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Challenges to Space Activities in the Context of Mega Satellite Constellations: A Focus on Environmental Impacts

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The advent of low Earth orbit (LEO) mega satellite constellations to accelerate high-speed internet worldwide represents a new technological advancement. However, this development raises concerns regarding militarization, orbital debris, environmental protection, and their effects on space tourism. Despite these challenges, existing space law treaties have not addressed these issues. This article highlights the gaps in current treaties and emphasizes the need for advancements to mitigate emerging challenges and ensure long-term solutions. This study explores the legal challenges associated with possible smashes flanked by existing satellites in orbit and newly launched satellites as part of mega-constellations, which could jeopardize mission safety and threaten the sustainability of space activities. It also analyzes the significant issues related to space debris, particularly given the anticipated increase in satellite constellations in LEO over the coming decades. The increase in small satellites with shorter lifespans is likely to contribute to greater debris generation. Finally, these findings suggest the need for a suitable international legal structure to facilitate the efficient deployment and operation of satellite techniques.

Keywords: long-term sustainability, space environment challenges, mega satellite constellations, space commercialization

1. INTRODUCTION

Currently, a new space race is unfolding among satellite producers, all striving to envelop the Earth with the deployment of “mega-constellations.” The surge in satellite development stems from significant technological advancements in the private sector. In addition, this race aims to revolutionize global connectivity by offering dedicated, high-speed internet access to remote and underserved areas, a development that could transform digital accessibility globally. Between 2013 and 2020, annual satellite launches increased tenfold, and this exponential growth trend is expected to continue in the years ahead (Lin et al. 2024). This reflects the rapid shift towards privatization and the expanding scope of private enterprises in space exploration. low Earth orbit (LEO) refers to an orbit around the Earth at altitudes ranging from approximately 200 km to 2,000 km above the planet’s surface (Crisp et al. 2020).

This orbit is the closest orbital region to Earth and is commonly used by various satellites, including those for communication, observation, and specific scientific experiments (NASA 2022). Starlink is set to revolutionize global internet connectivity by deploying an extensive constellation of satellites in LEO. As of January 2024, Starlink has launched over 5,200 satellites, making it the largest satellite operator (McDowell 2023). It plans to increase this number to 12,000 by 2027, potentially expanding up to 42,000 in the future (Chyba 2020). Other notable LEO mega-constellations currently in development include OneWeb, Iridium Next, Globalstar, and Flock. Additionally, Samsung, Boeing, Telesat, and Amazon have proposed LEO mega-constellations comprising hundreds to thousands of satellites.

A mega-constellation is a large group of satellites operating in coordinated orbits designed to provide widespread network coverage or comprehensive Earth observation

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capabilities. Although no universally defined threshold number distinguishes a mega-constellation, the term generally applies to systems comprising hundreds or thousands of satellites. Starlink, a pioneering project by SpaceX, is an ambitious satellite internet constellation devised to provide global broadband coverage, particularly in underserved areas. This epitomizes the shift from government-led space initiatives to private enterprise-driven advancements and technological breakthroughs.

Throughout 2023, SpaceX achieved a notable milestone by successfully launching 61 rockets, thereby expanding its mega-constellation with the addition of more than 1,500 satellites. This endeavor substantially outperformed the activities of established space entities, such as the European space agency (ESA), which launched only six rockets that year and maintained a satellite fleet of less than 50. This comparison underscores the rapid shift towards privatization and the expanding scope of private enterprises in space exploration.

The history of satellites began with the launch of Sputnik 1 on October 4, 1957, as the first artificial satellite made by humans (Sullivan 1957). Recently, competition among satellite service providers has increased, with many companies leveraging modern technology and innovation to enhance both ground systems and satellite designs. Some are concentrating on deploying geostationary Earth orbit (GEO) satellites, particularly high-throughput variants, while others are developing large-scale non-geostationary satellite constellations.

Early space law agreements were founded on the principle of humanity's shared heritage, addressing the exploration and utilization of space. However, despite the progress in space exploration, existing treaties have proven insufficient in addressing emerging challenges, given the current discoveries and advancements. Regarding several related issues that have not been fully addressed by treaties, such as military use, orbital debris, environmental protection, and their impact on space tourism, further investigation is required to identify which legislative bodies outside UN agencies are suitable to address these pressing concerns.

The extraordinary increase in mega satellite constellations in LEO aims to provide high-speed internet globally, strengthened by strategies from international organizations, governments, and private enterprises (Morssink 2019). The abundance of medium-sized constellations in LEO offers a cost-effective and easily accessible solution for commercial use, leading to rapid expansion in this sector. Several private companies, beyond SpaceX, are planning to launch mega-constellations. For instance, Amazon aims to launch 3,236 satellites, OneWeb intends to launch 2,730, and Samsung plans to launch 4,600 into orbit (Henry 2019). Furthermore, several countries, such as Norway, have registered 4,257 satellites to line up with the International Telecommunication Union (ITU), while France and Canada have registered 4,000 and 794 satellites, respectively (Nair 2019).

Owing to advancements in space technology, it has become increasingly difficult to distinguish between large and small satellites, resulting in constant discussions about their definitions. The term “small satellite” covers various classifications that distinguish them from larger, less advanced counterparts. Satellites are typically classified, from smallest to largest, as follows: minisatellites: weighing from 100 to 1,000 kg, microsatellites: weighing from 10 kg to 100 kg, nanosatellites weighing from 1 to 10 kg, and picosatellites weighing less than 1 kg. However, with respect to radiofrequency assignments, the ITU-R defines “minisatellites” as those weighing less than 500 kg. (Pelton & Madry 2020).

Finally, it must be noted that both the International Academy of Astronautics and ITU-R definitions of minisatellites are solely based on mass, without considering other characteristics such as shape or maneuverability (ITU-R 2023). A satellite is, in technical terms, a large object that moves around another body in space, such as the moon orbiting the Earth. Nevertheless, in this case, we mean the term artificial satellites. The most notable of these was Sputnik, launched in 1957, which was approximately the size of a volleyball and marked the beginning of the Space Race era.

A mega-constellation refers to the operation of hundreds or even thousands of satellites working together as an organized system (Ravishankar et al. 2020). Two key aspects are driving states, international organizations, and private companies to capitalize on small-satellite constellations: the significant reduction in hardware costs for these satellites and the surging global demand for internet connectivity (Dornik & Smith 2016). As a result, these companies can extend high-speed internet services at more reasonable costs.

