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An Examination of Incentives for Information Sharing to Accomplish Transparent Space Activities and Responsible Conjunction Avoidance

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Abstract

With the advent of mega-constellations in Low Earth Orbit (LEO), now more than ever, comprehensive information and knowledge sharing is critical to ensure space actors have equitable and undisrupted access to their operational orbits without fear of maneuvering stand-offs or the creation of more space debris. Orbit Fab in this paper will examine methods to incentivize information sharing in order to encourage responsible and sustainable use of outer space.

Identifying the metrics for space sustainability is explored in this work and used to scope what data is valuable to share. This could include fuel capacity and level, fuel type, thruster(s) specific impulse(s), wet mass, dry mass, current orbit, ideal/target orbit(s) and ConOps, lifetime station-keeping needs, predicted remaining avionics life, predicted remaining fuel life, and a variety of other parameters. These parameters can help parties understand each stakeholder's needs and interests in conflicts, and provide transparency to operational handicaps allowing them to understand each other's positions and negotiate ahead of time with the least amount of friction possible. How resolutions might be reached will be further explored in this paper along with how data sharing can be quantified to connect to sustainability-based incentive frameworks. These incentive frameworks cover concerns over privacy and competition while enabling sustainable growth that meets the needs of people on Earth and increases orbital carrying capacity.

The belief of the authors is that long term, this could be implemented with a refueling architecture and some form of 'Refueling Credit' system that could incentivize and track responsible space actors to act in good faith to keep space safe, which will be further elaborated on in this work.

Keywords: data sharing, debris, sustainability, tragedy of the commons

Acronyms/Abbreviations

3 C's Congested, Contested, and Competitive
ADCS Attitude Determination and Control System
ALoS Average Levels of Service
ASAT Anti-Satellite
Comm Communications
ConOps Concepts of Operations
DoD Department of Defense
ESA European Space Agency
GEO Geostationary Earth Orbit
ISS International Space Station
LEO Low Earth Orbit
LoS Levels of Service
MEO Medium Earth Orbit
NOTAM Notice to Air Missions
RPOD Rendezvous, Proximity Operations, and Docking
SDG Sustainable Development Goal
SSR Space Sustainability Rating
UN United Nations

Nomenclature

c Confidence Metric
P_c Percent Confidence
x Variable Shared Status
w Parameter Impact Weight

1. Introduction

Space is becoming increasingly more congested, contested, and competitive as exponentially more countries and commercial companies enter the market. Everyone wants a piece of the pie, but the current laws and regulations are outdated and offer little guidance on how to operate as a responsible space actor. The free-for-all attitude enabled by the lack of widely-accepted standards, norms, and formal policies is resulting in the overextension of space's environmental boundaries. With a little more than 5,000 active satellites, we are already seeing orbital congestion, heightened collision risks, competition for spectrum allocation, and more – and we haven't even reached a small fraction of the number of on-orbit satellites expected to exist in the next decade or so. If we don't take action now, there's little hope for us to be able to solve environmental strains in the future. These strains may lead to the Kessler Syndrome (a scenario where the amount of debris in orbit reaches a point that collisions multiply into a cascading effect and create more and more space debris) and a tragedy of the commons scenario in space where we have depleted many or all of the resources and denied access to space for future generations.

How we solve this issue has been the topic of many studies, thought leader conversations, and attempts to create policy for many years. This paper explores an incentive-based comprehensive data sharing structure as a solution to this issue, and argues that widespread industry adoption of good data sharing practices and cooperation with each other is the key to maintaining a safe and just operating space for future space growth.

First, in Section 2, this paper will examine the current state of space to discuss the driving factors behind the congested, contested, and competitive nature of space to level set the issues at hand. We also explore the concept of space as a commons – a shared resource for the benefit of all that, if not managed properly, can be depleted and destroyed.

Next, in Section 3, we create a "Space Doughnut Model" based on the terrestrial doughnut model in economics that visually depicts the safe and just space for humanity built on meeting social foundations while not overshooting Earth's ecological ceilings. The Space Doughnut Model helps us visualize the safe and just region for space growth, also built on social foundations – the 17 United Nations' Sustainable Development Goals – while not overshooting the space environment ceilings such as orbital congestion or space resource depletion. The key to maintaining that "sweet spot" ring on the doughnut model is data sharing.

Ideally, every space actor is transparent and shares all relevant data with everyone. Data sharing like this can go a long way in avoiding conjunctions, preventing the creation of more space debris, raising space environmental ceilings, and more. In practice though, completely transparent data sharing is not realistic given considerations such as sensitive information and the ability to gain competitive information from public data. To rectify this, in Section 4 we establish a "levels of sharing" rating, and to encourage players to adopt these data sharing standards, we introduce an incentives structure. A variety of different data sharing incentives are explored that symbiotically benefit each other and promote more data sharing as a whole. Ultimately, the data sharing structure benefits everyone, protects sensitive and competitive data, cyclically promotes more data sharing, and overall takes great strides toward preventing and reducing debris and other space environmental ceiling strains.

2. State of Space

In 2011, the United States National Security Space Strategy described outer space for the first time as "congested, contested, and competitive." [1] Now commonly referred to as the "3 C's", this assessment is becoming more relevant by the day. Historically, space has been dominated by a few major world players including the United States and Russia, and primarily occupied by governments for civic and military purposes. But now more than ever, new countries and commercial companies are entering the space sector at an exponential rate. While this brings about economic growth, new capabilities, and healthy competition, it is also exacerbating orbital congestion, increasing the contested nature of space, and spurring unhealthy and detrimental competition in some cases. The following subsections examine the current state of space from the lens of each of the 3 C's in order to set the scene for why data sharing is of paramount importance in the very near term. We end this section by discussing the inherent commons nature of space and how the 3 C's are increasingly leading to a tragedy of the commons scenario in space.

