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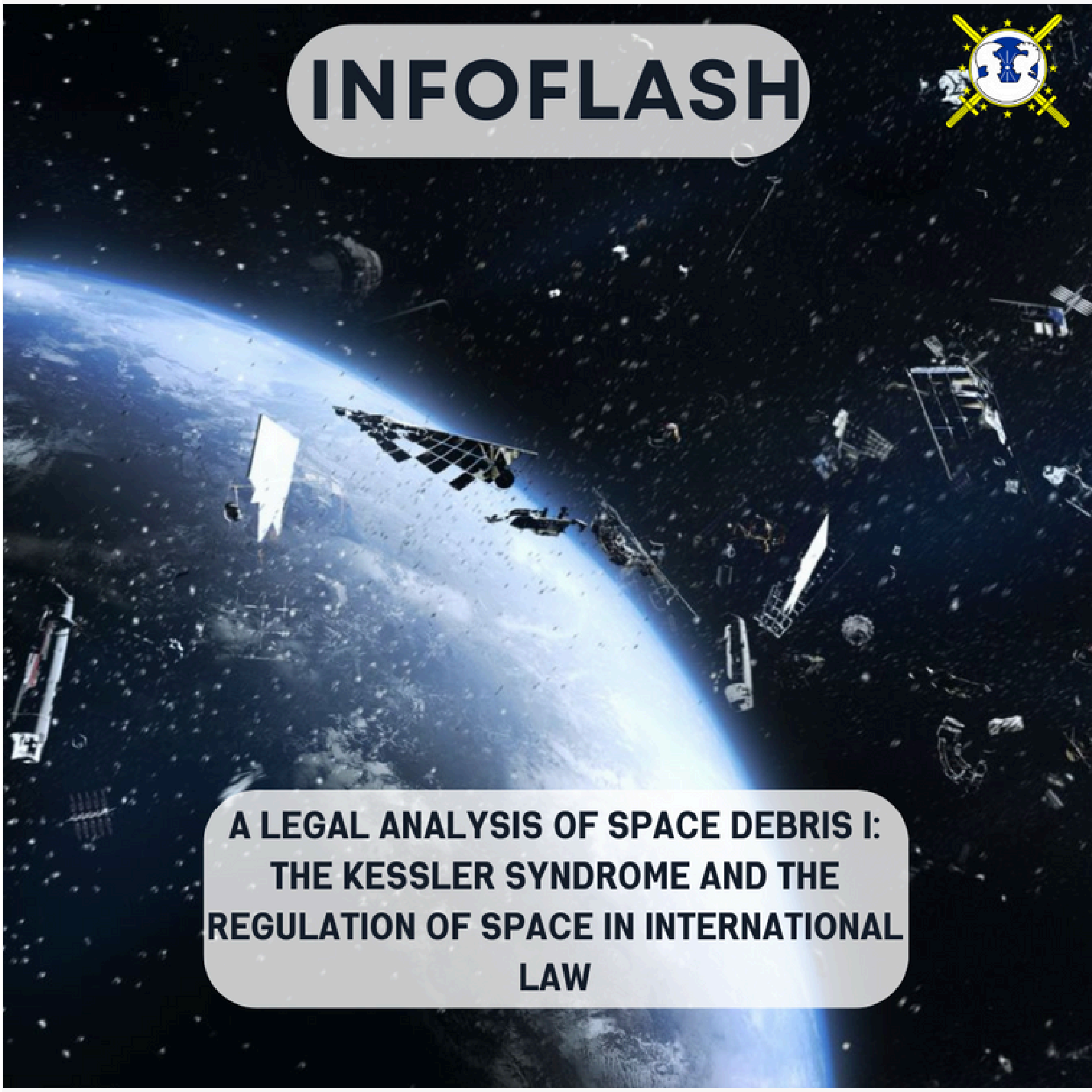

WRITTEN BY
JAIME TORAL GARCÍA

EDITED BY
BENJAMIN ROBITAILLE

SUPERVISED BY
NELLIE BYLUND

Introduction

Since the beginning of the Space Age in 1957, almost 7,000 rockets have been successfully launched, placing more than 20,000 satellites in Earth's orbit. According to the European Space Agency (ESA), only around 11,000 of those satellites are still functioning. Although approximately 33% of the launched satellites are no longer in space, the total mass of all space objects orbiting the Earth is over 13,500 tonnes, 2,000 tonnes more than in December 2023 (ESA, 2025). This mass of non-functional, artificial objects in Earth's orbit or re-entering the atmosphere, including fragments and elements thereof, is defined as space debris (UNOOSA, 2010).

