Centre for International
Governance Innovation

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For publications enquiries, please contact publications@cigionline.org.

67 Erb Street West
Waterloo, ON, Canada N2L 6C2
www.cigionline.org

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About the Author

Ruth Stilwell is the executive director of Aerospace Policy Solutions LLC, core faculty member in Norwich University's Master of Public Administration program, and a leading authority on integrated space and aviation policy and governance. Her work was recently published in the *Journal of Space Safety Engineering*.

An air-traffic controller for 25 years, experienced labour leader and policy expert, Ruth is also an accomplished researcher and lecturer. Her numerous publications and presentations, which cover a wide range of space and aviation, public safety, human factor, administration, financing and industry reform topics, have influenced key US legislation and, in many cases, have been required reading for administration officials. Ruth's specific areas of expertise include: integrating commercial space operations in civil airspace; projecting air traffic controller retirement and staffing requirements; Federal Aviation Administration (FAA) funding and financing structures; workers' rights and more. In March 2018, she was named a Fellow in the Royal Aeronautical Society (FRAeS). FRAeS is an award granted to individuals who the Royal Aeronautical Society judges to have made outstanding contributions in the profession of aeronautics and have attained a position of high responsibility in this field.

Ruth served from 2010 to 2015 as the industry expert representing air traffic controllers on the International Civil Aviation Organization Air Navigation Commission in Montreal. Her air traffic control experience includes 25 years of operational duty at the Miami Air Route Traffic Control Center, two years as liaison to the FAA Requirements Service and six years as executive vice president of the National Air Traffic Controllers Association.

The founding chairperson of the Air Traffic Services Committee of the International Transport Workers' Federation, a position she held for four years, Ruth currently serves on the International Academy of Astronautics Commission 5 — Space Policies, Law and Economics.

Ruth earned her bachelor's degree in labour studies at the National Labor College and her master of public administration and doctor of public administration at the University of Baltimore.

Acronyms and Abbreviations

ADR	active debris removal
ASAT	anti-satellite
CA	conjunction assessment
CDM	conjunction data message
COMSPOC	Commercial Space Operations Center
COTS	Commercial Orbital Transportation Services
ESA	European Space Agency
GPS	Global Positioning System
ISAM	In-Space Servicing, Assembly and Manufacturing
ISS	International Space Station
LAWS	lethal autonomous weapons systems
LEO	low-Earth orbit
OODA	observe, orient, decide, act
OOS	on-orbit servicing
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
SPD-3	Space Policy Directive-3
SSA	space situational awareness
TraCSS	Traffic Coordination System for Space

Executive Summary

The emergence of large constellations of small satellites has disrupted the field of space safety services and changed how we think about the risk of collisions in space. The risk from space debris is compounded by the growing congestion from operational satellites in low-Earth orbit (LEO), particularly between 300 and 700 km above the Earth. These satellites have created an opportunity for commercial operators to assume roles that were once the exclusive domain of military or other state actors. While increasing commercial interest in providing the essential safety functions of space situational awareness (SSA) and conjunction alerting may increase the pace of innovation, and emerging technologies may enable new approaches to reduce collision risk on orbit, there are associated core governance issues of safety, sustainability and security in outer space that must be considered.

The evolution of licensing and oversight of commercial space launch services can be instructive in some ways but do not fully capture the international considerations of safety services for objects in orbit. Space sustainability challenges will not be solved without deliberate action. Governments should consider how to appropriately foster a viable, resilient commercial industry for space safety services and what standards are necessary to ensure the competence of individual providers of those services.

Introduction

Space has always captured the human imagination. The desire to learn more about our universe drives space exploration, and the technology developed to explore space leads to breakthroughs in innovation that can transform life on Earth. Space has become a critical resource for humanity, enabling tools for communication, Earth observation, positioning, navigation, timing and connectivity. As human activity in space has increased, so has the economic value of space services. In its 2024 report, the World Economic Forum (2024) concluded, “The global space economy will grow from $630 billion in 2023 to $1.8 trillion by 2035, serving an increasingly connected and mobile world.”

The commercialization of space and its rapid growth follows the familiar pattern of industrialization. Opportunity and technology create new standards of living and transform societies, but they also come with environmental pollution and its effects. The response to these challenges includes the development of new technologies and approaches to ensure sustainability; consequently, this technology cycle drives new policies and business models. This paper categorizes these downstream effects and innovations as aftershocks: the less noticeable, but significant activity triggered by less obvious and measurable change. The obvious and measurable change in space activity today is the commercialization of LEO, which is the result of decades of deliberate policy and investment, particularly in the United States, to encourage the growth of the private spaceflight sector (National Aeronautics and Space Administration [NASA] 2014).