Currently, most satellites delivering internet access are located in GEO, exactly 36,000 km (approximately 220,236 miles) above the surface of the earth (Wittig 2009). Geosynchronous satellites remain fixed with respect to their location on the ground; thus, they are ideal for use where an uninterrupted service is the goal. Several companies, such as OneWeb, SpaceX, Samsung, and Amazon, are deploying satellite networks in LEO, at altitudes between 180 and 2,000 km—approximately the distance between Florida and New York City. It is anticipated that LEO satellites can significantly reduce latency to a large margin and offer internet speeds up to 20 times faster than those of current

GEO-based systems (Handley 2019).

2. CHALLENGES OF MEGA SATELLITE CONSTELLATIONS

2.1 Hostile Satellite Crash

With the advent of small satellite constellations, the risk of collisions with current objects in outer space, LEO in particular, has significantly increased. This raises the possibility of catastrophic scenarios, often referred to as 'Kessler Syndrome.' According to National Aeronautics and Space Administration (NASA), LEO may become congested in the future, leading to more accidents and debris falling back to Earth (Kessler et al. 2010). The most remarkable case was when the inactive Cosmos Satellite 2251 collided with Iridium Satellite 33 and triggered panic in the space sector concerning protecting the environment in space (Jakhu 2010). The outer space treaty (OST) places considerable importance on collision prevention rather than intrusion into outer space. It asserts that it is the responsibility of all states to avert such occurrences.

Although this treaty outlines the principles of collaboration, its vague language and lack of specific guidelines make it inadequate for preventing orbital collisions or addressing satellite accidents. In addition, OST does not discriminate between small and mega satellites, and all of its provisions are primarily designed for large satellites and seek to extend the same benefits and obligations to small satellites without accounting for their unique needs (Marboe & Mosteshar 2016). The OST (1967; UN 1966) and the Liability Convention (LC) (1972; Convention on International Liability for Damage Caused by Space Objects 1971), administer the regulation of space objects (Abbas 2024). While composing the OST, there were no legal provisions regarding the deployment and operation of MSCs in any orbit. Both treaties classify satellites as space objects without differentiating between large and small satellites. Instead, they focus on damages resulting from space activities. They created a structure for getting compensation, granting participants who undergo losses to pursue compensation from those who defiant treaty commitments. Article VII of the OST holds each member state legally responsible for any damage sustained during space operations. Article VII of the OST clearly emphasizes that all member states are responsible for any damage suffered during their space activities. Article I of the LC states that the states that launch the satellite or that launch satellites from its territory are accountable. Article II establishes that launching states are liable for every and any damage to space objects.

Moreover, the OST and, particularly its Article VI, imposes the responsibility for the damages incurred during outer space activities on member states. It also extends this responsibility to non-governmental organizations involved in these activities, provided they operate with the consent and authority of their respective governments. As a result, states become liable for the activities of private companies providing services in space from these states. However, the OST does not define "damage" or specify liability limits; instead, Article 1(a) of the LC defines damage to include personal injury, loss of life, property damage—whether to individuals or states—and health-related issues. Some scholars argue that only recoverable damage caused physically by small satellites in space should be emphasized (Christol 1980).

2.2 Uncertainties Regarding Mega-Constellations

In a recent report to Congress (FAA 2023), the USA Federal Aviation Administration (FAA) expressed concerns regarding the potential dangers posed by SpaceX Starlink satellites when they re-enter the Earth's atmosphere. The FAA's concerns specifically relate to the space debris released by these satellites, which poses a risk to individuals on the ground or aircraft in flight. The report, submitted in September 2023, suggested that if current trends continue, by 2035, debris from such re-entries is likely to result in one fatality every two years. Thus, the FAA is addressing the issue of space debris management and the safe deorbiting of defunct satellites with urgency. The FAA report also specified that over 85% of the risk to both ground populations and aviation in 2035 from re-entering debris would be attributed to Starlink satellites. Therefore, Starlink is a major source of risk in the space domain. The FAA report also assessed the potential risks to individuals on the ground and in aircraft associated with the debris released by the unplanned re-entry of satellites positioned in LEO. The report assumes that by 2035, 12 major satellite constellations will achieve full operational status in orbit and will adhere to satellite deorbiting protocols (Schrogl et al. 2018).

In a detailed interaction with the Federal Communication Commission, NASA expressed concerns about Starlink's development and the potential for increased orbital collisions. The National Telecommunications and Information Administration submitted a five-page document, accompanied by an additional note from the National Science Foundation, on behalf of NASA (2022). A significant increase in the number of satellites that SpaceX intends to launch has drawn attention from NASA, which states that there is an inherent risk of debris-generating collision events owing to the sheer quantity of objects involved in such an increase (Grotch 2022). This assertion reflects deep-seated concerns about the crowding of specific orbital regions owing to SpaceX's initiative to expand its Starlink constellations. As noted by NASA, Starlink expansion represents a major threat, increasing the likelihood of space debris generation and the frequency of collisions given the increasing number of satellites and the confined nature of their operational altitudes.

2.3 Orbital Debris

Space debris has emerged as a significant global challenge, jeopardizing the sustainability of space activities and necessitating proactive management. In recent years, an increase in collision incidents has contributed to the accumulation of debris, transforming space into a congested environment filled with hazardous materials (Sheer et al. 2023).

Even the smallest particles of space debris pose a substantial threat, as they can travel at speeds of nearly 10 km/s (approximately 6.21 miles/s)—equivalent to ten times the speed of a bullet—resulting in considerable momentum and potential for catastrophic damage. This debris can trigger chain reactions, creating a debris belt around the Earth and exacerbating the risk of collisions with operational satellites (Sheer & Li 2019a). Even tiny fragments can generate significant energy, increasing their potential for destruction and endangering astronauts aboard the International Space Station, as well as other satellites. For instance, OneWeb currently operates a macro-constellation network consisting of approximately 1,000 functional satellites in LEO (Foreman et al. 2017), with plans to double this number in the future. The growing volume of debris poses a serious threat to these operational satellites, particularly given their relatively short lifespan of just three to five years. This short operational period is likely to lead to an even greater accumulation of space debris as small satellite constellations continue to be deployed. The expansion of mega-constellations amplifies the requirement for effective space traffic management. These constellations are formed by launching a dense distribution of assets into orbits, mainly in LEO, which raises the likelihood of collisions, resulting in the generation of space debris (McClintock et al. 2023).

