Insurance of Space Activities in the Era of Satellite Constellations

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Abstract

The rapid expansion of satellite constellations has transformed the legal, technical, and financial structure of contemporary space activities. Traditional space-insurance models were developed for individually valuable satellites, discrete launch missions, and comparatively limited orbital traffic. They are therefore increasingly unable to address the systemic, cumulative, and transnational risks associated with large constellations. This article examines the adequacy of existing international and national legal frameworks for insuring space activities in the constellation era. Using a descriptive-analytical and comparative legal approach, it evaluates the relationship between space insurance, State responsibility, launching-State liability, registration obligations, national licensing systems, and commercial risk allocation. The analysis identifies major challenges, including correlated losses, batch-launch failures, orbital congestion, collision and debris risks, autonomous operational systems, cyber-physical incidents, spectrum interference, data-related liability, service interruption, fragmented jurisdiction, and limited insurance-market capacity. The article argues that conventional first-party, launch, in-orbit, and third-party liability policies cannot adequately respond to these interconnected risks. It therefore proposes a multi-layered insurance regime composed of compulsory operator financial responsibility, constellation-level systemic coverage, an industry mutual-risk pool, conditional State-backed excess protection, and an international compensation fund. The proposed framework is further supported by harmonized minimum standards, expanded registration and transparency requirements, specialized insurance products, standardized contractual clauses, international loss databases, and technically informed dispute-resolution mechanisms. The article concludes that space insurance should function not merely as a compensatory device but also as a regulatory instrument capable of promoting safer design, cybersecurity, collision avoidance, debris mitigation, operational transparency, and responsible end-of-life practices. A coordinated and risk-sensitive insurance regime is essential for protecting victims, limiting State exposure, sustaining commercial investment, and preserving outer space as a secure, equitable, and sustainable environment.

Keywords: Space insurance; satellite constellations; international space law; launching-State liability; orbital congestion; third-party liability; risk management; international compensation fund

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1. Introduction

The contemporary space environment is undergoing a structural transformation that is fundamentally altering the legal, economic, and technological foundations of space activities. During the first decades of the space age, outer space was dominated by a limited number of States, a relatively small number of highly valuable satellites, and missions whose technical and financial risks could be assessed on an individual basis. Space activities were closely associated with national security, scientific prestige, and governmental programs, while private participation remained marginal. In that historical setting, space insurance developed primarily as a specialized commercial mechanism for protecting launch vehicles, satellites, and mission investments against catastrophic losses. The traditional insurance model was therefore centered on the individual spacecraft, the launch event, and the possibility of a clearly identifiable technical failure. The gradual commercialization of outer space, however, has transformed this model. Private operators, multinational corporations, start-ups, launch service providers, data companies, and financial institutions now participate in an increasingly complex space economy. As Jakhu explains, national regulation has become indispensable because States must reconcile their international responsibilities with the commercial activities of private entities operating under their jurisdiction (Jakhu, 2010). At the same time, the global character of space operations means that purely national approaches are no longer sufficient for managing the legal and financial consequences of accidents, service interruptions, collisions, and other emerging risks.

The emergence of satellite constellations, particularly large constellations deployed in low Earth orbit, represents one of the most significant developments in this transformation. Unlike traditional satellite systems composed of one or a small number of expensive spacecraft, contemporary constellations may consist of hundreds or thousands of satellites operating as an interconnected network. Their commercial and strategic value does not arise solely from the value of each physical satellite, but from the combined performance of the system as a whole. Constellations support broadband communications, Earth observation, navigation, climate monitoring, agricultural management, disaster response, military surveillance, financial transactions, and a wide range of data-dependent services. Lyall and Larsen emphasize that modern space activities can no longer be understood exclusively through the traditional State-centered framework because the functional and economic integration of space systems has created relationships involving numerous public and private actors (Lyall & Larsen, 2025). This systemic structure introduces forms of risk that were largely absent from the classical space era. The failure of a single satellite may be economically insignificant, yet the simultaneous failure of a launch batch, a common software platform, a ground-control network, or an orbital plane may cause substantial operational and financial disruption. Accordingly, the central object of insurance is shifting from the individual satellite toward the performance, continuity, and resilience of an interconnected space-based service.

The increasing density of orbital regions further intensifies these risks. The deployment of large constellations has substantially increased the number of active satellites, collision-avoidance maneuvers, conjunction alerts, and interactions among operators. The legal significance of orbital congestion extends beyond the physical possibility of collision. It also raises questions concerning the standard of care expected from operators, the reliability of tracking data, the responsibility to maneuver, the allocation of fault when several objects are involved, and the financial consequences of debris generation. Polkowska and Toumi observe that the development of space traffic management has become increasingly urgent because existing legal arrangements do not provide sufficiently detailed rules for coordinating the conduct of multiple operators in congested orbital environments (Polkowska & Toumi, 2024). The insurance implications are equally significant. Insurers must evaluate risks arising from the behavior of other operators, the availability and accuracy of space situational awareness data, the probability of chain collisions, and the possibility that one event may affect numerous satellites insured under different policies. Traditional actuarial methods, which depend on historical loss information and the relative independence of insured risks, are difficult to apply where losses are correlated, data are limited, and the technological environment changes rapidly.

The international legal framework governing space activities provides essential principles of responsibility and liability, but it does not establish a comprehensive insurance regime. The Outer Space Treaty recognizes that States bear international responsibility for national activities in outer space, including activities conducted by non-governmental entities, while the Liability Convention establishes rules for damage caused by space objects. These instruments remain the foundation of international space law, yet they were adopted at a time when commercial constellations, private launch companies, autonomous satellite operations, cyber-dependent infrastructure, and global data services did not exist. Masson-Zwaan and

Hofmann explain that the classical treaties were drafted in broad terms in order to establish general principles capable of enduring technological change, but this generality also leaves important regulatory questions to national implementation and subsequent interpretation (Masson-Zwaan & Hofmann, 2019). Insurance is one of the areas in which this gap is particularly visible. The treaties do not require operators to obtain insurance, do not prescribe minimum levels of coverage, do not regulate insurer participation in claims, and do not provide detailed rules for losses involving multinational commercial systems. Consequently, insurance obligations are primarily determined by domestic licensing laws, contractual arrangements, and market practice.