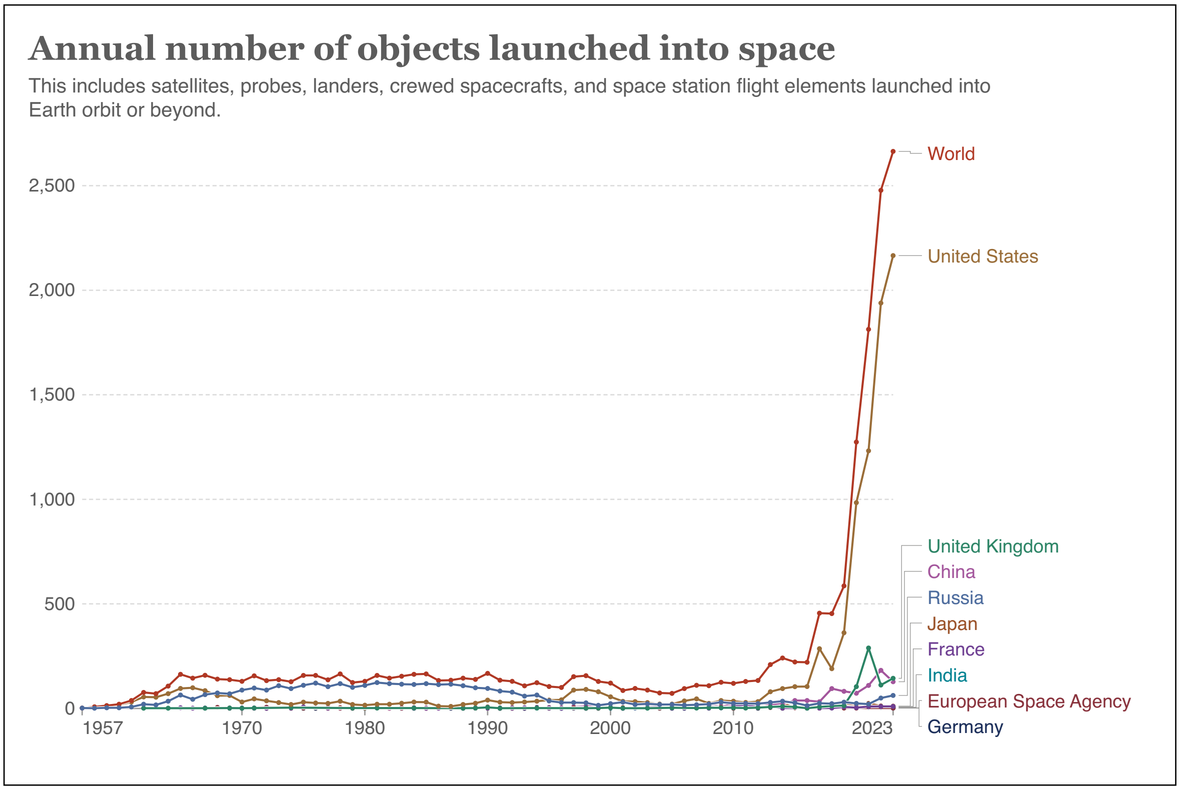
The aftershocks include the need to regulate and oversee new commercial industries in a way that ensures sustainable utilization of space and the development of technology and services to mitigate the risks from rapid commercial growth. Since space is recognized as an international domain, domestic policies must be developed in a way that considers the consequences of commercial activity for both national policy and international relations. Sustainable utilization of space is a complex issue that requires development in technology, legal frameworks, business models and diplomacy, as well as an understanding of how these fields intersect.

Disrupting the Space Environment

The space environment is constantly changing. On June 21, 2024, Look Up Space reported that more than 10,000 active satellites were in orbit around Earth for the first time, 9,254 of which are in LEO (Faleti 2024). The rapid growth of objects in orbit is a recent phenomenon (see Figure 1) and is expected to continue.

The first three decades of the Space Age were defined by competition for superiority in space between the United States and the Soviet Union; these two countries were responsible for 93 percent of all satellites launched through 1990, and only

Figure 1: Growth in Number of Satellites in Orbit



Source: https://ourworldindata.org/grapher/yearly-number-of-objects-launched-into-outer-space.

four percent of these were commercial (Harrison et al. 2017, 2). The end of the Cold War coincided with shifts in commercial and defence strategies on the use of space and the proliferation of space capabilities around the world. The period after the Cold War has been described as the "Second Space Age" (ibid., 4). From 1991 through 2016, 39 percent of satellites launched were from countries other than the United States or Russia, and more than 36 percent were commercial (Harrison et al. 2017, 6). From a policy perspective, there are two definable shocks that led to the development of the space economy as it is today: the ending of the Cold War and of the US space shuttle program. Each event triggered fundamental changes in the development of commercial space markets.

End of the Shuttle Era Gives Rise to "New Space"

In the United States, the end of the shuttle program in 2011 is credited with ushering in the era of "New Space," which is characterized by the shifting dynamics of the global commercial space sector to business models that are reliant on private investment and venture capital (Garriott 2011). New Space reflects significant increases in private actors in the space sector, the number of nations with space ambitions and capabilities, and the development of new activities, including mega-constellations,[1] on-orbit servicing (OOS), private human spaceflight and exploitation of space resources (Brockmann and Raju 2022, 5). By 2021, the global space industry included over 10,000

1 The term "mega-constellation" is a common lay term to describe constellations of hundreds or thousands of satellites; the astronomical community prefers the term "large constellation."

companies with more than 5,000 large investors and 130 state agencies (Signé and Dooley 2023).

The dramatic increase in congestion in LEO over the last decade (see Figure 1) can be tied to specific key events, but it is the activity and policies coinciding with these events that either enable or stifle progress. The development of a reusable spacecraft, the US space shuttle, created an opportunity to build the International Space Station (ISS), enabling humans to conduct research in a low-gravity space environment. The shuttle program also provided launch services for satellite missions and deployed 180 payloads in orbit over its 30-year life cycle (Malik 2011).

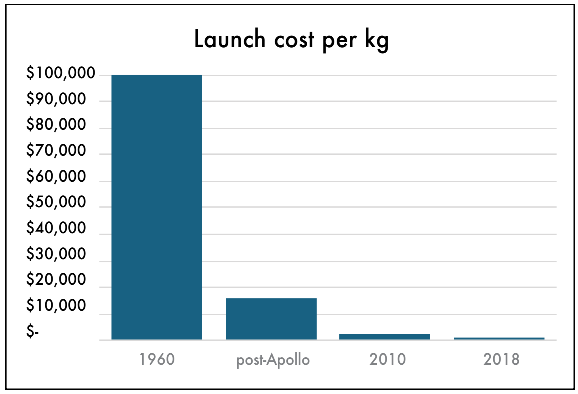
The US Commercial Space Launch Competitiveness Act of 1984 allowed the US government to create a licensing regime, enabling private launch companies to access government facilities and creating liability insurance requirements.[2] This period included a fundamental change in thinking about the role of government in providing launch services and examined whether a policy change could enable the development of a commercial launch sector.

