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Orbital Battlefields: A Proposal for Debris Mitigation Strategies in Space Conflict

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About the Author

Victor Freiherr von Suesskind has been an alumnus of Kings College London since 2023. At King's, Victor graduated in science and international security. Before, he obtained a bachelor's in aerospace engineering at Kingston University. Victor is a reserve officer in the German armed forces. Trained in the newly founded German space command, he has gained valuable insight and connections in the emerging space economy. In March 2023, Victor founded Planetfall Ltd – a UK aerospace start-up that develops balloon-based high-altitude payload delivery systems. At the same time, he has pursued a second master's in Space resources from the Colorado School of Mines in the US. Victor's research interests range from the uses of UAVs in today's battlefields to the utilisation possibilities of the distant asteroid fields of our solar system. He is interested in future cube sat utilisations for defence and probing of celestial bodies.

Abstract

As space militarisation intensifies, responsible strategies for mitigating debris from potential space conflicts become imperative. This article examines and compares distinct approaches, weighing pragmatic near-term solutions using existing frameworks versus ambitious long-term strategies needing new mechanisms. Analysing different strategies reveals trade-offs in feasibility, cost, and comprehensiveness. Immediate solutions demonstrate near-term viability but may lack long-term sustainability due to high cost and or complexity. Comprehensive long-term strategies promise enduring impact and protection but face adoption obstacles. A balanced pathway fusing fast, necessary, and practical approaches is recommended, adopting pragmatic guidelines initially while gradually implementing a proposed Space Preservation Fund. This holistic approach encompasses risk identification, fail-safe incentives, advanced tracking, and responsive debris removal. It tackles immediate concerns while enabling sustainable space management with open-source and public funding. Additionally, multilateral cooperation is emphasised as essential to curb existing and upcoming threats, like anti-satellite weapons, and ensure the peaceful preservation of space through collective stewardship. Past successful collaboration in space safety and deconflicting provides models for joint action on this pressing global challenge.

Space Operations as an Outcome of History

In contemporary military operations, space has evolved from a benign realm into a strategic battleground. Satellites, a groundbreaking advancement in communication, navigation, intelligence, and early warning systems, are now pivotal components called the "central nervous system of the Information Age".[1] Military strategies increasingly emphasise denying adversaries access to space, driving the development of anti-satellite weaponry to prevent the loss of communications and protect warning networks.[2] The importance of space systems in military endeavours is paramount; their potential loss would severely compromise almost all military functions of a modern network-connected military complex.[3] NATO and other defence alliances depend on their critical communications infrastructure for space-based assets. Thus, ensuring comprehensive space situational awareness has emerged as a critical factor in military space operations.[4] As human geopolitical competition short of physical conflict extends into space, bridging international legal frameworks to define justifiable and proportional responses becomes a pressing demand.[5] This necessitates harmonising space law with international humanitarian law.[6] Establishing legal doctrines and manuals guiding space-based military operations is pivotal in avoiding misinterpretations and escalations.[7] In an era where space is increasingly contested, nations must delineate clear objectives, mission and asset termination criteria, and mechanisms for controlling escalation in any military operations conducted in space.[8]

> "Anti-satellite weapons could trigger a domino effect of high-velocity debris

The escalating significance of space exploration and satellite systems heightens the potential for conflicts to spill into space, potentially resulting in a drastic surge in space debris.[9] The deployment of anti-satellite weapons could trigger a domino effect of high-velocity debris, commonly known as the Kessler syndrome.[10] This could encircle Earth with an impenetrable debris field, disrupting access to critical orbits.[11] Such an outcome poses a significant risk to the sustained functionality of space operations and contradicts the principles of preserving space for peaceful purposes. Thus, a cautious approach to impending militarisation is vital to safeguard the integrity of space.[12] An expansion of international law becomes imperative to address the ramifications of potential space warfare, including managing space debris.[13] Recognising space's collective nature necessitates a global commitment to its preservation for the prosperity of future generations, a problematic commitment for many countries to accept and act to.

Amidst the growing militarisation and commercialisation of space, the need for responsible debris mitigation strategies is paramount and should present the lowest common denominator. These strategies should encompass regulatory, technical, and diplomatic dimensions to prevent weaponisation, mitigate debris proliferation, facilitate removal, and promote transparency and collaboration among space-faring nations. This pursuit is pivotal in safeguarding outer space as a global common and preventing irreversible damage.

This article first explores the complexities of modern space warfare doctrines and the impacts of advancing technologies and asymmetric threats. It then examines space debris' sources, risks, and distribution across different orbital regimes in logical order. Potential space conflicts' legal, ethical, and policy dimensions are analysed, including gaps in existing frameworks. To address debris concerns, the article proposes establishing conflict boundaries in space and evaluates five conceptual mitigation strategies based on criteria like technological feasibility, implementation difficulty, and effectiveness. It concludes by recommending pragmatic near-term approaches while advocating for the gradual development of a so-called Space Preservation Fund for comprehensive long-term debris prevention and remediation through international cooperation. Insights are offered on the critical role collaboration must play in ensuring humanity's continued peaceful and sustainable access to space amidst rising geopolitical tensions and new technological advancements.

