DOI: 10.13009/EUCASS2023-432
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Promoting responsible space practices: A primer on the Space Sustainability Rating

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Abstract

More than one million objects larger than one centimetre are currently orbiting the earth. Among them, less than one percent are active satellites, leaving an overwhelming majority of the orbital population being composed of inactive objects, also referred to as space debris. As the space industry is developing rapidly, a growing number of actors and plans for large constellations are emerging in a complex regulatory landscape where best practices, guidelines, and norms need to be enforced. Latest long-term simulation of the space environment suggests that the absence of a behavioural change towards a more responsible use of the space would result in an unstable environment, in which the collision rates would increase exponentially. 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.

In that context, the Space Sustainability Rating (SSR) has been developed since 2019, and is operated by a non-profit organisation. The SSR is an innovative tool that aims to promote a responsible and sustainable use of outer space. It supports satellite operators such as governments, space agencies, and commercial companies, to understand the impact of their activities on the space environment, and to identify opportunities to reduce those impacts. The SSR is a rating system based on a set of criteria that cover a range of areas, including the mission's collision risk footprint, collision avoidance and post mission disposal strategies, data sharing, compliance to existing standards, detectability and trackability, and readiness to on-orbit servicing and removal. As the SSR went through a beta testing phase in which the rating methodology and process were streamlined and fine-tuned, the first official ratings were delivered in 2022.

This paper provides an updated guide to the SSR, covering the process for using the rating system, including the steps involved in completing and maintaining a rating valid. It explains the background and purpose of the SSR, and outlines the key principles that underlie the rating system. A description of the rating computation among the different scoring categories is also being discussed. It describes its various modules, including the scoring methodology of the quantitative modules used to evaluate space activities. It is hoped that this updated guide will provide a useful resource for space actors looking to understand and use the SSR, and will help to promote the long-term sustainability of outer space activities.

Keywords: space sustainability, space debris, rating, guide

Acronyms

ADOS	Application of Design and Operation Standards
ASO	Anthropogenic Space Object
CAD	Computer Aided Design
COLA	COLlision Avoidance capabilities
CONFERS	COnsortium For Execution of Rendezvous and Servicing operations
DIT	Detectability, Identification, and Trackability
DS	Data Sharing
ECOB	Environmental Consequences of Orbital Breakups
EOIR	ElectrO-InfraRed
ES	External Services

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GSN	Ground Sensor Network	PMD	Post Mission Disposal
IADC	Inter Agency space Debris coordination Committee	RAAN	Right Ascension of the Ascending Node
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference	SSR	Space Sustainability Rating
MI	Mission Index	STK	Systems Tool Kit

1. A general introduction to the Space Sustainability Rating

The current launch traffic in Low Earth Orbit (LEO), as of end of 2023, is 27 times higher than it was ten years ago. While more than 80% of active payloads are located in this orbital region, it also comprises 96% of the total payload fragmentation debris [1]. This accumulation of debris and active satellites poses significant risks for the rest of the environment, as well as challenges and increasing costs due to an growing number of conjunction alerts. Recent long-term extrapolation scenarios [2], [3] suggests that the current launch traffic coupled with a minimal desirable level of compliance with space debris mitigation guidelines will lead to an unstable environment with collision rates increasing exponentially within the next 200 years. In a context where it is necessary to adopt more sustainable behaviours for space activities, most of the guidelines and best-practises are non-binding and need to be enforced. The Space Sustainability Rating (SSR) system was therefore developed with the purpose to incentivize satellite operators to implement more sustainable design and operation practises

Since the first developments of the SSR system, many testing and ratings have been performed and contributed to gather feedback on the importance of transparency when it comes to communicating on the rating methodology. As previous work [4], [5], [6], [7] provides insight on the rationale for the SSR, a description of the modules methodology, of the rating process, as well as use cases, this work intends to summarize and provide an updated guide: a primer on the Space Sustainability Rating. As the SSR methodology is intricate and cannot be detailed in a single academic paper, additional references are provided when necessary and the SSR team encourages readers to consult these references to have a deeper understanding of certain specific concepts.

1.1. Goal of the Space Sustainability Rating

1.1.1. Scope:

As of 2023, the SSR provides an assessment of the sustainability level of a *satellite mission*, operating in *Earth's orbits*. As an applicant can operate many different missions that will have different architectures, number of spacecrafts, or designs, the rating is applicable to a *mission*. A mission is defined by the SSR as a functional unit of spacecraft, launch vehicle, and mission related objects aimed at providing a specific service, by means of design and operations, for which they need to access and use part of the space environment. A mission can consist of a single satellite, a satellite and a launch vehicle, or combinations of these elements. The rating is computed considering the contribution from all the objects. (single satellite, a satellite and launch vehicle, or a larger combinations of these elements, e.g. several satellites and launch vehicles).

The Space Sustainability Rating is a tool whose goals are to: (i) incentivize and promote for further adoption of current guidelines for space debris mitigation and space sustainability by allowing satellite operators to understand their level of compliance with currently advised best-practises; and (ii) provide recommendations to satellite operators on how to implement more sustainable design and operation practises. The SSR is a *voluntary initiative* in which satellite operators are *willingly participating*, both enabling the evaluation of the level of implementation of space debris mitigation measures in their missions by an independent, unbiased third-party entity, and allowing the communication of their sustainability performance to the large public. The core objective of the SSR is to serve as a transparent tool that facilitates comprehension of measures required to mitigate the impact of a specific mission on the space environment. This accessibility empowers operators, regulators, policy makers, investors, and insurers to make informed decisions and take appropriate actions.

1.1.2. Rating tiers and labels:

As described in [4], [5], [6], [7], 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 (described in section 2), where different aspects of space sustainability are covered. The output of a rating is

DOI: 10.13009/EUCASS2023-432

a set of scores, the main one being the tier score allowing the mission to be awarded a rating label, as show in Figure 1 (left side). The Space Sustainability Rating allows applicants to be rewarded with a bonus "Step" indicator (second score mentioned above), 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 1, right side). Bonuses are reported separately and do not contribute to the baseline rating of a requesting entity. The SSR tiers and bonus steps are achieved for the scores indicated in Table 1.