The planned retirement of the shuttle program triggered the development of NASA's Commercial Orbital Transportation Services (COTS) program. COTS created the need for legal frameworks that permitted government to partner with industry, allowing NASA to help develop LEO transportation services in partnership with private industry and later purchase those services as a customer using Space Act agreements (NASA 2014, 21). The NASA investment enabled the development of a commercial reusable rocket that, in turn, drove down the cost of accessing space, accelerating the commercialization of LEO.

Commercialization of LEO

The New Space commercialization of LEO saw new commercial actors emerging in all segments of the space domain, including the Moon, although the overwhelming commercial activity in the sector is in LEO. This development is largely due to the decrease in launch costs (see Figure 2) and miniaturization of satellites. In the mid-1960s, launch costs were more than $100,000 per kg; in the post-Apollo era, costs for NASA-contracted services dropped to $16,000 per kg for medium and heavy payloads and $30,000 per kg for light payloads. The development of the reusable SpaceX Falcon 9 rocket further drove costs down to $2,500 per kg in 2010, and the Falcon Heavy rocket decreased costs to $1,500 per kg by 2018 (Pethokoukis 2024). Lower launch costs opened the door to new space actors who are not connected to government space programs.

Figure 2: Launch Cost



Source: Author.

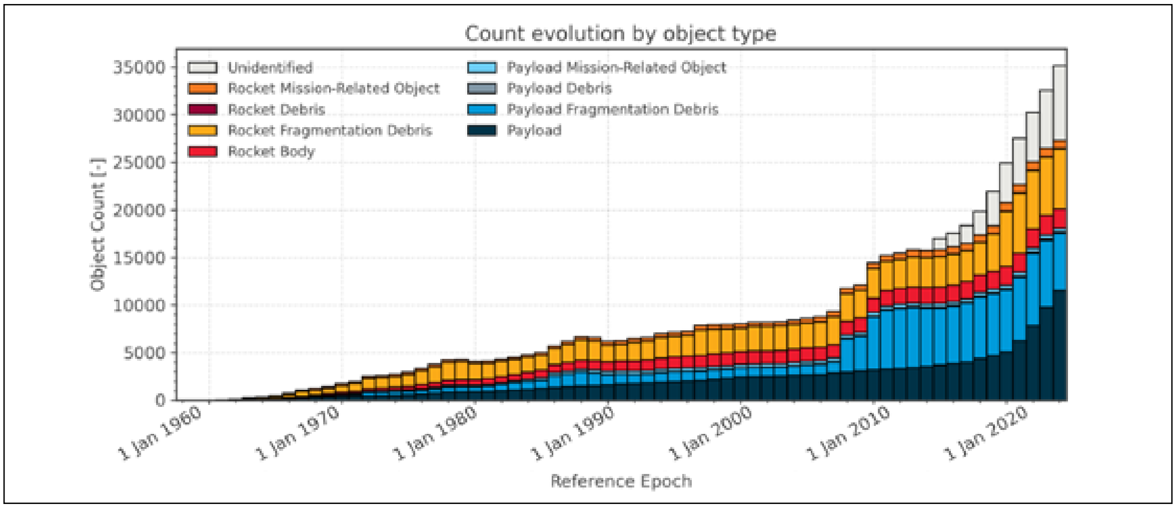
The miniaturization and mass production of satellites allowed for more affordable and rapid deployment but brought a significant reduction in operational lifespan. For example, while an Iridium communications satellite assumes a 15-year lifespan, a Starlink satellite is expected to be replaced after five years. These shorter lifespans add to the frequency of launches and an increase in the population of defunct or derelict satellites.

The desirability of LEO in delivering affordable telecommunications services, particularly broadband internet, is driving much of this growth. The time period of development of reusable launch capacity and the reduction in satellite size and cost has corresponded with a dramatic increase in the demand for broadband connectivity. In addition to the economic value of the telecommunications industry, there is a societal interest in expanding connectivity to remote and rural areas as a matter of equity and access to digital resources. Earlier failed efforts, such as Teledesic in the 1990s, were based on larger satellites and higher launch costs.

While it may be too soon to project the long-term financial stability of commercial LEO telecommunications infrastructures, Starlink has

2 See www.faa.gov/sites/faa.gov/files/about/history/milestones/Commercial_Space_Industry.pdf.

Figure 3: Number and Type of Objects in Orbit



Source: ©ESA/ESA Space Debris Office (2024, 19).

already disrupted the space environment with its first-generation constellation. In addition, Amazon's Project Kuiper was granted a licence to operate 3,236 satellites at altitudes between 590 km and 630 km and began launching satellites to provide internet service in October 2023 (Kohnstamm 2023), while Eutelsat OneWeb began trial services from its constellation in April 2024 (UK Telecoms Innovation Network 2024).[3]

Space Debris

In addition to growth in the number of satellites, space debris is also a significant and growing problem (see Figure 3). Major causes of space debris are satellites that have reached end of mission but have not completed post-mission disposal, abandoned mission related objects, fragmentation events, collisions and destructive anti-satellite (ASAT) tests.

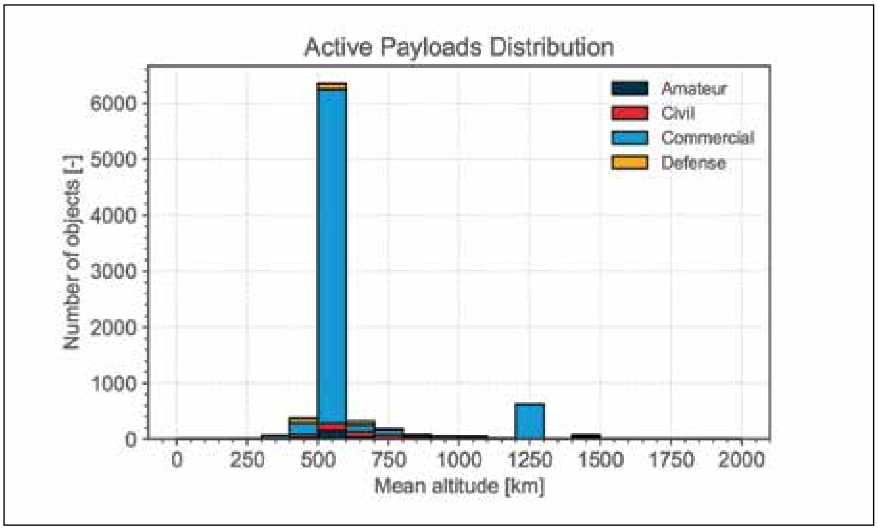
While orbital debris includes any human-made object in orbit around the Earth that does not serve a useful purpose, certain objects may break up, creating large amounts of new debris. The first satellite fragmentation event in June 1961 increased the population of objects in orbit by 400 percent and was followed by increasingly frequent breakup events throughout the following decades. Debris risk from fragmentation events led to extensive global research activities into space debris and its potential consequences (Anz-Meador, Jacobs and Liou 2022, 20). Fragmentation events are often the result of the explosion of unspent propellent in mission-related objects, such as spent rocket bodies and defunct satellites.[4]