Navigating the Complexities of Modern Space Warfare Doctrines

For a conceptual understanding of space and its warfare possibilities, this article sees space power doctrines as significant in understanding and mitigating future space debris creation and in-orbit conjunctions. Space warfare, often analogised with land, air, and maritime strategies, requires a distinct perspective for its unique domain. In invoking Clausewitz's timeless argument that war is the continuation of politics through different means, Bleddyn E. Bowen characterises space power as the "continuation of Terran politics by other means".[14] Among these metaphors, the maritime analogy stands out as the closest to the space domain. John Klein, a notable US Navy commander delving into space warfare, argues against mirroring Mahan's noteworthy command of sea lanes, advocating for Sir Julian Corbett's decisive engagements and control of communication lines for a space strategy.[15] However, Bleddyn E. Bowen counterpoints, suggesting Mahan's broader economic and bureaucratic view aligns better with the required holistic approach for space power strategy.[16]

Both Klein and Bowen concur that existing frameworks must more adequately encapsulate the necessary elements for a potential space warfare strategy. This underscores the transitional nature of space, where satellites navigate orbital "sea lanes." Yet, unlike maritime chokepoints, the intricate physics of orbital mechanics render persistent space control considerably more intricate than governing fixed seas.[17] This is an essential point of understanding to render future space mitigation strategies able to compensate for as many military operations as possible.

Moreover, concentrating space forces for decisive actions face challenges due to space's vastness and satellite manoeuvrability.[18] Nevertheless, within most maritime-oriented concepts, space is likened to a sea or coastal region in tandem with terrestrial politics.[19]

The airpower metaphor also finds resonance, portraying satellites as the "eyes and ears" akin to airborne ISR platforms. Klein advocates for a space strategy mirroring Douhet's command of the air doctrine,[20] suggesting that all space-bound objects are, to some extent, subservient to airpower theory.[21] However, this metaphor overemphasises the significance of space forces in terrestrial conflicts. Satellites primarily serve as supporting entities rather than autonomous war-winning capabilities akin to strategic bombing or air superiority fighters in airpower theory.[22] While satellites indirectly influence battlefields, they lack the immediate intervention capability seen in airborne engagements on the ground or sea. Moreover, adjusting satellite orbits or repositioning constellations to adapt to evolving conflict dynamics is a time-consuming endeavour, unlike the swift responsiveness of airborne assets.[23]

> "Orbital mechanics limit sustained control of key orbital areas

Additionally, constrained access due to high launch costs and payload limitations hinders the massing of space forces for decisive effects as advocated in airpower theory.[24] The land power metaphor underscores space forces' infrastructural nature, likening satellites to logistical bases rather than direct combat platforms. This aligns with their supportive role in terrestrial forces. However, unlike labour-intensive terrestrial bases, the land power metaphor underestimates space's global reach, offering instantaneous global access.[25] Orbital mechanics limit sustained control of key orbital areas, yet strategies and doctrines from terrestrial domains, as outlined by Paul Szymanski, find application in space warfare.[26] Foundational assumptions from terrestrial warfare, like mass attacks and troop movements detailed by Sun Tzu in his Art of War, see adaptation and potential in space warfare if adequately utilised.[27]

This all comes into play when a framework to mitigate space debris is developed. Future military approaches and foresight play a critical role in all policy recommendations and in understanding the why and where of global military players. Understanding military thinking clears the path to sustainable solutions, overcoming geopolitical tensions, and decreasing the underestimation of space power behaviours.

Advancing Technologies and their Implications on Space Warfare

The realm of space warfare is poised for transformation owing to burgeoning technological advancements across satellite hulls, engines, weaponry, soldiers in the loop, and electronic combat capabilities. The evolution of anti-satellite weapons, including ground-based lasers and railguns, promises enhanced power and extended range, facilitating attacks on spacecraft from terrestrial locations with diminished warning time.[28] Emerging space situational awareness capabilities offer rapid detection, tracking, and identification of celestial objects.[29] Artificial intelligence and autonomous systems empower satellites to analyse threats, execute defensive measures, and effectively counteract adversarial assaults. The surge in offensive cyber capabilities complicates satellite defence, potentially endangering space assets through virtual rather than physical means.[30] Innovative materials like graphene hold promise for crafting lighter, sturdier satellite structures, while radiation hardening and thermal management developments augment spacecraft resilience and survivability.[31] The looming threat of low-cost offensive kinetic weapons, such as space mines or just kinetic spacecraft, pose substantial risks due to their resilience and affordability, challenging effective countermeasures.[32] Sustaining military-technological supremacy and aligning strategic frameworks with cutting-edge space technologies become imperative for the success and dominance of space-faring nations. These pursuits will delineate the boundaries for future debris mitigation strategies.[33]

> "Low-cost offensive kinetic weapons, such as space mines or just kinetic spacecraft, pose substantial risks

The 21st-century landscape of space power grapples with multifaceted challenges posed by asymmetric threats and emerging actors. Advanced technologies offer asymmetric options, including direct-ascent anti-satellite missiles and cyber weapons capable of electronically disrupting satellite operations.[34] Moreover, the widespread accessibility of dual-use commercial space technology fosters asymmetric threats,[35] potentially repurposing benign technology for military use against space assets by state and non-state actors.[36] These developments intricately challenge space powers in safeguarding assets, countering surprise assaults, maintaining numerical superiority, and protecting civilian space assets to utilise commercial space capabilities optionally; these can range from research spacecraft to CubeSats used for data acquisition. Devising innovative strategies tailored to address these unique asymmetric threats becomes imperative, moving beyond traditional military paradigms to effectively operate within the space domain.[37] Space forces face the mandate of formulating inventive national operational concepts to counteract asymmetric challenges. With the proliferation of state and non-state space actors, preserving space power necessitates adaptability in strategic planning, the evolution of space doctrine, international financial engagement, and, above all, a mandate for flexibility.[38]