The fragmented character of national regulation creates additional uncertainty. Some States require commercial operators to obtain third-party liability insurance as a condition of authorization, while others rely more heavily on governmental guarantees, contractual indemnities, or case-by-case administrative decisions. According to von der Dunk, national space legislation frequently performs the practical function of translating international obligations into domestic licensing, supervision, and financial responsibility requirements (von der Dunk, 2015). However, national models differ considerably in relation to the amount of compulsory coverage, the calculation of maximum probable loss, the use of liability caps, the availability of State indemnification, the treatment of in-orbit operations, and the scope of recourse against private operators. These differences may encourage regulatory competition and may create unequal conditions for operators. More importantly, they complicate the settlement of claims when a constellation involves satellites manufactured in one State, launched from another State, registered in a third State, financed by investors in several jurisdictions, and controlled through ground stations located in different parts of the world.

Space insurance itself is also confronted with serious market limitations. The space insurance market is comparatively small and concentrated among a limited number of specialized insurers and reinsurers. The underwriting of space risks requires technical expertise, substantial financial capacity, and access to reliable mission data. Malinowska explains that risk assessment in space insurance is particularly difficult because each mission may involve unique technological characteristics, limited historical evidence, and potentially catastrophic loss exposure (Malinowska, 2017). These difficulties are amplified in the context of satellite constellations. Mass production may reduce the value of individual satellites, but it may also create common-mode risks because multiple satellites share the same design, manufacturing process, software, and operational architecture. A defect affecting one component may therefore affect an entire batch or fleet. Similarly, a single launch failure may destroy dozens of satellites, while a cyber incident may compromise the control system of an entire constellation. The possibility of correlated losses challenges the ability of insurers to diversify exposure and may result in high premiums, restrictive exclusions, substantial deductibles, or the refusal to provide coverage for certain risks.

The legal and economic importance of insurance extends beyond compensation after an accident. Insurance can also function as a mechanism of governance, supervision, and risk prevention. Through underwriting requirements, policy conditions, technical warranties, deductibles, and premium differentiation, insurers can influence operator behavior. Malinowska notes that insurance is capable of supporting responsible conduct because access to coverage may depend on compliance with technical standards and effective risk-management practices (Malinowska, 2016). In the constellation context, this regulatory function may be particularly valuable. Operators that maintain reliable maneuvering capability, share accurate orbital data, implement robust cybersecurity systems, comply with debris-mitigation standards, and demonstrate effective end-of-life disposal may qualify for more favorable coverage. Conversely, operators that increase orbital risk may be required to pay higher premiums or provide additional financial guarantees. Insurance can therefore complement public regulation by converting technical and legal standards into financial incentives.

The central problem addressed in this article is that the traditional framework of space insurance is no longer adequate for the scale, interconnectedness, and systemic character of satellite constellations. Existing policies remain largely organized around launch failure, physical damage to individual satellites, and conventional third-party liability. They often do not adequately address network-wide service interruption, autonomous operational failures, cyber-physical incidents, data-related liability, spectrum interference, cascading collisions, or losses whose origin cannot be clearly attributed to a particular operator. Amiri and PourGhassab argue that the progressive development of international space law requires closer attention to insurance because the expansion of commercial activity has exposed gaps in liability allocation and compensation mechanisms (Amiri

& PourGhassab, 2016). The constellation era makes this need more urgent by creating risks that are simultaneously technical, financial, environmental, and transnational.

This article aims to evaluate the capacity of existing legal and insurance mechanisms to respond to the risks generated by satellite constellations and to develop a coherent framework for reform. It argues that the future of space insurance requires a multi-layered model combining compulsory operator coverage, constellation-level protection, industry risk pooling, conditional State support, and an international compensation mechanism. Such a model must be supported by harmonized standards, improved registration and transparency, specialized insurance products, stronger international coordination, and effective dispute-resolution procedures. The objective is not to eliminate all risks from space activities, which would be impossible, but to ensure that risks are identified, allocated, priced, and compensated in a manner that promotes accountability, protects victims, supports commercial innovation, and contributes to the long-term sustainability of outer space.

2. International Legal and Conceptual Foundations of Space Insurance

Space insurance occupies a distinctive position at the intersection of insurance law, international law, national regulation, commercial contracting, and aerospace technology. It is not a single uniform product but a group of specialized mechanisms designed to transfer financial risks arising throughout the life cycle of a space mission. These risks begin during design, manufacturing, testing, transportation, and integration, continue through launch and orbital insertion, and remain present during satellite operation, servicing, deorbiting, re-entry, and disposal. Kardarbalash describes satellite insurance as a necessary response to the financial vulnerability of satellite construction and launch, particularly where technological development creates substantial national and commercial investment (Kardarbalash, 2008). In its most basic form, space insurance protects the insured party against the loss of a spacecraft or related equipment. In its broader legal function, however, it also supports compensation for third-party damage, protects public finances, facilitates private investment, and contributes to the implementation of State responsibility.

The traditional classification of space insurance distinguishes between first-party insurance and third-party liability insurance. First-party insurance protects the owner, operator, investor, or other financially interested party against damage to or loss of the insured space asset. This category includes pre-launch insurance, launch insurance, in-orbit insurance, and, in some cases, coverage for re-entry or recovery. Launch insurance generally covers the period from a contractually defined moment before or during ignition until successful orbital insertion and initial operation. In-orbit insurance may cover total failure, partial loss of capacity, propulsion malfunction, communication failure, power-system breakdown, or premature termination of the mission. Third-party liability insurance, by contrast, covers the legal obligation of the operator or another insured party to compensate persons or entities harmed by the space activity. Malinowska explains that the distinction between property coverage and liability coverage is essential because the insured interest, triggering event, method of valuation, and legal basis of compensation differ significantly (Malinowska, 2016). In the satellite-constellation context, this traditional distinction remains relevant but is no longer sufficient because many important losses involve system performance, data integrity, service availability, or environmental consequences rather than the physical destruction of a single satellite.