The first documented collision between two satellites occurred on February 10, 2009, involving a defunct Soviet Cosmos satellite and an operational commercial Iridium satellite. The collision created both a significant number of new debris fragments and highlighted the shortcomings of the screening systems at the time (Weeden 2010). This single event triggered fundamental change in how conjunction analysis is conducted, and the US government provided services available to commercial operators. The 18th Space Defense Squadron now screens predicted trajectories of tracked satellites against its catalogue and distributes conjunction warning messages to the affected satellite operators (Silverstein 2023). The European Space Agency (ESA) established a Space Surveillance and Tracking Framework in 2014, offering a communications portal to allow operators to deconflict actions (ibid.). The Asia-Pacific Space Cooperation Organization was formed to support shared SSA information and

3 The OneWeb constellation, with only 648 small satellites, is much smaller than that of Starlink or Kuiper, and operates at 1,200 km.

4 See www.esa.int/Space_Safety/Space_Debris/About_space_debris.

Figure 4: Payload Distribution by Altitude



Source: ©ESA/ESA Space Debris Office (2024, 60).

launched the initial capacity of the Ground-Based Space Object Observation Network in 2012.

Satellite development in the defence sector has brought a corresponding interest in ASAT technology. Four countries — China, India, Russia and the United States — have collectively conducted 80 ASAT weapons tests between 1959 and 2021, at least 15 of which are considered destructive events generating known and tracked debris (Secure World Foundation 2022). While there was no overt international moratorium, ASAT testing had become increasingly rare after the mid-1980s. The destructive, debris-generating ASAT tests conducted by Russia in November 2021 triggered international backlash. The United States announced a self-imposed ban on direct ascent, destructive ASAT missile tests in April 2022, followed quickly by Canada, Australia, Germany, Japan, New Zealand, South Korea and Switzerland (in order of acceptance). By November of that same year, the seventy-seventh session of the UN General Assembly First Committee on Disarmament and International Security adopted a resolution calling for countries to ban ASAT tests (Foye and Hernández 2022).

While destructive events dramatically increase the number of debris fragments in LEO, they cannot be uncoupled from the growth in active payloads. As we increase the number of active satellites while simultaneously reducing satellite lifespan, we also dramatically increase the number of mission-related objects, including spent rocket bodies and derelict satellites, thereby increasing the debris risk

Distinctions within LEO

The concentration of commercial space objects in specific altitudes (see Figure 4) creates a challenge unique to that domain, and policies should reflect that risk. Too often the discussion is overly broad, using expressions such as "space is getting crowded." From a public policy standpoint, this generic description risks diverting attention away from a specific problem by treating space as a homogenous environment. Even confining the discussion to LEO may be overly broad, as LEO is defined as orbits between 200 and 2,000 km above the Earth's surface (ITU News 2023). A more precise statement of the problem is that rapidly increasing congestion in LEO between 300 and 700 km above the Earth (Figure 4) has reached a point in which existing safety services and governance structures are inadequate to ensure sustainability of the domain. In addition to the concentration of satellites in this band, the two operational space stations, the ISS and China's Tiangong, operate between 350 and 450 km above the Earth. Safety services must consider the risk to humans in space, which may have a different risk threshold than that among space objects without humans on board.

Space Safety Services

The current state of space safety services is advisory in nature and provided to reduce the risk of collision in space. However, there is no internationally harmonized space traffic management or collision avoidance framework in place. It is recognized that avoiding a collision in space is in the interests of a diverse community. In the event of a collision, a satellite operator may lose a valuable asset, the users of the services provided by that satellite may be deprived of a valuable resource, and current and future satellite operators may be harmed by a collision in space because it generates new debris that makes the environment less safe for the future.

Current civil space safety services include two categories, SSA and conjunction assessment and alerting. These services evolved from military applications. While military space surveillance began in the 1960s, it was not until 2001 that the United States evolved its service beyond tracking and cataloguing to providing SSA (Sturdevant 2008, 16). The SSA sharing program, Space Track, gives access to unclassified information from the US military's Space Surveillance Network to non-government-affiliated entities (Chow 2011, 4), including those outside the United States. High-risk events triggered the need for additional safety services, and, in 2009, the US Strategic Command began providing no-cost basic emergency space safety services that include launch conjunction assessment (CA) and on-orbit CA and collision avoidance screenings (Space-Track.org 2018) to any satellite operator choosing to participate. CA screenings seek to determine a time of closest approach with another object in the future. This process generates a conjunction data message (CDM) that is emailed to the affected operator(s). It is important to note that the CDM is not a collision warning system[5] but rather a proximity alert: the operator still needs to construct a collision risk assessment and determine if an avoidance manoeuvre is required.