Figure 1: Space Sustainability Rating tier labels on the left, and bonus steps (for a gold rating) on the right.

Table 1: Tiers and bonus levels based on the SSR tier and bonus scores

Tier level	**Tier** Score	**Bonus** Step	**Bonus** Score
Bronze	Between 40% and 55%	No bonus star	Between 0% and 25%
Silver	Between 56% and 70%	One bonus stars	Between 25% and 50%
Gold	Between 71% and 80%	Two bonus stars	Between 50% and 75%
Platinum	Between 81% and 100%	Three bonus stars	Between 75% and 100%

1.2. Rating Process

1.2.1. Prerequisite questions:

Prior to any 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) guidelines [8]. 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. Here below is the list of prerequisites questions for the SSR:

- Will your mission comply with IADC guideline 5.3 for post mission disposal?
- Do you commit to passivate your spacecraft at the end of operations, as defined in IADC guideline 5.2.1?
- Do you have a space debris mitigation plan, as defined in the IADC guideline 4?
- Does your mission avoid the intentional destruction of any space object?
- Do you commit to provide supporting documentation to the SSR issuer during the rating process?

Each question can be answered with "Yes", "No", or "Partially", in which case the operator will be requested to provide a rationale for answering the latter.

1.2.2. Score computation steps:

Whereas the entire SSR process includes contractual phase, computation phase, as well as a post-rating phase for communication [7], this work will exclusively describe the technical rating computation steps. Each SSR score computation follows the following steps (Figure 2): data collection, data verification, score computation, feedback loop.

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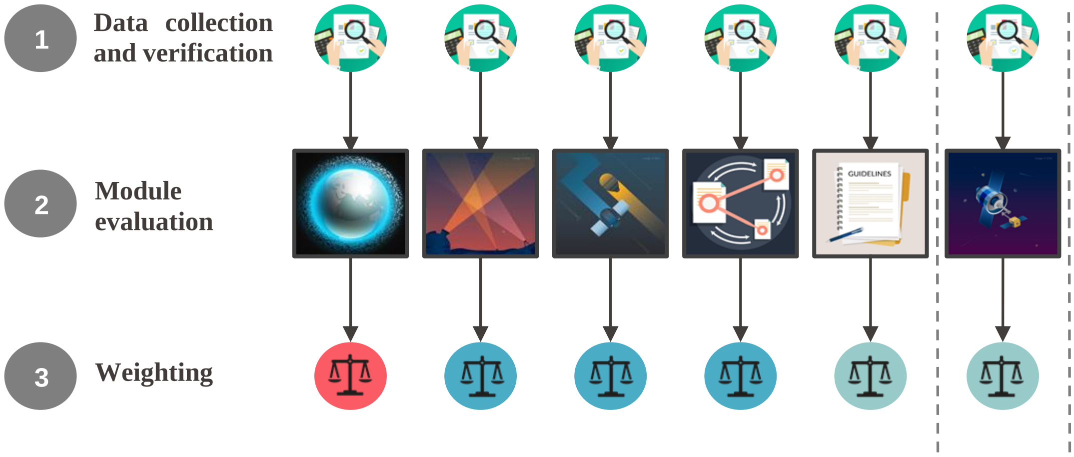

Figure 2: Space Sustainability Rating process diagram (from data collection to score computation)

a. *Data collection:* The SSR is a voluntary initiative. In that regard, no score can be computed without mission data being provided by the operator to the SSR issuer. The first step following the prerequisites questions then consists in collecting the mission data for the computation of each modules. In order to maximize the positive impact the SSR can have, it is primordial that the data necessary to compute a score is easy to obtain to obtain for and from satellite operators. In other words, the data shall be accessible at any mission phase, as well as easily shareable with the SSR issuer. In that regard, SSR focusses on system capabilities rather than satellite design features (e.g. an applicant will have to identify the probability of successfully implementing post mission disposal procedures, and inform the SSR issuer on the method used to compute this probability, but not disclose technical implementation details such as sub-system design).

b. *Data verification:* As the SSR data verification process is extensively detailed in both [4], [5], [6] and [7], only a reminder is described in this work. It is assumed that the SSR application does not involve an in-depth review of the mission design. Instead, emphasis is placed on the level of verifiability of the data provided. The SSR evaluation uses a data verification process in order to ensure the quality and accuracy of data provided that will be used to assess compliance with various rating criteria. Operators can verify the data 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. For *each SSR criteria* contained in the questionnaire, a *weighting is to be attached* to the verification of the applicant's statements, which will be traced through the SSR issuer's use of that information. In other words, the points earned for a given input are computed as $points_{earned} = p_{input} \times factor_{verif}$ with Table 2 summarizing both the definition and the weight ($factor_{verif}$) associated with each the level or verification. The number of points awarded for each input differs and can be found in past work ([4], [5], [6]) as well as on the SSR website ([9]).

Table 2: SSR verification level description 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

c. *Score computation:* The computation methodology of each module is applied, as described in section 2. Based on the score of each modules, the final tier score is computed using the weights as defined in section 2, Table

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4. The bonus score is simply the total number of bonus points earned divided by the total number of available bonus points.

d. *Feedback loop:* Additionally to the rating score and badge awarded based on the rating score, the SSR issuer performs an analysis after the mission's evaluation and issues a set of recommendations (e.g., Table 3) based on the results of the rating. This analysis is provided to the SSR applicant by the issuer. Each recommendation issued is associated with a potential score increase and allows the SSR to act as an incentive tool for operators to implement more sustainable design and operational practises. The final score after potential implementation of the recommendations is also reported. A visualization of the module score increase for a mission with and without the recommendations is presented in Figure 3. During each rating process, the SSR issuer allows *one score recomputation* taking into account that some recommendations can be directly implemented. This way, an entire feedback loop can be performed as part of an evaluation and satellite operators can use the SSR as an actionable tool to increase the sustainability level of their mission. Based on previous ratings performed, the SSR team has noticed that issuing reasonable[1] recommendations for most missions resulted in their implementation. Additionally, even in cases where missions were already operating and satellite design modifications were not possible, operational practices such as data sharing were successfully implemented.