Understanding Space Debris: Origins, Categories, and Orbital Distribution

Space debris, a growing concern, emanates from various sources and is categorised into accidental and intentional break-ups, spacecraft and launch vehicle operations, and collisions between orbiting objects.[39] A significant portion of catalogued debris stems from spacecraft and rocket body fragmentation post-mission, underscoring the crucial need for end-of-spacecraft life rules and passive debris prevention.[40] In 2007, a Chinese anti-satellite (ASAT) test boosted the trackable space object population by 25%, contributing substantially to debris proliferation (Figure number 1). Presently, the US Space Force monitors approximately 44,800 objects, with only 8,600 classified

Figure 1 *LEO Debris, (Margarette and Vereen 2023)*

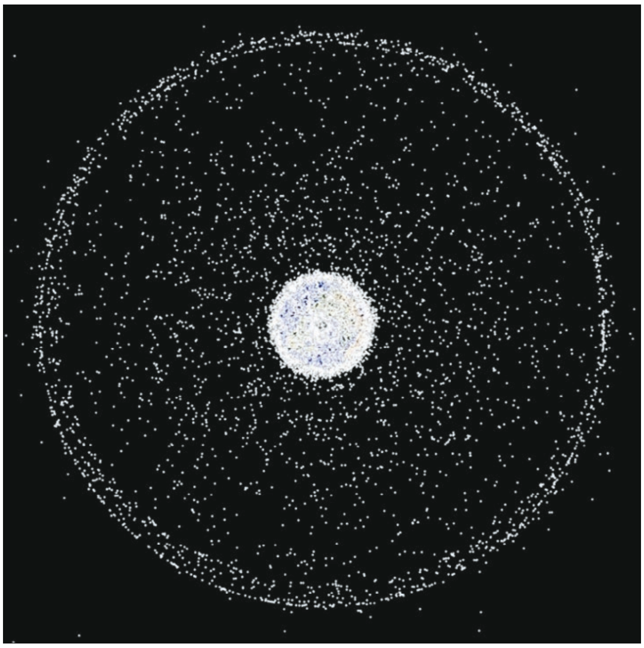

Figure 2 *GEO Debris side, (Margarette and Vereen 2023)*

as active payloads.[41] Many more examples could present the danger of uncontrolled ASAT testing outcomes. Still, the Chinese 2007 test pushed debris creation into the public sphere and is now a commonly known event that shows active debris creation.

The taxonomy of space debris includes mission-related objects intentionally released, fragments from accidental and deliberate break-ups, and non-functional spacecraft and rocket bodies.[42] These debris parts consist of but are not limited to sensor covers, separation mechanisms, and deployment components.[43] Fragments generated from accidental or intentional break-ups create potentially hazardous debris clouds.[44]

Derelict spacecraft and rocket bodies, particularly in higher orbits like orbits like the Geosynchronous Equatorial Orbit (GEO), represent another significant category of space debris.[45] Space debris is further classified by size: micro-particulate matter (1–100 microns), small debris (1 cm to 10 cm), medium debris (10 cm to 1 m), and large debris (greater than 1 m). In Low Earth Orbit (LEO), debris is monitored from 5-10 cm, while in Geostationary Orbit, only debris ranging from 30 cm to 1 m is tracked; in larger than 1 m, debris is more visible and therefore, the tracking resources are focused on small debris parts.[46] According to ESA's statistical model, over 900,000 objects larger than 1 cm clutter orbital spaces.

Debris poses a substantial challenge across all orbital regimes, particularly in LEO below 2000 km, owing to the dense concentration of operational satellites.[47] Figure 1 illustrates a detailed view of debris accumulation around Earth,[48] showcasing tracked non-functional satellites and debris, each dot symbolising a monitored object.[49] Note that the dots are visually enhanced for clarity and do not represent actual sizes.

Notably, altitudes around 900 km to 1400 km witness elevated debris density.[50] Moreover, the Geosynchronous region, situated approximately 36,000 km from Earth, grapples with the congestion of telecommunication satellites and encounters escalating challenges stemming from debris proliferation.[51] Figure 2 illustrates the dispersion of debris within the GEO region, featuring visually enhanced points that do not correspond to the actual sizes of objects. The initial view aligns with the sun-earth solar system orientation, distinctly revealing the GEO satellite

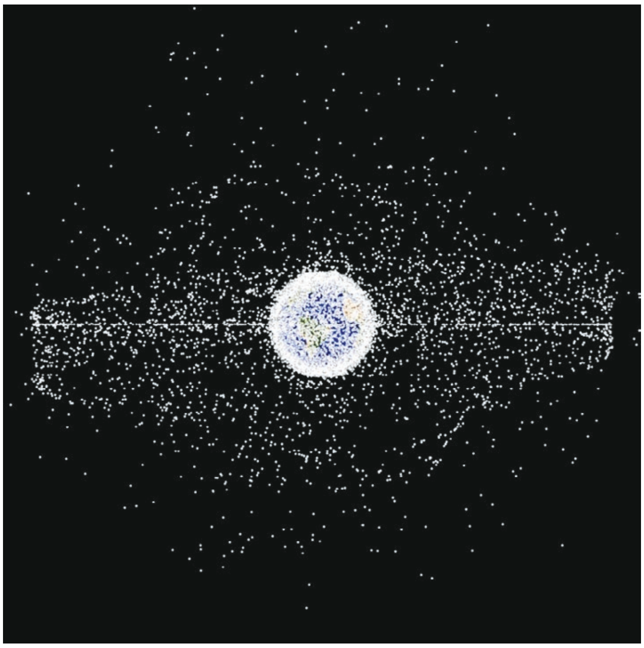

Figure 3 *GEO Debris top, (Margarette and Vereen 2023)*

cemetery orbit, characterised by the orbital plane inclination. This means all GEO satellites adjust their orbit at the end of their expected life to reduce the danger to other active satellites; this is done by adding a low angle to the existing orbit to differentiate the active orbit from the cemetery orbital plane.[52] Additionally, Figure 3 presents a graphical representation showcasing the distribution concerning distance from Earth. Efforts to mitigate space debris necessitate region-specific strategies, particularly addressing debris spanning from Low Earth Orbit (LEO) to Geosynchronous Orbit (GEO). Currently, LEO demands the utmost urgency for mitigation efforts.[53]