From Debris to Congestion

The decade from 2013 to 2023 saw unprecedented growth in both the number of payloads launched into space and the number of operational satellites in orbit (see Figure 1). In LEO in particular, the pace of growth dramatically increased beginning in 2019 with the launch of the Starlink constellation. This explosive growth is almost entirely attributable to the commercial space sector and is expected to continue. While other orbital bands are primarily concerned with the risk of collision with debris, the 300-to-700 km band in LEO must consider the increasing risk of collision between two operational satellites. This possibility is relevant because the available mitigation strategies are different for a conjunction risk with an operational satellite than with debris, which creates new complexity in developing standards and rules of behaviour. The disruption from large constellations of hundreds or thousands of satellites in LEO fundamentally changes how we look at collision risk and the tools available to mitigate it

A conjunction risk between a manoeuvrable satellite and debris triggers a straightforward course of action. The operator evaluates the conjunction data message, performs a collision risk analysis and determines whether to manoeuvre the satellite, as well as when and how to go about doing so. For the provider of a safety service, when the risk is debris, the system can be improved with increased surveillance coverage and accuracy and improved analytic capabilities. Non-functional objects require surveillance that detects an object without the object providing information to the system. Examples of non-cooperative surveillance include primary radar, lidar and telescopes. However, better detection is only of value when an operator has the capability to manoeuvre away from the debris object. In February 2024, a 660 kg non-manoeuvrable NASA satellite that was launched in 2001 passed within 20 metres (as estimated by LeoLabs) of a defunct 2,000 kg Cosmos satellite launched in 1992. A collision between these two large objects would have created a huge quantity of new debris and was of grave concern to the space community. Since neither object had the capacity to be manoeuvred, no preventive action was possible.

The response to a conjunction risk with another operational satellite is not as clear as a conjunction with debris. The behaviour of debris represents a predictable trajectory, but predicting the behaviour of an operational satellite requires information, prompting questions such as: Do the operators have enough information about one another to determine who should give way? How is priority determined? Is there an agreement in place? Are both operators from countries with

5 See www.nasa.gov/cara/step-1-conjunction-event-prediction/.

common principles to determine priority or is there a conflict in expected behaviour? Is the other satellite functional? Can you communicate with its operator to coordinate action? Can alternative actions be negotiated? Do both operators believe there is a collision risk that requires action? Is the risk high enough to justify the consequences of the manoeuvre? Does the planned action create a situation in which a future manoeuvre will be required with a third object? Without standards for sharing information, these questions may be unanswerable.

Aftershocks

Having identified the introduction of large constellations of small satellites as the shock, this paper will show that its aftershocks have considerable diplomatic and safety consequences. The absence of policy and regulation for collision avoidance in highly congested orbits has not slowed the growth in the number of satellites in LEO, but the domain has felt the effects of its lack. For example:

- In 2021, China accused SpaceX of a close call that required it to manoeuvre the Tiangong space station (Reuters 2021).
- In 2019, the ESA (2019) had to manoeuvre its Aeolus satellite to avoid a collision with Starlink 44.
- By 2023, satellites in the Starlink constellation were manoeuvring nearly 50,000 times per year and a Commercial Space Operations Center (COMSPOC) study predicted that without mitigation, the satellites would collectively encounter two million close approaches over a 10-year period, with the potential for six environmentally altering and 71 mission-ending collisions (Oltrogge et al. 2024, 17).

Dominant operators in a highly congested orbit have a particularly keen interest in preserving the integrity of that domain. For example, SpaceX has implemented mitigation strategies that include automated manoeuvring and augmentation of government-provided SSA with commercial services. The higher standards adopted as mitigation strategies should serve as a model for future operators seeking to access the domain, and governments should consider higher standards when approving launches into highly congested orbits. It is important to note that the risk to any individual satellite is not based on the size of its constellation. An operator with a single satellite in a highly congested orbit has the same risk as that of a single satellite that is part of a large constellation. Standards, capabilities and principles of behaviour should be based on the planned destination of the satellite, not its operator.

The stress on highly congested orbits has led to the development of new commercial services, technologies and investments that may support governments' role in ensuring a safe and sustainable space environment. But commercial services do not negate the need for policies and standards that prevent debris-generating behaviour, such as standards for unexpended propulsion in abandoned satellites and spent rocket bodies, requiring both SSA and manoeuvrability for operational satellites, efficient post-mission disposal and design for demise. Technology that extends the life of existing satellites through OOS and allows for the removal of high-risk objects using promising technologies for active debris removal (ADR) creates new opportunities for effective space sustainability policies, but we cannot rely solely on commercial actors to raise standards in a shared domain.

Plato famously wrote that "our need will be the real creator," a saying that has been more commonly expressed as "necessity is the mother of invention." The disruption in LEO triggers aftershocks that will accelerate the development of technologies that have been under consideration for years by creating a viable commercial market for these services. But the development of new commercial services in response to the increasing risk in orbit can create a new burden on governments to ensure that these services do not create new risks or have unintended consequences for other domains.

Commercial SSA

The development of commercial space surveillance and situational awareness is a clear aftershock of the growth of space objects in highly congested orbits. The government-provided free advisory service may be adequate in uncongested orbits, where high-risk encounters are infrequent, but highly congested orbits may require more detailed and precise services, and it may not be appropriate for the public to fund these additional services for commercial operators. The public policy challenge occurs when the community becomes dependent on a commercial provider for an essential safety service.

Commercial space safety services can augment government services. However, commercial SSA has barriers to market viability that differ from the commercialization of both space launch and LEO operations. Comparing and contrasting the development of commercial space safety services with commercial launch services can provide insights into the steps necessary to ensure that a viable commercial SSA industry will emerge.

The free SSA service provided by the US military began a process of transition to a civil agency in 2018 under the auspices of Space Policy Directive-3 (SPD-3): Space Traffic Management, but organizational change on this scale does not happen quickly. The transition dictated by executive policy was subject to review and authorization by the legislative branch of government, and, in 2020, the National Academy of Public Administration (2020, 101) issued a report to Congress reinforcing the decision in SPD-3. Delays in the transition to the civil authority created an opportunity for commercial actors to fill the perceived gap in services. This was not an entirely new industry. Private sector organizations for SSA began to emerge after the Iridium-Cosmos collision in 2009 when the Space Data Association formed a consortium of satellite operators sharing information to improve SSA data. In 2014, AGI opened COMSPOC as a commercial companion to the Joint Space Operations Center. LeoLabs, a private company, has been building commercial space radar at sites around the globe since 2016. Slingshot Aerospace launched its Beacon platform for space traffic coordination in 2021. As the transition from military to civil agency for SSA nears completion, commercial services are already maturing.