The relationship between space insurance and international responsibility begins with the Outer Space Treaty. Article VI establishes that States bear international responsibility for national activities in outer space, whether those activities are conducted by governmental agencies or non-governmental entities. Non-governmental activities must be authorized and continuously supervised by the appropriate State. This principle creates the legal foundation for national licensing systems and allows States to require insurance or other forms of financial security from private operators. Jakhu explains that authorization and continuing supervision are the principal domestic mechanisms through which States control private space activities and protect themselves against the consequences of international claims (Jakhu, 2010). Insurance is therefore closely connected to the licensing function. A State that authorizes a commercial launch or in-orbit operation may require the operator to demonstrate sufficient financial capacity to respond to potential claims. Such a requirement does not transfer the State's international responsibility to the operator, but it can distribute the financial burden within the domestic legal system.

Article VII of the Outer Space Treaty and the Liability Convention establish the principal international rules concerning damage caused by space objects. The Liability Convention distinguishes between absolute liability for damage caused on the surface of the Earth or to aircraft in flight and fault-based liability for damage caused elsewhere than on the Earth's surface.

Williams notes that the Convention reflects an attempt to balance victim protection with the special conditions of space operations by applying a more protective standard to terrestrial damage and a fault-based standard to interactions between space objects (Williams, 1997). From an insurance perspective, absolute liability is comparatively easier to conceptualize because compensation does not depend on proving negligence or wrongful conduct. Fault-based liability in orbit is more difficult because the claimant must establish that the conduct of the launching State or persons for whom it is responsible failed to satisfy the applicable standard of care.

Satellite constellations complicate the application of fault-based liability. A collision may involve incomplete tracking data, conflicting conjunction assessments, delayed communication, autonomous maneuvering systems, or the failure of one operator to coordinate with another. The relevant standard of care is not clearly defined in binding international law. It may be influenced by national licensing requirements, technical standards, industry guidelines, debris-mitigation practices, and emerging principles of space traffic management. Tronchetti explains that the effectiveness of international space law often depends on the interaction between treaty obligations, national implementation, and non-binding standards developed by technical and professional communities (Tronchetti, 2013). For insurers, this uncertainty creates difficulty in assessing whether a claim is covered, whether the insured operator acted negligently, and whether recovery may be pursued against another operator or State.

The Liability Convention also operates primarily through State-to-State claims. Private individuals and corporations do not ordinarily present claims directly under the Convention. A private victim must generally rely on the State of nationality or another entitled State to present the claim at the international level. Goh observes that the diplomatic structure of space-law dispute settlement can create delays and uncertainty, particularly where commercial actors require rapid and technically informed resolution (Goh, 2007). This framework is poorly suited to a commercial environment in which insurers, reinsurers, operators, investors, manufacturers, and service users may all have independent financial interests. It also does not expressly regulate subrogation, although an insurer that compensates its insured may seek recovery under domestic law or contractual arrangements. The absence of clear international rules concerning private claims and insurer recovery reduces predictability and may discourage market participation.

The identification and registration of space objects are equally important for insurance and liability. The Registration Convention requires launching States to provide specified information concerning space objects carried on their registries. Registration helps identify the relevant launching State and supports the attribution of responsibility. Momeni Rad and Zabihi Shahri emphasize that registration is a critical component of the international legal order because it connects a space object to the jurisdiction and obligations of a State (Momeni Rad & Zabihi Shahri, 2022). However, the traditional registration model was designed for a smaller number of objects and may not provide the level of detail required for modern constellations. Insurers need accurate information concerning ownership, beneficial control, operator identity, technical capability, orbital status, maneuverability, and changes in mission configuration. Where satellites are transferred, deactivated, replaced, or controlled through multinational corporate structures, formal registration data may not reflect the full operational reality.

The concept of the launching State creates another area of difficulty. A single space object may have several launching States because the definition includes a State that launches, procures the launch, or provides the territory or facility from which the object is launched. Lyall and Larsen explain that multiple launching States may bear joint and several liability under the international framework, although the internal allocation of financial responsibility may depend on agreements among them (Lyall & Larsen, 2025). Satellite constellations may involve repeated launches from different territories and facilities, which means that the constellation as a whole may be connected to several launching States. From an insurance perspective, this fragmentation complicates the determination of applicable law, policy beneficiaries, indemnification obligations, and rights of recourse. A constellation operator may be licensed in one jurisdiction while individual launches are conducted under the authority of other States. A loss involving several satellites may therefore trigger multiple national insurance regimes.

National legislation has developed as the primary mechanism for addressing these issues. States have adopted different combinations of licensing, mandatory insurance, financial guarantees, liability caps, indemnification, and contractual cross-waivers. Von der Dunk explains that national space laws differ because States seek to balance international responsibility, public safety, industry competitiveness, and the promotion of private investment (von der Dunk, 2015). The United States relies on a risk-based approach under which commercial launch operators must obtain insurance up to a level determined

through an assessment of maximum probable loss. France imposes insurance obligations and provides a structured relationship between operator liability and possible State support. Other States employ more flexible or case-specific approaches. These models demonstrate that compulsory insurance can protect the public and reduce State exposure, but their diversity also creates regulatory fragmentation.

The conceptual foundation of space insurance must also include the contractual allocation of risk. Space missions are governed by complex networks of agreements involving satellite manufacturers, launch providers, operators, customers, investors, ground-segment providers, and insurers. These contracts typically contain indemnities, limitations of liability, exclusions, cross-waivers, warranties, and dispute-resolution clauses. Masson-Zwaan and Hofmann note that contractual arrangements are especially important in commercial space activities because international treaties generally regulate relations among States rather than the detailed obligations of private actors (Masson-Zwaan & Hofmann, 2019). Insurance policies operate within this contractual network. The scope of coverage may depend on how risks have been allocated among the parties, whether liability has been waived, and whether the insured complied with technical and disclosure obligations.

Soft law also plays an important role in shaping insurance practice. Debris-mitigation guidelines, technical standards, sustainability principles, and emerging space traffic management proposals influence the assessment of reasonable conduct. Jakhu and Pelton argue that global space governance increasingly depends on institutional cooperation and non-binding norms because formal treaty-making has not kept pace with technological and commercial developments (Jakhu & Pelton, 2017). Insurers may incorporate these standards into policy conditions, risk assessments, and exclusions. An operator that fails to maintain maneuverability, disregards conjunction warnings, or lacks an adequate disposal plan may face reduced coverage or higher premiums. In this manner, insurance may contribute to the implementation of soft-law standards even where those standards are not directly enforceable.