Debris Risks to Military and Civilian Space Assets

> Deploying weaponry in near-earth orbit amplifies the debris hazard

The escalating presence of space debris poses a mounting threat to satellites and spacecraft, encompassing natural micrometeorites and remnants from previous space missions.[54] Even minuscule particles below 1 cm in size can cause potential catastrophic damage to spacecraft at hypervelocity speeds, reaching up to 10 km/s in Low Earth Orbit (LEO).[55] The unrestrained propagation of space debris, notably in LEO below 2000 km, has been likened to a runaway phenomenon. Collisions among existing debris generate additional fragments, amplifying the probability of subsequent collisions in a cascading chain reaction, coined as the Kessler Syndrome.[56] Deploying weaponry in near-earth orbit amplifies the debris hazard, rendering operations riskier than weaponry usage in outer space.[57]

Both military and civilian space assets encounter substantial risks from debris, with untracked fragments capable of causing non-visible harm to space assets.[58] Various guidelines, like ESA and NASA, consenting on an End-of-life agreement for Satellites and debris mitigation, exist, yet their efficacy remains constrained by voluntary compliance. As mentioned above ESAs & NASAs strategy involves post-mission disposal through controlled deorbiting, safely directing satellites to re-enter and disintegrate in the atmosphere upon reaching their end-of-life.[59] However, implementing these solutions consistently across the burgeoning satellite population presents practical challenges. An alternative solution involves post-debris creation tethering, actively increasing the drag of debris components to expedite their descent.[60]

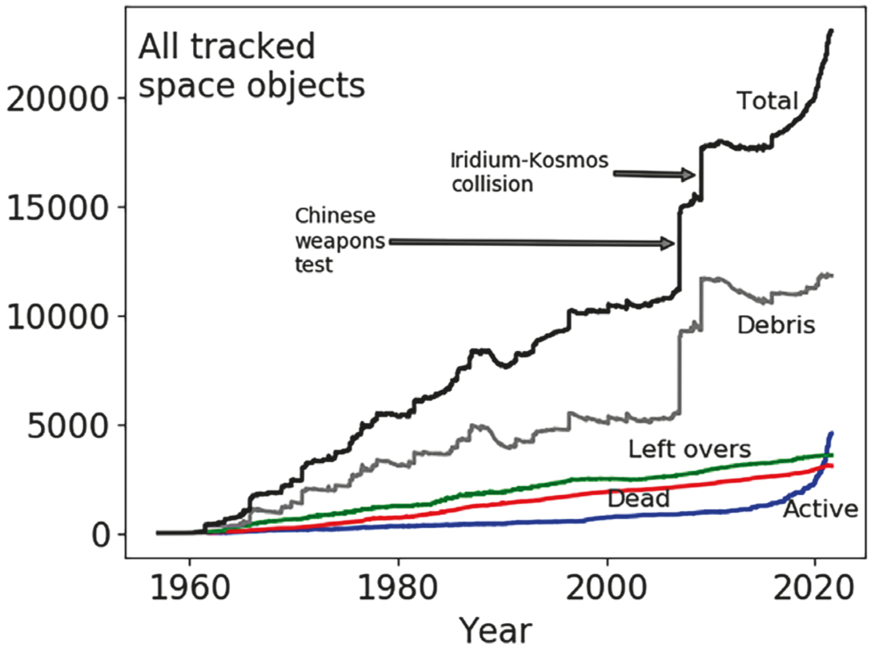

Figure 4 *Growth of all tracked objects in space over time, (Lawrence et al. 2022)*

The visual surge in space debris, evident in Figure 4, underscores the escalating magnitude of the challenge.[61] Mitigating these risks mandates the curtailment of deliberate and unintentional debris generation. Concurrently, implementing post-mission deorbiting strategies and collision avoidance measures stands vital.[62]

Lagrange Points: A Nexus in Space Exploration

Lagrange points, pivotal in both military and civilian space endeavours, denote locations in space where the gravitational forces between two celestial bodies, such as the Earth and Moon or Earth and Sun, achieve equilibrium. These points offer spacecraft the ability to maintain positions with minimal fuel consumption. Within the Earth-Moon and Earth-Sun systems, five Lagrange points exist.[63] Among these, L4 and L5 emerge as the most stable and functionally beneficial.[64] Refer to Figure 5 for an illustration depicting the sun-earth/earth-moon system.

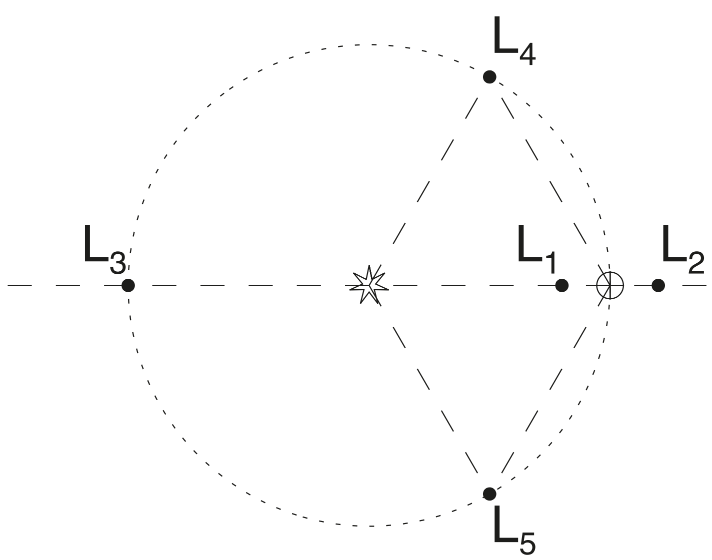

Figure 5 *Lagrange points (Landgraf and Jehn 2001, 1)*

As space becomes more crowded and contested, hazardous debris increasingly compromises the advantages of Lagrange points for military and civilian space assets.[65] Thus, tailored mitigation and remediation measures are necessary for the debris challenges at Lagrange points, where satellites and space observatories are increasingly situated in optimal positions to preserve these unique vantage points for future satellite missions.