Table 3: example of a recommendation list as provided by the SSR issuer ("MI", "COLA", "DIT" refers to module names as defined in the acronyms, data in the tab are hypothetical).

Recommendations	**Description (mock data)**	**Score increase (module)**	**Score increase (Tier[2])**
MI_1	Accepted Collision Probability Level threshold could be lowered to 10^{-5} in order to achieve a mitigated collision risk of 90%.	+3.5%	+1.75%
MI_2	Verification level of disposal success rate can be improved to "public release of the technical documentation".	+6.6%	+3.3%
DataSharing_1	Regular updates of satellite operational status to SSA providers could be implemented.	+4%	+0.66%
COLA_1	Documented procedure for collision screening could be implemented.	+12%	+1.98%
DIT_1	Enhance custody maintenance of the spacecraft to track it 1 day after deployment and thereafter.	+5%	+0.6%
…		…	…
Total SSR Score increase			**+8.29%**
New tier			**Gold**

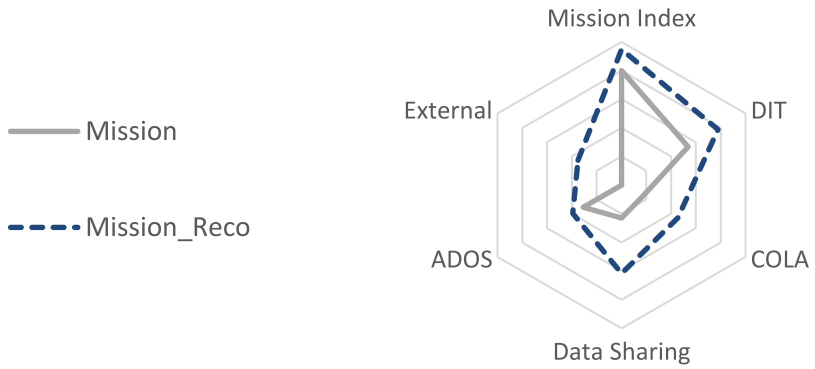

Figure 3: Module score comparison (for visualisation) between a given mission ("Mission") and the scenario including the implementation of the recommendations ("Mission_Reco")

[1] Reasonable in the sense that a mission already in orbit for instance cannot change past events, nor satellite design.
[2] The tier score is different than the module's score since each module is weighted as defined in section 2, Table 4.

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1.3. Mission phases, rating validity

Whereas significant changes on the design of a mission are more likely to happen in the preliminary definition phases, the SSR can evaluate missions at any development phase, even in the case of a mission already in orbit, or terminated. In fact, regular evaluations of a mission by the Space Sustainability Rating is encouraged, and necessary for maintaining the validity of a rating over time. As for any rating scheme, monitoring is essential in order to ensure the trustworthiness of the evaluation. A rating score consequently has a *validity period of 12 months*, after which a re-evaluation needs to be performed to ensure that the mission still comply to the SSR criteria at the same extent. Re-assessment are also opportunities for operators to improve their score if recommendations issued during the first assessment are implemented in the mission.

2. The rating modules

The Space Sustainability Rating is a modular evaluation that encompasses several different rating categories, or modules. Those modules are associated with different weight based on their importance (Table 4). While most modules are qualitative (i.e., ”compliance-based”), the majority of the rating‘s weight (62%) is based on quantitative assessments (i.e., model-based). As previous section describes the rating process in general, this section defines the scoring methodology of both the quantitative and qualitative modules.

Table 4: SSR module weight and types (e.g., qualitative of quantitative)

Modules	Weight	Type
Mission Index	50%	**Quantitative**
Collision Avoidance Capabilities	16.5%	Qualitative
Data Sharing	16.5%	Qualitative
Detectability, Identification and Trackability	12%	**Quantitative**
Application of Design and Operation Standards	5%	Qualitative
External Services	Bonus[3]	Qualitative

2.1. Qualitative modules

Whereas most of the rating weight is related to quantitative analysis (i.e. 62% of the total weight through the “mission index” and “Detectability, Identification and Trackability” modules), a higher number of modules are qualitative. This section describes the evaluation methodology of the qualitative modules, namely: Collision Avoidance Capabilities (COLA), Data Sharing (DS), Application of Design and Operation Standards (ADOS), and External Services (ES).

Previous work [4], [5], [6], [9] extensively describes the content of these modules, this work will consequently not detail their exact content, but will rather describe the approach for computing the score of the modules, and how peculiar evaluation cases such as constellation missions are handled.

2.1.1. <u>General approach</u>

Qualitative modules of the SSR follows a compliance based-approach, meaning that a list of criteria is provided, the mission is then evaluated based on the compliance to these criteria. An example as part of the collision avoidance capabilities module can be: *“The operator has documented procedures for collision screening, assessment, and mitigation. The operator also regularly screens operational spacecraft and planned manoeuvres against SSA sharing organisation catalogue”.* A predefined number of points (p_{input}) are then awarded for each compliance to the rating’s criteria, according to a rating scale defined during the SSR design phase. Previous works and existing resources such as the SSR website [9] provides the points awarded for each individual inputs within modules. The general score of a given SSR module is finally computed as follows:

$$S_{module} = \frac{\sum_{j=1}^{n}(p_{input_j} \times factor_{verif_j})}{Available\ points_{module}} \qquad \text{Equation 1}$$

With:

[3] See 1.1, 1.2 for the bonus rating score definition.