2.1 Congested

It is often thought that there is plenty of room in space for everyone, but the reality is far from that. In fact, space is already congested with only about 5,500 active satellites in orbit [2], and we haven't even realized a small fraction of the mega-constellations from operators like SpaceX and OneWeb who expect to put tens of thousands of satellites in Low Earth Orbit (LEO) in the coming years [2]. There is already a non-negligible collision risk for any satellite operator due to the millions of pieces of orbital debris, both natural and man-made, larger than 1 cm. That collision risk will soar as the number of satellites in orbit increases exponentially in the coming years. While this growth will largely be due to the mega-constellations, as shown in the data trends reported by Bryce Tech in Figure 1 [3], there are also a significant number of new countries and entrepreneurial start-ups entering the playing field every year who all aim to put satellites on orbit.

The risk of collision is also heightened by the ever-increasing contested nature of space that oftentimes results in nefarious countermeasures, such as anti-satellite (ASAT) tests, that create more orbital debris. The United States, Soviet Union/Russia, India and China, have at some point since 1968 designed and tested ASAT weapons. ASAT tests have a tremendously negative impact on orbital congestion. The 2007 Chinese ASAT test instantaneously created nearly 25% of all space debris that exists today [4]. In 2009, a derelict Russian military communications satellite accidentally collided with an Iridium commercial communications satellite, creating over 2,000 large pieces of debris when both satellites were catastrophically destroyed [5]. And just recently in November of 2021, Russia performed an ASAT test with one of their satellites near the International Space Station (ISS), creating over 1,500 pieces of large space debris and forcing the astronauts to take emergency shelter [6].

According to a 2009 global cross-space agency study, "even with a 90% compliance of the commonly-adopted [debris] mitigation measures…the LEO debris population is expected to increase by an average of approximately 30% in the next 200 years. Catastrophic collisions will continue to occur every 5 to 9 years." [7] Therefore, collectively identifying and adopting common standards for data sharing, cooperation, and conjunction avoidance maneuvers across the global space industry is critical for preventing the Kessler Syndrome from materializing in the coming decades.

2.2 Contested

From the very beginning, space has been a contested domain. In fact, the very reason humanity sent objects into space in the first place was to prove space-based warfighting capabilities. For most of our space-faring history, the United States and the Soviet Union controlled the majority of space-based assets, and most were used for military purposes [8]. Additionally, as noted in detail in the previous section, many world powers have been testing ASAT counterspace weapons for decades.

Space is even more contested now as wars cannot be fought without the use of space technologies – GPS, communications, spy satellites, etc. As with any terrestrial asset used during war, space assets are highly targeted by adversaries whether through physical, electronic, or cyber counterspace measures. Furthermore, now that more nations around the world are developing space capabilities – all with their own

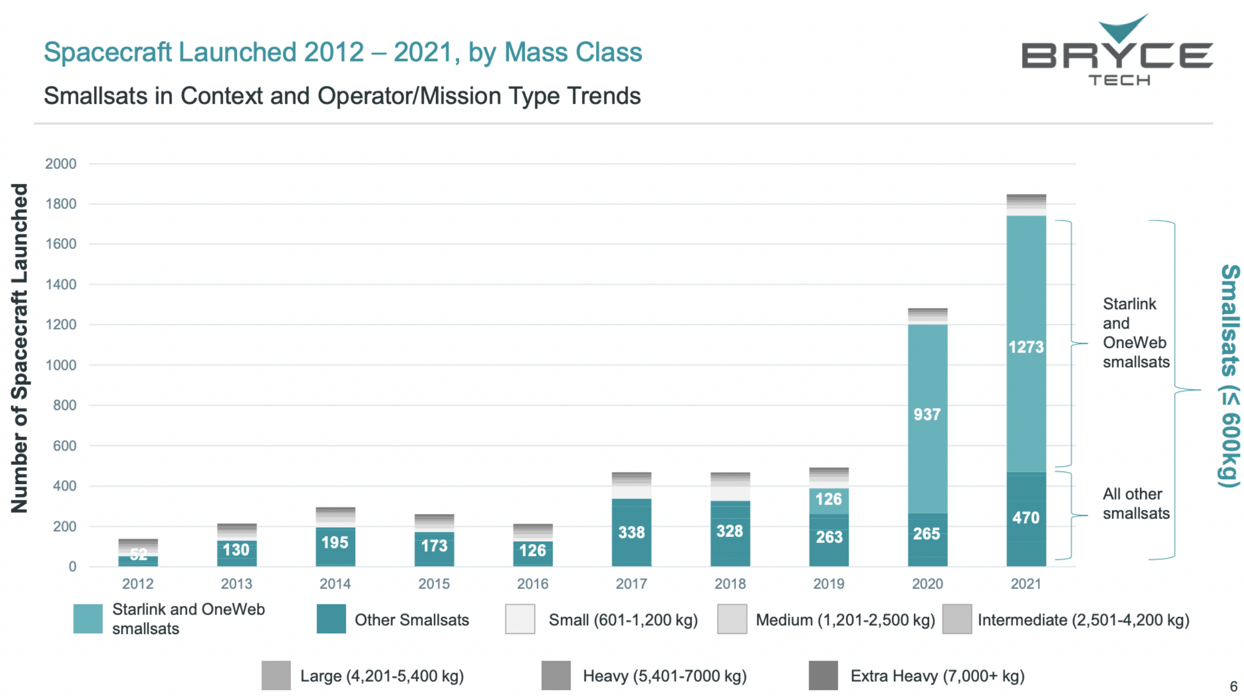

Figure 1. The number of spacecraft launched between 2012 and 2021 increased at an exponential rate, with the majority of recent satellites being LEO mega-constellations and other smallsats [3].

interests to secure prime orbital slots, space resources, and control over other celestial bodies – there are increasingly greater risks of in-space conflict and counterspace attacks. Any counterspace attack has the potential to dramatically increase the amount of orbital debris and deny sustainable and persistent use of outer space for current and future generations.