The proliferation of space debris could trigger a serious threat to space activities and assets: this is known as the Kessler Syndrome. Although it will be explored later on, the Kessler Syndrome can be defined as a cascading effect of space debris colliding with space assets that would potentially hinder spacecrafts´ access to space. This paper constitutes the first of a series of three articles analysing the space debris threat and the Kessler Syndrome risk from a legal perspective. The purpose of this first part is to explore the phenomenon of space debris, its causes, evolution and risks, and analyse the international legal framework applicable to space debris. The second part will focus on the weaponisation of space and the weaponisation of space debris from a legal perspective. Finally, the third part will explore the different relevant international guidelines, instruments and operations to mitigate and eliminate space debris from Earth's orbit, with particular attention given to the role, approach and instruments of the European Union.

Hence, this paper will address the study of space debris, attending to its regulation in International Law. Firstly, this paper will analyse the overall era of space exploration and activities, the conceptualisation of space debris and the Kessler Syndrome. Secondly, it will explore the regulation of space debris and space weaponisation in International Law.

2. Framing the Space Debris Challenge

The Space 4.0 era's characteristics and challenges

Bohlmann and Petrovici (2019) identify four different eras since the beginning of space activities sixty years ago. According to the authors, the first one refers to the discovery of the celestial bodies' movements and mechanics, the second one encapsulates the competition era during the Cold War marked by the launching of the first satellites and the creation of the first legal framework, while the third one was characterised by international cooperation (Bohlmann & Petrovici, 2019). The authors stress that the current Space 4.0 era reflects the concept of Industry 4.0 driven by contemporary automation, manufacturing technologies and big data, with innovation as its core element. Furthermore, Bohlmann & Petrovici (2019) also associate the increasing relevance of the space sector for both industry and society to its use of interconnections with other technology fields and innovative mechanisms. These interconnections are further implemented for improving spacecraft manufacturing and advanced general-use technologies for space missions.

This new industrial model has opened the gates to space activities for many new actors and entities. Consequently, the number of actors involved in space activities and launching objects into space is higher than ever, from the inclusion of relatively smaller nations' governments — Argentina, Australia, Turkey or Singapore — to private investors. A second effect of this new situation is the exponential increase of objects in Earth's orbit, both functional and non-functional. In this context, business models based on creating mega-constellations of small satellites like SpaceX exacerbate this problem (Bohlmann & Petrovici, 2019), which could pose great risks for space activities and assets, as this paper will address below.

Space debris proliferation and the Kessler Syndrome

The increasing amount of objects in orbit multiplies the probability of anomalous events such as collisions, break-ups or explosions, which will inevitably lead to fragmentation and the subsequent spread of hundreds or thousands of fragments across Earth's orbit.

The ESA's Space Environment Statistics in February 2025 (ESA, 2025) reveal the presence of more than 40,000 objects bigger than ten centimetres, over a million objects between one and ten centimetres and more than 130 million fragments from one millimetre to one centimetre. As repeatedly stated in many studios, the smaller fragments could disable spacecraft or destroy sensitive components, whereas the larger fragments could utterly destroy spacecraft creating hundreds or thousands of new fragments in orbit (IADC, 2025).

The aforementioned collisions between space objects would produce more fragments moving at a high speed in orbit, each of which would increase the probability of further collisions. This potential domino effect of collisions, multiplying the number of fragments in orbit and forming a debris belt around the Earth, is known as the Kessler Syndrome. Its name comes from Donald Kessler, who laid out the basic idea in his study "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt" in 1978 (Wall, 2022). The study predicted that satellite collisions would become a source of space debris in the XXI century and pose a bigger threat to spacecraft and space assets than meteoroids (Kessler & Cour Palais, 1978). Furthermore, as Bechlová, Harašta and Kasl (2024) state, in the potential scenario where the accumulation of space debris reaches a critical mass, the access of spacecraft to space and the satellites' operational capability would be seriously compromised. This scenario would have catastrophic consequences for space exploration and space-related services, like the Internet, telecommunications and the global navigation satellite system (Bechlová, Harašta and Kasl, 2024), but also in the field of security and defence.

In addition to the collision with space debris, the notion of the weaponisation of space has emerged as a threat with collateral consequences for the proliferation of space debris in recent years. From the use of Anti-Satellite Weapons (ASAT) to the weaponisation of space debris through the manipulation of its trajectory, the weaponisation of space poses a threat to space-based assets and a risk of triggering the Kessler Syndrome. However, achieving an agreement among major powers has been impossible thus far, as even defining space weapons poses a complex challenge. Regardless of the lack of definition, there are clear threats to space assets, such as ASATs, which can be divided into those that use kinetic energy to collide with satellites and the non-kinetic types, which rely on cyberattacks, jamming or even blinding satellites with lasers (Smith, 2022). Countries like the USA, China, Russia, and India have destroyed their own satellites during ASAT testing, creating thousands of pieces of debris with each incident. So far, the USA is the only country to announce its plan to ban ASAT tests against satellites (Erwin, 2022). However, the implementation of this measure and its continuity under different administrations remains unclear.