However, it is expected that state laws regarding the disposal of defunct satellites and the relevant launcher upper stages will be implemented. It would be obligatory for each operator to demonstrate a plan for safely deorbiting their satellites towards designated graveyard orbits at the end of their mission. In addition, operators should have an insurance policy in place to bear the burden of rescue costs in case of mission failure (Sheer & Li 2019b).

2.4 Space Environmental Impact

Sustainable space activities involve the responsible and efficient use of resources while minimizing negative impacts on both Earth and space environments (Durrieu & Nelson 2013). Although space exploration and utilization offer tremendous opportunities, they also present several challenges in terms of sustainability. Some key issues related to sustainable space activities, such as space launches and operations, can have environmental impacts on both Earth and space. Rocket launches produce greenhouse gas emissions, and the disposal of rocket stages can contaminate ecosystems (Sirieys 2022). The placement of satellites in specific orbits can interfere with astronomical observations and hinder scientific research. Sustainable space activities involve minimizing these impacts through cleaner propulsion systems, responsible launch practices, and coordination among stakeholders. Satellite manufacturers and operators should take responsibility for cleaning up space debris. Another challenge in outer-space innovation is balancing this responsibility while advocating international cooperation on issues such as cybersecurity and the growing number of medium-sized satellite constellations (Hassan & Sheer 2024).

Space activities involve numerous countries, organizations, and commercial entities. Sustainable space exploration requires international cooperation to establish common guidelines and frameworks for the responsible and equitable use of space resources, debris mitigation, and environmental protection. Effective governance mechanisms are required to address issues such as space traffic management, resource allocation, and dispute resolution.

As space activities expand, ethical considerations have become increasingly important. These include the preservation of pristine celestial bodies, respect for indigenous rights in space exploration, equitable access to space resources, and the potential militarization of space. Sustainable space activities require addressing these ethical concerns and ensuring responsible and inclusive practices (McClintock 2023).

The United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) describes space sustainability as ensuring the stability and safety of the space environment while keeping space "open for exploration, use, and international cooperation by current and future generations." The sustainability of outer space is essential for forthcoming access and exploitation. Efforts to harmonize rapid advancements in satellite technology with the principles of space sustainability are crucial to ensure the continued exploration and use of space and its preservation as a shared and equitable resource for all nations and future generations (West 2020).

The proliferation of orbital space debris poses a hazard to both ongoing and future space activities. Starlink aims to enhance global broadband access; however, its extensive network of satellites adds complexity to the orbital environment, increasing the risk of collisions and the creation of additional debris. A safe, secure, and peaceful space environment is essential for ensuring continued access to and use of space-based infrastructure (Höyhtyä 2022). The societal benefits of mega-constellations must be balanced with the need to maintain the sustainability of the space domain. The increasing number of satellites and space missions can affect scientific observation and research. Light pollution from satellites can interfere with astronomical observations and affect both professional and amateur astronomers (Varela-Perez 2023). Preserving space as a platform for scientific research is crucial for sustainable space activities, and efforts should be made to minimize interference with scientific observations.

Addressing these issues requires a multifaceted approach involving technological advancements, policy frameworks, international collaboration, and public engagement. By promoting sustainable practices and responsible behavior in space activities, we can ensure the long-term viability and benefits of space exploration and utilization while minimizing the negative impacts on both the Earth and space environments (Carrio 2022).

3. SATELLITE RADIO FREQUENCY AND ORBITAL SLOT DIVISION

All satellites communicate with Earth stations via radio waves. However, the availability of orbital slots and radio frequency spectra is limited. It is estimated that approximately 30,000 tiny satellites will function in LEO. Nevertheless, in addition to environmental considerations, the increasing number of satellites raises the risk of conflicts over frequency bands, which can lead to congestion in space and within specific orbits. This may also lead to a shortage of frequencies available for use. Given that radio frequencies are considered a limited resource, the launch of additional satellites is likely to exacerbate this issue (Exarchou 2023). These challenges are becoming more pronounced with each large-scale constellation launch, and the current resources of ITU are insufficient to fully address them. As stated in Article I of the ITU Constitution, its objectives include fostering and expanding intercontinental support among all member states to guarantee the appropriate use of telecommunications (ITU Constitution 1992; Constitution and Convention of the International Telecommunication Union, 1994).

To improve the effectiveness of telecommunications networks, the ITU also seeks to improve technological infrastructure and its beneficial uses. Furthermore, it collaborates with local, non-governmental, and international organizations to develop a holistic approach to address communication challenges within the global economy and society.

In pursuit of these objectives, the ITU undertakes the task of allocating and regulating radio frequency bands. These goals aim to avert undesirable interference between radio stations across territorial boundaries. For example, one of the resolutions of the ITU states that it should help radio communication by coordinating the usage of various communications and frequencies employed in all services, including those utilized via satellite orbits (Suwijak & Shouping 2021).

3.1 Hazardous Interference

The ITU defines harmful interference as any disturbance that impairs the functionality of radio navigation and other critical safety services or significantly interrupts services that comply with radio regulations. According to ITU Article 45, all radio stations must operate in a manner that prevents harmful interference with the radio services or communications of other member states or any entities authorized to operate in accordance with radio regulations. The ITU identifies unauthorized use of transmitting devices and military operations near conflict zones as the leading causes of such interference.

The integral role of space in supporting the economic, commercial, and military interests of technologically advanced nations makes harmful interference a considerable threat to satellite operations. This risk is further compounded in the context of LEO satellites, which are primarily used for communication and are central to national security (ITU 2020). The escalating reliance on these satellites increases the chances of contested space scenarios, intensifying their vulnerability to harmful interference. Moreover, the advent of mega-constellations and the growing involvement of private satellite ventures introduce additional complexities to national security considerations.

Competition for access to the radio spectrum is increasing. The ITU plays a crucial role in assigning frequencies to communication satellites. However, satellite companies do not directly interact with the ITU or participate in these agreements. Instead, they secure licenses through their national regulatory bodies, which, in turn, submit a general outline of the satellite proposal—including details on the intended frequencies and orbits—to the ITU during the early planning stages, on behalf of satellite companies (Byers & Boley 2023). Moreover, unauthorized access to satellite networks represents a significant national security concern, particularly when it compromises intelligence and surveillance capabilities. Unauthorized access is defined as the unlawful infiltration of satellite networks by state or non-state actors, which allows them to intercept, manipulate, or disrupt the flow of information. This is an espionage risk, as confidential state or commercial data could be compromised, threatening the operational integrity of critical national infrastructure that may depend on satellite systems. The sovereignty of a nation is inherently tied to its ability to control and protect its communication channels and surveillance capabilities.