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- S_{module} the score of the module
- j a given input out of n number of inputs contained in the module
- p_{input} the number of points awarded for the compliance to the input criteria. More details about the points awarded for each SSR criteria are provided in [4], [5], [6], [9].
- $factor_{verif}$ the weight of the verification factor as presented in Table 2, evaluated for each input.
- $Available\ points_{module}$ the total number of points available in the evaluated module

The total number of points available in each module $Available\ points_{module}$ can also vary depending on the type of mission. As an example, a mission performing close proximity or rendezvous operation is requested by the SSR to comply to the CONFERS guidelines [10] as part of the Application of Design and Operation Standards module. If a mission is not performing such operations, the total number of points is decreased taking into account that this compliance criteria is excluded in order to avoid penalizing mission based on their primary mission goal.

2.1.2. The case of constellations, aggregated parameters:

In the case of a mission with multiple assets, compliance shall be evaluated for each objects when it can be applied, and a weighted average score is computed for each input. For instance, the aggregated passivation success probability for a fleet of satellites can be estimated from design for a spacecraft in orbit that did not passivated whereas already passivated spacecraft can justify of the successful passivation (their success ratio is then set to one). As opposed, a spacecraft whose passivation failed can be considered to have a zero passivation success rate. In that case, a weighted average value of the successfully passivated spacecraft (Passivation Success, p_{PS}=1), failed spacecraft (Passivation Failure $p_{PF}\ = 0$), and passivation success ratio from design ($p_{P\ design}$) is computed.

$$p_{P\ fleet} = \frac{p_{PS} \times N_{PS} + p_{PF} \times N_{PF} + p_{P\ design} \times N_{no\ attempt\ yet}}{N_{fleet}} \qquad \text{Equation 2}$$

With :

- p the probability
- PS the “Passivation Success” scenario
- PF the “Passivation Failure” satellite scenario
- N the number of satellite for each scenario

The example of the passivation was used but this type of weighted average parameter computation is performed for all inputs that can lead to different outcomes scenarios depending on the spacecraft for a fleet of satellites.

Whereas all qualitative modules follow similar scoring methodologies, the quantitative modules of the SSR are unique and cannot be generalized with a single scoring formula. The next section then describe in details the two SSR quantitative modules: *Mission Index* and *Detectability, Identification and Trackability*.

2.2. Mission index

The mission index is a quantitative model based on ESA’s space debris index framework [11]. The mission index assesses the mission’s risk as the product of the probability p_c and severity (effect) e_c of a collision, integrated over the object(s) orbital lifetime. It is computed for all objects of the mission, and is then normalised based on the index share consumed by the mission over the total environment available *capacity* (i.e., the total index compatible with a long-term stable evolution of the space environment). The mission index also accounts for operational risk mitigation actions through the risk reduction achieved thanks to the collision avoidance strategy, as well as the post mission disposal strategy.

The index value I is computed using a model simulating the state and behaviour of all space objects (operational satellites as well as the population of debris[4]), including the planned mission. An index value is computed for one space object, but the total index of a mission can be a sum accounting for all objects of a given mission. The index allows to account for the different phases within the lifetime of a satellite (parking, raising, operation, disposal, potential failure), and the risk mitigation strategies implemented (collision avoidance, post mission disposal).

[4] extracted from ESA MASTER version 8.0.3, using available population files.

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Once the mission index value is known for the entire mission, it is normalized considering the space environment capacity [11], in order to provide a score for the module between 0 and 1. A low score (close to 0) would be the result of a high index, i.e. a strong impact on the space environment, while a high score indicates that the mission has little impact on the space environment. Figure 4 summarizes the steps to compute the mission index score of a mission.

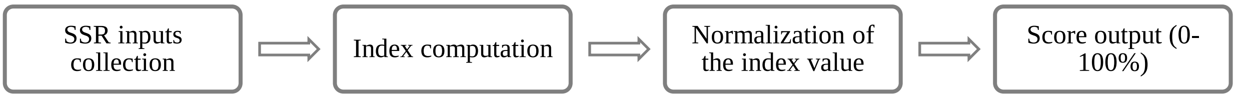

Figure 4: Mission index analysis flowchart

2.2.1. SSR inputs for the mission index module

In order to compute the index value, several inputs need to be provided to the SSR issuer, these inputs are listed in Table 5. The use of the different inputs will be detailed in the next sections.

Table 5: Mission index input list

Mission Characteristics	
Number of satellites	[]
Operational lifetime during primary mission	[years]
Deployment duration (if constellation)[5]	[years]
Spacecraft characteristics	
Mass	[kg]
Cross sectional area (in randomly tumbling motion [12])	$[m^2]$
Orbital parameters during operation	
Semi-major axis	[km]
Inclination	[°]
Eccentricity	[]
End of life management	
Target end of life apogee (after disposal manoeuvres)	[km]
Target end of life perigee (after disposal manoeuvres)	[km]
Expected post mission disposal success rate	[0-1]
Disposal strategy description	Qualitative description
Collision avoidance strategy	
Possibility to perform collision avoidance manoeuvres?	Yes/No
Accepted collision probability level	[0-1]
Lead time required to manoeuvre	[days]
Additional qualitative description of deployment and early operations:	
The rocket bodies used to deploy the satellite(s) are immediately disposed	Yes/No
If no, what is the payload mass share used in the launch vehicle?	[0-1]
TLE/orbital elements of the rocket bodies at the epoch of deployment (if not disposed), and stage name/cross sectional area	TLE format or orbital elements + area $[m^2]$
Satellite(s) deployment altitude (if different from operating altitude)	[km]
Number of satellite(s) deployed at a given altitude	[]
Duration and altitude(s) of potential parking orbit(s)	Qualitative description
Description of the early operation and End of Life: propulsion type and transfer time	Qualitative description
Potential inclination and altitude modification during the mission operation	Qualitative description

2.2.2. Index computation

The impact of a mission in term of risk introduced in the space environment is measured using a derived formulation of the Environmental Consequences of Orbital Breakups (ECOB) formulation [11]. It is a risk indicator, built from the general expression:

[5] Deployment duration here means the duration between the date of first satellite launch to deployment of the full constellation. This parameter is used to normalize the index against the yearly orbital capacity.

