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The Space Sustainability Rating: An operational process incentivizing operators to implement sustainable design and operation practices

Adrien Saada[a*], Emmanuelle David[a], Florian Micco[a], Jean-Paul Kneib[a], Mathieu Udriot[a], Danielle Wood[b], Minoo Rathnasabapathy[b], Dennis Weber[c], Francesca Letizia[c], Stijn Lemmens[c], Moriba Jah[d], Simon Potter[e], Nikolai Khlystov[f], Miles Lifson[b], Kristi Acuff[b], Riley Steindl[b] , Maya Slavin[b]

[a] *École Polytechnique Fédérale de Lausanne (EPFL) eSpace, Switzerland*
[b] *Space Enabled Research Group, Massachusetts Institute of Technology (MIT), United States*
[c] *European Space Agency (ESA), Germany*
[d] *The University of Texas at Austin, United States*
[e] *BryceTech, United-Kingdom*
[f] *World Economic Forum, Switzerland*

[*] Corresponding Author: Adrien Saada Email adrien.saada@epfl.ch

In 2021, more than one million objects larger than 1cm are orbiting the Earth, including a large number of artificial inactive objects. These objects, also referred to as space debris, are posing significant challenges to current and future operations in the space environment as well as risks on Earth, in case of loss or disruption of space-based infrastructures or activities due to a collision. In recent years, a growing number of actors, and plans of large constellations are emerging in a complex regulatory landscape in which standards, norms, and guidelines need to be enforced. There is consequently a critical need to consider implementing tools that will incentivize space actors to foster responsible behaviour and implement debris mitigation measures in order to ensure long-term sustainability of the space environment.

The Space Sustainability Rating (SSR) was first conceptualized within the World Economic Forum's Global Future Council on Space in 2016, with the goal of providing a standardized and flexible tool to measure the sustainability level of a mission. In 2019, an international, transdisciplinary consortium composed of BryceTech, the European Space Agency (ESA), the Space Enabled Research Group at the Massachusetts Institute of Technology (MIT) Media Lab, the University of Texas at Austin, and the World Economic Forum (WEF) was appointed to lead the development of the SSR design and methodology. The SSR provides an assessment tool to encourage mission designs that are compatible with sustainable and responsible operations, as well as on-orbit behaviours that reduce potential damage to the orbital environment and impact on other operators. Designed as a composite indicator, the SSR consists of six modules highlighting key related decisions faced by space operators in all phases of the mission. In 2021, eSpace - the EPFL Space Centre has been selected to host and operate the SSR, which went live in June 2022.

This paper will provide a short overview of the SSR methodology and modules. An emphasis on use cases will be presented, highlighting how the SSR scoring methodology constitutes an incentive for satellite operators to implement sustainable behaviours. The operational rating process of a mission will be also presented, including a description of the input gathering phase, computational phase, and results communication phase. Finally, the SSR recommendations and feedback loop will be presented, showing how rating's results are analysed and how several areas of improvement can be identified and incorporated in the rated missions.

Keywords: Space Sustainability Rating, Space Debris, Sustainable behaviour.

Acronyms and Abbreviations

ADOS	Application of Design and Operation Standards
ADR	Active Debris Removal
CCSDS	Consultative Committee on Space Data Systems
COLA	COLision Avoidance
DIT	Detectability, Identification, and Trackability
EPFL	Ecole Polytechnique Fédérale de Lausanne
ES	External services
ESA	European Space Agency
GEO	Geostationary Orbit
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Standardisation Organisation
ITU	International Telecommunication Union
LEO	Low Earth Orbit
MI	Mission Index
MIT	Massachusetts Institute of Technologies
NDA	Non-Disclosure Agreement
OOS	On Orbit Servicing
SSA	Space Situational Awareness
SSR	Space Sustainability Rating
UN	United Nations
WEF	World Economic Forum

1. Introduction

During the past decade, the global space economy experienced a major disruption. The overall costs to build, launch and operate satellites decreased and allowed both a growth of the number of commercial space actors and a diversification of the mission's architectures, especially in low earth orbit (LEO). The emergence of new space players and constellation missions resulted in an increase of an order of magnitude in the number of operational satellites in orbit in less than ten years (see Figure 1).

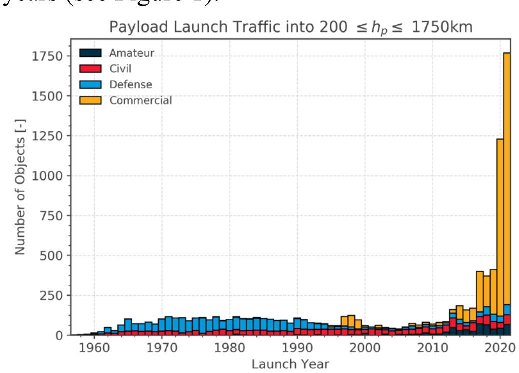

Figure 1: Payload launch traffic in LEO [1]

As the number of objects in orbit is increasing and will continue to do so, space traffic management challenges are rising in crowded orbits. Fragmentations events can imply severe consequences on the long-term use of given orbital shells. There is consequently a critical need for operators to take actions to design and operate missions in a way that will mitigate their impact on the space environment, and reduce risks.

In that regard, a consortium of organizations led the development of the Space Sustainability Rating (SSR) and selected eSpace – EPFL Space Center to host and operate the rating system in June 2021. The SSR provides a series of metrics to measure the sustainability levels of satellite missions (focusing on space debris mitigation), as well as recommendations on how to improve and incorporate best advised practises. The rating system aims at supporting an operator's adherence to existing guidelines and incentivizing positive behaviours by rewarding operators taking actions to mitigate the impact of their missions on the space environment. Comprised of six modules and including a data verification process, the SSR encompasses different aspects of space sustainability such as the risk mitigation achieved by the planned mission design, the spacecraft's ability to be detected and tracked, the operator's collision avoidance capabilities, the sharing of spaceflight related data, the compliance to existing space debris mitigation guidelines and standards, and the use of new solutions towards On-Orbit Servicing (OOS) or Active Debris Removal (ADR). After a three-year development process including beta-testing with satellite operators, the first official rating was delivered on 23 June 2022 at the occasion of the 4th Summit for Space Sustainability in London.