3.2 Fair Access Principle and Benefit Sharing

The ITU follows the principle of equity, recognizing that every state has a natural right to gain access to space (Copiz 2002). Such provisions are contained in Article 44(2) of the ITU Convention, designated specifically and quite exclusively to the GEO, which is located approximately 35,785 km (22,236 miles) above the equator. However, the prevalent "first come, first served" policy for allotting orbital slots and frequencies has raised concerns. As developing countries strive to launch their satellites using innovative technologies, they may find that the GEO is already saturated (Cappella 2019). In this regard, Article 44 emphasizes the special character of zones such as the GEO, stressing that radio frequencies and satellite orbits are restricted natural wealth, which should be used with reason, effectiveness, and economy.

Therefore, all member states are obliged to control the continuous utilization of these resources, considering the special requirements of developing countries. Furthermore, the principle of equitable access is embedded in the preface to the radio regulations. Remarkably, Article 44, Clause 2 of the ITU Constitution facilitates the conception of equitable access as a prerequisite for the economical and efficient usage of orbits. The same issue has been a concern regarding the growing number of mega satellite constellations in LEO.

3.3 Spectrum Allocation Management

The massive spectrum required for mega-constellations has intensified competition among operators. Due to the ITU "first-come, first-served" policy, spectrum slots are quickly claimed and reserved—often with little thought given to equitable access and coordination. In international orbit/spectrum resource management, the ITU Constitution, Convention, and radio regulations (Radio Regulations 2020), balance them to foresee the rights, responsibilities, and responsibilities of ITU member countries (ITU Constitution 1992). International treaties stipulate fundamental rules leading to fundamental characteristics such as the dispersal of radio frequencies among various radio communication services, fellow nations' entitlement to utilize orbital natural resources, and the global recognition of these benefits and rights.

In the Master International Frequency Register (MIFR), frequency allocations and any linked orbits, such as geostationary satellite orbits that are in use or anticipated to be used, are recorded. These guidelines serve as the cornerstone for the efficient use of orbital resources and the radio frequency spectrum, guaranteeing fair access and efficient international communication (UNOOSA & ITU 2015). A key aspect of ITU radio regulations for satellite services is maintaining non-interference in the operation of satellite networks while enabling the efficient, rational, economic, and justifiable deployment of orbital slots and radio frequency band resources.

Important procedural measures include the notification and fixation of certain radio frequencies in the MIFR, coordination among members, and the advance dissemination of certain information. This radio frequency spectrum enables international cooperation and communication by enabling the effective and efficient management of the radio frequency spectrum. Furthermore, there is a need for the worldwide acceptance of frequency usage, which includes all applications of radio frequencies. For instance, an aspiring satellite organization or non-government agency must check the MIFR before choosing a frequency.

Each administration that intends to launch operations in non-geostationary and geostationary fixed Satellite Services is typically required to submit an application to the ITU within two years of either making or commencing operations within the network. If such frequency allots are not utilized within the designated timeframe, a three-month notice will be issued to the administration concerned, and the ITU will cancel the frequency allocation. In addition, there is an urgent demand for developing a regulatory framework to ease the deployment of small-satellite constellations.

4. REGULATORY AND INSTITUTIONAL FRAMEWORK FOR THE DEPLOYMENT AND OPERATION OF MEGA-CONSTELLATIONS

Currently, no autonomous international authority has the power to supervise, coordinate, or enforce regulations for the deployment and operation of mega-constellations. Existing organizations, such as UNCOPUOS and the ITU, are limited by their mandates and lack enforcement powers, making them inadequate to address these issues. While multiple UN bodies are implicated in various aspects of space activities, many do not effectively safeguard the global public interest. UNCOPUOS operates through two subcommittees, the Scientific and Technical Subcommittee and the Legal Subcommittee, and makes decisions based on consensus among its members. One of its earliest achievements was the creation of a registration form for space objects under General Assembly Resolution 1721 B (XVI) in 1961 (UNOOSA 1721), later pointed out in the 1976 Convention on Registration of Objects Launched into Outer Space.

However, its efficiency has declined over the last few decades because of political tailbacks, raising concerns about its ability to adapt to the evolving landscape of space authority. While UNCOPUOS remains the primary forum for the peaceful exploration and use of outer space, it does not systematically address international legal aspects concerning the deployment and operation of satellite constellations. Although certain elements related to satellite constellations are discussed within specific agenda items of the UNCOPUOS subcommittees, comprehensive items are missing. In particular, the Scientific and Technical Subcommittee continues to address the agenda item “Recent developments in global navigation satellite systems” (UNOOSA 2021b). However, its efficacy is hindered by the rapid pace of technological developments as well as geopolitical tensions among space-faring nations. Failure to agree on binding agreements often results in bureaucratic inertia, which can pause decision-making and delay timely responses to arising risks due to inadequate enforcement mechanisms.

Similarly, the International Committee on Global Navigation Satellite Systems (ICG), founded in 2005, focuses on specific subjects related to global navigation satellite systems. It serves as an informal platform that promotes collaboration regarding concerns about shared interests in civil satellite-based positioning, navigation, timing, and value-added services. The committee also centers on guaranteeing compatibility and interoperability among GNSS systems while advocating their use to support sustainable advancement, particularly in developing countries.

In addition, the ITU is a specialized UN agency that plays a crucial role in managing global satellite operations for internet services by regulating radio frequencies and orbital positions, thus facilitating international dialogue and conflict resolution (ITU Constitution 1992). Nonetheless, the ITU encounters notable challenges owing to its limited enforcement power, lack of regulation on space debris accumulation control, slow responsiveness to new technologies such as LEO satellite networks, and reliance on member states' collaboration. These obstacles, along with a disjointed regulatory environment and the rapid evolution of technology, hinder its ability to effectively oversee satellite communications. For Instance, in the case of SpaceX’s Starlink project, which involves deploying thousands of LEO satellites for global internet services, traditional operators, such as Viasat, have raised concerns about potential interference and collision risks. The ITU regulatory framework has been criticized for its slow response to new technologies and limited enforcement, leaving disputes to be resolved through national regulatory bodies, such as the FCC in the US (Jason 2024).