DOI: 10.13009/EUCASS2023-432

$$Risk = Probability \cdot Severity = p_c \cdot e_c \quad \text{Equation 3}$$

where the Probability term (p) captures the likelihood that an object is involved in a fragmentation event and the Severity term (e) quantifies the consequences of such an event. The subscript c indicates that the term is related to a collision event. The term p_c is the probability of collision, computed considering only objects large enough to trigger a catastrophic collision, i.e. a collision where enough energy is released that the parent object is destroyed, using the standard energy-to-mass ratio criterion of 40J/g[6].

2.2.3. The probability of collision p_c

The probability of collision p_c can be modelled using a commonly used analogy with the kinetic theory of gas under the form of a cumulative distribution function of the Poisson distribution. The cumulated probability of collision is then formulated as:

$$p_c = 1 - e^{-\rho \cdot \Delta V \cdot A \cdot \Delta t} \quad [11] \quad \text{Equation 4}$$

With:

- ρ the density of object large enough to trigger a catastrophic collision (collision with an energy-to-mass ratio above 40 J/g).
- ΔV the relative impact velocity.
- A the cross-sectional area (in randomly tumbling motion [12]), requested as an input of the SSR.
- Δt the timestep increment value.

Both ρ and ΔV parameters are retrieved from ESA MASTER[7].

It is worth noting that as the collision probability depends on the density of objects located in a given orbital region. Consequently, the collision probability p_c changes if a spacecraft is manoeuvring from an orbit to another. This dependency allows to capture the evolution of the collision probability along the object's lifetime and accurately assess the cumulated collision probability value.

2.2.4. The severity of a collision e_c

The term e_c quantifies the severity of the potential fragmentations in terms of the increase in the collision probability for operational satellites. It is focusing on the evolution of the consequences of a fragmentation.

In order to compute the severity term, the model simulates catastrophic collisions to obtain the distribution of fragments based on the initial orbit and object mass [13] (using the NASA break-up model [14]). These fragmentations are simulated on different inclinations and semi-major axis *bins* (e.g., 10 km semi-major axis steps and 10° inclination steps in LEO). The generated debris cloud is then propagated ([15], [13] section 4). In order to quantify the severity, a set of representative objects (*targets*) are defined based on the distribution of the orbital population ([13], section 3). *Targets* are generated in *bins* where the sum of the cross sectional area considering all objects is the highest. Those *targets* are synthetic objects, with a simulated mean value of cross sectional area ($A_{target} = A_{bin\,total}/N_{bin}$, where $A_{bin\,total}$ is the sum of the cross sectional area of all objects in the *bin*, and N_{bin} is the total number of objects in the *bin*).

The collision probability between the debris cloud and each of the *targets* is computed and the severity term is derived from the increased collision probability for the *targets*.

More precisely, the severity term is a weighted sum of the cumulated collision probability between the debris created and the *targets*. The weights are the ratio between the cross sectional area of the objects present in the orbital region (i.e., in the *bin*) over the total cross-sectional area of all *bins* where targets are generated.

$$e_c = \frac{1}{A_{tot}} \sum_{i=1}^{N_t} p_c(t = 15ys) A_i \quad \text{Equation 5}$$

Where:

[6] Defined in the NASA Standard Satellite Breakup Model, the 40J/g criterion is widely accepted in the scientific community.
[7] https://www.esa.int/ESA_Multimedia/Images/2013/04/ESA_s_MASTER_software_tool

DOI: 10.13009/EUCASS2023-432

- e_c is the total collision severity term. e_c can also be computed separately for each *bin*.
- A_{tot} represents the total cross sectional area of the objects considered for the analysis.
- $p_c(t = 15ys)$ represents the cumulative probability of collision between the debris cloud and the i-th target, over 15 years.
- A_i represents the total cross sectional area of the bin considered.

A more detailed approach on the severity term e_c is described in [16], and [13] section 3.

As for the $p_c$term, the severity term e_c depends on the orbital regime. The mass used for simulating a breakup also have an impact on the severity term as the fragment distribution changes based on the initial fragmentation mass. Finally, it is interesting to note that an object's severity profile can evolve over time with the trajectory evolution. This is captured as part of the index computation.

2.2.5. The index value I

From the computation of the sub-parameters p_c and e_c, the index value at a given timestep is simply expressed as:

$$I(t) = p_c \cdot e_c \qquad \text{Equation 6}$$

As a reminder, the index value can evolve over time as both p_c and e_c depends on the object's orbit.

Figure 5 shows an index map for different semi-major axis and inclination values. It is worth noting that this index map does not have index value labelled. The reason for this is that different spacecraft mass will result in different index values. The index value of a spacecraft of mass M be extrapolated from the index of a reference mass M_{ref} using the following extrapolation equation [16]:

$$I_M = \left(\frac{M}{M_{ref}}\right)^{0.75} I_{M_{ref}} \qquad \text{Equation 7}$$

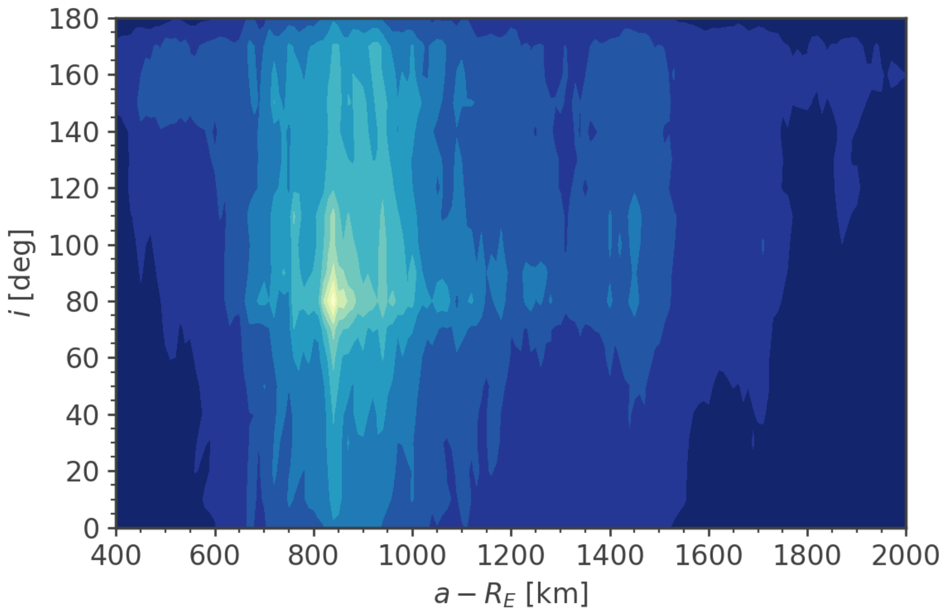

Figure 5: LEO index map in satellite altitude and inclination for the LEO region (without considering collision avoidance and post mission disposal strategies). Courtesy: ESA space debris index frontend