There was a major lull in ASAT weapons testing from the 1990s until the late 2000s [9]. When these activities resumed, it was mostly the actions of nations like India and China who have made tremendous progress and wanted to demonstrate the increase in space power they had attained as a show of military force. There are numerous ways data sharing and independent open source verification could enable these shows of force without the generation of debris. Current semi cooperative semi antagonist wargames are often employed terrestrially for the same purpose.

For example, in space observation by a third party could verify an ASAT weapon launched and targeting a region of empty space. This verification would provide the expected military outcome without the negative exploitation of the commons. This is similar to the embargo on active nuclear weapons testing which has not precluded the development or knowledge that new capabilities have arisen over time. The United States announced in 2022 that it will stop ASAT weapons testing which is a step towards such a future [10]. The exact methods for how data sharing solutions such as this could be sculpted will be explored in *Section 4* below.

2.3 Competitive

Space has historically been dominated by a small handful of major world powers – namely the United States, Russia, and China – and a few large space "primes" (e.g., Lockheed Martin, Northrop Grumman, Boeing, etc.). However, in the past few years, there has been a boom of new countries and commercial companies entering the space market. This has resulted in a substantial increase in the valuation of the global space industry, from $179.7 billion in 2005 to $423.8 billion in 2019 [11], and we are now seeing intense competition within the industry for resources such as talent, investment, and government contracts. This competition will only get stronger as the space industry grows to a projected one trillion dollars by 2040 [12].

The competitive nature of space extends into the physical realm as well. Orbital slots in the higher orbits like Geostationary Earth Orbit (GEO) have always been recognized as prime real estate due to their scarcity. The lower orbits like LEO and Medium Earth Orbit (MEO) have historically not been as competitive, but are quickly becoming so due to the sheer amount of satellites that have been launched in the last few years and the thousands that are planned in the near future.

While competition can be healthy at times and fuel innovation, it can also be detrimental to the orbital ecosystem. For example, collision avoidance maneuvers expend a lot of precious fuel, so a company or national agency whose satellite is facing an imminent collision with another party's satellite could say, "I'm not going to move *my* spacecraft and use *my* fuel, so you have to move yours." SpaceX may have done this when the European Space Agency (ESA) in 2019 sent them an email about a possible collision with one of their Starlink satellites. SpaceX claimed to miss ESA's email, but many saw this as a stand-off, assuming that SpaceX didn't want to have to use their fuel or expend other company resources [13]. This is a prime example of why it is imperative that we adopt a set of norms and standards throughout the industry to prevent stand-offs between companies and countries that could lead to the creation of more debris and catastrophic destruction. Currently, maneuvering satellites in space to avoid collisions represents a technical, economic, humanitarian and often tactical trade which is often made more by gut than by analysis of sufficient data.

2.4 A Commons

Many countries, including the United States and member States of the European Union, recognize outer space as a global commons [14] – a shared resource to be used for the benefit of all. However, commons are inherently susceptible to a scenario known as a "tragedy of the commons", which is defined as "a situation in which individuals with access to a public resource (also called a common) act in their own interest and, in doing so, ultimately deplete the resource" [15]. Outer space is not exempt from that risk. In fact, the increasing nature of congested, contested, and competitive space is signaling that space players are indeed acting in their own interests without much or any thought given to how their actions might deplete precious space resources, including orbital space, materials, and spectrum.

3. Doughnut Model – The Safe and Just Region for Space Growth

In order to prevent a tragedy of the commons scenario in space, we must first understand the boundaries in which we can responsibly operate in space without overshooting the environmental constraints. When extended to the space ecosystem, the Terrestrial Economic Doughnut Model shown in Figure 2 can help us define these boundaries. The terrestrial model visually depicts the safe and just space for humanity to thrive where the needs of society are being met while not overextending the ecological limitations of Earth.

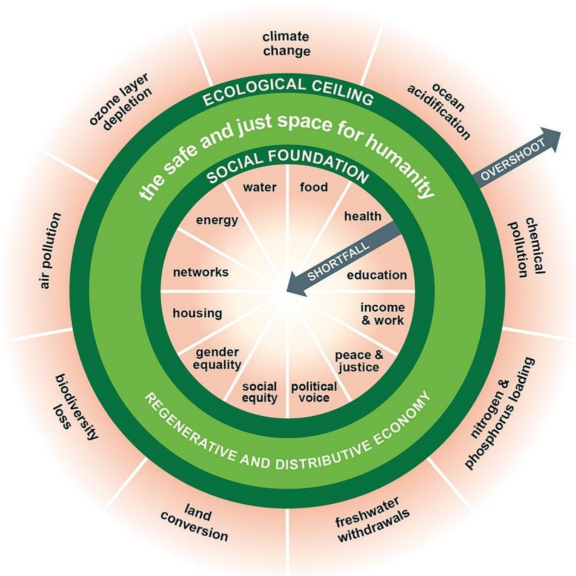

Figure 2. The Terrestrial Economic Doughnut Model provides a visual representation of the safe and just space for humanity [16].