Despite its strengths, the ITU faces several challenges that limit its effectiveness in addressing rapid technological changes and evolving market dynamics in satellite-based internet services. For instance, in the case of “frequency squatting” or misuse of orbital slots, the ITU can only encourage member states to comply with regulations but cannot directly revoke rights or impose sanctions. In the case of Tonga, the ITU faced criticism for leasing satellite slots to private companies that failed to launch any satellites, leading to disputes over orbital slots. While ITU regulations mandate countries to launch satellites within a specific timeframe, they do not prevent countries from engaging in such practices, leading to the misuse of orbital slots and crowding in certain areas of space. Therefore, its monitoring and enforcement are limited and loopholes in regulations exist (Thompson 1996).

The ITU regulatory frameworks are often slow to adapt to new technologies, such as LEO satellite constellations (e.g., SpaceX’s Starlink and OneWeb). These new technologies require novel approaches for frequency allocation, interference management, and orbital debris mitigation. Traditional ITU processes, which rely on consensus building among member states, may lag behind the pace of technological advancements and deployment of large satellite networks.

It is noteworthy that Asian-Pacific countries have contested ITU allocation. Indonesia not only paid no attention to an ITU allotment and proceeded with the launch of their Palapa Bl satellite into a Tongan slot but also claimed that the ITU Regulatory Board did not have the authority to halt them. In addition, Indonesia's Palapa Satellite Organization, Hong Kong's Asia Satellites, and Thailand's Shinawatra Satellites have all launched satellites into orbital slots allotted to other countries. These incidents highlight the urgent need for a revision of the current allocation mechanism.

The case of Indonesia's Palapa satellite system in the 1970s illustrates the limitations of ITU in enforcing allocation decisions. Indonesia's request for an orbital slot led to disputes with other nations due to concerns about frequency interference. Although the ITU mediated the dispute and proposed technical solutions, its lack of enforcement power prevented it from imposing a binding resolution. The dispute was ultimately resolved through political negotiations outside the ITU framework, where Indonesia adjusted its satellite position to avoid interference. This case highlights the reliance of ITU on voluntary compliance and political processes, which undermines its authority in resolving such disputes (Cahill 2000).

The effectiveness of ITU is highly dependent on the cooperation and goodwill of its member states. Powerful countries or large private operators may choose to bypass ITU regulations or engage in unilateral actions, further undermining the organization's authority. For example, the allocation of spectrum for 5G services has been a contentious issue, with some countries implementing national policies that diverge from ITU recommendations. Additionally, the fixed satellite service (FSS) and broadcasting satellite service (BSS) sectors have a history of disagreements over C-band frequencies.

The ITU attempted to balance the two sectors during the WRC-15 and WRC-19 conferences. However, it faced significant weaknesses, including its inability to impose binding decisions and the influence of political interests. Decisions made at ITU conferences were often manipulated by political considerations rather than technical assessments, leading to outcomes that favored more powerful member states or industries.

To address this, first, national space laws should align with core principles of international space treaties, specifically addressing the unique challenges posed by mega satellite constellations, such as space traffic management and debris mitigation.

Second, the licensing process currently managed by the Space Agency, should be expanded to include detailed requirements for mega-constellations. This could involve mandatory space traffic management plans, collision avoidance measures, and compliance with international debris-mitigation standards. Clear procedures for collision avoidance, coordination with other satellite operators, and real-time tracking of space assets should be ensured. The incorporation of the UN Space Debris Mitigation Guidelines into national space law makes them binding for all satellite operators under a country's jurisdiction.

This policy should include specific design requirements, deorbiting protocols, and active debris-removal initiatives for mega-constellations. Space law can adopt principles from environmental and maritime laws, such as the precautionary principle (requiring comprehensive environmental impact assessments before satellite deployment) and the polluter-pay principle (assigning liabilities for debris creation and incentivizing sustainable practices). Countries can also pursue bilateral and multilateral agreements with other spacefaring nations to coordinate satellite operations, share space situational awareness (SSA) data, and collaborate on debris mitigation and STM initiatives. Countries can develop a code of conduct for satellite operators under their jurisdiction, establishing best practices for safe and sustainable satellite operations, including active debris removal, end-of-life disposal, and real-time data sharing. By adopting a comparative approach to other regulatory frameworks and integrating international principles into national space law, the deployment and operation of mega-constellations can be efficiently controlled.

4.1 Non-Binding Guidelines for the Operation of MSCs and Space Debris Mitigation

In international treaties directing space activities, there are various "soft law" documents that can be applied by both states and space operators. One of the key benefits of these soft law instruments is their flexibility in design and modification, as they do not impose a formal procedure for amendments. The only concern is the adoption of documents endorsed by the UN Committee on the Peaceful Uses of Outer Space, particularly when these documents are approved by consensus. The following documents affect the activities of satellites encompassed in various satellite constellations:

The United Nation General Assembly adopted a resolution suggesting that countries willingly offer more detailed and standardized information about the space objects they launch. This resolution aims to enhance the Registration Convention (1976; Convention on Registration of Objects Launched into Outer Space 1974), which requires states to register their space objects with the UN. The new recommendations and decisions include additional data, such as the date and time of a particular space object being launched, its orbital parameters, and the operational status of space objects, thereby allowing for better identification and tracking of such space objects in orbit (UNGA 2008).

The countries' acceptance of liability in International Direct Television Broadcasting includes the provisions of responsibility, even for the control and management of the satellite orbits in the Indian-Oceanic region. "States are to undertake international responsibility for the activities associated with the satellite international direct television broadcasting which they conduct, or authorize to be conducted, within their jurisdiction" (von der Dunk 2019).

In 2019, UNCOPUOS adopted 21 Guidelines for the Long-Term Sustainability of Outer Space Activities, which address the critical issue of space debris mitigation in both the short and long term (UNOOSA 2019). As non-binding instruments, these guidelines provide a roadmap for space operators and manufacturers to selectively address the foundation for establishing minimum standards in the design of mega-constellations. Over several years, UNCOPUOS has been actively considering certain aspects of outer space activities and their sustainability. The Scientific and Technical Sub-Committee of this body has been working diligently to develop these guidelines, with particular attention to security and operational issues. The main purpose of these international guidelines is to ensure the sustainability of outer space activities, which could be challenged by problems such as the rapid rise of satellite constellations (MSCs), increased collision hazards, and growing space debris. These guidelines are very important and necessary and have gained official endorsement through a resolution aimed at addressing these challenges.