One can notice that several orbital regimes are naturally inducing a higher index (i.e., lower score), which is caused by the proximity of more objects (debris or other operational missions). This simply translates the fact that some orbits are more crowded than others, and that spacecrafts located in these regions will have a higher collision probability and potential for collision severity. This however does not mean that the index computation only considers the size, mass, and orbital regime. The index computation also accounts for actions that can be implemented by operators to mitigate their impact on the space environment. It has been demonstrated that missions operating in "high risk regions" (i.e., the high index zones in Figure 5) can also score high scores in the mission index module [7] thanks to mitigation actions. The two actions to mitigate one's mission index that are accounted for in the rating system are the

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implementation of collision avoidance, and the orbit clearance after the end of operation, or Post Mission disposal (PMD). These considerations are described in the next sections.

2.2.6. Integration of the index value

The risk metric I is not computed at a single epoch (e.g. $I(t)$), but rather evaluated along the mission profile of an object, from deployment to the implementation of disposal strategies at the end of the mission [16]. The previously formulated index can be simplistically discretized as follows, where t_0 represents the deployment epoch and t_f the end-of-mission epoch:

$$I = \int_{t_0}^{t_f} (p_c \cdot e_c)\, dt \qquad \text{Equation 8}$$

This allows to account for the evolution of the trajectory during the mission. As mentioned in previous sections, the index computation also accounts for the collision avoidance strategy efficiency during the operation (expressed here as γ, the "mitigated collision risk" parameter), and the possible paths of evolution of the trajectory (depending on the success rate α of the post-mission disposal strategy), so that the index computation becomes:

$$I = I_{operation} + I_{disposal}$$

$$I = \underbrace{\int_{t_0}^{t_{EOp}} (1-\gamma) I_{op}(t)\, dt}_{\text{Operational lifetime}} + \underbrace{\alpha \int_{t_{EOp}}^{t_{\mathrm{EOL_D}}} I_D(t)\, dt}_{\text{PMD success}} + \underbrace{(1-\alpha) \int_{t_{EOp}}^{t_{\mathrm{EOL_{ND}}}} I_{ND}(t)\, dt}_{\text{PMD failure}} \qquad \text{Equation 9}$$

Where:

- t_0 represents the deployment epoch;
- t_{EOp} represents the epoch of end of operations;
- t_{EOL_D} represents the epoch of end of life in case of successful disposal (D);
- $t_{EOL_{ND}}$ is the minimum between 100 years (simulation upper limit) and the epoch of re-entry in the case the object is not disposed (ND, i.e. abandoned in its operational orbit);
- γ is the mitigated collision risk; and
- α is the post mission disposal success rate.

It is important to note that the index values I for the operation, disposal, and no disposal scenarios are different. They present different trajectory evolutions (inducing different values of $p_c$and e_c). The formulation above can also be adapted depending on the mission to account for different mission phases and hence, trajectory evolutions (e.g. if there are parking orbit, orbit raising, or if collision avoidance can be performed during the disposal phase).

The next sections will describe in details the impact of the collision avoidance and disposal strategies on the index value.

2.2.7. Collision Avoidance strategy in the mission index: mitigated collision risk γ

The mission index accounts for the risk reduction achieved by the collision avoidance strategies from trackable objects. Currently, only objects larger than 10 cm are considered to be part of the trackable population in the index collision avoidance computation. Future updates will consider an equation allowing to characterize the diameter of trackable object as a function of the altitude using the following equation:

$$d_t = d_{ref} \left(\frac{h}{h_{ref}}\right)^2 \quad [13] \qquad \text{Equation 10}$$

In addition, the adoption of a collision avoidance strategy is not treated as a binary option (yes/no), but rather with a parameter that measures its efficiency. The "mitigated collision risk" parameter, noted γ, is thus defined and quantifies

DOI: 10.13009/EUCASS2023-432

the risk reduction achieved by the implemented collision avoidance strategy with respect to the case where no manoeuvre is performed. As such, *the mitigated collision risk of spacecrafts that are unable to manoeuvre is 0%.*

The first term of Equation 9, representing the index during all phases where collision avoidance can be performed can be further detailed as follows:

$$I_{phases\ COLA} = \int_{t_0}^{t_{EOphase}} \left[(1-\gamma)\left(p_{c_{trackable}} \cdot e_c\right) + p_{c_{non-trackable}} \cdot e_c\right] dt \qquad \text{Equation 11}$$

Where the debris density used for computing $p_{c_{trackable}}$ and $p_{c_{non-trackable}}$ are different based on the definition of trackable debris specified above.

One can notice from the equation above that a high mitigated collision risk (i.e. a high value of γ) can significantly decrease the index value during the phases where collision avoidance can be performed, hence resulting in a higher SSR score.

A complete understanding of the γ parameter's computation method is encouraged by the SSR issuer in order to better characterize the risk associated with the selected collision avoidance strategy for its mission. In order to compute γ, the ARES tool, from the ESA DRAMA suite[8], is freely available. [17] describes the ARES framework and how it can be used to determine γ. It also allows the operator to understand what a target γ value implies in term of number of manoeuvres per year. For the sake of brevity, the process is not defined in this work but can be provided on request by the SSR team.