Despite these foundations, the existing framework remains incomplete. International law does not impose a universal obligation to obtain insurance, determine minimum coverage, or create a direct compensation mechanism for private victims. National laws apply inconsistent financial responsibility standards, and commercial policies often exclude emerging risks such as cyber operations, interference, data loss, and systemic service failure. Amiri and PourGhassab identify the absence of coordinated insurance mechanisms as one of the principal challenges facing the progressive development of space law (Amiri & PourGhassab, 2016). The constellation era exposes these deficiencies because losses may be transnational, cumulative, technically complex, and difficult to attribute. A modern legal framework must therefore move beyond the traditional assumption that each satellite can be insured as an isolated asset and must instead recognize the networked nature of contemporary space systems.

3. Insurance Challenges Created by Satellite Constellations

Satellite constellations alter the economic unit that is subject to insurance. In the traditional model, the insured object was usually a single satellite whose value could be calculated by reference to manufacturing cost, launch cost, expected revenue, and replacement expense. The failure of that satellite constituted a discrete loss. A constellation, by contrast, is an integrated system in which the operational value of each unit depends on its relationship with other satellites, ground infrastructure, communication links, software platforms, and customer networks. The financial significance of a loss therefore cannot always be measured through the market value of the damaged satellite. A small and comparatively inexpensive satellite may perform a critical function within the architecture of the constellation. Its failure may reduce geographic coverage, create delays, require other satellites to consume additional fuel, or undermine contractual service levels. Malinowska explains that the valuation of space losses is already complex because partial failure may affect future performance without producing immediate total destruction (Malinowska, 2017). Constellations intensify this problem by creating a distinction between the physical condition of individual units and the functional condition of the network.

The first major challenge is the accumulation and correlation of risk. Insurance depends on the possibility of distributing independent risks across a sufficiently broad portfolio. Constellations, however, may concentrate risk because numerous satellites share the same design, production process, software, supplier network, launch provider, ground system, and orbital environment. A manufacturing defect may affect hundreds of units. A software error may be transmitted through a fleet-wide update. A cyberattack may compromise a common control platform. A single launch accident may destroy dozens of satellites.

A solar event may affect an entire orbital region. Malinowska notes that space insurers must account for the possibility of catastrophic losses even in conventional missions, but the limited availability of reliable statistical data makes such assessment difficult (Malinowska, 2016). In the constellation context, historical data are even less reliable because the scale and architecture of present systems have few precedents. The insurer may therefore be exposed not merely to the loss of one asset but to a series of simultaneous or closely connected claims.

Batch launches illustrate this problem. Constellation operators frequently deploy many satellites on a single launch vehicle in order to reduce cost and accelerate deployment. From an operational perspective, this strategy is efficient. From an insurance perspective, it creates a large concentration of exposure at one moment. A launch failure may destroy an entire batch and delay the planned expansion or replenishment of the network. The economic loss may include not only the value of the satellites but also lost revenue, contractual penalties, additional launch costs, and reduced system capacity. Traditional launch insurance can cover the physical loss of satellites, but it may not fully compensate the wider economic impact on the constellation. Kardarbalash emphasizes that launch insurance is essential because the launch phase has historically represented one of the most financially dangerous stages of a satellite mission (Kardarbalash, 2008). The constellation model increases the scale of that danger by placing multiple assets and a substantial portion of network capacity on the same vehicle.

Orbital congestion and collision risk represent a second major challenge. Low Earth orbit is becoming increasingly populated by operational satellites, inactive spacecraft, rocket bodies, and debris. Satellite constellations increase the number of objects that must be tracked and the frequency of conjunction assessments. Polkowska and Toumi explain that space traffic management proposals are developing in response to the inadequacy of existing coordination mechanisms (Polkowska & Toumi, 2024). Insurance depends on predictable standards of conduct, yet there is no universally binding rule that determines which operator must maneuver in a potential collision situation. The decision may depend on the maneuverability of the satellites, the reliability of the data, communication between operators, fuel availability, mission priority, and automated risk calculations. If both satellites maneuver, their actions may create a new risk. If neither maneuvers, a collision may occur. Establishing fault under the Liability Convention may therefore require a highly technical analysis of operational decisions and available information.

The generation of debris creates consequences that extend beyond the initial collision. A collision involving a constellation satellite may produce fragments capable of threatening numerous other spacecraft. The resulting losses may affect operators who had no contractual relationship with the original parties. The debris may remain in orbit for years, generating continuing risk and additional avoidance costs. Von der Dunk notes that the legal treatment of space debris remains problematic because international law does not provide a complete regime for removal, ownership, responsibility, and cost allocation (von der Dunk, 2015). Insurance policies may cover direct collision damage while excluding long-term environmental consequences or debris-remediation expenses. A large-scale event could also exceed available commercial insurance capacity. The possibility of cascading collisions raises the question whether a single occurrence should be treated as one insured event or a series of separate events, an issue that can significantly affect policy limits and deductibles.

A third challenge arises from autonomous systems and artificial intelligence. Satellite constellations rely on automated processes to manage station-keeping, routing, collision avoidance, communication links, system health, and end-of-life operations. Autonomous systems are necessary because human operators cannot manually control thousands of satellites in real time. However, automation complicates the attribution of fault. A defective maneuver may result from errors in the algorithm, incorrect sensor data, an inadequate software update, a design defect, insufficient operator supervision, or malicious interference. Tronchetti explains that space regulation must adapt to technological developments that alter the relationship between human decision-makers and space systems (Tronchetti, 2013). For insurance purposes, the central question is whether the event falls within ordinary operational risk, product liability, professional negligence, cyber risk, or an excluded software defect. The answer may determine which policy responds and which party bears the loss.

The use of artificial intelligence also creates evidentiary problems. A continuously learning system may modify its decision-making process during operation. After an incident, it may be difficult to reconstruct why the system selected a particular maneuver. Insurers and regulators therefore require access to operational logs, software versions, training data, decision parameters, and communication records. Yet operators may consider such information commercially sensitive or relevant to national security. The absence of mandatory data-retention standards may make claims investigation extremely difficult.