To extend this model to the space ecosystem, we need to define the social foundations and environmental ceilings of outer space. In the Terrestrial Economic Doughnut Model, the social boundaries are a condensed version of the United Nations' (UN) 17 Sustainable Development Goals (SDG) [17], which are:

1. No Poverty
2. Zero Hunger
3. Good Health and Well-Being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation, and Infrastructure
10. Reduced Inequalities
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life Below Water
15. Life on Land
16. Peace, Justice, and Strong Institutions
17. Partnerships for the Goals

If the economy is lacking on any one of those social foundations, portions of society don't have access to life's necessities such as food, water, healthcare, and education. To determine if the 17 UN SDGs apply as social foundations for the space economy, we mapped each space market segment to each of the 17 goals, shown in Figure 3, considering whether each space market segment has an impact on the given goal.

As to be expected, each space market segment directly impacts at least one of the 17 SDGs, and as such, these goals were set as the social foundations for the Space Doughnut Model. If any one of these social foundations are not met, that is a clear indication that the space economy has some shortfalls. These shortfalls could take many forms such as not focusing on any of the right space activities, or over-focusing on one area by taking away resources from another. Ideally, all social

	No Poverty	Zero Hunger	Good Health & Well-Being	Quality Education	Gender Equality	Clean Water & Sanitation	Affordable & Clean Energy	Decent Work & Economic Growth	Industry, Innovation, & Infrastructure	Reduced Inequalities	Sustainable Cities & Communities	Responsible Consumption & Production	Climate Action	Life Below Water	Life On Land	Peace, Justice, & Strong Institutions	Partnerships for the Goals
Science	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☐	☑
Earth Observation	☑	☑	☑	☑	☐	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Communication	☑	☐	☑	☑	☑	☐	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Position, Navigation, Timing	☑	☑	☐	☑	☑	☐	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Servicing, Assembly, Manufacturing, and Power	☐	☐	☐	☐	☐	☑	☐	☑	☑	☐	☑	☑	☑	☐	☐	☐	☑
National Security	☐	☐	☐	☐	☐	☐	☐	☑	☑	☐	☑	☐	☐	☐	☐	☑	☑
Space Domain Awareness	☐	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐	☐	☐	☑	☑
Space Tourism	☐	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐	☐	☐	☑	☑

Figure 3. Mapping space market segments to the SDGs proves their applicability to the social foundations of the Space Doughnut Model.

foundations are equally and adequately supported by space infrastructure.

The upper boundary of the safe and just region for space growth is the space environmental ceilings. These are commonly discussed throughout the industry and based on physical limitations of the space ecosystem similar to the ceilings defined in the terrestrial model. For example, damage to Earth or congestion of space are two space environmental ceilings. Overshooting even one of the many ceilings can lead to a tragedy of the commons, which in turn can limit or blatantly deny access to space for current and future generations.

The Space Doughnut Model using these social foundations and environmental ceilings can be seen in Figure 4. The middle ground where we meet all of the social foundations with our space assets while not overshooting the constraints of the space environment is where we need to operate to sustain safe and just space growth with a persistently regenerative and distributive space economy. This model can also be used to visually depict the extent to which parties or markets are failing to meet social foundations or overshooting environmental ceilings. While valuable to explore for different orbital regions, that is outside the scope of this paper and will be addressed in future work.

The key to maintaining this middle ground and, by extension, ensuring all space actors have equitable and undisrupted access to their operational orbits is comprehensive data sharing. At a minimum, data sharing will allow space actors to better estimate conjunction events, prevent collisions and debris creation, and track and broadcast ongoing space