Previous SSR related papers [2], [3] focused on the scoring methodology and the definition of the different modules. As such, only an overview of the rating methodology will be featured in the following section. This paper will for its part provide an emphasis on several test cases as well as on the rating process, and how it aims at incentivizing sustainable design and operations.

2. General SSR Methodology

As described in Rathnasabapathy et. al. [2] and [3], the Space Sustainability Rating comprises a tiered scoring system that recognizes efforts and incentivizes sustainable building and operation practises. It is based on a points aggregation system in which more points contribute to a higher rating. It is formulated as a combined score based on the evaluation of individual modules, where different aspects of space sustainability are covered. Any satellite mission can be rated, regardless of the number of satellites, type of orbit, or mission phase. A rating shall remain valid for a given mission phase and shall be re-evaluated when entering a new mission phase. Additional re-evaluations can also be requested by the SSR applicant if changes are to be implemented, as it will be presented in section 4.3.

Prior to an SSR evaluation, compliance with prerequisite questions are necessary. These questions address the bare minimum standards that an operator must perform to achieve a particular SSR, and were informed by the Inter-Agency Space Debris Coordination Committee (IADC) [4] guidelines. They include compliance with post-mission disposal, passivation, intentional debris generation, and creation of a space debris mitigation plan. These prerequisite questions also request the operator to confirm a willingness to share baseline spacecraft information with the SSR issuer over the rating period. Operators who cannot achieve compliance with these questions, or who are unwilling to provide the necessary information to the SSR issuer may be limited to a lower tier of rating or denied a rating even if they would perform strongly in other categories.

2.1 SSR modules

The Space Sustainability Rating is a composite indicator that encompasses six different modules [2]. For the purpose of this paper, only a brief description of each module is provided. Additional references are provided for in-depth details and scoring methodology.

(i) Mission Index (MI)

Any mission and object associated therewith leaves a trace in orbit. In the best case, it is just using a portion of the space environment sustainably. In the worst case, it will cause harmful interference with other objects in the environment.

This module quantifies the level of harmful physical interference, intended as the risk of potential generation of space debris, caused by the planned design and mission operations considering mission characteristics, collision avoidance strategy, and post mission disposal strategy. More details about the mission index will be provided to explain the rationale of the test cases that will be studied in Section 3.1. References [2] and [5] are providing an overview of the mission index module while references [6], [7], [8], and [9] are providing an in-depth description of the debris index methodology developed by ESA.

(ii) Collision Avoidance Capabilities (COLA)

In absence of a perfect space surveillance capability and depending on the operators' capabilities, there are various ways a mission can choose to operate in a congested environment. This module aims to emphasise the steps which can be taken by operators to reduce the risk of accidental collision with debris and among active operators. This module is a questionnaire which is further described in references [2] and [10].

(iii) Data Sharing (DS)

Sharing of space situational awareness and other information by operators is critical to space safety. At the same time, some operators have sensitivities about sharing certain kinds of information. In other cases, operators simply do not share certain information, but have no particular objection to potentially doing so. This module quantifies the amount of relevant information an operator shares with various communities and the contribution of this information to spaceflight safety. More details about the module's methodology can be found in references [2] and [11].

(iv) Detectability, Identification, and Trackability (DIT)

Small objects which might be operational but cannot be reliably included in space surveillance and tracking products form a risk to other objects in the space environment. Moreover, identification is required for registration and liability purposes. This module aims to cover these aspects. As space surveillance and tracking capabilities improve and become more accurate in tracking satellites, this module is expected to undergo updates with each SSR version. This module is based on a simulation and computed by the Space Enabled Research Group at MIT and the University of Texas at Austin. More general details about the module's methodology can be found in references [2], [12] and [13].

(v) Application of Design and operation Standards (ADOS)

Successfully addressing the problem of space sustainability when it comes to avoiding the creation of space debris and operating in congested environments can only be achieved by means of common understanding and objectives. As such, a part of the SSR emphasis is placed on the adoption of standardisation concepts in design and operations where possible. Standardization is a continuous process based on the availability of technologies and understanding of the environment. As such, changes in the standards need to be included when releasing a new SSR version and the implementation is considered relevant for bonus ratings where they are not mandatory. More details about the module's methodology can be found in references [2] and [14].

(vi) External Services (ES)

Innovations taking place in the area of close proximity operations have the potential to improve space sustainability and as such are of interest. However, their application can be widely different for individual mission concepts. As such, they are considered relevant for bonus ratings. As external services develop and are successfully proven and utilized, the External Services module of the SSR will be updated accordingly. More details about the module's methodology can be found in references [2] and [15].

2.2 SSR weighting

Each module is individually evaluated and weighted according to the importance relative to space sustainability criteria. The weights (Table 1) were defined from an iterative process following the beta testing but could be revised as part of the future evolutions of the SSR [16].

Table 1: SSR Modules Weight

Modules	Weight
Mission Index	50%
Collision Avoidance Capabilities	16.5%
Data Sharing	16.5%
Detectability, Identification and Trackability	12%
Application of Design and Operation Standards	5%
External Services	Bonus[1]

2.3 Data Verification

As presented in Rathnasabapathy et al. [3], *"an over-arching verification assessment is implemented in the SSR design to allow satellite mission owners to provide information to confirm that their responses to the SSR questionnaire is high quality. A satellite mission owner can choose to verify their responses by providing related technical documents; providing materials from official filings about the mission submitted to a regulatory body; by providing technical documents generated by a third party or by providing evidence of a review of their documents by an independent technical expert. A verification weighting will be attached to inputs provided by the operator to both reflect the SSR issuer's confidence that its assessment of the operator or system's conformance with various SSR requirements is accurate and to incentivise entities to provide better verified data as part of their submission."*

In that regard, the different levels at which each and every information of the SSR evaluation can be verified are requested. Table 2 shows the weighting associated with each verification levels. As the verification levels weights are applied to each input of the SSR, the impact of the data verification assessment on the score is significant. Figure 2 shows the cumulated score of a same mission with the exact same SSR inputs, but using four different overall levels of verifications.