2.2.8. Post-mission disposal strategy in the mission index

The simplified approach defined in section up to 2.2.5 ($I_c = p_c \cdot e_c$) shows that some mission configurations, without considering mitigation measures will always score a higher footprint because they operate in more crowded orbits. This simply translates the fact that missions willingly operating in high-risk regions are expected to implement mitigation measures to reduce the risk of creating debris. It has however been demonstrated that regardless of the altitude or number of satellites, high SSR scores can be reached when following the best de-orbiting practises [7]. The following section will describe the central role of implementing a post mission disposal strategy and describe its impact on the index score.

Below is the formulation of the index as expressed in section 2.2.6, excluding the operational phase:

$$I_{disposal} = \underbrace{\alpha \int_{t_{EOp}}^{t_{\mathrm{EOL_D}}} p_{c_D} \cdot e_{c_D}\, dt}_{\text{PMD Success}} + \underbrace{(1-\alpha) \int_{t_{EOp}}^{t_{\mathrm{EOL_{ND}}}} p_{c_D} \cdot e_{c_D}\, dt}_{\text{PMD failure}} \qquad \text{Equation 12}$$

With the indices D and ND respectively describing the Disposal and Non-Disposal cases. It is worth noting that p_{c_D} and $p_{c_{ND}}$, as well as e_{c_D} and $e_{c_{ND}}$ are different values as a non-disposed satellite will remain on its operational orbit, whereas a disposed satellite will change its orbit.

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

i. Be located in low-risk regions, resulting in a lower value of collision probability and severity, and hence a lower index value (i.e. a better mission index module score).
ii. In most LEO cases, a disposal manoeuvre significantly reduces the orbital lifetime (time interval from t_{EOp} to t_{EOL}) as the natural decay will occur faster/immediately. This results in a smaller integration interval and a reduced index value (i.e. a better mission index module score).

[8] Available for download at https://sdup.esoc.esa.int/drama/

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2.2.9. Index value of multiple object missions

It is possible to rate missions that includes one spacecraft, launch vehicle, or a larger combination of these elements. In order to do so, the index values associated with each object is summed, allowing to capture the impact of the entire mission. The total index value of the mission shall be computed as the sum (from object $i = 1$ to object n) of the individual index values, including the sub-index components (i.e., associated with different mission phases). Depending on the mission complexity, additional phases can also be accounted for and added to this formula (different parking orbits, disposal strategies, satellite failure cases…).

The final index value for the entire mission finally becomes:

$$I_{mission} = \sum_{i=1}^{n} (I_{i_{early\ phases}} + I_{i_{operation}} + I_{i_{disposal}}) \qquad \text{Equation 13}$$

2.2.10. From the Index value to the mission index score: the normalization

While above sections describes how to compute the index value of a given mission, this section focusses on how the index value is normalized to a value comprised between 0 and 1.

The index in itself can be used to compare different missions, but a normalization approach is needed to include its contribution in a composite indicator such the SSR and make it compatible with the other modules. The normalization approach adopted for the SSR is based on the concept of environmental capacity [18], i.e. the number and type of missions that are compatible with the long-term stability of the environment.

As detailed in [2], long-term simulations of the environment can be used to choose a reference scenario a desirable level of compliance to space debris mitigation guidelines and associated total index. This scenario is then compared with the actual use of orbital resources, intended as the sum of the index for all objects in orbit, considering their expected mitigation strategies. Currently, post-mission disposal (PMD) plans and their expected success rate are not systematically shared by operators. Nevertheless, thanks to space surveillance data, the activity of a spacecraft can be derived and the evolution of its orbit can be predicted, enabling the assessment of the status of the environment [2].

A share of the orbital capacity is consumed by inactive satellites and rocket bodies, whereas the remaining part can be used for active and new missions. It is this value (the available capacity) that can be used to normalize the mission index within the SSR.
From the computed mission index value $I_{mission}$, the mission index score is normalized through two components with different weights:

- Absolute mission index score S_{abs} (80% weight within the module): intended as the evaluation of the risk metric for the mission (as described in the previous sections) and normalized using the concept of environmental capacity.
- Relative mission index score S_{rel} (20% weight within the module); intended as the ratio between the absolute mission index $I_{mission}$ and the one corresponding to the reference mitigation scenario (more details in section 2.2.12).

2.2.11. Absolute mission index score

Let's consider $I_{mission}$ the total integrated index value of a given mission considering and the contribution of all objects of the mission. The general approach of the normalization process is as follows:

1. Quantitative assessment of the total capacity (procedure described in [2]): the approach consists in simulating long-term extrapolation scenarios for the space environment, and select a scenario compatible with a stable evolution of the space environment. The selected scenario's total index is then used for the mission index normalization. In the frame of the SSR, the scenario selected considers the extrapolation of the launch activities between 2009 and 2014 (Hereafter noted "*2014-PMD90*"), under the assumptions that all missions performs a disposal within 25 years with a 90% success rate. Index-wise, this scenario is almost equivalent to an extrapolation of the 2021 launch rate, considering the same post mission disposal assumptions expect for constellation missions, for which a 99.5% disposal success rate within a year after end of mission is

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considered. More details about the extrapolation can be found in [2], the citation below is a rationale for the total capacity selection. Figure 6 shows the extrapolation scenarios plots from [2].