Masson-Zwaan and Hofmann emphasize that continuing supervision requires States to maintain effective oversight over private space activities (Masson-Zwaan & Hofmann, 2019). In the constellation era, this supervisory responsibility should include requirements for algorithmic accountability, record preservation, and the technical auditability of autonomous systems.

Cybersecurity presents a fourth category of risk. Satellite constellations depend on complex digital infrastructure connecting satellites, ground stations, cloud services, user terminals, and data-processing systems. A cyberattack may interfere with commands, manipulate data, disable communication, redirect satellites, or cause physical collision. It may also result in the theft or disclosure of sensitive information. Conventional space insurance often focuses on physical loss, while cyber policies may exclude damage to spacecraft or events involving hostile State action. Malinowska observes that the boundaries of insurable space risk are influenced by exclusions, technical uncertainty, and the capacity of insurers to evaluate new forms of exposure (Malinowska, 2017). The separation between space insurance and cyber insurance may therefore leave significant gaps. An integrated cyber-physical policy is needed to address incidents that begin as digital intrusions but produce operational, physical, and third-party consequences.

The attribution of cyber incidents is especially difficult. A constellation may be targeted by criminals, competitors, activists, terrorist groups, or State actors. The legal characterization of the event may determine whether war-risk or hostile-act exclusions apply. If an attack is attributed to a State, questions of international law may arise, but the insurer may still need to determine whether the loss is covered under the policy. The operator's cybersecurity practices will also be relevant. Failure to implement reasonable protective measures may be treated as a breach of warranty or negligence. Jakhu and Pelton emphasize that effective global space governance requires cooperation among governments, private actors, and technical institutions (Jakhu & Pelton, 2017). Cybersecurity cannot be addressed solely by individual operators because vulnerabilities may affect shared infrastructure, supply chains, and cross-border communication networks.

Spectrum interference creates another form of loss that may not involve physical damage. Constellations depend on access to radio frequencies, and interference can disrupt communications, navigation, remote sensing, and control functions. Interference may be accidental, negligent, or deliberate. It may arise from another satellite system, terrestrial infrastructure, equipment malfunction, or unlawful jamming. The economic consequences can be substantial even when the satellite remains physically intact. Customers may lose service, data may be delayed, and the operator may incur contractual liability. Lyall and Larsen explain that the use of radio frequencies and orbital resources involves international coordination because harmful interference can affect operators across national boundaries (Lyall & Larsen, 2025). Traditional property insurance may not respond because there is no physical loss, while liability policies may exclude purely economic damage. The development of coverage for interference and service interruption is therefore essential.

Data liability further expands the scope of potential claims. Earth-observation constellations produce information used in agriculture, environmental monitoring, insurance, logistics, defense, urban planning, and disaster management. Communications constellations carry personal, commercial, and governmental data. Liability may arise from inaccurate information, delayed transmission, unauthorized disclosure, privacy violations, or unlawful surveillance. A navigation error based on corrupted satellite data may cause physical or economic harm far removed from the spacecraft itself. Existing space treaties do not regulate these private-law consequences in detail. Jakhu observes that national regulation must address commercial activities that fall within the broad international framework but generate specific domestic legal relationships (Jakhu, 2010). Data-related harm may therefore be governed by privacy law, contract law, tort law, telecommunications regulation, and cybersecurity law in several jurisdictions simultaneously.

The multinational structure of constellation projects creates additional legal complexity. Satellites may be manufactured in one State, launched from another, registered in a third, operated by a corporation incorporated elsewhere, and financed by international investors. Ground stations may be distributed across several regions, and services may be delivered globally. Momeni Rad and Zabihi Shahri explain that the international obligations of States must be coordinated with national jurisdiction and registration responsibilities (Momeni Rad & Zabihi Shahri, 2022). In a constellation project, several States may qualify as launching States, while different States may exercise licensing or supervisory authority over different parts of the system. A single incident may therefore trigger multiple legal regimes and insurance policies. Conflicts may arise over applicable law, jurisdiction, policy interpretation, and the allocation of liability among operators, manufacturers, launch providers, and States.

Contractual risk allocation can reduce some uncertainty but cannot solve all problems. Cross-waivers of liability are frequently used to prevent project participants from bringing claims against one another for specified losses. Such waivers can support cooperation and reduce insurance costs. However, they do not bind third parties and cannot eliminate the international liability of launching States. Goh explains that space disputes may involve public and private legal relationships that require different forms of settlement (Goh, 2007). A contractual waiver between an operator and launch provider does not compensate another satellite operator harmed by debris, a terrestrial victim, or a customer suffering widespread service interruption. Insurance must therefore operate alongside contractual allocation rather than being replaced by it.

The economic insurability of constellations is itself uncertain. The low value of individual satellites may make conventional policies inefficient because administrative and underwriting costs are high relative to the value insured. At the same time, constellation-wide coverage may expose insurers to excessive systemic risk. Operators may choose to self-insure routine satellite failures while purchasing protection only against catastrophic events. This approach may be commercially rational, but it creates concern where losses affect third parties or exceed the operator's financial capacity. Amiri and PourGhassab argue that space insurance must develop in parallel with commercial expansion in order to ensure effective compensation and responsible activity (Amiri & PourGhassab, 2016). A viable regime must therefore distinguish between ordinary internal losses, which operators may retain, and external liabilities, which require compulsory financial protection.

These challenges demonstrate that constellation risks cannot be managed through a simple extension of conventional satellite policies. The legal framework must recognize correlated losses, network dependency, cyber-physical exposure, data liability, orbital congestion, and multinational responsibility. It must also create incentives for operators to reduce risk before damage occurs. Insurance should not merely assign a monetary value to destroyed satellites; it should support the resilience and sustainability of the orbital environment. This requires new products, new standards, and a new relationship between operators, insurers, States, and international institutions.