Table 2: SSR Verification levels and weight

Level of verification	Factor
Assertion Affirmative statement by the applicant is provided, without supporting documentation	0.5
Technical documentation supporting the assertion Supporting technical documentation on the mission design is disclosed to the SSR Entity	0.6
Public release of the technical documentation Supporting technical documentation is submitted to a government or non-profit available for public review	0.8
Authority – Independent technical Review An independent technical review or the confirmation of the compliance by a third-party technical expert is provided	1

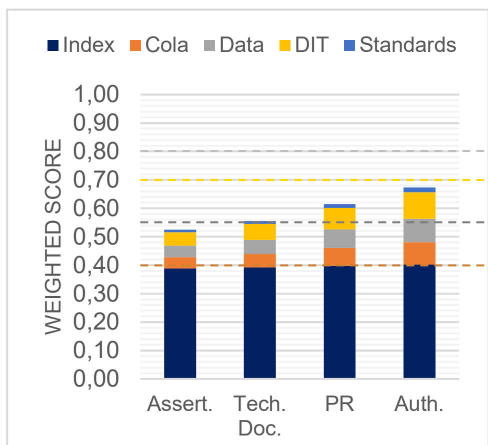

Figure 2: Aggregated tier scores for a simulated mission, with four different overall levels of data verification

As it can be seen for this fictive simulated mission[2], a significant increase of the score (approximatively 15% in

[1] See 2.3

[2] Small satellite operating in LEO orbit (about 500km altitude), no post-mission disposal other than natural decay, limited collision avoidance capabilities, data sharing of most of the satellite characterization information and contact information with SSA providers and other operators upon request resulting in an intermediate level of data sharing. More test cases with detailed analysis on the input impacts will be studied in section 3.

this case) can be achieved by operators that can justify the technical accuracy of the information provided to the SSR issuer. As such, missions that are at an early stage of development will, in most cases, be naturally limited as their envisioned design and operation measures will most likely not be verified at the highest level of verification. These missions will however benefit from the support of the SSR issuer to identify their possible areas of improvement and scoring potential early in the mission development based on the initial evaluation.

2.4 SSR Score aggregation and results

Following the individual evaluation of each module, the data verification process and the application of the weights as defined in Table 1, a single tier score value comprised between 0 and 100% is computed as well as a bonus score, also comprised between 0 and 100% (including bonus inputs and modules, such as External Services). The bonus scores are 'additional credit', aimed at recognising actors who take sustainable design and operational decisions and actions in areas that are still emerging, or are too new to be defined in rigid terms in the SSR tiers (e.g. OOS). The process is described in Figure 3.

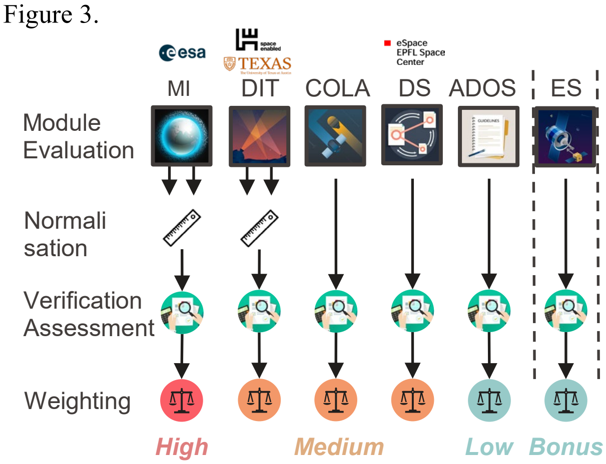

Figure 3: SSR score aggregation methodology

In the case where an SSR applicant earns a sufficient tier score (Table 3), an SSR badge (Figure 4) is awarded to the mission.

Table 3: Tier levels based on the SSR score

Tier level	Score
Bronze	Between 40% and 55%
Silver	Between 56% and 70%
Gold	Between 71% and 80%
Platinum	Between 81% and 100%

Figure 4: Space Sustainability Rating badges (Tier score)

In a similar manner, the Space Sustainability Rating allows applicants to be rewarded with a bonus "Step" indicator (Table 4), which highlights certain steps a mission can take to 'go over and above' the baseline rating. It is pictured by the inclusion of bonus stars on the side of the main badge (Figure 5). Bonuses are reported separately and do not contribute to the baseline rating of a requesting entity.

Table 4: Bonus step levels based on the SSR bonus score

Bonus step	Bonus Score
One bonus star	Between 25% and 50%
Two bonus stars	Between 51% and 75%
Three bonus stars	Between 76% and 100%

Figure 5: Space Sustainability Rating badge (Bonus score)

3. SSR use cases

This section will focus on the study of several use cases and show the impact of the selected parameters on a mission's score using several modules of the SSR. As the mission index accounts for 50% of the rating score, the study will focus on this module in section 3.1. An extended study will be performed including all modules of the rating in section 3.2.

3.1 The Mission Index as an incentive to implement Post-Mission Disposal

The mission index module is taking advantage of the space debris office debris index developed by ESA that quantifies the level of harmful physical interference caused by the planned design and mission operation. It measures the impact of a space mission on the space environment, using the Environmental Consequences of Orbital Breakups (ECOB) formulation [5]. The mission index is a risk indicator characterized by the general expression $Risk = Probability \cdot Severity$ considering mission characteristics, collision avoidance strategy, post mission disposal strategy and success rate.

The index value (I) is a risk indicator computed using a model simulating the state and behaviour of all space objects including the planned mission. This index value is normalized considering the space environment capacity [9] in order to provide score between 0 and 1 for the mission. A high index corresponds to a strong impact on the space environment and consequently results in a low mission index score.

A simplified formulation of the index at a given epoch is:

$$I = p_c \cdot e_c \text{ [5]}$$

Where the probability term p_c captures the likelihood that an object is involved in a collision event and the severity term e_c quantifies the consequences of such an event [9].

The risk metric is however not computed at a single epoch, but rather evaluated along the mission profile of an object, up to the end of its orbital lifetime. In particular, this is done by considering the possible paths of evolution of the trajectory depending on the success rate of the disposal strategy (α). In that regard, the index formulation becomes [7]:

$$I = \underbrace{\int_{t_0}^{t_{EOL}} I_{operation}\, dt}_{\text{Operational Lifetime}} + \underbrace{\alpha \int_{t_{EOL}}^{t_{f_D}} I_{disposal}\, dt}_{\text{PMD success}} + \underbrace{(1-\alpha)\int_{t_{EOL}}^{t_{f_{ND}}} I_{abandonned}\, dt}_{\text{PMD failure}}$$

Where t_{EOL} represents the epoch of end of operations, t_{f_D}, $t_{f_{ND}}$, the minimum between 100 years (simulation upper limit) and the epoch of re-entry in the case, respectively, where the object is disposed and in the event where it is not disposed (i.e. abandoned in its operational orbit).