Navigating the Legal, Ethical, and Policy Landscape of Space Activities

The year 1967 marked a milestone with the Outer Space Treaty, designating space as a haven for scientific exploration and global collaboration. This pivotal treaty explicitly forbids national claims of space and the placement of weapons of mass destruction in orbit. However, it remains silent on the prohibition of conventional weaponry in space. Accompanying this treaty, the Liability Convention of 1972 holds launching states accountable for damages caused by their space objects, while the Registration Convention of 1975 mandates the registration of space objects with the UN to reinforce liability.[66] Although the Moon Agreement of 1979 aims to deter military activities on celestial bodies, its effectiveness is restricted as major space powers, including the US, have refrained from ratifying it.[67] While these treaties champion preserving space for peaceful pursuits, growing concerns advocate for new multilateral agreements to deter irresponsible conduct and curtail destabilising military expansions in outer space.[68]

> Verification mechanisms like on-site inspections of research labs and ground stations could play a pivotal role

The legal framework promoting peaceful space endeavours lacks comprehensive provisions prohibiting military actions in space. This legal gap raises alarms about potential arms races and hazardous debris resulting from destructive anti-satellite weapons tests.[69] It's imperative for national policies to exhibit greater consistency, necessitating new treaties or amendments explicitly banning the testing and deployment of conventional weapons in space.[70] To enhance transparency regarding military space programs, verification mechanisms like on-site inspections of research labs and ground stations could play a pivotal role, aligning with principles fostering international cooperation and providing free access to space activity information.[71] To maximise impact, universal acceptance of agreements by major space powers is vital.[72] To sustain space as a peaceful domain, proactive measures are indispensable to avert destabilising weaponisation and arms races through legal and economic strategies, adapting international space law to evolving technological landscapes and security challenges.[73]

The creation of debris resulting from anti-satellite strikes raises ethical quandaries concerning space's peaceful use and environmental protection, as underscored by international law presented by the United Nations Office for Outer Space Affairs (UNOOSA).[74] The extensive debris generated by kinetic strikes could render orbits unusable for extended periods, barring access to space for all nations, irrespective of their involvement in conflicts.[75] Additionally, threats to space assets providing vital services like weather monitoring and GPS navigation infringe on humanitarian ethics, endangering civilian lives. Embracing diplomatic resolutions stands ethically superior to provocative tests and space weaponry deployments that could heighten tensions and breach the principle of upholding international peace.[76] Ethical navigation of shared domains like space necessitates environmental stewardship and universal access principles to steer international policies, curbing arms races and space conflicts through multilateral treaties and transparent norms against weaponisation.[77]

Decisions regarding space weapons entail intricate policy considerations.[78] While deploying such capabilities can deter adversary satellites, the potential repercussions of debris and arms proliferation necessitate thorough evaluation.[79] Diplomatic resolutions uphold shared space access.[80] Decision-makers must weigh multiple factors, including second-order effects on the space environment.[81] Overall, decisions demand a comprehensive analysis encompassing technical, legal, ethical, environmental, political, and humanitarian dimensions.[82] These decisions are likely being pushed by national interests and individual states hoping for their strategic advantage.

Defining Boundaries for Space Conflict: Mitigating Debris Risks

Establishing Conflict Boundaries: A Solution to Debris Menace

Space debris looms as a mounting peril for satellites and space endeavours. To mitigate these risks, experts advocate the creation of conflict boundaries for military space operations.[83] These boundaries propose specific zones as restricted areas or "safe zones" to limit debris generation.[84] Enforcing compliance through verification measures such as launch notifications and object registries stands essential to this approach.[85] The overarching aim remains to strike a balance between military space activities and sustainability.[86] However, political hurdles, including mistrust between major space powers, present formidable challenges in establishing these boundaries. Additionally, leading space nations must be convinced to adapt and comply with these rules. Nevertheless, if successfully implemented, they hold the potential to foster peaceful and sustainable space utilisation.[87]

> "Boundaries involve intricate orbital criteria, encompassing proximity, altitude, inclination limits, and debris mitigation measures

Establishing space conflict boundaries involves intricate orbital criteria, encompassing proximity, altitude, inclination limits, and debris mitigation measures.[88] Proposed boundaries could prohibit attacks within 250 km of another satellite, below 2000 km altitude (LEO), and in specific orbital inclinations such as heliosynchronous (96–98°) and geostationary (0°) orbits. A designated safe zone at geostationary orbit (35,786 km altitude, 0° inclination) could be instituted. Nonetheless, relying solely on orbital criteria might prove insufficient, necessitating consideration of additional measures.

Boundaries can safeguard critical satellites providing public safety services like weather monitoring or disaster response, although defining "strategic" assets remains contentious.[89] Debate persists on whether intelligence or military communication satellites should be considered targets.[90] This means policymakers setting space conflict boundaries to protect certain satellites might tilt the balance toward defence and deterrence over offensive capabilities.