Bechlová, Harašta and Kasl (2024) exemplified these above-mentioned risks and threats pointing out two notable and distinct cases. First, China's ASAT test on an old weather satellite — Fengyun-1C — in 2007 resulted in the creation of more than 2,600 pieces bigger than ten centimetres and over 100,000 in total. Second, the collision of a Russian satellite (Cosmos 2251) and a US (Iridium 33) satellite in 2009 created more than 2.000 sizable fragments and numerous untraceable ones that remained in orbit for years (Bechlová, Harašta and Kasl, 2024).

To conclude, industrial and technological evolution has led to an increase in the number of actors capable of launching objects into space, as well as the deployment of mega-constellations in the Low Earth Orbit by private companies such as SpaceX. The increasing number of objects in orbit amplifies the risk of collisions and, consequently, the potential for triggering the Kessler Syndrome. Additionally, ASAT systems and other dual-use technologies pose a threat to space assets. In the following chapter, this paper will explore the international law applicable to space debris and the flaws and gaps it presents to adequately address the new challenges of the new space era.

3. The regulation of space in International Law and the International Law applicable to Space Debris

During the Cold War, five multilateral treaties were concluded: the Outer Space Treaty (OST), the Rescue and Return Agreement, the Liability Convention (LC), the Registration Convention (RC), and the Moon Agreement.

Complemented by the Registration Convention, the OST and the Liability Convention contain the main provisions applicable to space debris. Article VII of the OST (UNOOSA, 1967) and Article I of the LC (UNOOSA, 1972) establish the responsibility and jurisdiction of the launching State over any space object that launches or procures the launching, also of those from whose territory or facility it has been launched. Furthermore, the OST clearly states in Article IX that State Parties shall avoid harmful contamination when conducting their studies and exploration of outer space. Although this provision may seem clear, the concepts of responsibility and liability present multiple challenges when addressing the potential triggering of the Kessler Syndrome. In Article VI, the OST establishes that State Parties are responsible for the national activities of both government and non-government entities (UNOOSA, 1967). Furthermore, Article III LC makes the launching State liable to pay compensation for damage caused to a space object in outer space if the damage is due to its fault or the fault of a person for whom it is responsible (UNOOSA, 1972). However, these provisions present several flaws in addressing current scenarios, particularly those related to space debris weaponisation. Firstly, the treaties couldn't foresee the role of private companies in space activities and thus laid all the responsibility on the launching States. Secondly, the liability regime doesn't include private actors and presents difficulties in proving the fault necessary for liability, as well as in addressing the intentionality of the damage and the ownership of the fragments responsible for the damage.

The responsibility of States and the role of private actors in space activities and exploration

As discussed above, the OST and LC unequivocally assert that a launching State is responsible for the activities of non-governmental entities as well as for the space objects registered and launched from its territory or facilities and the space debris originating from them. In addition, according to Article VIII OST, a State Party which registers an object launched into space will retain jurisdiction and control over such object, and that jurisdiction will not be affected by its location in outer space or return to Earth (UNOOSA, 1967). The Treaty does not define any temporal or spatial limit, which implies that the State will retain jurisdiction over the object — and its fragments — indefinitely. Hence, space law also holds states responsible for the space objects launched by licensed private companies from their territory indefinitely, including their space debris. The obvious consequence of this situation would be that the state holds full responsibility for the damage or the destruction of another state's space assets, regardless of whether the act is unintentional or constitutes a wrongful act. Furthermore, Bechlová et al. (2024) point out that, due to the non-transferable nature of the registry and the unlimited temporal responsibility over space objects, states could be held responsible for the damage caused to space debris if they act out of their jurisdiction. For instance, in case of an unintentional collision between a space object ,or a fragment of it, owned by a private actor and a space asset from another State Party to the treaties — which has not yet taken place —, the launching State would be liable to pay compensation for the damage. As Bechlová et al. (2024) illustrate, although some states have national legislation foreseeing this scenario and holding these companies accountable, the State would be targeted by international sanctions. Accordingly, Ziemblicki and Oralova (2021) connect the absence of international regulation on the liability of private actors with the adoption of national laws covering this area.

Ziemblicki and Oralova (2021) exemplify the need for international regulation of liability for damages caused by private actors with the case of Swarm Technologies. The American company had its application for a license to launch four small-size satellites (10 cm3) rejected in the US due to the difficulty of tracking them with the current space debris radars, increasing the risk of collisions (Ziemblicki & Oralova, 2021). However, the company got a contract with the Indian company Antrix to launch their four satellites through an Indian rocket. The US rejected any liability, considering that according to the OST, India was the launching State. As India also rejected any responsibility, the authors note that the current space law regime is incapable of solving a disagreement in which two states interpret Articles VI and VII of the OST differently (Ziemblicki & Oralova, 2021).