The previous expression highlights the importance of a post mission disposal strategy implementation, with a high success rate. A post mission disposal will both significantly reduce the index value I since in most cases, the disposal orbits will:

1. Be less crowded, resulting in a lower collision probability risk and hence a lower index value (i.e. a better mission index module score); and
2. Reduce the lifetime in orbit (time interval from t_{EOL} to t_{f_D}) , resulting in a smaller integration interval and a reduced index value (i.e. a better mission index module score).

The previous formulation is defined as "absolute" index and accounts for 80% of the SSR mission index score.

Additionally, 20% of the mission index score corresponds to a "relative" score, that is a ratio of the absolute index over a baseline scenario of the exact same spacecraft(s) in a scenario compliant with a 25-years natural decay rule (for LEO missions) with a 90% post mission disposal success rate. This relative part of the mission index allows to reward operators that are implementing better than required behaviours.

In order to better understand what are the impact of the planned design and operations on the mission index score, test cases were defined using a limited set of parameters to allow for a reasonable number of simulations. As a high number of small satellites are set to be launched in LEO in the coming years, studying mission with similar spacecraft characteristics is of great interest for this paper. The parameters defined in Table 5 were hence used to perform the use cases.

Table 5: Use cases spacecraft and mission fixed characteristics

Spacecraft characteristics	
Mass (kg)	320 kg
Cross sectional area	1.75 m^2
Inclination	98°
Operational lifetime	5 years
Deployment (for constellations)	Within 1 year

It has also been considered that the levels of verification levels for the mission index inputs were set as "Authority – Independent technical Review". The cumulated impact of the verification levels on the rating's score will also be studied in section 3.2.

Other mission parameters were defined in order to compare the impact of the orbit and number of satellites. The number of satellites in the mission is used, as well as two different operational circular orbits altitudes, and different post-mission disposal scenario. The first altitude is 500km and is is naturally compliant with the 25 years disposal rule, whereas the second altitude, 1200km, is not. The post-mission disposal success rate is also considered, 90% being the baseline of the IADC guidelines [4], and 99% being used as a best-practise. The goal of the study is to compare a "best-practises" scenario against a "minimal effort" scenario in term of post mission disposal (PMD) and collision avoidance (COLA) strategy for different orbital regimes. The parameters mentioned are summarized in Table 6:

Table 6: Use cases variating mission parameters

Mission parameters	
Number of satellites	1
	10
	100
Operational altitude	500 km
	1200 km

Targeted End of Life altitude	Perigee lowering to 100km (near-immediate re-entry, considered as a good disposal practise).
	Circular disposal orbit at 600km (minimal compliance with the IADC 25 years rule for LEO satellites with an A/m ratio of 0.005 m^2/kg)
	No disposal (but still compliant with the 25 years rule)
PMD Success rate	99%[3]
	90% (IADC baseline)
Mitigated Collision risk	90% (The collision avoidance strategy allows to mitigate 90% of the collision compared to a case where no maneuvers are performed)
	0% (No collision avoidance capabilities)

Different mission scenarios were defined from these parameters with the goal to compare minimal levels of compliance with the existing space debris mitigation guidelines ("minimal effort"), and "best-practises" scenarios for both single satellite missions and constellations. The following scenarios were hence defined as follows:

(i) "Best-practises" vs. "minimal effort" impact on single satellite missions

The first analysis compared test cases at both 500 km and 1200 km operational altitudes using different end of life scenarios:

- A "best-practise scenario":
  - Perigee altitude lowered at 100km after the end of operations;
  - 99% PMD success rate; and
  - Collision avoidance to reach a mitigated collision risk of 90% (see Table 6)
- A "minimal effort" scenario:
  - No perigee altitude lowering for operational orbits at 500km (already compliant with the IADC baseline);
  - Altitude lowering to a 600km circular orbit (IADC baseline for a A/m=0.005 m^2/kg spacecraft [4]) for the 1200km operational orbits; and
  - 90% PMD success rate (IADC baseline).

A summary of the test cases performed are presented in Figure 6 and the results of the simulations are presented in Figure 7 and Table 7.

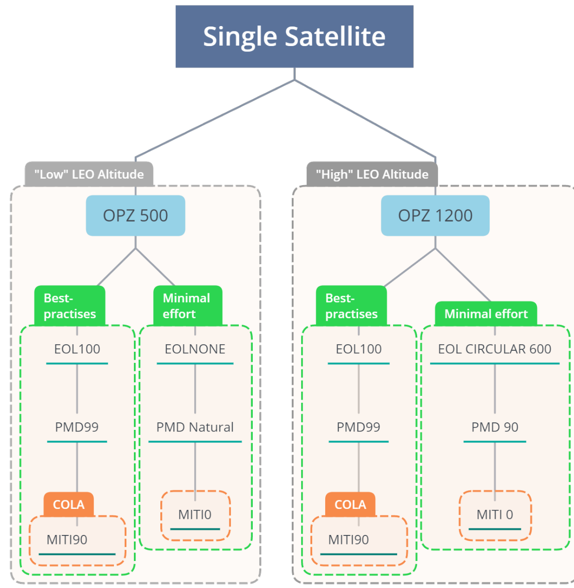

Figure 6: Single satellite mission index test cases

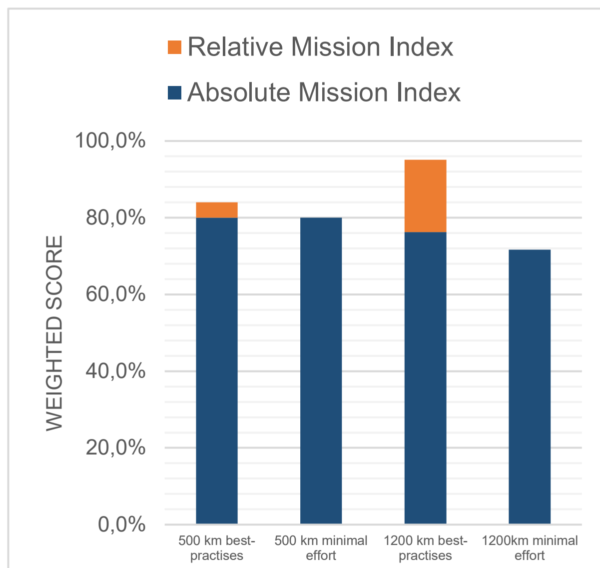

Figure 7: Best practises and altitude impact on the mission index score for single satellite missions (cumulative score)

Table 7: Best-practises and altitude impact on the mission index score for single satellite mission (index values)

Test cases	Absolute	Relative	MI Score
500 km best-practises	100%	19.9%	**84%**
500 km "minimal effort"	100%	0%	**80%**
1200 km best-practises	95.3%	94.2%	**95.1%**
1200 km "minimal effort"	89.6%	0%	**71.7%**

[3] A 99% post mission disposal success rate is considered as a best practise as it seems more adapted to a stable evolution of the space environment, especially for large constellation missions operating at altitudes that are not naturally compliant with the 25 years rule.