The implementation of these recommendations can further enhance the level of interstate cooperation for the nonaggressive use and utilization of activities in outer space. They apply equally to both governmental and non-governmental entities engaged in space activities. The guidelines have been organized into four sections: 1) It considers the methods for organizing and formulating policies for carrying out space operations; 2) It deals with the provision of safety and security of outer space; 3) It concentrates on comprehension, development, and international interaction; 4) It focuses on innovation in technology and research in science (UNOOSA 2021a).

An important institution facilitating international cooperation on space debris mitigation is the Inter-Agency Debris Coordination Committee (IADC) (IADC Space Debris Mitigation Guidelines 2002), which creates operational documents applicable to all space-related activities aimed at addressing the alarming issue of space debris—whether of natural or artificial origin (Yakovlev 2005). Managing space debris appears to be an important task, given that the guidelines offered by the IADC are not legally binding. The primary objective of these guidelines is to facilitate the coordination of research activities and the dissemination of relevant information among member space agencies, to the end that, debris delimitation approaches will be analyzed and effective transnational efforts aimed at the prevention of abusive practices in outer space will be reinforced. Moreover, the IADC guiding principle was useful to UNCOPUOS, as its recommendations were implemented.

In 2007, UNCOPUOS adopted seven Space Debris Mitigation Guidelines to reduce space debris and ensure sustainable outer space activities (UNCOPUOS 2007). Some of the issues that these guidelines seek to address are unintentional debris generated through normal operations, break-ups and collisions, intact spacecraft without a purpose in LEO and GEO, and the purposeful destruction of spacecraft. The degree of commitment of the states to implement these guidelines varies. Some states have adopted national laws to address this issue, registering laws based on these guidelines (Larsen 2017). Accordingly, these states prohibit the launching of small satellite constellations until it is demonstrated that their operations cause no damage to space vehicles or their components while performing regular operations. In addition, these licenses aim to promote the prohibition of harmful or destructive behaviors in space, constrain post-mission break-ups due to stored energy, and mandate the deorbiting of spacecraft after completing low-Earth missions.

These "voluntary guidelines" are followed informally on a global scale, without any legal sanctions for non-compliance. Such guidelines are, therefore, not fully adhered to by states or private space operators. In addition, because of the absence of a proper framework for enforcement, certain space activities contribute more debris than is acceptable (Mejía-Kaiser 2020).

The Code of Conduct for Space Debris Mitigation is a voluntary, self-regulatory instrument expected to be adopted by the ESA and national space agencies in Europe, along with their contractors. While these standards were established by the ESA, these shortcomings were addressed in relation to additional efforts by the Centre National D'Études Spatiales, which included debris mitigation strategies, safety concerns, and recommendations concerning space debris (Alby 2004).

These standards describe the precautions that must be integrated when designing and using space platforms to eliminate or reduce the chances of producing space debris. It also provides guidance on securing space objects from the danger of space collisions and proposes access methods for carrying out the directives and procedures specified in the standards regarding space operations. European space industries, national space agencies, and all stakeholders involved in the design, construction, launch, exploration, enhancement, program execution, planning, or management of missions, ‘within’ and ‘outside’ Europe, are expected to follow and apply the recommendations aimed at ESA guidance. All spacecraft in orbits around the Earth must abide by the established standards. It is essential for stakeholders to consult the Debris Mitigation Handbook, published by the ESA, before reviewing the directives contained in these guidelines (Wouters et al. 2016).

4.2 Current Space Law Inadequacy for Addressing Challenges

Rapid advancements in satellite technology and mega-constellations have surpassed the development of international space law, which remains fragmented and outdated (Abashidze et al. 2022). The primary legal framework governing these activities is the 1967 OST (OST 1967). This Treaty establishes two key principles for satellite constellations. It serves as the foundational legal framework for space activities but faces significant challenges in addressing the complexities of modern mega-constellations. Article I of the OST states that outer space is free for exploration and use by all states without discrimination. However, this principle does not account for the saturation of Earth's orbits owing to mega-constellations, which may effectively limit access for other satellites and actors, raising concerns about the equitable use of space resources. Article II prohibits any state from claiming sovereignty over outer space or celestial bodies (OST 1967).

This principle aims to prevent exclusive rights in space; however, the deployment of large satellite constellations may lead to the de facto appropriation of orbital slots, hindering other nations' abilities to operate in these regions (Johnson 2020). Article VI mandates that states bear international obligations for national activities in outer space, whether acted upon by governmental or non-governmental entities. This provision emphasizes that states must ensure compliance with the OST's principles; however, the treaty lacks specific enforcement mechanisms to address violations related to mega-constellations.

Article VII addresses the liability for harm triggered by space objects (LC 1972). As the volume of satellites increases, so does the risk of collisions and the resulting debris, which could lead to significant damage to the Earth or in orbit. The OST provides a framework for liability but lacks robust mechanisms for managing the risks associated with increased satellite traffic.

Despite these provisions, OST is often criticized as outdated and insufficient for regulating the rapid growth of commercial space activities and mega-constellations. Its vague language and reliance on principles, rather than binding rules, limit its effectiveness in ensuring sustainable practices in space. It should be amended to include more detailed regulations and binding rules that can adapt to new technologies and operational realities, specifically tailored to manage mega-constellations and their impact on space traffic and debris.

These principles have also led to succeeding treaties, including the 1972 LC, which outlines state liability for damage caused by space objects, and the Registration Convention, which dictates the registration of launched objects and distribution of information to the UN Secretary-General (Registration Convention 1976). While existing treaties grant a foundation, they must be renewed to effectively manage the unique challenges posed by modern satellite technologies.

5. CONCLUSION

In conclusion, the evolution of space law is imperative to keep pace with technological developments and the mounting complications of space activities. A legally binding framework is required to hold satellite producers and operators liable for space debris clean-up, while also endorsing international cooperation on issues such as cybersecurity and the proliferation of medium-sized satellite constellations. By amending existing treaties, establishing a thorough regulatory regime, and incorporating both hard and soft law instruments, we can address the legal and liability challenges posed by these developments. Moreover, substantial modifications in the ITU are critical to boost its execution capacity and efficiently supervise orbital congestion. Establishing an international regulatory body for private satellite governance is also crucial to ensure compliance with global norms and prevent the monopolization of orbital resources. Ultimately, these measures will ensure long-term sustainable manned space operations and protect against exploitative human activities in outer space.