4. Toward a Multi-Layered Insurance Regime for Satellite Constellations

A modern insurance regime for satellite constellations should begin with the recognition that no single level of coverage can adequately address the full range of risks. Individual operator insurance is necessary but insufficient because some losses may exceed commercial limits, involve multiple operators, or remain unattributable. State guarantees are also insufficient because they may expose public finances to unlimited liability and may reduce incentives for responsible private conduct. A purely international fund would be equally inadequate if operators were not required to maintain their own financial responsibility. The most effective structure is therefore a multi-layered regime in which responsibility is distributed across operators, insurers, industry pools, States, and an international compensation mechanism. This approach reflects the complex allocation of responsibility already present in space law while adapting it to the systemic character of satellite constellations.

The first layer should consist of compulsory operator financial responsibility. Every operator should be required, as a condition of authorization, to maintain insurance or another approved form of financial security for third-party liability arising from launch, in-orbit operations, and re-entry. Jakhu explains that national licensing systems are the principal instruments through which States ensure that private activities comply with international obligations (Jakhu, 2010). Insurance requirements should therefore be integrated into the authorization process rather than treated as a separate commercial matter. The amount of required coverage should not be identical for all missions. It should be determined through a risk-based assessment that considers the number of satellites, orbital altitude, maneuverability, launch profile, re-entry characteristics, reliability record, cyber architecture, expected operational life, and potential exposure to third parties.

A risk-based model is preferable to a universal fixed amount because constellation risks differ substantially. A small experimental constellation operating at low altitude with reliable deorbit capability may present less long-term risk than a large system deployed in a congested orbital region. Malinowska emphasizes that insurance requirements should reflect the technical and legal characteristics of the mission rather than relying on abstract or uniform assumptions (Malinowska, 2017). The assessment should include both maximum probable loss and systemic exposure. Traditional maximum probable loss calculations often focus on launch accidents and terrestrial damage. In the constellation context, they should also consider orbital collisions, common-mode failures, cyber incidents, and service disruption. The operator should remain responsible for losses within a defined retention or deductible in order to preserve incentives for careful risk management.

The second layer should consist of constellation-level insurance. This coverage would address losses affecting multiple satellites or the functional performance of the network. Conventional policies often insure each satellite or launch separately, but this structure may not respond adequately when the value of the loss is systemic. A constellation-level policy could cover batch-launch failure, common manufacturing defects, fleet-wide software errors, ground-control failure, coordinated cyberattacks, solar events, and the loss of a significant portion of network capacity. Malinowska notes that insurance products must evolve in response to changing technological risks and the specific structure of space operations (Malinowska, 2016). The policy trigger could be defined by reference to the loss of a specified percentage of satellites, a measurable decline in service capacity, or the failure of a critical operational segment.

Constellation-level coverage should combine indemnity-based and parametric mechanisms. Indemnity insurance compensates the actual financial loss established through evidence, while parametric insurance provides payment when an objective trigger occurs. A parametric policy might respond when communication with a defined number of satellites is lost for a specified period, when a launch fails to deploy a minimum proportion of the batch, or when constellation capacity falls below an agreed threshold. Such mechanisms can accelerate payment and reduce disputes over valuation. However, they must be carefully designed to avoid basis risk, which arises when the trigger does not correspond precisely to the actual loss. Parametric coverage should therefore complement rather than completely replace traditional indemnity insurance.

The third layer should be an industry mutual-risk pool. Commercial insurers may be unwilling or unable to cover catastrophic and correlated losses associated with very large constellations. A mutual pool could distribute exceptional risks among operators and insurers. The maritime insurance sector demonstrates how mutual arrangements can provide coverage for liabilities that exceed the capacity or appetite of ordinary commercial markets. Although outer space has distinct legal characteristics, the principle of collective risk sharing is transferable. Jakhu and Pelton emphasize that global space governance increasingly requires collaborative institutions capable of coordinating public and private interests (Jakhu & Pelton, 2017). A constellation risk pool could be established at the regional or international level and financed through contributions from licensed operators.

Contributions to the pool should be risk-sensitive. Operators that create greater orbital exposure should contribute more. Relevant factors could include fleet size, orbital density, satellite mass, maneuverability, reliability, disposal success, collision-avoidance performance, cyber resilience, and compliance with reporting obligations. This approach would convert insurance contributions into incentives for sustainable behavior. An operator that maintains effective end-of-life disposal, shares accurate orbital data, and responds promptly to conjunction warnings could benefit from lower contributions. An operator that repeatedly fails to deorbit satellites or withholds relevant information would face higher costs. Polkowska and Toumi explain that effective space traffic management depends on reliable information and coordinated conduct (Polkowska & Toumi, 2024). Linking insurance costs to such conduct would strengthen compliance even before binding international traffic rules are adopted.

The industry pool could cover exceptional third-party claims, debris-removal expenses, emergency response costs, and losses caused by unidentified or insolvent operators. It could also support technical investigations following major incidents. However, access to pooled compensation should be conditional. An operator that failed to maintain compulsory insurance, violated licensing conditions, or engaged in wilful misconduct should not receive the same protection as a compliant operator. The pool should retain rights of recovery against responsible parties where appropriate. This structure would preserve accountability while ensuring that victims are not left uncompensated because of insolvency or excessive loss.

The fourth layer should consist of conditional State-backed excess coverage. States remain internationally responsible for national space activities and may face claims under the Liability Convention. Masson-Zwaan and Hofmann explain that States cannot avoid their international obligations merely by authorizing private entities to conduct space activities (Masson-Zwaan & Hofmann, 2019). Nevertheless, domestic law can allocate financial responsibility between the State and the operator. A State may require the operator to maintain insurance up to a prescribed limit and may provide indemnification for losses exceeding that limit. Such support can encourage commercial investment because operators cannot realistically obtain unlimited insurance. At the same time, State protection must be conditional in order to avoid moral hazard.

State-backed excess coverage should apply only where the operator complied with authorization requirements, maintained the required insurance, implemented approved safety measures, and acted without gross negligence or wilful misconduct. The State should be entitled to recover payments where the operator concealed material information or violated essential conditions.

Von der Dunk notes that national space laws frequently seek to balance industry development with the protection of public interests and State finances (von der Dunk, 2015). A conditional excess regime can achieve this balance. It provides certainty to operators and investors while ensuring that public support is linked to responsible conduct.