As expected, the scores of the “best-practises” scenarios are higher than the “minimal effort” scenarios. Additionally, the mission index score difference between best-practises and “minimal effort” is about 4% for the 500km operational altitude scenario, whereas it is 23.4% for the 1200km scenario. This is due to the fact that a single satellite mission operating at a 500km altitude not taking any mitigation actions already has a relatively small impact on the space environment in terms of collision severity (over the entire lifetime of the object), as a natural decay will occur in a short period of time. On the other hand, the variability of the 1200km case is much higher as the natural decay period is substantially longer both resulting in an increase of the collision probability and the severity of such an event. The disposal strategy used by the operator hence have a stronger impact on the mission index score.

One can notice that the 1200km best-practises test case score is higher than the 500km best-practise scenario due to the high relative mission index score. Indeed, the relative mission index (20% weight within the module) is a ratio of the absolute index over a baseline scenario complying with the 25 years rule. By lowering the perigee at 100km, the orbit clearance of the 1200km orbit is much faster compared to a case where the orbital lifetime of the object is 25 years, resulting to a high relative mission index score. The scoring methodology of the mission index hence put an emphasis on the implementation of best-practises for missions operating in the most critical orbits, that would have a large impact on the space environment if no action is taken.

(ii) Best practises vs. “minimal effort” impact on multiple satellites missions

Best-practises and “minimal effort” scenarios were simulated in a similar manner to compare the effect of multiple satellites missions, namely 10 and 100 satellites respectively. These simulation use-cases are summarized in Figure 8 and results are presented in Figure 9 and Table 8.

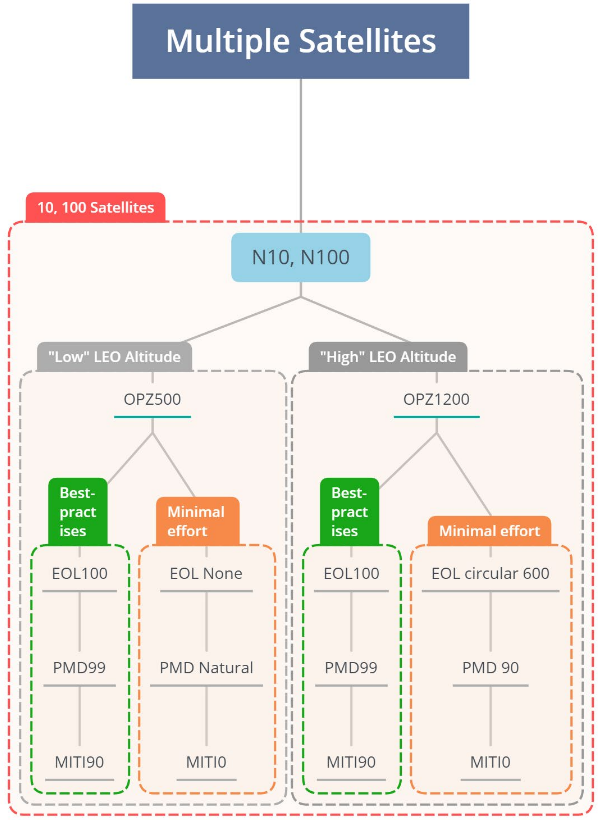

Figure 8: Multiple satellites mission index test cases (8 cases total considering 4 scenarios for both 10 and satellites)

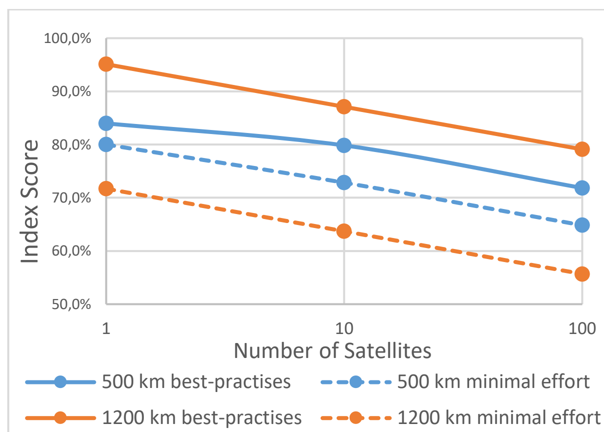

Figure 9: Number of satellites impact on the mission index score for best-practises and “minimal effort” cases

Table 8: Best practise impact on the mission index score for multiple satellite missions (index values)

Test cases	Number of satellites		
	1	10	100
500 km best-practises	84%	79.6%	71.8%
500 km “minimal effort”	80%	72.8%	64.8%
1200 km best-practises	95.1%	87,1%	79.1%
1200 km “minimal effort”	71.7%	63,7%	55.7%

The single and multiple satellite test cases show similar scoring patterns but the scores are slightly lower for the multiple satellite missions. This is due to the inherent impact of the number of satellites on the probability and severity of a collision. It is however important to note that for a 1200km orbit, the score difference between the “minimal effort” and “best-practises” scenarios are averaging 23.4% regardless of the number of satellites. The previous simulations are showing that by following the best practises on collision avoidance and post-mission disposal, despite a high number of satellites, the impact of a mission on the space environment can be reasonably low, resulting in a high mission index score.

The mission index encompasses for 50% of the SSR score. The following section will hence focus on an extended study on all SSR modules.

3.2 Complete SSR tests cases

As in the previous section, a comparison of “best-practises” against “minimal effort” scenarios were performed, also extending the analysis to other SSR modules. The spacecraft and orbit parameters of this study are that used in Section 3.1. Only 1200km operational orbit for both a mission containing single satellite and constellation missions are analysed in this section. A simplified summary of the inputs used to perform the analysis is presented in Table 9.