Boundaries could restrict kinetic kill attacks, favouring non-destructive methods like dazzling lasers, cyber-attacks, or electronic jamming to minimise debris.[91] Bans on electromagnetic pulse attacks might prevent unintended collateral damage.[92] However, the deterrence potential of non-destructive methods could be inferior to destructive demonstrations.[93]

Operational Protocols

Protocols may necessitate warnings before targeting foreign satellites or limit persistent satellite stalking to avert collisions.[94] Safety zones around human-crewed spacecraft aim to safeguard human spaceflight. Similar to existing treaties on avoidance of incidents at Sea.[95] Post-attack data sharing could prevent miscalculations and aid collision avoidance.[96] While preserving intelligence advantages, operators might protect data on satellite movements while assisting astronauts in distress.[97]

Weapon System Constraints

Limitations could ban direct ascent or co-orbital anti-satellite missiles in near-Earth orbits while permitting non-kinetic attacks like cyber infiltration or electronic jamming to neutralise threats and limit debris.[98]

Proposed Strategies to Mitigate Space Conflict and Debris Risks

Strategies aiming to mitigate space conflict and debris risks must be meticulously evaluated. This article presents the summarised strategies and delineates the evaluation process. It focuses on presenting the core elements of each strategy and what separates it from the other proposed policy frameworks.

Strategy One – Space Security Pact (SSP): Orbital Zones, Pushing Back Dangers and Creating Synergies with Emerging and Existing Space Powers

The proposed Space Security Pact presents an innovative approach to reducing space debris by establishing "protected orbital zones" during both peacetime and post-conflict periods. These zones, encompassing crucial orbits like geostationary and heliosynchronous, aim to prohibit intelligence gathering, manoeuvres, or weapons testing, thereby preventing accidental or intentional debris-generating events that could jeopardise space assets. This initiative mirrors the proposed protected orbital regions by the Inter-Agency Space Debris Coordination Committee and aligns with Szymanski's Space Defence Identification Zones.

The pact mandates stringent construction standards for satellites to minimise debris creation, necessitating redundancy for critical components and controlled deorbiting at end-of-life, overlapping with existing space regulations of most space-faring nations. Additionally, it proposes measures to ensure transparency and confidence-building, aiming to verify compliance with protected zone restrictions and satellite construction standards. Violations of the pact could trigger penalties such as economic sanctions, asset launch bans, or suspension of membership privileges – a facet not currently present in existing legal frameworks. It, therefore, does not just cover protected zones but also any used orbital plane.

The administration of the Space Security Pact would involve collaboration among leading space agencies, with enforcement backed by established ground-based space object monitoring networks and proposed on-orbit surveillance systems, including entities like the German Space Situational Awareness Centre (GSSAC), United Kingdom Space Agency (UKSA), Space Operations Command (SpOC-USA), and private firms like LeoLabs Inc.[99] By curtailing irresponsible military space conduct, preserving scientific exploration and commercial development, and actively addressing debris remediation, the Space Security Pact endeavours to reduce destructive debris-generating events significantly. The allocation of protected orbital zones, insistence on minimum satellite construction standards, and application incentives and penalties are pillars for ensuring compliance, safeguarding the space environment, and sustaining various space-related endeavours.

Strategy Two – Space Registration Regime (SRR): Fostering Accountability in Space Activities and Implementing an International Framework

The next strategy proposes a Space Registration Regime (SRR) that aims to revolutionise space governance by establishing a comprehensive international framework for registering space objects and ensuring rapid attribution of debris-generating events to their responsible entities. This initiative effectively merges an extended registration convention with establishing national space awareness centres, facilitating a collective effort to oversee space activities.

Under the SRR, all nations and commercial entities engaged in space endeavours are obligated to register every spacecraft, rocket body, and debris fragment larger than 10cm in a centralised database. This registry, overseen by the United Nations Office for Outer Space Affairs (UNOOSA), leverages the existing UN Registry Convention and requires detailed information for each space object, encompassing ownership, launch details, orbital parameters, expected lifespan, material composition, power systems, propulsion specifics, and intended disposal methods. Continuous updates to the registry, reflecting alterations in orbital characteristics and ownership transfers for decommissioned assets, are mandated. This framework stands to empower financially underprivileged nations to venture into space by providing a foundational basis for their space endeavours.

> This scheme introduces a benefit-and-penalty structure, a novelty yet to be incorporated into current space law

The UNOOSA-managed database offers secure, real-time access to authorised governmental users, enabling cross-referencing of data to identify potential risks such as dual-use capabilities, abnormal manoeuvres, or technologies contributing to debris proliferation. Deviations between registered information and observed characteristics would trigger investigations into potential unreported irresponsible behaviours or events causing debris. However, implementing such a regime might need more support, notably from significant stakeholders, considering the prevailing distribution of space tracking information by the US government.

To encourage participation, compliant operators would receive incentives like priority radio frequency access, enhanced conjunction warnings, collision avoidance support, and reduced insurance rates. Conversely, penalties for non-compliance encompass fines, liability for damages, and potential suspension of launch or operation licensing by national authorities. Unlike existing voluntary space treaties, this scheme introduces a benefit-and-penalty structure, a novelty yet to be incorporated into current space law frameworks.

The overarching goal of the Space Registration Regime is to instil responsible conduct in space activities and expedite the attribution of debris-related events to their accountable actors. By meticulously documenting space object characteristics and fostering seamless data exchange, this initiative holds promise in holding entities accountable for actions contributing to space debris and violations of established norms, ultimately promoting safer and more responsible practices in space.