The satellite industry recognizes that increasing risk in LEO requires services above those provided by the government, and as in the early commercial launch industry, the early commercial SSA providers also have a connection to government. This government connection provides operators with an assurance of competence absent a formal regulatory structure. For US launch providers to offer services without a government connection, the regulatory structure for a launch licence was needed. The launch licence provides the consumer of launch services with an assurance that the launch provider is competent. For commercial SSA, there is no regulatory authority that authorizes the commercial entity to provide the services, nor are there formally adopted industry standards. This gap can have consequences that go far beyond collision risk. An operator relying on a commercial service that proves inadequate, resulting in a collision, can have consequences for both national security and diplomatic relationships.

The state of commercial SSA is currently an augmentation of government-provided services, but it is a growing field. The global SSA market was estimated at $1.21 billion in 2020 and is expected to grow to more than $1.73 billion by 2028.[6] It is unclear whether this growth projection anticipates an independent free market basis or an industry that is dependent upon government contracts. The US transition to a civil agency is in progress, and the US Department of Commerce's Office of Space Commerce launched the Traffic Coordination System for Space (TraCSS) and announced the TraCSS Consolidated Pathfinder project in 2024, contracting with three commercial SSA providers (COMSPOC, LeoLabs and Slingshot Aerospace) to incorporate commercial capabilities into their system.

The TraCCS strategy is to add commercial data and SSA services in phases (Office of Space Commerce 2024). While this would seem to be a straightforward approach to commercialization, SSA has distinct differences over the commercialization of either launch services or LEO. On the surface, SSA commercialization is following a familiar pattern, as shown below in Figure 5.

Figure 5: Commercialization of Launch versus SSA

Government-Provided Service	
NASA launch	Space Track
NASA-Contracted Launch	
NASA-contracted launch	TraCCS Pathfinder
Commercial Services Supplant Government Service	
Competitive launch market	Competitive market?

Source: Author.

6 See www.fortunebusinessinsights.com/space-situational-awareness-ssa-market-105446.

Figure 6: Commercialization of Weather, GPS and SSA

Government-Provided Service		
NOAA weather sensors	GPS constellation	Space Track
Commercial services augment government service		
NOAA Commercial Data Program	WAAS, LAAS, GBAS	TraCCS Pathfinder
Commercial services developed using government data		
Commercial weather	Commercial applications	Collision risk and planning tools

Source: Author.

Note: WAAS = Wide Area Augmentation System; LAAS = Local Area Augmentation System; GBAS = Ground Based Augmentation System

The commercial launch industry benefited from public policy shifts that actively reduced access to government-provided launch services. Rather than competing with a government-subsidized service, commercial launch providers enjoyed significant government investment in their early development and created additional revenue opportunities by selling ride-share space on government launches. By contrast, for SSA, the US government expects to continue to offer a free basic service, and commercial actors would need to provide an augmented service to access the market.

In addition, a given payload capacity on a launch is only sold once, whereas SSA data can be sold to multiple customers. This is where we encounter the first challenge in reaching commercial viability. The providers of commercial SSA data, such as LeoLabs, ExoAnalytic Solutions and others, develop business models based on an expectation that space sensor data can be sold multiple times to multiple customers. However, if the observations from commercial sensors are sold to the government, which, in turn, provides a free service based on this data, the resale revenue stream becomes unavailable, threatening the viability of a competitive commercial SSA market. Without a viable commercial market, government dependence on commercial data requires increasing government expenditure to ensure the economic survival of commercial companies. This can have the unintended consequence of discouraging new industry entrants and restricting innovation, while also increasing the public burden to fund the service.

Conjunction analysis and alerting services may find a healthier market condition than the providers of space sensing, since the free government service is limited to a "basic" service, thereby creating a commercial opportunity for bespoke analytics beyond the services offered by government. This type of market mirrors that for commercial weather services in which a government agency, such as the National Oceanic and Atmospheric Administration (NOAA), provides data from weather sensors and forecasts and commercial providers process the data into a consumer product. This market scenario is also similar to the Global Positioning System (GPS), where the government infrastructure is used to provide a signal that forms the basis for a panoply of commercial services (see Figure 6).

As an emerging new industry, commercial SSA is developing outside the routine regulatory structures that would apply to other space services. For example, a US satellite used for remote sensing of the Earth is subject to a licensing requirement under the US Code of Federal Regulations, Title 15 Part 960: Licensing of Private Remote Sensing Space Systems. An antenna or telescope on Earth used to sense the position of objects in space does not fall within the definition of remote sensing contained in the statute: "Remote sensing means the collection of unenhanced data by an instrument in orbit of the Earth which can be processed into imagery of surface features of the Earth." No SSA companies are listed as having a NOAA licence on the Office of Space Commerce website.[7] However, SSA providers that use the frequency spectrum, such as LeoLabs and NorthStar Earth & Space, require a licence from a national regulator with authority over radio communications. These licences are designed to protect the frequency spectrum from harmful interference, not to ensure the quality of the safety services provided by a commercial SSA company.

In the decades of its development, SSA has been recognized as a space safety service. SSA has unique characteristics that need to be considered in the policy construct. In a traditional safety net, such as airborne collision alerting systems in aviation, the consequences of catastrophic failure apply to the two aircraft on a collision course. For SSA, a catastrophic failure has additional consequences for all operators in the congested domain for years to come. This is evidenced by the continuing need for avoidance manoeuvres away from debris caused by the 2007 Fengyun-1C ASAT test, the 2009 Iridium-Cosmos collision and the 2021 Russian ASAT test. The interest in ensuring the quality of space safety services in highly congested orbits goes beyond the contractual relationship between the provider and consumer of the services. Frameworks ensuring that companies that provide SSA services are competent to do so have not yet emerged.