Table 9: Extended “best-practises” and “minimal effort” test cases considering all SSR modules (summarized inputs)

Module	« best-practises » scenario	« minimal effort » scenario
Mission Index	Perigee lowering to 100 km with a 99% success rate	Disposal to a 600km circular orbit with a 90% success rate (IADC baseline [4]) as defined in section 3.1
	90% Mitigated Collision risk (definition in Table 6)	No collision avoidance is envisioned as part of the normal operation
COLA	Orbital state knowledge of objects maintained within < 1 km in any direction until the spacecraft is placed into graveyard orbit or is disposed through atmospheric re-entry. Orbit determination of the operated satellite is updated when a manoeuvre or other event induces a change to the orbit that would cause the operator’s state estimation to be worse than the required orbital state knowledge. Covariance of the orbit determination is characterized/validated	Third party public SSA provider is used for state information
	A system for routine conjunction assessment is implemented, with capability to respond to concerns 24 hours per day via human or computer system capable of supporting near-immediate coordination and reaction for urgent issues.	Ability to coordinate in response to emergencies only (but not necessarily on a routine basis)
	Documented procedures is implemented for collision screening, assessment, and mitigation Operational spacecraft and planned manoeuvres are regularly screened against SSA sharing organization catalogues.	No dedicated process for conjunction screening, assessment, or mitigation. The operator may be unable to or chose not to ever manoeuvre in response to conjunctions
Data Sharing	The same information is shared with both SSA providers, other operators upon request, network of operators, and with the public	Most the data sharing inputs (defined in [2], [11]) are shared with an SSA provider only
DIT	Satellite is detectable and trackable, custody of the operated satellite is maintained by the operator of contracted SSA provider within 1 day of deployment and thereafter Verifiable radiometric and photometric data are shared by the operator with the SSR issuer (bonus points).	Satellite is detectable and trackable but the operator relies on Space-track or other third-party public SSA providers
ADOS	Total compliance to the IADC [4] or UN space debris mitigation guidelines [17], compliance to either a verifiable national space debris mitigation national law or ISO 24113 [18], compliance to CCSDS on orbit data message [19] or	Partial compliance to space debris mitigation guidelines (IADC or UN), compliance to ITU-R regulations

	conjunction data message [20], compliance to ITU-R regulations	
	Any debris released as part of the operations is smaller than 1 mm	Debris are released by the spacecraft or launcher as part of the operations
	Explosion risk is characterised and kept under 10^{-3}	Explosion risk is not characterized
	Spacecraft is passivated	Spacecraft is not passivated
	Launch vehicle chosen is disposed through atmospheric re-entry directly after the satellite's deployment	Launch vehicle chosen to deploy is passivated and placed into a disposal orbit
	Payload and associated objects are registered in the UN COPUOS space's Register of Objects Launched into Outer Space	
External services **(Bonus)**	OOS features are installed in preparation to create a fail-safe option. Examples include but are not limited to visual fiducials, standardised interfaces, grapple fixtures, mechanical fixtures, grasps features and items to make it easier to track the object in case of radio failures such a beacon.	None

Using these inputs, the rating scores were computed from different mission parameters:

- Number of satellites:
  - Single satellite mission
  - 100 satellites mission
- Levels of data verification:
  - Authority – Independent technical review ("Auth." In Figure 10, Figure 11)
  - Technical documentation supporting the assertion ("Tech: Doc." In Figure 10, Figure 11)

The results for a single satellite mission are displayed in Figure 10 and Table 10.

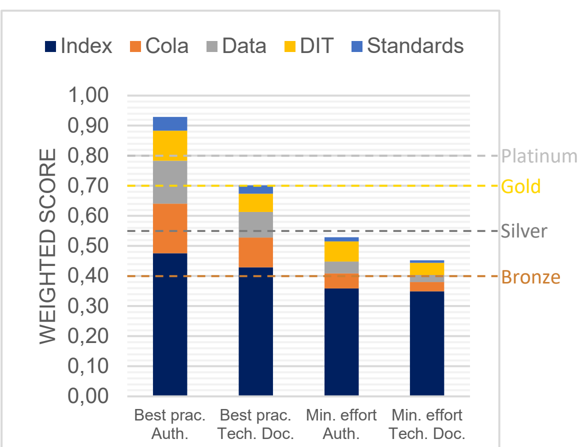

Figure 10: Single satellite mission full SSR computation for best-practises and "minimal effort" scenarios, at different levels of data verification (cumulated score)

Table 10: Single satellite mission full SSR computation for best-practises and "minimal effort" scenarios, at different levels of data verification (score values)

Modules	Test cases			
	Best practises	Best practises Tech. doc	Min. effort	Min. Effort Tech. Doc.
MI	95,1%	85,8%	71,7%	69,9%
COLA	100,0%	60,0%	30,6%	18,3%
DS	86,5%	51,9%	23,9%	14,3%
DIT	83,3%	50,0%	55,6%	33,3%
Standards	92,8%	55,7%	28,6%	17,2%
External	50,0%	30,0%	0,0%	0,0%
Tier	**93,0%**	**70,1%**	**52,9%**	**45,2%**
	Platinum	**Gold**	**Bronze**	**Bronze**
Bonus	**74,5%**	**43,7%**	**5,3%**	**3,2%**
	2 stars	**1 star**	**0 star**	**0 star**

One can notice that following the best-practises for a same mission (same spacecraft, same operating orbit) results, depending of the data verification level, in scores ranging from 70.1% to 92.9% (Figure 10) which corresponds to either gold or platinum ratings. It shows that following the best-practises allows a mission to reach the highest SSR tiers.

The "minimal effort" scenarios (as defined in Table 9) were designed to be compliant to what is currently expected from operators: deorbiting within 25 years (LEO), sharing crucial spaceflight related data with SSA providers, compliance with major space debris mitigation guidelines. For a single satellite mission, the scores resulting for the analyses are ranging from 45.21% (Technical Documentation verification level) to 53.93% (Authority verification level). This corresponds for both uses-case to a bronze rating without any bonus star. Such mission is considered, as defined in Rathnasabapathy et. Al. [2], to "meet the pre-requisite requirements to apply for an SSR [...] demonstrates willingness to increase mission's sustainability" but that "current sustainable practices need to be incorporated into the mission".