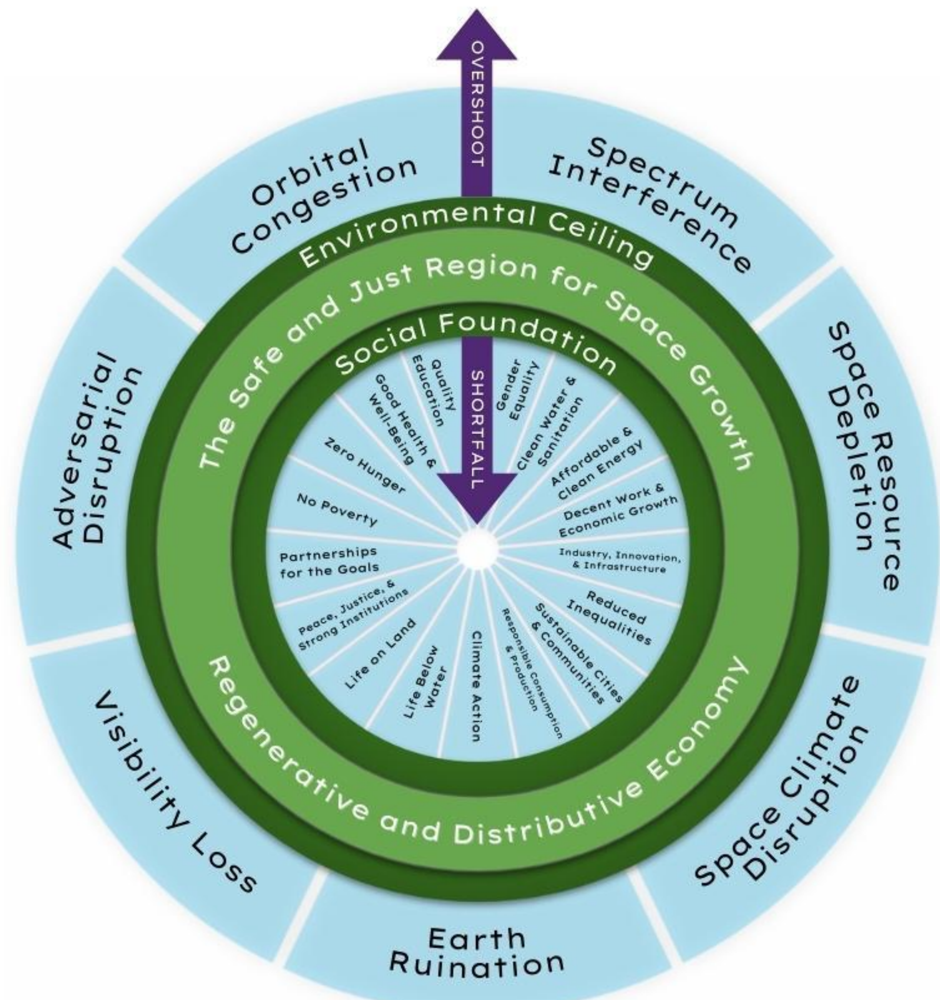

Figure 4. The Space Doughnut Model provides a framework for visualizing and the safe and just region for space growth.

activities and environmental concerns. Additionally, data sharing can help the creation of statistics databases which can aid in industry and market research to more sustainably place constellations and create new market segments. This can support ongoing operations or even invent new ones. The remainder of this paper will explore what data should be shared, how to protect competitive and sensitive data, and how to incentivize data sharing across the industry.

4. Data Sharing and Incentives Structure

4.1 What Data to Share

In short, the more data that is shared, the better we will be able to maintain the middle ground in the Space Doughnut Model and not overextend the environmental limitations of space such as orbital carrying capacity. Table 1 defines at a high level some of the many types of data that can be shared to support a healthy space economy. There will, of course, be limitations on how much is shared in reality due to considerations such as the desire to protect competitive or sensitive information. That's where levels of sharing and incentives come into play.

4.2 Levels of Sharing

One of the major concerns with data sharing is oversharing to a point where competitive or sensitive information is compromised. While actors can always "opt out" of sharing specific data parameters or sharing data with specific parties, we don't want to punish parties for protecting their business interests. Instead, we want to use each data parameter that is shared to benefit the respective party and the industry as a whole.

As such, we introduce a Level of Sharing (LoS) metric that represents how much and what data a party is sharing.

$$LoS = \sum_{i=1}^{n} x_i w_i c_i \quad (1)$$

For each satellite there are n variables that a party can share a value for, with a summation of the inputs and multipliers generating the LoS score. Each of these n variables has an index of i. The first term is x which represents a binary for whether or not a variable i was shared, with 0 meaning 'not shared' and 1 meaning 'shared'.

For each variable i there is an assigned 'parameter impact weight', w, which is calculated based on the importance of that variable in supporting sustainability, as outlined by the Space Doughnut Model, and in resolving conflicts such as conjunctions. This weight can be rebaselined as more data becomes available, as will be discussed in *Section 6* on levels of Sharing Weighting.

Of note, it is important to validate the variables provided to ensure that the information being provided isn't intentionally or unintentionally false. This validation comes in the form of variable c, which is the confidence metric. The confidence metric is a term which exists between 0 and 1 on an inverse logarithmic scale. Here 1 would mean 100% confidence in a variable's accuracy and a 0 would mean a 0% confidence in a variable's accuracy. A low confidence metric does not inherently mean that data is false, but can also mean that there is not enough information to validate the inputted value of variable

Table 1. Ideal data types to share in order to maintain safe and just space growth.

Data Type	Specifics
Spectrum	Transmitting/receiving wavelength(s), comm duty cycles
Mass	Launch, wet, dry, historic, current, future projections
Fuel	Capacity, current % full, type(s)
Thruster	Specific impulse(s), thrust(s), power required/available, firing modes/configs
Bus	Average power per mode, control authority, pointing accuracy, thermal, reflectivity
Orbits	Historic, current, future, ideal
ConOps	Operational modes, deployment dV, average operations or station-keeping dV, number of budgeted operations, operations cadence, disposal dV, fuels/thrusters used per step, operational orbits
Lifetime	Fuel lifetime remaining, avionics lifetime and margin, rad-tolerance, health index
Ground Station	Requirements for operations, duty cycle, average number of passes over period, data throughput required/available
Serviceability	Refuelable, grappleable, hot-swappable
Cost	Spacecraft cost, launch cost, operations cost over period/modes, disposal cost, revenue over period/modes
Ownership & Regulation	Country of origin, country of owner/operator, owner/operator

i. In practice, every variable i would need a separate formula incorporating the other variables, systems of equations with error bounds, external data fusion, and industry trends from external sources to validate and generate a confidence metric. This makes the confidence metric a significant undertaking which warrants further study to refine, but in principle generates significant benefit. Who assigns this metric is another topic for future discussion, but ideally it would be managed and assigned by some unbiased third party with continuing industry input.

Because more data enables more inputs to feed into confidence models, higher confidence metrics can be achieved with more data sharing. One potential method to drive this sharing would be to use a heavy inverse logarithmic scale promoting parties to share 'good data'. The equation below describes this:

$$c_i = \frac{b^{P_c} - 1}{b - 1} \quad (2)$$

Here, P_c represents the percent confidence that the value of variable i is accurate, and b represents the base for the inverse logarithm which scales it. Unscaled, a 50% confidence would equal a 0.5 confidence metric, but with $b = 10$, a 50% confidence would equal a confidence metric of 0.24, and in a normalized base 100 inverse logarithm a 50% confidence would equal a confidence metric of 0.09. Thus the scaling system effectively weights towards 'good data' without disproportionately benefiting parties who may share large quantities of 'bad data' to accomplish a better LoS score.