As government-provided services become reliant on augmentation from commercial sensor data and analytics, government will have an increasing interest in ensuring the viability of a commercial SSA sector. The commercial space launch model becomes relevant here. The launch sector not only benefits from research and development resources, but could also rely on government as a consistent and valuable consumer of launch services. This approach can provide a degree of resilience but risks market distortion. In addition, as SSA serves a global stakeholder community, an overreliance on US-provided services is suboptimal. But this could be self-correcting in the same way that concerns over US control of the GPS constellation provided an impetus for other states to develop global navigation satellite system constellations, resulting in a more robust space-based positioning, navigation and timing infrastructure.

Other Emerging Commercial Space Services

OOS

OOS (also referred to as "in-orbit servicing") is a category of In-Space Servicing, Assembly and Manufacturing (ISAM). OOS can act as debris mitigation by either extending the useful life of a satellite, delaying the need to place an additional object in orbit, or by accelerating post-mission disposal, reducing the amount of time a non-functional object remains in the orbital regime. While crewed missions have conducted servicing and repair of the ISS and other satellites in orbit, the emerging discussion of OOS to support sustainable use of space focuses on uncrewed robotic operations to extend the useful life of a satellite. In writing for the Aerospace Corporation, Hanna Duke (2021, 2) offers this description: "OOS encompasses inspecting, refueling, repairing, relocating, or upgrading a satellite while in orbit. For example, a servicing vehicle can extend the lifetime of a satellite by conducting a maintenance repair, taking over station keeping and manoeuvre functions, or transferring propellant." The US Federal Communications Commission (2024) proposes this definition of "servicing" in its notice of proposed rulemaking: "The 'servicing' aspect of ISAM includes activities such as the in-space inspection, life extension, repair, refueling, or alteration of a spacecraft after its initial launch. The term 'servicing' is also used to describe transport of a spacecraft from one orbit to another, as well as debris collection and removal."

In OOS, there is a contractual relationship between the owner of the satellite and the entity providing the service. This concept is straightforward in legal regimes, and the state licensing the activity has responsibility for the continuing supervision of this activity under the Outer Space Treaty. However, there are still legal questions to be addressed, particularly if the provider of OOS is licensed and supervised by one state while the recipient of services is supervised by another. The question of liability in the case of an accident, particularly one that results in debris generation, may be unclear.

7 See www.space.commerce.gov/regulations/commercial-remote-sensing-regulatory-affairs/.

ADR

ADR has been an exciting topic in the space community for more than a decade. While there are still promising technologies in the development stage, it is unclear when the space sector would be willing to take the risk of demonstrating their capability on a high-risk object. Kerry Buckley (2022) of the MITRE Corporation offers this caution: "ADR has the potential to help solve a massive problem and be very lucrative in the process. Unfortunately, the challenges of ADR are probably harder than many people realize, and the ramifications of failure are also likely higher than most suspect." Both OOS and ADR require robust and precise information about objects in orbit in order to conduct rendezvous operations, pointing back to the role of other commercial space safety services.

ADR is considerably more challenging than OOS; the ability to intercept a functional and cooperative satellite is easier than attempting to interact with a large, tumbling object that may contain explosive materials. The purpose of ADR is to remove high-risk objects, but the very characteristic that makes ADR worthwhile also introduces significant complexity into the mission. A current effort, ADRAS-J, conducted as part of Japan's JAXA Commercial Removal of Debris Demonstration, included an on-orbit demonstration of the rendezvous phase and beginning of the proximity approach on April 11, 2024 (Astroscale 2024), which brought the rendezvous vehicle within a few hundred kilometres of the target object. This is the first such demonstration, and the program is expected to progress this year.

ADR presents legal and political barriers that OOS does not. A derelict object remains the responsibility of the state of launch; however, that state may not have the same interest in removing the object as other operators that are absorbing the risk of a shared orbit. This is a barrier that has been overcome in the maritime domain through treaty instruments regarding salvage and the removal of wrecks; the space community should look to these models in developing tools to address such barriers.

Policy Action Can Reduce Risk in Highly Congested Orbits

Proactive mitigations require action from governments and regulatory structures. There is ongoing discussion in the space community in support of the development of norms of behaviour in space, but other than the aspirational Guidelines for the Long-Term Sustainability of Outer Space Activities, adopted by the Committee on the Peaceful Use of Outer Space in June 2019, formal international engagement on the topic has not matured.

Currently, there is no global standard that requires satellites to have the capacity to avoid derelict objects already deposited in certain regions, either by previous missions or due to orbital decay from higher altitudes. Hitherto, operator interest in protecting the asset has been relied upon to incentivize manoeuvre capability, in the hope that non-manoeuvrable satellites would avoid highly congested orbits. But this laissez-faire approach does not ensure sustainable growth. Governments should consider a more proactive stance to ensure that objects launched into congested orbits have appropriate capability based on the risk level of the desired orbit.

In the absence of established standards, operators are developing independent approaches, often through bilateral agreements, that may not be adequate in an increasingly competitive environment. For example, a 2021 Space Act agreement between NASA (2021) and SpaceX states that SpaceX will "use reasonable efforts to: Perform evasive action by on-orbit Starlink satellites to mitigate close approaches and avoid collisions with all NASA assets. These evasive actions will be performed because Starlink utilizes automated onboard collision avoidance for risk assessment and maneuver execution." This agreement gives NASA assets, including those used for human spaceflight, priority over commercial assets operated by SpaceX. While this is a reasonable approach, it is based on a contractual relationship and lacks the policy underpinnings generally associated with operational priority.