The variability of the score between a best-practises scenario with the highest level of verification and the "minimal effort" with a "technical documentation supporting the assertions" verification level is approximatively 47.8%. The score range is shown to be heavily dependent on the operator's willingness to implement the currently advised best-practises supplemented by evidence of such an implementation.

A similar analysis was performed for a 100 satellites mission and the results are displayed in Figure 11 and Table 11.

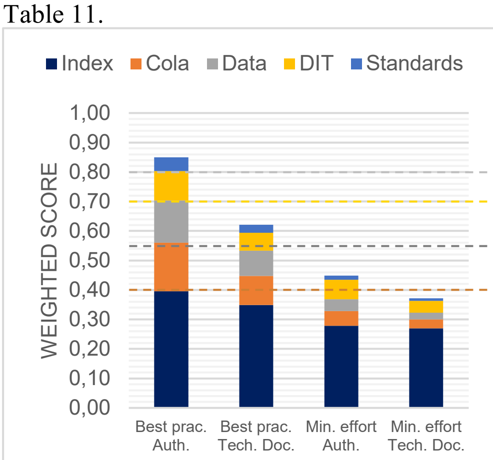

Figure 11: 100 satellites mission full SSR computation for best-practises and "minimal effort" scenarios, at different levels of data verification (cumulated score)

Table 11: 100 satellites mission full SSR computation for best-practises and "minimal effort" scenarios, at different levels of data verification (score values)

Modules	Test cases			
	Best practises	Best practises Tech. doc	Min. effort	Min. Effort Tech. Doc.
MI	79,1%	69,8%	55,7%	53,9%
COLA	100,0%	60,0%	30,6%	18,3%
Data	86,5%	51,9%	23,9%	14,3%
DIT	83,3%	50,0%	55,6%	33,3%
Standards	92,8%	55,7%	28,6%	17,2%
External	50,0%	30,0%	0,0%	0,0%
Tier	**85,0%**	**62,1%**	**44,9%**	**37,2%**
	Platinum	**Silver**	**Bronze**	**None**
Bonus	**74,5%**	**43,7%**	**5,3%**	**3,2%**
	2 stars	**1 star**	**0 star**	**0 star**

Similarly to the previous analysis, the 100 satellites missions also has a 47.8% variability between best-practises with an "Authority" verification level and minimal-effort with the "Technical Documentation" level of data verification. The best-practises scenario with the "Authority" level of data verification achieves a score of 84.96%, corresponding to a platinum rating. On the contrary to the previous analysis however, the "minimal effort" scenario with a "assertion supported by technical documentation" level of data verification does not meet minimal score to validate a bronze rating.

It is interesting to note that a 100 satellites mission, that presumably has a stronger impact on the space environment than a single satellite mission due to its higher number of assets, is able to secure a platinum tier score. The ratings levels of best practises and "minimal effort" scenarios range from the highest tier (platinum) to a scenario where no rating tier is achieved. The scoring methodology hence shows that operator's actions induce a large variability on the SSR score, meaning that the operators are incentivized to take actions to increase their SSR score, and by extension, to ensure a minimal impact of the mission the space environment.

As part of this study, a limited number of test cases were performed but a deeper study considering different satellite's characteristics and orbits would be needed to obtain more granularity on the parameters impact on the score. The orbit considered for this analysis are not particularly crowded, hence, the collision avoidance parameters has a marginal impact on the score compared to the disposal strategy. A similar analysis at a polar orbit near 800km altitude could reveal the importance of the collision avoidance strategy. This study mainly focused on LEO, but the methodology is also applicable to GEO, considering the relevant design and operations best practises for this orbital regime. Despite a limited number of use cases, similar scoring patterns are expected on different orbits and with different spacecraft characteristics when using best-practises and "minimal effort" scenarios.

4. The SSR Process

The comparative analysis conducted in Section 3.1 and 3.2 highlights that following best-practises results in higher rating scores, even for missions with a large number of satellites and with different altitudes. Based on the experience working with different operators on evaluating their missions, it was deemed necessary to supplement the scoring with a feedback process by the SSR issuer that helped operators identify areas of improvement, as well as incentives for implementing the improvements that would lead to higher SSR scores and hence the mission's sustainability.

This section will detail how the rating process constitutes an incentive for operators to apply for a rating.

A rating is divided in three main phases:
(i) Contractual phase;
(ii) Input gathering phase and computation; and
(iii) Feedback and re-computation loops

4.1 Contractual phase

The contractual phase sets a legal framework for performing a rating. This part of the process is crucial, as the SSR is voluntary and requests satellite operators' data to perform an assessment. Whereas the Space Sustainability Rating promotes transparency between space stakeholders, it is not mandatory for participating operators to publicly share any mission related data. In that regard, a Non-Disclosure Agreement (NDA) between the parties is signed in order to protect any sensitive mission information provided by the applicant to the SSR issuer used in order to compute a rating. Along the NDA, a rating agreement describing the role of each party is also signed between the satellite operator and the SSR team.

This initial phase is designed to incentivize operators to participate in the SSR, knowing that it will act as a third-party evaluation of their sustainability level performed without disclosing sensitive mission data or proprietary information. The results of the evaluation are the applicant's property. It is consequently the operator's decision to publicly communicate the results of the rating, which is encouraged to increase transparency and convince more operators to evaluate and enhance their sustainability level.

4.2 Input gathering phase and computation

In order to compute a rating, many different information, or "inputs" are needed from the applicant. A list of the requested information can be found in [2]. Assistance is provided to operators to be introduced to, and familiarized with the different rating inputs and requirements. Once all of the latter are available to the SSR issuer, the computation of the score can be performed.

4.3 Feedback and re-computation phase

(i) Scoring results

After the first computation of the score, results are communicated to the applicant and based on the rating score, a badge is awarded to the applicant (Figure 4) as well as a rating certificate (Figure 12). These documents are acting as formal recognition of the applicant participation and outcome in a rating.

Figure 12: Rating certificate for a simulated mission

(ii) Score analysis and recommendation report

Alongside the results, the SSR team also issues a score analysis and recommendation report, allowing the applicant to have a more detailed understanding of the score of each module, and to identify areas for improvement.