Regardless of the inverse logarithmic scale used, at the beginning the confidence metric will be consistently low scoring for all parties and need significant development. However, overtime as more data sources become available and as models are generated, the metric could serve as an extremely valuable secondary weight for the level of sharing and filter for the Statistics Database that will be discussed in Section 5.1.

As the intention of Level of Sharing is to inform a data sharing incentive structure, it is important to ensure that it equitably benefits parties of all scales with any number of spacecraft in orbit. Thus the equation below is used:

$$ALoS = \frac{1}{m} \sum_{j=1}^{m} LoS_j \quad (3)$$

Here ALoS represents the Average Level of Sharing where m is the number of spacecraft owned by a party and j correlates to the index of each spacecraft out of the total m, each with their own LoS calculated using Equation 1 above.

As a party launches or retires spacecraft and shares or omits data, a party's ALoS can change over time. Additionally, as both the parameter impact weight and confidence metric of each variable in Equation 1 are dynamic in value, individual LoS and thus the ALoS can increase or decrease over time as markets change and as databases get smarter. This rebaselining and dynamic system continually helps drive the industry toward sustainability and helps identify bad actors when connected to incentive structures discussed below, such as the Space Sustainability Rating.

5. Incentive Structure

To promote data sharing, one of the most important points of discussion is an incentive structure. Without an adequate incentive structure, it's nearly impossible to realize the comprehensive industry-wide data sharing practices necessary for maintaining the middle ground of safe and just space growth. We have formulated the following five incentives:

- Statistics Databases
- Business Collaboration and Innovation
- Automated Conflict Resolution
- Space Sustainability Rating
- Refueling Credits

As you can see in Figure 5, these incentives connect to the ALoS metric. In this structure, the ALoS metric helps to inform and augment each incentive, and each incentive in turn increases the overall levels of sharing across the industry. Additionally, each incentive can mutually benefit other incentives. This interconnectedness will be described in further detail in subsequent sections.

Figure 5. All incentives are interconnected and increase the overall level of data sharing.

5.1 Statistics Database

Data that has been opted for public consumption by the respective parties would be shared into a Statistics Database. When combined with data that already exists today from different databases like those from the Union of Concerned Scientists [2], this database would comprehensively keep track of activities in space, such as rocket launches and payloads, spectrum allocations and usage, historic orbits and maneuvers for spacecraft, debris catalogs and data, spacecraft use cases, party conflict resolution statistics, various shared spacecraft parameters, and much more.

The data shared into the Statistics Database could also be used to inform and scope Space Sustainability Ratings connected to the Space Doughnut Model. By pulling data from the Statistics Database, the current state of space can be significantly better and faster understood to generate effectively a report card on how well the industry or specific parties are doing at meeting social foundations and staying within environmental ceilings. Additionally, these parameters can be pulled to inform smarter conflict resolutions or the parameter impact weighting described above and elaborated on in *Section 6*.

The more a party shares, and the more parties that contribute, the better this database is. Utilizing the models discussed in *Section 4.2* to create a percent confidence along with the fusion of data sources, additional parameters could be generated and estimated with some confidence level to enhance the database. The user could then filter this constructed and inputted data sources by confidence level to cut out less likely parameters. This would significantly aid in comprehensive market studies allowing for greater and easier access to Business Collaboration and Innovation.

5.2 Business Collaboration and Innovation

A common predicament when innovating new approaches or seeking partners is that there is very little data readily available to inform data driven decision-making. To help solve this, ideally the database described above, for at least basic functionality, would be open to all. This would allow parties without significant funds or operational spacecraft to interact with the industry and ideate innovations that could support sustainability or business models.

This helps reduce the barriers to entry for small parties helping to promote greater access to space or allows legacy parties to better examine and innovate more sustainable approaches. Overall this can help increase transparency and education, demystifying many industry trends and painting a clearer picture of the state of space. When connected with the other incentives outlined in this paper, the enabled Business Collaboration and Innovation could greatly benefit sustainability.

To summarize, by enhancing and consolidating public databases, parties are significantly more capable in understanding the state of space, helping them understand what problems or markets exist today that can be benefitted or utilized to create or innovate business models at lower costs while helping the collective good.

5.3 Automated Conflict Resolution

When it comes to conjunction avoidance, ideally whichever party will incur the least amount of cost and expend the least amount of fuel should move. Over time, this efficiency promotes sustainability, decreases costs, and prevents exploitation throughout the entire industry. We also want these maneuvers to be automatically calculated with high-fidelity maneuver suggestions sent to the parties ahead of any potential conjunction. An automated conflict resolution system will make spacecraft operations easier, promote fair and sustainable actions in space, and enable parties to perform automated maneuvers without a human in the loop as several mega-constellation operators wish to achieve in the future.

Slingshot Aerospace has initiated this automated conflict avoidance coordination with their Beacon platform. Beacon ingests data from multiple sources and facilitates “the exchange of each operator's high-accuracy data, ephemeris, mission plans, maneuver plans, timelines, and constraints so that potential conjunctions are efficiently resolved.” [18] With Beacon’s real time chat and data exchange, operators can coordinate with each other to de-risk conjunctions and ultimately save time and money.