Strategy Three – Space Traffic Network (STN): Orchestrating a Collaborative Multinational Space Endeavour for Peaceful and Sustainable Space Usage

The proposed Space Traffic Network (STN) envisions a collaborative international effort to monitor militarised space assets, coordinate debris-mitigating manoeuvres, and forestall potential escalations of space conflicts. This innovative initiative presents a more decentralised approach to managing space tracking and control data, reducing legal hurdles and operational complexities while fostering efficient functionality without a central governing authority.

Multinational coordination centres are at the core of this network, staffed by major space-faring nations. These centres would consolidate data from national space surveillance systems, ensuring continual monitoring of military satellites, anti-satellite weapons, and defence-related space assets. The decentralised nature of this approach allows for smoother operations, unencumbered by singular state or institutional control, thereby enhancing effectiveness even with a reduced number of participating nations.

Participants in the STN would be obligated to share comprehensive updates on orbital dynamics, manoeuvre plans, and telemetry related to dual-use satellites and potential debris-generating systems.[100] This concerted effort seeks to foster transparency and enable thorough risk assessments through the maintenance of a comprehensive database of militarised assets by these centres.

Employing historical data and simulations, these centres, similar to the already existing LeoLabs facilities as mentioned already, aim to identify periods of heightened collision risks during potential space conflict scenarios. To mitigate such risks, they would have the authority to recommend stand-down periods for provocative manoeuvres or weapon tests. Participation in such practices would require involved nations to cede control over certain space assets to diminish collision threats, ensuring a safer space environment.

In the unfortunate event of an actual space conflict, the network's vigilance would extend to monitoring resultant debris fields, data sharing to prevent secondary collisions, and implementing strategies to deflect or remove spacecraft to mitigate potential threats. Similar to proposed orbital regions, temporary protected zone restrictions would be enacted and communicated via NOTAMs to alert crews of all space-faring nations about the risk in specific orbital locations.

A comprehensive contractual agreement among interested space-faring nations would facilitate voluntary participation in this multinational effort. Financial incentives for data sharing and compliance with debris-mitigating guidelines would further incentivise participation and expand the network's capabilities. Additionally, nations could collaborate on debris clean-up missions to actively reduce orbital debris.

In essence, the Space Traffic Network aspires to deter irresponsible actions, curtail conflict escalation, and manage debris stemming from potential space warfare. Effective monitoring of military and civilian space activities is a crucial step toward preventing global arms races and safeguarding planetary orbits from environmental degradation. With a bottom-up approach, this initiative aligns with the future aspirations of most space-faring nations, aiming for a peaceful and sustainable use of space that benefits all stakeholders.

Strategy Four – Orbital Access Fee (OAF): Financial Incentives to Curb Debris Generation

The Orbital Access Fee would impose graduated usage charges on all satellites operating in high-risk debris-generating orbits, applicable to defence agencies and civilian/commercial entities, to curb behaviours that could produce long-lasting debris from military operations, civilian activities, accidental collisions, or related events. A balanced approach in the new space economy is seen as a valid solution to satisfy the high equity needs of the private space sector.[101] Under such a proposal, all satellite operators would pay annual licensing fees proportional to spacecraft mass, orbital parameters, manoeuvrability, shielding, end-of-life deorbit plans, and other design factors influencing debris generation risks. Currently, this has been partly introduced by the United Kingdom in its Outer Space Act from 1986 (updated in the Deregulation Act 2015), where launch, operation, and any space activity require a licence.[102] Higher access fees would adjust for provocative orbital regimes frequently used for anti-satellite testing and exercises, creating financial incentives to shift these activities to lower altitudes whenever feasible.

"Collected fees would finance expanding space-tracking infrastructure and data-sharing agreements

A sizable portion of collected fees would finance expanding space-tracking infrastructure and data-sharing agreements. This aims to enable real-time situational awareness and rapid forensic debris mapping following major fragmentation-causing events. Advanced tracking data processing using AI algorithms and other modern data processing techniques could identify collision risk factors and predict areas of high debris density following hypothetical events. This has proven to be technically feasible and presents a highly usable feature.[103] Furthermore, the pricing mechanisms would encourage discontinuing obsolete spacecraft and outdated rocket body designs. Older legacy systems lacking proper manoeuvrability, shielding, or deorbit/disposal capabilities would face significantly higher fees. However, temporary waivers could be granted for essential civil, commercial, or defence systems already in orbit where retrofitting is infeasible. This aims to balance financial incentives with practical constraints across existing satellites and upper stages.

Moreover, a segment of the orbital access fee revenue would provide consistent funding for R&D towards next-generation, cost-effective and rapidly deployable orbital debris removal technologies developed by commercial companies as well as research centres and or governmental institutions. This would enable active remediation of key high-traffic orbits shortly after major collisions, explosions, or fragments from warfare, helping curb dangerous collision cascade effects. This could be done by placing damaged or end-of-life satellites in a different GEO inclination.[104] While universally mandated implementation faces diplomatic challenges, the adaptation of these aforementioned factors by all major space-faring nations could help with forming strong international norms of behaviour. A possible start from the western-space-faring nations, including the other pro-western space nations like Australia and Japan, could bring this into reality quickly. These include designing all satellites and upper stages for demise, manoeuvrability, and quick deorbit, providing real-time tracking data, and conducting operations cautiously with collision avoidance. This would help in making reckless debris generation expensive for all nations, further deterring irresponsible behaviour. However, it must be mentioned that applying the Orbital Access Fee to nations and companies will pose challenges, as space powers like China and India have to be made aware of and settle their fees.

Concerning oversight and administration, the world's major space agencies could jointly manage the access fee system. They could assess graduated fee levels proportionate to debris risks based on a host of scientifically relevant factors. An international scientific council could guide updates to the fee model as technology evolves.