In the scope of this report, a separate analysis is performed by the SSR team including modifications of the applicant's input according to recommendations that could be implemented to the mission. A projected score is computed including this new set of recommendations and is compared to the initial score (Figure 13, Figure 14).

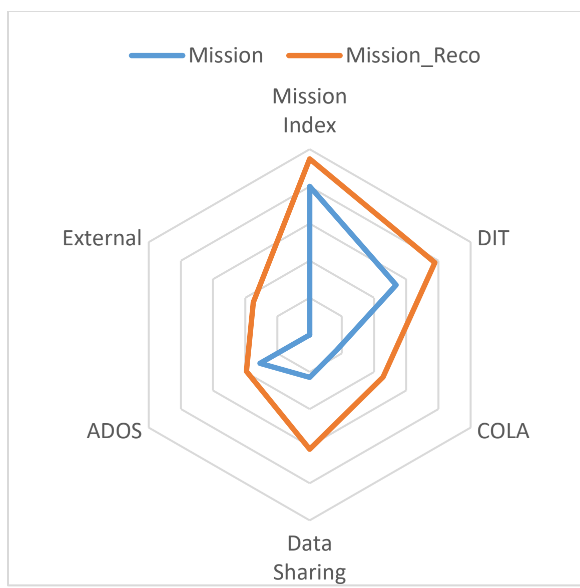

Figure 13: Module score comparison (for visualisation) between the actual mission and the scenario including recommendations

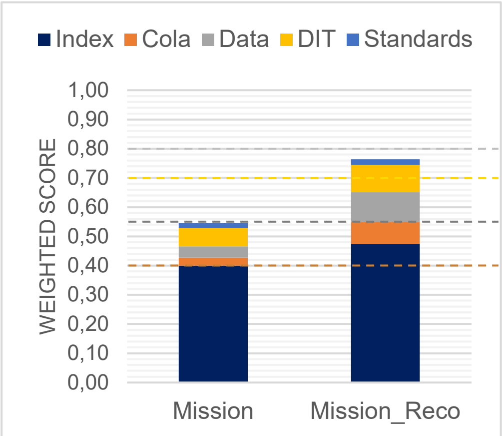

Figure 14: Aggregated tier scores of a simulated mission and projected tier score of the same mission including recommendations

As the Space Sustainability Rating emphasizes both design and operation practises, the recommendation does not necessary imply major changes to the satellite design or mission architecture. The beta-testing phase of the SSR showed that quick gains contributing to a score increase (and hence, to more sustainable behaviours) can usually be identified. Those gains can be achieved on several areas, including for instance the verification levels of the inputs provided to the issuer, more transparency in the data sharing, alignment with existing guidelines, etc.

(iii) Feedback and re-computation loops

Based on the recommendation report, the operator can decide to incorporate any recommendations into the mission. In that case, a score recompilation is performed by the SSR issuer to account for the operator's effort and the new score is issued. The SSR goal is to allow the operator to identify areas for improvement as well as incentivize to implement the currently advised best-practises. By performing recompilation of the score in case of inclusion of a recommendation, operators can reach higher scores, ultimately resulting in more sustainable behaviours.

4.4 Summary, timescale

Based on beta-testings, a rating is usually computed within 3 weeks from the initiation of data collection (excluding the contractual phase). The most time-consuming step being the correct completion of the input file as the operators need to familiarize with the SSR methodology and understand what information is expected. After a first rating computation, the recompilation of a score is relatively straightforward, depending on the amount of input change. The process including the different phases described in the previous section is summarized in Figure 15.

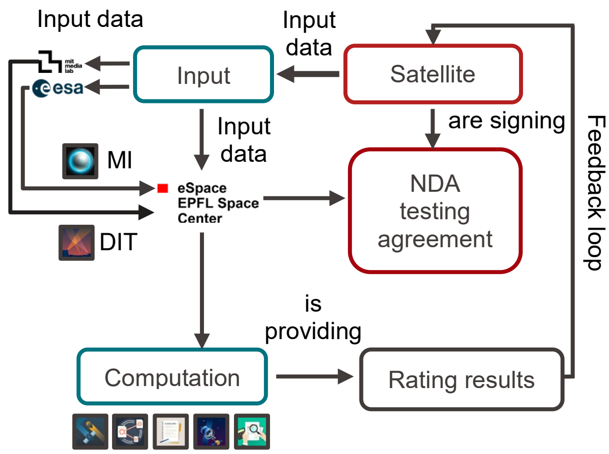

Figure 15: SSR process diagram

5. Conclusion

As new challenges are emerging from the disruption in the number of objects that will be sent to space, the Space Sustainability Rating offers an innovative approach to space debris mitigation. It provides an assessment system enforcing existing guidelines and incentivizing operators to implement sustainable behaviours.

The Space Sustainability Rating methodology showed, through beta-testings and first ratings, to be a robust assessment system. It has been demonstrated, in the analysis performed as part of this study, that the SSR allows operators to score in a large range of tiers depending on their design and operation choices. The analysis showed that the highest SSR tier level (platinum) can be achieved, regardless of the number of satellites or the altitude, as long as best-practises are followed.

Various types of parameters have an impact on the SSR score: data sharing, collision avoidance strategy and processes, post-mission disposal strategy, compliance with existing guidelines, detectability and trackability, verifiability of the mission's information, etc. These parameters mainly depend on the operator's decision, and induce a large variability in the SSR score. The operator's actions and decisions therefore have a significant impact on the rating's outcome, underlining the goal of the SSR to act as an incentive tool.

This paper studied the impact of a limited set of parameters using simulated mock mission data. In future work, performing more simulations with different spacecraft characteristics, a wider range of altitudes and more granularity in the input parameters would allow operators to better understand on which parameters to focus to be more sustainable based on their mission design. Performing more ratings with actual mission data would also allow to build a strong database that could be used (in an aggregated and anonymised manner, and with the agreement of the rated organizations) to analyse the state of the art of space sustainability, according to the SSR criteria.

The SSR process does not solely consist of performing one assessment of the mission's level of sustainability, but rather supports the operators to identify areas for improvement and measures to implement. This part of the process is crucial as it incentivizes operators, through multiple score computations, to take actions to make their mission more sustainable. The Space Sustainability Rating consequently consists, by both its methodology and its process, of an active incentive in which operators are encouraged to participate to increase transparency, drive positive impact and contribute to space sustainability.

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