However, platforms like this can be greatly augmented with additional data that are critical for calculating the most efficient conjunction avoidance maneuvers across multiple parties including:

- Fuel performance
- Satellite lifetime limiting factors such as fuel and thrust throughput availability as well as wear-and-tear on attitude control and determination systems (ADCS)
- Financial parameters such as lost revenue from ConOps disruption, operations planning costs, ground station re-tasking costs, and overhead costs
- ConOps parameters such as fuel and time accessibility to future and ideal orbits

The more a party shares, the better their automated suggestions will be, and the less money they may have to spend on conjunction avoidance analysis or last minute, inefficient, maneuvers.

Even with an automated and high-fidelity suggestion, the party with the most efficient avoidance maneuver might not want to move. This can lead to on-orbit stand-offs as we are already seeing and expect to see more of as orbital congestion worsens. In this scenario, thanks to the incorporation of cost data that enables us to know exactly how much it costs to move a satellite out of the way now and in the future, that party could offer to pay the other party to move instead – a "pay to stay" resolution. Incentives connected to good actors resolving these conflicts are discussed further in the *Section 5.5* on Refueling Credits.

An additional consideration on the topic of conjunction avoidance is that maneuvering satellites may be generating a number of false conjunction flags while future ones are entirely missed. Having a better way to communicate and plan ahead for these maneuvers is extremely valuable especially as satellite servicing and other close proximity inspection, repair, refueling, and general rendezvous, proximity operations, and docking (RPOD)-derived in space services grow in number and in scope.

To implement a warning system, the current 'Notice To Air Missions' (NOTAM) [19] system that is in use by the United States Department of Defense (DoD) for activities such as aerial refueling [20] may be a model for this future service; tools such as Slingshot's Beacon may enable this as well. These activities are complex due to the two or three-plus party nature and possibility of RPOD activities giving the appearance of a collision-like event to third uninformed parties. As such this information distribution, including conjunction cleared flight path plans, is key to exploring the repeatability of these activities by corporate, nonprofit, and government entities and to ensure different governments are not confused or surprised leading to the escalation of in-space conflict. The authors strongly believe a "Notice to Space Missions"-like system will be an essential service to the future of space operations. Future work by the authors and others at Orbit Fab will present our findings on the best methods, information, and practices for these notifications, specifically for satellite servicing activities.

Models such as these for other types of conflicts may be studied in future work by the authors and partners to ensure comprehensive solutions are possible, but for early stages conjunction avoidance serves as a valuable and immediately important test case.

5.4 Space Sustainability Rating

The World Economic Forum's Global Future Council on Space launched a Space Sustainability Rating (SSR) in June 2022. The SSR is a composite indicator that weighs various aspects of mission design for space actors to gauge how sustainable their activities are. The current model helps assess a "missions' impact on the space environment and other operators" by incorporating:

- Detectability and Identification Tracking
- Mission Indexing
- Data Verification
- Standards and Regulations
- External Services
- Collision Avoidance Processes
- Data Sharing [21]

While this is a good start, proliferated data sharing combined with a sustainability-forward incentive structure can drive this further. Coordinating tools and platforms to actively track the manner in which actors resolve conflicts, and comparing that against changing market conditions in the Statistics Database can better reward and boost the most responsible and sustainable operators with a higher rating.

The Space Doughnut Model aims to help us maintain a space economy that is regenerative and sustainable while meeting the needs of people on Earth and protecting/improving environmental limitations. The 17 social foundations and 7 environmental limitations would provide excellent input and weighting into making sure the SSR is truly representative of its goal. This rating can be continually reweighted and baselined as the in-space economy expands, problems are solved, and new ones arise.

Additionally, a party's ALoS score should be used to inform their SSR, as increased data sharing leads to a plethora of primary and secondary benefits that can support sustainability. The ideal impact and sensitivity of ALoS on a party's level of sharing warrants further study in future work by the authors, but remains a theoretically valuable input.

Another valuable consideration is that investors for businesses have and likely will continue to use SSR as a factor in due diligence stages of the investment process. Having a dynamically updating and transparently visible SRR (rather than the static one assigned in the planning process that exists today) may be very important to both investors and companies. Investors will likely want to see that a company's behavior is responsible and sustainable, while companies will want to be seen for their good behavior and be able to use it as leverage or marketing.

As the goal of this is to reward good actors rather than punish poor ones, this SSR should be averaged across a party's total number of assets (like a party's ALoS score), ensuring that new actors have a fair chance against legacy or well-funded actors to implement sustainable practices that support the Space Doughnut Model. This can help support third-party business models and innovation in historically less-profitable segments, such as debris removal, to ensure that the environment isn't ruined and needs aren't met as a consequence of unsustainable growth.

5.5 Awarding Refueling Credits

As mentioned above, the goal is to use metrics such as the Space Sustainability Rating to reward good actors. The problem is, without concrete benefit or policies, all of these sustainable aspirations could be easily neglected until problems become too large to ignore. To get ahead of these problems and promote activities and business models which steward the space environment and UN Sustainability Goals, this paper recommends study of awarding Refueling Credits as an incentive structure.

Refueling Credits could be a great incentive option because fuel is a common commodity across all satellites, orbits, and business models. Currently, the biggest lifetime limiter and thus the biggest effective revenue/use limiter of a spacecraft is its fuel capacity. Any burn that is unplanned ahead of launch, e.g. a conjunction avoidance maneuver, reduces an asset's lifetime. Thus, rewarding actors in a unit that is directly correlated to this without the complexities of trying to guess future revenue or actual lifetime leaves fuel as one of the best metrics. By tracking conflict resolution statistics and a party's continually updating SRR, refueling credits can be awarded to the most sustainable and responsible space actors incentivizing this good behavior and pushing others to it for competitive advantage.