The fifth layer should be an international compensation fund. Certain losses cannot be adequately addressed through operator insurance, industry pooling, or State support. Damage may be caused by an object that cannot be identified, an operator may be insolvent, several States may dispute responsibility, or a systemic orbital event may produce losses exceeding available national mechanisms. The international fund would provide compensation in such exceptional circumstances. Amiri and PourGhassab emphasize that the development of insurance mechanisms is essential to fill gaps in the existing international liability system (Amiri & PourGhassab, 2016). The fund could be financed through contributions from launching States, licensing fees, operator levies, registration charges, and a proportion of industry-pool contributions.

The fund should not replace the Liability Convention but should supplement it. It could provide provisional compensation while legal responsibility is being determined, thereby protecting victims from lengthy diplomatic or judicial processes. It could also compensate losses where attribution is impossible despite reasonable investigation. The right to compensation should be subject to clear eligibility criteria, evidentiary requirements, and limits. The fund should retain subrogation rights against responsible operators or States once liability is established. This mechanism would strengthen victim protection while preserving the existing principles of responsibility.

A supplementary protocol to the Liability Convention would provide the most coherent legal basis for this system. The protocol could define compulsory insurance, establish minimum categories of coverage, recognize insurer subrogation, regulate claims involving private entities, and create procedures for losses involving multiple launching States. Lyall and Larsen explain that the existing treaty framework provides broad principles but leaves many commercial and procedural matters unresolved (Lyall & Larsen, 2025). A protocol would allow States to develop detailed financial rules without reopening the entire structure of the foundational treaties. It could initially be optional, enabling willing States to establish a higher standard that may gradually influence broader international practice.

The protocol should recognize systemic and constellation-wide damage. Traditional legal concepts often focus on direct physical damage to identifiable property. A modern regime should also address reasonable costs associated with loss of control, emergency maneuvers, debris mitigation, restoration of essential services, and damage to network functionality. It should clarify the treatment of indirect economic loss, which remains controversial because unlimited recovery could create unmanageable exposure. Compensation should be limited to losses that are sufficiently direct, foreseeable, and documented. Clear rules would improve insurability because insurers could more accurately assess the scope of potential claims.

Registration and transparency must support the multi-layered regime. Momeni Rad and Zabihi Shahri emphasize that effective implementation of space-law obligations depends on accurate registration and national supervision (Momeni Rad & Zabihi Shahri, 2022). Constellation operators should be required to provide updated information concerning ownership, operator identity, control facilities, orbital status, maneuverability, insurance coverage, and disposal plans. Changes in ownership or control should be recorded promptly. The registration system should also indicate whether a satellite is active, inactive, or incapable of maneuvering. Sensitive commercial or security information could be protected, but sufficient data must be available to support collision avoidance, claims investigation, and liability attribution.

An international insurance database should be established to collect information on policies, losses, claims, technical failures, and risk-management practices. The space insurance market currently suffers from limited and fragmented data. Insurers often treat loss information as commercially confidential, while operators may hesitate to disclose anomalies. Yet actuarial development requires reliable evidence. Malinowska explains that the lack of statistical information is one of the principal obstacles to accurate risk assessment in space insurance (Malinowska, 2017). A confidential or partially anonymized international database could improve underwriting without exposing sensitive information. It could be managed by an international coordinating body and made available to regulators, qualified insurers, and researchers under appropriate safeguards.

Institutional coordination should develop gradually. The immediate creation of a new international organization may be politically unrealistic. A specialized working group could first be established under an existing United Nations space body. Jakhu and Pelton argue that institutional evolution is often more practical when it builds on existing governance structures

(Jakhu & Pelton, 2017). The working group could prepare model insurance clauses, risk-assessment standards, reporting guidelines, and recommendations for national legislation. It could also coordinate with insurers, reinsurers, satellite operators, technical experts, and arbitral institutions. Over time, this mechanism could evolve into a permanent international space-insurance coordinating body.

Dispute resolution must also be specialized. Space insurance disputes may involve complex questions of orbital mechanics, software engineering, cybersecurity, policy interpretation, international liability, and national insurance law. General courts may lack the technical expertise required to resolve such cases efficiently. Goh proposes a multi-door approach to space dispute settlement in which different mechanisms are used according to the nature of the dispute (Goh, 2007). A specialized chamber within an established arbitral institution could hear disputes between operators, insurers, reinsurers, manufacturers, and other commercial parties. Its panels should include legal experts and technical specialists. Procedures should permit emergency measures, confidential evidence, expert determination, and consolidated proceedings where several policies or parties are involved.

Standardized contractual clauses would further improve predictability. The international community and insurance industry should develop model definitions for launch, orbital insertion, partial loss, total loss, systemic failure, cyber incident, interference, debris event, and service interruption. Masson-Zwaan and Hofmann explain that commercial space law relies heavily on contractual precision because treaties do not regulate private transactions in detail (Masson-Zwaan & Hofmann, 2019). Standard clauses could also address aggregation of losses, notification, disclosure, policy cancellation, sanctions, applicable law, subrogation, and dispute resolution. These clauses should remain adaptable to mission-specific circumstances, but a common baseline would reduce interpretive disputes.

New insurance products should address the specific risks of constellations. Systemic failure insurance would respond when the loss of part of the fleet materially affects network performance. Cyber-physical insurance would cover digital incidents that cause operational or physical consequences. Data liability insurance would address claims arising from inaccurate, corrupted, delayed, or unlawfully disclosed data. Debris-remediation insurance would cover the cost of tracking, mitigation, removal, or controlled disposal following an accident. Cross-collision insurance would address interactions between satellites belonging to the same operator or affiliated entities, which may be excluded from ordinary third-party policies. These products should be coordinated to prevent overlaps and gaps.

The success of the regime ultimately depends on the use of insurance as a preventive instrument. Premiums, deductibles, coverage limits, and access to public protection should reflect operator conduct. An operator that adopts reliable collision-avoidance systems, maintains propulsion reserves, protects command links, and complies with disposal requirements should receive financial benefits. An operator that creates avoidable risk should bear higher costs. Tronchetti emphasizes that effective space policy must combine legal rules with practical incentives capable of influencing behavior (Tronchetti, 2013). Insurance can provide such incentives because it translates abstract standards into immediate financial consequences.

