a hand—Courtesy of NASA.

As orbital congestion increases, Space Traffic Management (STM) is becoming a core requirement rather than an optional coordination practice. STM depends on the integration of high-fidelity SST data, uncertainty propagation, and automated conjunction assessment pipelines that can scale to mega-constellation traffic volumes [13,21,37,38]. AI/ML-based methods increasingly support anomaly detection, orbit prediction, and decision-level fusion within SSA systems, yet their effectiveness remains dependent on sensor coverage, interoperable data-sharing, and standardized reporting frameworks [12,13,37,39].

Despite the progress of COPUOS and IADC mitigation guidelines, current international legal regimes remain largely non-binding and lack enforcement mechanisms proportional to the emerging scale of commercial activity [17,33]. Proposals for stronger accountability frameworks, including binding reporting and remediation obligations, highlight the need for updated governance structures capable of preventing regulatory fragmentation across jurisdictions [29,32].

Future research priorities therefore include: (i) improving quantitative SST performance and uncertainty reduction, (ii) developing scalable ADR and servicing architectures for high-risk derelict objects, and (iii) implementing interoperable STM practices supported by enforceable international coordination mechanisms [19,21,22]. Together, these advances will determine whether orbital space remains a sustainable operational domain under accelerating traffic growth.

6. Conclusions

Space debris has become a critical threat to the safety, accessibility, and long-term sustainability of near-Earth space. The combined effects of fragmentation events, deliberate debris-generating activities, and the rapid expansion of large satellite constellations

have transformed Low Earth Orbit into an increasingly congested and collision-prone operational environment.

This review emphasizes that sustainable debris control requires an integrated strategy combining high-fidelity Space Surveillance and Tracking, rigorous mitigation compliance, and selective Active Debris Removal. Current sensing architectures remain essential for catalog maintenance and conjunction assessment, yet significant limitations persist for smaller debris populations that are difficult to track but capable of catastrophic damage. AI/ML-enabled situational awareness pipelines offer promising improvements in automation and prediction, but cannot substitute for global interoperability and coordinated traffic management practices.

Mitigation measures provide a necessary baseline for preventing further debris growth. However, mitigation alone cannot address the legacy population of large non-maneuverable objects already in orbit, reinforcing the need for scalable removal and servicing solutions despite their operational, legal, and economic constraints.

Ultimately, preserving orbital sustainability will depend on coordinated advances across sensing, automation, mitigation enforcement, removal technologies, and international governance. Without such integrated action, the long-term usability of near-Earth space for scientific, commercial, and societal benefit will be increasingly at risk.

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