Licensed private debris removal providers could bid on contracted missions funded by fee revenue.[105] To build consensus and participation, incentives could be offered, like back-channel priority access to tracking data, reduced insurance rates, and flexible payment plans.

Once in place, the combination of financial disincentives, norm-setting, and funding capabilities would curb debris generation from civilian and, eventually, military space activities in key orbital zones. This comprehensive strategy addresses the full scope of potential threats rather than just defence-related risks.

Strategy Five – Space Preservation Fund (SPF): Safeguarding Space through Collaborative Action

The Space Preservation Fund (SPF) is the last proposed strategy in this article, establishing an international funding mechanism to address debris challenges arising from potential space conflicts swiftly. The Fund aims to collect annual contributions from major space-faring nations based on factors driving debris risks, ensuring equitable distribution of costs among stakeholders influenced by activities contributing to space hazards.

> “The SPF would focus on pre-conflict mitigation and post-event remediation

Operated under the oversight of an independent Scientific Committee of Experts, similar to the UNOOSA, the SPF seeks to allocate grants for technology development and missions dedicated to rapid debris mitigation. As devoid of political pressures as an independent committee can be, this committee's decisions would prioritise projects in consultation with contributing nations and commanders, ensuring a transparent and unbiased process.

Financed programs within the SPF would focus on pre-conflict mitigation and post-event remediation strategies. Pre-conflict efforts emphasise advanced debris tracking, risk modelling, and fail-safe technologies to minimise debris resulting from accidental peacetime collisions or malfunctions. Policies exploring responsible testing of anti-satellite weapons in brief lifetime orbits aim to limit the persistence of long-term debris.

The proposed Fund's post-conflict response would involve rapidly deploying low-cost spacecraft to eliminate large fragments in critical orbits before potential cascade effects from collisions occur. Collaborative efforts between ground stations and commercial services enhance debris visualisation and mapping, providing swift protection for civil and commercial assets vulnerable in hazardous orbits. Furthermore, the Fund supports an international active debris removal program, emphasising adaptable launch capabilities and modular spacecraft tailored to each post-conflict scenario.

Though voluntary, the SPF offers compelling incentives for both civilian and military stakeholders, including collective defence assurances and priority access to cutting-edge mitigation technologies and data. By focusing on comprehensive monitoring, mitigation, research, and enabling rapid response capabilities, the SPF seeks to minimise debris risks associated with potential space conflicts, ensuring a more secure and sustainable space environment for all.

Assessing Strategies for Feasibility

Strategies One (SSP) and Three (STN) emerge as the most viable options for mitigating space warfare debris by their operational capabilities. These strategies adopt approaches that either incrementally enhance existing defence frameworks (Strategy One) or present disruptive but pragmatic pathways outside conventional legal frameworks (Strategy Three).

Strategy One focuses on an incremental, legal approach via a treaty framework. It aims to establish protected orbital zones and satellite construction standards, employing incentives and penalties gradually to secure compliance.

Strategy Three follows a voluntary pathway, coordinating data sharing and debris guidelines through multinational centres, prioritising pragmatic services over formalisation. Both strategies leverage existing capabilities, avoiding associated costs and potential resistance from national stakeholders.

In contrast, *Strategy Two* mandates comprehensive space object registration, disrupting established information flows and escalating legal and economic challenges despite attribution benefits.

Strategy Four utilises graduated usage charges to disincentivise debris hazards but needs more defence stakeholder buy-in, undermining its feasibility.

Distinctively, *Strategy Five* pursues pre-conflict risk identification and post-event rapid response supported by a preservation fund financed by major space nations. However, this approach confronts adoption difficulties due to its unprecedented nature.

Key Findings

> "Addressing space warfare debris requires foresight, technical prowess, and international cooperation

The Space Security Pact and Space Traffic Network stand out for their incremental yet practical steps. The former builds upon current defence space architectures and policies, making them faster and simpler to incorporate, while the latter introduces a voluntary approach that does not rely on established frameworks. The Space Preservation Fund, comprehensive in its overall capabilities by providing the necessary funding, provides similar effectiveness through holistic debris threat reduction, making it a promising long-term strategy. Balancing security imperatives with the sustainable use of space remains crucial for all proposed policy approaches. Pursuing the Space Security Pact guidelines and initiating gradual collaborative capability development as proposed by the Space Preservation Fund are recommended for national and international stakeholders.

Future research in space debris propagation, advanced tracking technologies, and policy integration will further strengthen these strategies to a point where parts could be incorporated into existing frameworks. Multilateral cooperation remains pivotal in ensuring a peaceful and sustainable future in the space domain, requiring sustained efforts across various avenues ranging from funding to defence operations and ending at stakeholders. Addressing space warfare debris requires foresight, technical prowess, and international cooperation of all kinds. Using known issues and approaches from arms control and other proliferation treaties can bring the necessary oversight and leverage to pursue functional cooperation in space. By investing in collective responsibility and collaboration, space can continue to be a frontier for exploration, scientific discovery, and inspiration for future generations.

The renowned 19th-century military strategist Baron de Jomini astutely observed, "Every maxim of war will be good when it shall have for result, the assuring the employment of the largest sum of means of action at the opportune moment and point."[106] This timeless insight on coordinating resources and strategy still rings true today as we grapple with the complex challenges of space militarisation and debris mitigation. Waiting too long to decide on the perfect strategical approach will not bring safety and stability; concise action will. By thoughtfully combining policy, technology, and diplomacy at this critical juncture, we can work to ensure space remains viable for peaceful exploration and scientific discovery for generations to come. With foresight and collective responsibility, we can avoid the catastrophic outcomes of unconstrained space warfare.

Our future as a space-faring civilisation depends on it.

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