Implementation should occur in stages. In the short term, States can improve licensing rules, require proof of insurance, mandate operational reporting, and encourage constellation-specific policies. Regional organizations can develop shared standards and risk pools. In the medium term, international institutions can establish databases, model clauses, and specialized dispute procedures. In the long term, States can negotiate a supplementary protocol and create an international compensation fund. The proposed regime does not require complete uniformity. It requires a common minimum structure within which national systems and commercial policies can operate coherently.

5. Conclusion

The rapid development of satellite constellations has transformed the nature of space risk. The traditional space-insurance model was developed for an environment in which satellites were relatively few, individually valuable, technically distinct, and predominantly operated by States or a limited group of major commercial actors. Contemporary constellations differ in scale, architecture, ownership, operational dependency, and economic function. They consist of interconnected fleets whose value arises from network performance rather than from the isolated value of each satellite. Their operation depends on shared software, autonomous systems, ground infrastructure, communication links, data-processing platforms, and continuous coordination with other actors in increasingly congested orbital regions.

These characteristics create risks that cannot be adequately addressed through conventional launch and in-orbit insurance alone. Batch launches concentrate exposure, common designs create correlated technical failures, shared software increases the possibility of fleet-wide disruption, and cyberattacks may affect both digital and physical components of a constellation. Orbital congestion increases collision risk and generates difficult questions concerning maneuver responsibility, fault, causation, and debris. Spectrum interference and data-related harm may cause substantial loss without physical damage to a spacecraft. The multinational structure of constellation projects further complicates the determination of jurisdiction, applicable law, launching-State responsibility, contractual liability, and insurance coverage.

The existing international legal framework remains essential but incomplete. The foundational space treaties establish the responsibility of States, the liability of launching States, and the obligation to register space objects. They do not create a comprehensive system of compulsory insurance, private claims, minimum coverage, insurer subrogation, or compensation for systemic losses. Their State-centered structure does not correspond fully to a commercial environment in which operators, insurers, manufacturers, service providers, investors, and users may be located in numerous jurisdictions. National laws have attempted to fill this gap, but their approaches differ significantly. The resulting fragmentation produces uncertainty, uneven protection, and the possibility of regulatory arbitrage.

A sustainable response requires a multi-layered insurance regime. The first layer should require operators to maintain financial responsibility for launch, in-orbit, and re-entry liability. The level of required coverage should reflect the actual risk of the mission rather than a single fixed amount. The second layer should provide constellation-level coverage for correlated and systemic losses, including batch-launch failure, software defects, cyber incidents, and significant degradation of network capacity. The third layer should consist of an industry mutual-risk pool capable of addressing catastrophic claims and risks beyond the capacity of ordinary commercial insurance. The fourth layer should provide conditional State-backed excess protection where operators have complied with licensing, insurance, safety, cybersecurity, and sustainability requirements. The final layer should be an international compensation fund for exceptional cases involving unidentified objects, insolvent operators, disputed responsibility, or widespread losses exceeding national mechanisms.

This financial architecture must be supported by legal and institutional reform. Registration systems should provide updated information concerning ownership, control, operational status, maneuverability, insurance, and disposal plans. A shared database should collect reliable information on technical failures, claims, and loss patterns. International model clauses should standardize key concepts while preserving contractual flexibility. Specialized insurance products should address systemic failure, cyber-physical incidents, data liability, debris remediation, and service interruption. A specialized dispute-resolution mechanism should combine legal and technical expertise and should be capable of handling complex, multi-party claims efficiently.

The international community should also develop a supplementary protocol dealing specifically with insurance and compensation. Such an instrument could establish minimum categories of coverage, recognize private and insurer interests, regulate claims involving multiple launching States, and provide the legal foundation for an international fund. It need not replace the existing space treaties. Its function would be to translate their general principles into a financial and procedural framework suited to contemporary commercial space activities.

Insurance should not be understood solely as a mechanism for paying compensation after an accident. It can also serve as an instrument of prevention and governance. Risk-sensitive premiums, deductibles, coverage conditions, and access to public guarantees can encourage operators to improve design reliability, maintain maneuvering capability, share accurate orbital information, protect control systems, comply with debris-mitigation standards, and implement effective end-of-life disposal. Operators that reduce risk should receive financial advantages, while those that create avoidable danger should bear higher costs. Through this mechanism, insurance can reinforce public regulation and contribute to the sustainable use of orbital resources.

The proposed regime must also remain proportionate. Excessive insurance requirements could exclude smaller operators, reduce competition, and concentrate the space economy in the hands of a few large corporations. Minimum standards should therefore be adjusted according to mission type, orbital environment, fleet size, and potential exposure. Governments and international institutions should support developing spacefaring States through technical assistance, regional risk pools, and access to reinsurance. Global space governance cannot be sustainable if effective insurance is available only to the wealthiest States and corporations.

The long-term viability of satellite constellations depends on public confidence, commercial stability, and the ability to compensate harm. Technological innovation alone cannot provide these conditions. The legal order must ensure that the financial consequences of accidents are not transferred entirely to victims, governments, or the broader orbital community. Operators must bear responsibility for the risks they create, while exceptional and systemic losses must be distributed through fair collective mechanisms.

A coordinated insurance regime would therefore serve several objectives simultaneously. It would protect third parties, reduce the exposure of launching States, strengthen the financial resilience of operators, support investment, improve technical standards, and promote responsible conduct. It would also contribute to the preservation of outer space as a secure and sustainable environment. Satellite constellations are becoming essential infrastructure for communications, data, security, science, and economic development. Their benefits can be maintained only if the legal and financial system evolves alongside their technological expansion.

The era of satellite constellations requires a transition from isolated, asset-based insurance toward an integrated system of risk governance. Compulsory operator coverage, constellation-level protection, mutual pooling, State-backed excess liability, and international compensation should operate as complementary layers rather than separate alternatives. Supported by transparency, harmonized standards, specialized institutions, and effective dispute resolution, this model can transform space insurance into a central pillar of global space governance. Such a transformation is necessary not merely for the commercial success of satellite constellations, but for the equitable, peaceful, and sustainable development of outer space.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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