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REFERENCES

Abashidze A, Chernykh I, Mednikova M, Satellite constellations: international legal and technical aspects, Acta Astronaut. 196, 176-185 (2022). https://doi.org/10.1016/j.actaastro.2022.04.019

Abbas S, Apprehensions with regard to commercial space flight: outlook on space law, J. Astron. Space Sci. 41, 235-247 (2024). https://doi.org/10.5140/JASS.2024.41.4.235

Alby F, Alwes D, Anselmo L, Baccini H, Bonnal C, et al. The European space debris safety and mitigation standard, Adv. Space Res. 34, 1260-1263 (2004). https://doi.org/10.1016/j.asr.2003.08.043

Byers M, Boley A, Who owns Outer Space? International Law, Astrophysics, and the Sustainable Development of Space (Cambridge University Press, Cambridge, 2023).

Cahill S, Give me my space: implications for permitting national appropriation of the geostationary orbit, Wis. Int. L. J. 19, 231 (2000).

Cappella M, The principle of equitable access in the age of mega-constellations, vol. 19, in Legal Aspects Around Satellite Constellations, ed. Froehlich A (Springer, Cham, 2019), 11-23.

Carrio L, Edwards CM, Marcinkowski A, Cichan T, Understanding sustainability in the human exploration campaign, Proceedings of the 2022 IEEE Aerospace Conference (AERO), Big Sky, MT, 5-12 Mar 2022.

Christol CQ, International liability for damage caused by space objects, Am. J. Int. Law. 74, 346-371 (1980). https://doi.org/10.2307/2201505

Chyba CF, New technologies & strategic stability, Daedalus. 149, 150-170 (2020). https://doi.org/10.1162/daed_a_01795

Constitution and Convention of the International Telecommunication Union, 1825 U.N.T.S. 331/1825 U.N.T.S. 390, adopted on 22 December 1992, entered into force on 1 July 1994.

Convention on International Liability for Damage Caused by Space Objects (1971) [Internet], viewed 2024 Feb 20, available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html

Convention on Registration of Objects Launched into Outer Space (1974) [Internet], viewed 2024 Feb 20, available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html

Copiz A, Scarcity in space: the international regulation of satellites, CommLaw Conspec. 10, 207-226 (2002).

Crisp NH, Roberts PCE, Livadiotti S, Oiko VTA, Edmondson S, et al., The benefits of very low earth orbit for earth observation missions, Prog. Aerosp. Sci. 117, 100619 (2020). https://doi.org/10.1016/j.paerosci.2020.100619

Dornik M, Smith M, Small satellite industry and legal perspectives in the United States, in Small Satellites, ed. Marboe I (Brill Nijhoff, Leiden, 2016), 67-82.

Durrieu S, Nelson RF, Earth observation from space: the issue of environmental sustainability, Space Policy. 29, 238-250 (2013). https://doi.org/10.1016/j.spacepol.2013.07.003

Exarchou E, Allocation of the radio-frequency spectrum and satellite orbits: jurisprudential perspectives, EUI, LAW, AEL, Work. Pap. 3 (2023).

Federal Aviation Administration (FAA), Report to congress: risk associated with reentry disposal of satellites from proposed large, Public Law No. 116-260 (2023).

Foreman VL, Siddiqi A, de Weck O, Large Satellite Constellation Orbital Debris Impacts: Case Studies of Oneweb and Spacex Proposals (AIAA SPACE and Astronautics Forum and Exposition, Orlando, 2017).

Grotch SE, Mega-constellations: disrupting the space legal order, Emory Int. Law Rev. 37, 101 (2022).

Handley M, Using ground relays for low-latency wide-area routing in megaconstellations, Proceedings of the 18th ACM Workshop on Hot Topics in Networks, New York, NY, 13 Nov 2019.

Hassan A, Sheer A, Cybersecurity challenges in outer space: innovation, collaboration and legal reforms, J. East Asia Int. Law. 17, 405-422 (2024). https://doi.org/10.14330/jeail.2024.17.2.08

Henry C, Amazon planning 3,236-satellite constellation for internet connectivity (2019) [Internet], viewed 2024 Oct 28, available from: https://spacenews.com/amazon-planning-3236-satellite-constellation-for-internet-connectivity/

Höyhtyä M, Boumard S, Yastrebova A, Järvensivu P, Kiviranta M, et al., Sustainable satellite communications in the 6G era: a European view for multilayer systems and space safety, IEEE Access. 10, 99973-100005 (2022). https://doi.org/10.1109/ACCESS.2022.3206862

IADC Space Debris Mitigation Guidelines (2002) [Internet], viewed 2025 Jan 20, Available from: www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf

ITU-R, Handbook on Small Satellites 2023 edition (International Telecommunication Union, Geneva, Switzerland, 2023).

Jakhu RS, Iridium-Cosmos collision and its implications for space operations, in Yearbook on Space Policy 2008/2009: Setting New Trends, eds. Schrogl KU, Rathgeber W, Baranes B, Venet C (Springer Vienna, Vienna, 2010), 254-275.

Jason R, Viasat seeking LEO capacity for all mobile broadband service (2024) [Internet], viewed 2024 Oct 28, available from: https://spacenews.com/viasat-seeking-leo-capacity-for-all-mobile-broadband-services/

Johnson CD, The legal status of megaleo constellations and concerns about appropriation of large swaths of Earth orbit, in Handbook of Small Satellites: Technology, Design, Manufacture, Applications, Economics and Regulation, eds. Pelton JN, Madry S (Springer, Cham, 2020), 1337-1358.

Kessler DJ, Johnson NL, Liou JC, Matney M, The Kessler syndrome: implications to future space operations, Adv. Astronaut. Sci. 137, 1-15 (2010).

Larsen PB, Small satellite legal issues, J. Air L. Com. 82, 275 (2017).

Lin M, Jin M, Li J, Bai Y, GEOSatDB: global civil earth observation satellite semantic database, Big Earth Data. 8, 522-539 (2024). https://doi.org/10.1080/20964471.2024.2331992

Marboe I, Mosteshar S, Authorisation of small satellites under national space legislation, in Small Satellites: Regulatory Challenges and Chances, ed. Marboe I (Brill Nijhoff, Leiden, 2016), 129-153.