Priority can be a complex issue, particularly in a multi-actor environment. On its surface, a policy construct that grants priority to space assets with humans on board is logical and defensible, as is one that grants priority to government assets over commercial assets, since government assets are operated in the public interest. However, one must also consider that a commercial human spaceflight operation may bring the two assumptions in conflict with one another. It is reasonable to propose that a spacecraft with humans on board has priority over all other manoeuvrable space objects, regardless of whether the operator is government, but reasonable assumptions fall well short of a standard. Governments and international diplomacy have a role to play in ensuring clear and common understanding of priority. Clarity is important in establishing the burden to give way, as there is a cost associated with manoeuvring. Some benefits of establishing priority through a policy construct, rather than a bilateral agreement, are that a policy construct can resolve conflicts between commercial competitors and serve as the basis for diplomatic discussion to establish global norms. However, a priority system cannot be implemented unless operators have access to adequate information about other operators in a shared domain. Effective information-sharing systems do not evolve organically — they require design, development, funding and legal structures facilitated via a proactive government role.

Ideal systems allow operators to make independent collision-avoidance decisions by applying standardized practices based on a reasonable assumption of how the other party will respond to the collision risk. This approach is particularly important in shared international environments where communication may be limited by geopolitical considerations. In addition to clearly defined and agreed-upon norms of behaviour, a common risk tolerance is also needed. Currently, each operator is free to establish their own risk threshold, which may be influenced by the relative health of the satellite or other factors. Dan Oltrogge, chief scientist and director of the Center for Space Standards & Innovation at COMSPOC, describes the issue: "The space community has struggled over the years to identify meaningful metrics and thresholds for space flight safety. Primary considerations are the criticality of the spacecraft operator's specific mission, safety, financial, cultural, and customer needs. They are not necessarily selected with the space environment or the long-term sustainability of space activities in mind. Thus, spacecraft operators employ diverse close approach metrics and standoff distances when determining whether a collision avoidance maneuver is warranted" (Oltrogge et al. 2024, 50). As a result, the risk tolerance is unknown to the other operator involved in the conjunction scenario. However, industry representatives are advocating for proactive principles such as a common risk threshold as best practices. OneWeb, SpaceX and Iridium, facilitated by the American Institute of Aeronautics and Astronautics (2022), created a document, "Satellite Orbital Safety Best Practices," with the recommendation to "plan/arrange for mitigation actions for conjunctions that, at the point at which a mitigation action must be committed, possess a Pc greater than 1E-04 (1 in 10,000) and are based on actionable supporting data." Government can look to industry-developed standards as the basis for a regulatory structure, but it should not assume that even well-articulated industry best practices wil become standard operating practices in the absence of government support.

Looking to other domains, including air and sea, can provide insights to establish which operator is expected to manoeuvre, or give way, in a conjunction encounter. For example, aircraft or naval vessels in distress have priority over all other operations. In order for this type of provision to apply in space, there must be an established method of notifying a distress condition as part of the SSA regime. Another common principle in priority is that the more manoeuvrable operator should give way to the less manoeuvrable operator. In the water, an operator can make a visual assessment of the conflicting vessel to determine relative manoeuvrability. This is not possible in space, which reinforces the need for an adequate information-sharing regime. A spacecraft's manoeuvrability may not be obvious and may change across its lifespan, with it becoming less manoeuvrable as it gets closer to its end of life. Commercial providers of SSA that include collision avoidance recommendations need a common understanding of priority in making that recommendation decision. Standards for manoeuvre priority require an appropriate regulatory environment that ensures that a priority doctrine does not create perverse incentives for operators to suboptimize manoeuvre capability in order to gain an operational advantage over a competitor.

Regulation can be an effective tool of proactive risk mitigation. Recognizing that a highly congested orbit carries higher risk, states can subject operators seeking access to those orbits to a higher performance standard. These standards can include minimum manoeuvrability requirements, post-mission disposal, information sharing, participation in an SSA regime and on-board collision avoidance systems. While certain actors may voluntarily meet such a standard, achieving it in a highly congested orbit is unlikely if the standard is solely reliant on voluntary compliance.

Space is an international domain, and proactive risk mitigation tools cannot be left for industry to achieve alone. While it is important to engage the commercial sector in the development of best practices that lead to appropriate regulation, global harmonization of those standards requires international agreement, which is a function of statecraft. The voluntarily adopted ban on direct-ascent destructive ASAT tests illustrates that unilateral action can lead to international agreement when it centres on our collective interest of safety and sustainability. In the absence of state action, operators will seek other means to fill the gap, which carries the risk of divergent approaches emerging that may not address the risk for the entirety of the affected domain.

Conclusion

LEO from 300 to 700 km above the Earth has become highly congested through the disruptive growth of large constellations of small satellites, and this growth is expected to continue with the addition of new operators and new generation constellations. As a result, we have seen the emergence of new commercial services to mitigate growing risk in the domain. Services intended to extend the life of satellites or remove debris from the environment rely on precise SSA. Avoiding collision between operational satellites or between an operational satellite and debris requires reliable SSA and conjunction identification, as well as collision risk analysis and manoeuvre capability. So far, governments have taken a laissez-faire approach with the emergence of a nascent commercial service industry, but a more comprehensive approach that considers the specific risk of this orbital domain would increase the likelihood of a sustainable future.

Establishing minimum operational standards for highly congested orbits, including manoeuvrability and information sharing, requires government action and international collaboration. There is also a need for government to assume a role in facilitating industry standards for commercial space safety services to ensure that providers have common risk thresholds to protect the integrity of the domain, rather than relying on the individual risk-cost analysis of operators. At the same time, the capabilities of operators in highly congested orbits provide opportunities for the development of agile governance that promotes the sustainable use of space. New industries are emerging as an aftershock to the rapid congestion that may spark rapid innovation and technological breakthroughs. It is important that standards do not stifle innovation, but that must not dictate a "do-nothing" approach. Government has an important role to play in creating frameworks for information sharing, safety management, operational priority and standards development. Sustainable use of a highly congested domain is possible if modern tools of statecraft are used to shape its future.

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Waterloo, ON, Canada N2L 6C2
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