A great model to learn from and compare to is Carbon Credits. Carbon Credits are intended to reduce greenhouse gas emissions and reduce in number overtime. They are a tradeable and saleable asset, which benefits good carbon actors by allowing them to generate excess revenue, allowing for sustainable and unique business innovation. This same model could be used with Refueling Credits, which could in turn be used for refueling services or traded to other parties to offset or increase revenue. This offset revenue can help cover the 'Valley of Death' which many young or transforming businesses encounter. Overall this allows for greater business innovation helping new sustainable actors or market segments emerge while helping old ones to transform.

Refueling Credits should be a government-backed incentive, and there are good reasons for national and/or multinational adoption. As space becomes increasingly more crowded, the threat of stand-offs leading to the generation of more space debris can create a major multinational liability thanks to the Outer Space Treaty's verbiage that liability in space falls to nations rather than individual parties [22]. Thus there very quickly becomes competing considerations: governments want to limit liability while maintaining economic growth and national security without exceeding the environmental limitations shown in the Space Doughnut Model.

By governments creating a structure which promotes conflict resolution with backed economic gain, many of the environmental limitations that plague space can be better mitigated. This is especially true when that structure uses fuel as the common language and benefit. As one of the top limiting factors to space capabilities and lifetime, having access to refueling is a game changer. Thus as an economic incentive and reward for responsible space activity, Refueling Credits could very well be backed by a multinational or national framework. The exact mechanisms of how this might work will be explored in future work

6. Levels of Sharing Weighting

Since the Average Level of Sharing score is used as one of the inputs to the Space Sustainability Rating, to make sure this framework incentivizes the most useful data being shared, it's important that we transparently show the users what weighting each metric has on their ALoS and SSR scores. Doing this helps promote the sharing of the most critical data to the economy. However, as the economy changes, so will the data required. Therefore, having a method to not only calculate, but rebaseline the parameter impact weights of each of the possible shared data types that contribute to the LoS (described in *Section 4.2*) helps ensure that the most important data in a changing economy continues to be shared. The framework for how parameter weighting in the ALoS model can be dynamically updated is shown in Figure 6.

This model would fuse data sources and metrics to weight each input parameter based on how hiding that parameter from the model affects the solutions generated. If it's a large difference without that

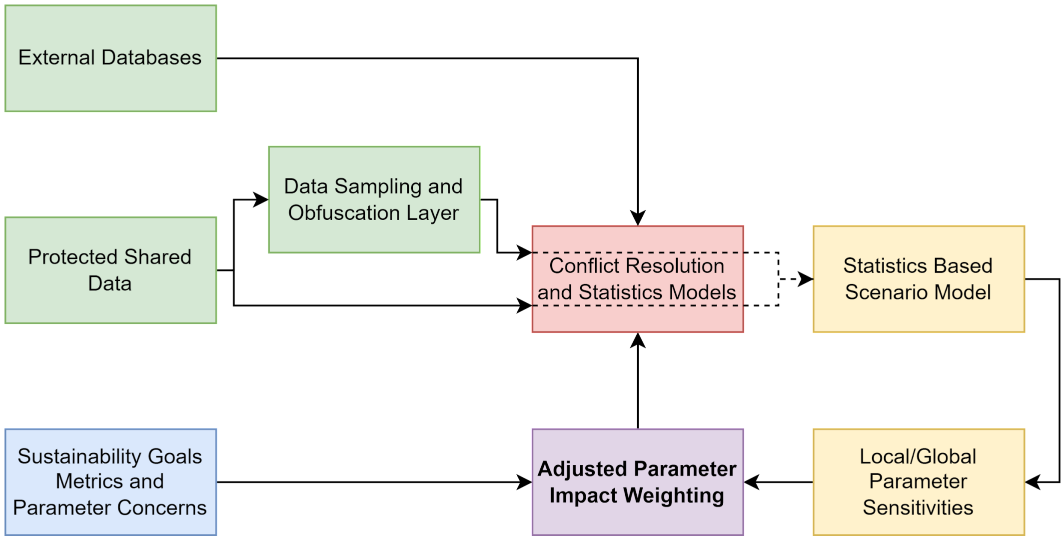

Figure 6. Framework for re-baselining Parameter Impact Weighting for LoS score.

parameter, then the weighting for it will be high. If the difference is negligible, the weight will be small.

As the in-space economy changes and new sources of information come online to fuse with the user data, the model can re-baseline the weighting to ensure that the model is asking for and rewarding the user sharing the most important data parameters.

Any data that can be derived from users benefits the capabilities and incentives structures outlined above and leads to more accurate estimations even in cases where little data is shared. As most parties would likely fall into some spectrum of "partial data sharing" to protect business models or their security, it is critically important that the data they do provide is proportionally rewarded within the incentive structure to promote as much sharing as possible. Overall, this generates inclusion based on a reward system, and attempts to protect from bad actors exploiting the system.

7. Conclusion

Comprehensive data sharing is important to ensuring a transparent and sustainable space economy that supports people on Earth without verging into destructive temporary growth that inhibits persistent, long-term growth. A number of solutions around incentives and how they might be implemented are discussed, but further work and feedback is required to understand how these methodologies could be implemented and in what contexts they're best suited. For now, the Space Doughnut Model serves as a great resource in trying to understand what data is important to help solve congested, contested, and competitive space problems without causing a tragedy of the commons.

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