To conclude, since these treaties were developed by states in the '60s and the '70s, an era where the costs of space activities were extremely high for any actor other than states, the legal framework has been outpaced by current industrial and technological developments. As previously stated, the Space 4.0 era is characterised by the emergence of private actors in the industrial aspect and the privatisation and commercialisation of space activities (Bohlmann & Petrovici, 2019). Therefore, many academics and stakeholders are calling for an update of the outdated space legislation to include private actors and commercial activities and an update to the liability regime to hold them accountable (Bechlová et al. 2024; Bohlmann & Petrovici, 2019; Ziemblicki & Oralova, 2021).

The fault-based liability regime and the difficulties in proving the fault, the intention to damage and the ownership of the fragments

To address this flaw in the international regulatory framework of space, it is worth clarifying that the distinction between responsibility and liability in the English version of the Treaties is not present in other versions, thus leading scholars to conclude that the wording difference is not relevant (Ziemblicki & Oralova, 2021).

The liability regime lays on two principles stated in articles II and III of the LC: absolute liability and fault-based liability. However, this fault-based principle faces several difficulties in its application. First, the LC doesn't provide a definition of fault, relying on the principle of fault in international law which establishes fault as "any act or inaction that violates an obligation (duty)" (Jakhu, 2009). Second, due to limitations in space situational awareness (SSA) and forensic capabilities, the determination of the causes behind satellite malfunction or destruction is challenging, making it even more difficult to prove responsibility for such incidents (Blazejewski, 2008). Furthermore, in cases when a small fragment of space debris causes damage to an in-space asset, determining the ownership or the country of registration of the object can be extremely challenging. This is further complicated by the potential scenario of a domino effect of collisions like the Kessler Syndrome. Further still, Article VI LC establishes liability exoneration when the damage results from gross negligence or an act or omission due to cause damage on the part of a claimant State or of natural or juridical persons it represents. In addition to the difficulty in determining the fault and the lack of SSA and forensic capabilities, proving the intention to cause damage would be even more problematic due to the dual-use capacity of many space technologies (Blazejewski, 2008). For instance, Bechlová et al. (2024) foresee a scenario where malicious actors take advantage of the difficulty of attributing cyber ASATs to the correct entities. The intentional use of space debris to target satellites will be addressed in the second part of this series of papers.

Third, the LC has proven insufficient in addressing third-party liability issues and dispute settlement, leading states to conclude bilateral agreements for space projects that include private actors (Ziemblicki & Oralova, 2021). As a result, the only time the LC was invoked to solve a dispute was over the 1978 dispute regarding the crash of a Soviet satellite in Canadian territory, where the parties settled the case themselves (Ziemblicki & Oralova, 2021). In another famous case like the Cosmos-Iridium collision in 2009, the weak legal positions of both countries — Russia didn't have the right to abandon its non-functional satellite, and the US was responsible as the launching State for its inability to prevent the collision and for not registering the Iridium 33 private satellite in the UN registry — led them to solve the case through a mutual understanding (Jakhu, 2009).

In conclusion, the OST and the LC are inadequate for addressing commercial activities in space, the role and liability of private actors, and dispute settlement. Thus, it is necessary to update the obsolete regulations to match the characteristics of the new space era.

Conclusion

The rapid evolution of industrial models applied to space technologies has opened the door to space exploration and activities for smaller states and private actors. This proliferation of actors and the improved access to launching objects into Earth's orbit has multiplied the amount of functional and non-functional objects in space, increasing the amount of space debris and the risk of triggering the Kessler Syndrome. Consequently, the international space regulation concluded in the '60s and '70s is now obsolete and does not address critical aspects of the new era, such as the commercial activities in space, the liability regime for private actors and dispute settlement.

This article has explored the phenomenon of space debris, its evolution throughout the last decades, as well as its main causes and risks, briefly introducing the risk of space weaponisation for the proliferation of space debris. Accordingly, this paper has also explained the potential scenario of the Kessler Syndrome, which could hinder space exploration and the survival of key space assets for telecommunications, the global navigation satellite system, the fight against climate change and even the fields of security and defence.

This paper has also analysed the main gaps in international space law related to space debris specifically found in the Outer Space Treaty and the Liability Convention. This analysis reveals an outdated regulation that doesn't include key aspects of space activities relevant to cases involving space debris creation or collisions with space debris. Namely, commercial activities in space, the liability regime for private actors and dispute settlement. In the next part of this series, the analysis will focus on the threat of space weaponisation as a potential trigger of the Kessler Syndrome, as well as the main legal gaps and challenges in the regulation of space weaponisation and arms control regimes.

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