McClintock B, International Space Traffic Management: Charting a Course for Long-Term Sustainability (Rand Corporation, Santa Monica, 2023).

McClintock B, Ligor DC, McCormick D, Herron M, Jukneviciute K, et al. The Time for International Space Traffic Management is Now (Rand Corporation, Santa Monica, 2023).

McDowell J, Jonathan's space pages (2023) [Internet], viewed 2024 Oct 30, available from: https://planet4589.org/space/con/conlist.html

Mejía-Kaiser M, Space debris mitigation guidelines of the committee on the peaceful uses of outer space, United Nations, in The Geostationary Ring, ed. Mejía-Kaiser M (Brill Nijhoff, Leiden, 2020), 390-394.

Morssink M, An equitable and efficient use of outer space and its resources and the role of the UN, the ITU and states parties, in Legal Aspects Around Satellite Constellations: Studies in Space Policy, ed. Froehlich A (Springer, Cham, 2019), 1-10.

Nair KK, Small Satellites and Sustainable Development: Solutions in International Space Law (Springer, Cham, 2019).

National Aeronautics and Space Administration (NASA), National Science Foundation, Letter to FCC Regarding Starlink Gen 2 (NASA, Washington, 2022).

Pelton JN, Madry S, Handbook of Small Satellites: Technology, Design, Manufacture, Applications, Economics and Regulation (Springer, Cham, 2020).

Radio Regulations (2020) [Internet], viewed 2024 Nov 15, Edition 442, available from: https://www.itu.int/pub/R-REG-RR/en

Ravishankar C, Gopal R, BenAmmar N, Zakaria G, Huang X, Next-generation global satellite system with mega-constellations, Int. J. Satell. Commun. Netw. 39, 6-28 (2020). https://doi.org/10.1002/sat.1351

Schrogl KU, Jorgenson C, Robinson J, Soucek A, Space Traffic Management: Towards a Roadmap for Implementation (International Academy of Astronautics, Paris, 2018).

Sheer A, Fatima S, Farooqui MO, Kasuri MR, A panacea to address the legal, administrative and economic aspects of space debris, Adv. Space Res. 72, 2616-2626 (2023). https://doi.org/10.1016/j.asr.2023.02.023

Sheer A, Li S, Space debris: a new broadway to address organizational and operational aspects for removal, J. East Asia Int. Law. 12, 269 (2019a). https://doi.org/10.14330/jeail.2019.12.2.02

Sheer A, Li S, Space debris mounting global menace legal issues pertaining to space debris removal: ought to revamp existing space law regime, Beijing Law Rev. 10, 423-440 (2019b). https://doi.org/10.4236/blr.2019.103025

Sirieys E, Environmental impact of space launches and societal response, PhD Dissertation, Massachusetts Institute of Technology (2022).

Sullivan W, Course recorded: navy picks up radio signals -4 report sighting device (1957) [Internet], viewed 2024 Oct 5, available from https://archive.nytimes.com/www.nytimes.com/partners/aol/special/sputnik/sput-02.html

Suwijak C, Shouping L, Legal challenges to the construction and operation of small satellite constellations, J. East Asia Int. Law. 14, 131 (2021). https://doi.org/10.14330/jeail.2021.14.1.07

Thompson JC, Space for rent: the international telecommunications union, space law and orbit/spectrum leasing, J. Air L. Com. 62, 279-281 (1996).

UNCOPUOS (2007) Space debris mitigation guidelines [Internet], viewed 2024 Dec 13, available from: http://www.unoosa.org/pdf/publications/st_space_49E.pdf

United Nations (UN), Treaty on principles governing the activities of states in the exploration and use of outer space, including the Moon and other celestial bodies (1966) [Internet], viewed 2024 Jan 25, available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

United Nation General Assembly (UNGA), Recommendations on enhancing the practice of States and international intergovernmental organizations in registering space objects (2008), [Internet], viewed 2025 Jan 20, available from: https://www.unoosa.org/pdf/gares/ARES_62_101E.pdf

United Nations Office for Outer Space Affairs (UNOOSA), General assembly resolution 1721 B (XVI): International co-operation in the peaceful uses of outer space (1976), [Internet], viewed 2024 Dec 20, available from: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/

resolutions/res_16_1721.html

United Nations Office for Outer Space Affairs (UNOOSA), Online Index of Objects Launched into Outer Space (2021a) [Internet], viewed 2024 Dec 20, available from: https://www.unoosa.org/oosa/en/spaceobjectregister/index.html

United Nations Office for Outer Space Affairs (UNOOSA), Report of the Committee on the Peaceful Uses of Outer Space: Appendix II/UN Document A/74/20, 62nd ed. (UN, New York, 2019).

United Nations Office for Outer Space Affairs (UNOOSA), Report of the Scientific and Technical Subcommittee on its Fifty-Eighth Session, Held in Vienna from 19 to 30 April 2021: UN Document A/AC.105/1240 (UNOOSA, Vienna, 2021b).

United Nations Office for Outer Space Affairs (UNOOSA), International Telecommunication Union (ITU), Guidance on Space Object Registration and Frequency Management for Small and Very Small Satellites (UNOOSA, Vienna, 2015).

Varela-Perez AM, The increasing effects of light pollution on professional and amateur astronomy, Science. 380, 1136-1140 (2023). https://doi.org/10.1126/science.adg0269

von der Dunk F, Oxford research encyclopedia of planetary science (2019) [Internet], viewed 2024 Oct 10, available from: https://oxfordre.com/planetaryscience/view/10.1093/acrefore/9780190647926.001.0001/acrefore-9780190647926-e-39

West JL, Space security cooperation: changing dynamics, in Handbook of Space Security: Policies, Applications and Programs, ed. Schrogl KU (Springer, Cham, 2020), 145-162.

Wittig M, Internet access for everybody: the satellite solution, Acta Astronaut. 64, 222-229 (2009). https://doi.org/10.1016/j.actaastro.2008.07.012

Wouters J, de Man P, Hansen R, Space debris remediation, its regulation and the role of Europe, Eur. J. Law Reform. 18, 66 (2016). https://doi.org/10.5553/EJLR/138723702016018001005

Yakovlev M, The “IADC space debris mitigation guidelines” and supporting documents, Proceedings of the 4th European Conference on Space Debris, Darmstadt, Germany, 18-20 Aug 2005.