"As the PMD90 scenario has de facto been regarded in the recent past as the reference target for sustainable operations, the introduction of large constellations in the last years has shifted the definition towards the more stringent PMD90Const99.5(1y), which can be regarded as a new minimum baseline for definition of how a sustainable environment could look like. This would imply that the risk level associated to the 2014-PMD90 is still accepted as a minimum target to achieve. The minimum is stressed here as clearly all scenarios analyzed in this work do imply an increase of risk between the current situation in orbit and the situation at the end of the 200-years simulation, as even in the case of no further launches the predicted risk is increasing. [...] On the other hand, having a numerical target such as the risk level associated with 2014-PMD90 as an upper limit gives an actionable constraint to derive guidelines and processes that can be followed by each and every mission toward reaching a long-term sustainable environment. Moreover, this is actionable now." [2]

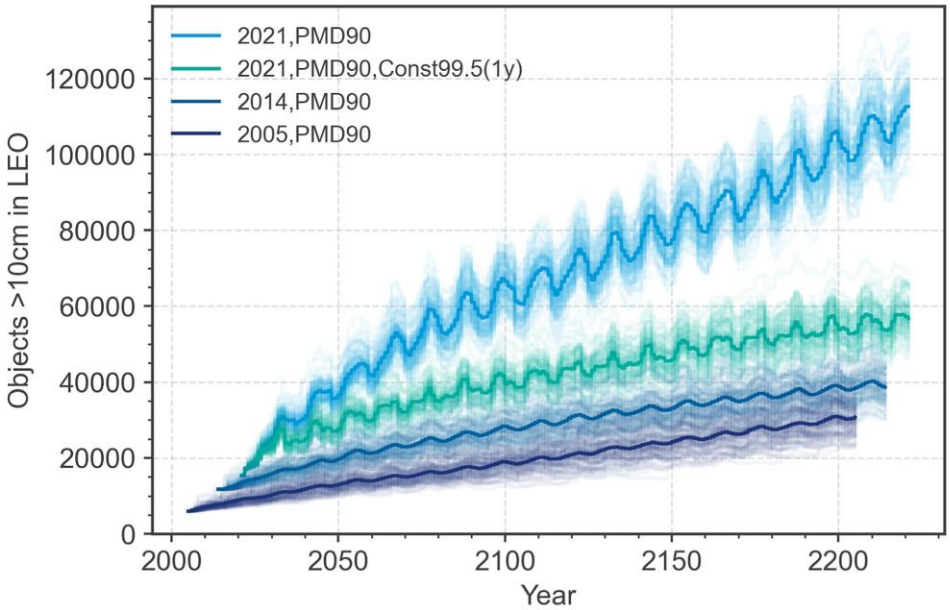

Figure 6: Extrapolation of the object count in LEO using different debris mitigation scenarios [2]

2. <u>From total capacity to the available capacity</u>: The capacity already used by active mission and inactive objects is then characterized, the available capacity can then be extracted ($C_{available} = C_{total} - C_{used}$). The available capacity is finally defined for a given launch year, noted C.
3. <u>Normalization process using the capacity [6]:</u> The available capacity is compared to the index obtained for a given mission. Let's define $\hat{I}$ the normalised mission index with respect to the yearly available capacity ($\hat{I} = I_{mission}/C$). The absolute score S_{abs} is finally obtained from:

$$S_{abs} = 0.5 - \frac{1}{\alpha_{norm}}\log_{10}(\hat{I}) - \frac{\hat{I}-1}{\beta_{norm}} \qquad \text{Equation 14}$$

where the logarithmic component is introduced to highlight the differences in order of magnitude in the risk metric, whereas the linear part penalises cases above the available capacity threshold. The functional dependence in the previous equation was preferred to definition of tiers to keep more granularity in the assessment of different missions. The two parameters α_{norm} and β_{norm} are set respectively to 10 and 50, where the values were selected by analysing the score distribution across the current population of active objects and its dependence on the mission mass. With these values, any mission below the available capacity threshold will have a score ≥ 0.5 and the maximum score can be achieved only by small and medium missions (with mass <1000 kg).

2.2.12. <u>Relative mission index score</u>

The SSR aspires to reward operators who implement better than required behaviours for what concerns mitigation efforts. In order to capture this aspect, besides the evaluation of the absolute debris risk, the computed footprint is

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compared to the one that the same mission would score in a reference scenario (I_{ref}). The reference scenario corresponds to a minimum required level of mitigation actions, defined in the following ways for the different orbit classes (based on commonly applied and internationally recognised space debris mitigation standards, e.g. IADC):

- LEO: 25-year with 90% PMD success rate,
- GEO: graveyard with 90% PMD success rate,
- Other: no action.

Hence, the relative index value I_{rel} is intended as the ratio between the mission absolute index $I_{mission}$ and the one corresponding to the reference mitigation scenario (I_{ref}) [6].

$$I_{rel} = \frac{I_{mission}}{I_{ref}} \quad \text{Equation 15}$$

As for the absolute index, the relative component of the mission index I_{rel} is normalised to be comprised between 0 and 1. The relative score S_{rel} is then obtained from the following equation:

$$S_{rel} = 1 - (I_{rel})^{\varepsilon} \quad \text{Equation 16}$$

where ε was set equal to 3 after a calibration phase based on the analysis of some reference missions with different disposal approaches. The relative scores is a way to reward operator with a lower index than the minimum advised bu current guidelines. In other words, a mission with better than-expected mitigation measure (e.g., deorbited within one year for LEO for instance), will:

1. Have a better absolute score S_{abs} since the mission index will be lower as the mission stays for a shorter period of time in the environment, reducing the cumulative collision risk; but will additionally
2. Be rewarded by implementing better mitigation measures than the reference case scenario I_{ref}

It is important to notice that S_{rel} can be lower than 0, if $I_{mission} > I_{ref}$ i.e. if the mitigation measures are less effective than the reference mitigation scenario.

2.2.13. Final mission index score aggregation:

The final score for the mission index module is defined as the weighted sum of the absolute and relative score S_{abs} and S_{rel}. The weight repartition selected providing the desired balance between recognising the difference in the absolute risk assessment, and rewarding operators for implementing better than required behaviours through the relative component [6].

$$S_{mission\ index} = \max\,(0.8 \times S_{abs} + 0.2 \times S_{rel}, 0) \quad \text{Equation 17}$$

The mission index, while relying on a set of high-level parameters, allows to capture the differences among alternative operational concepts, considering collision avoidance efficiency, and the implementation of disposal strategies.

During the implementation phase of the SSR, it has been identified that being able to pre-compute the index score would be an asset for an applicant, in order to iterate different mission scenarios and understand their projected SSR scores. This capability would especially be of interest for missions in preliminary phases, as index studies could drive systems and sub-systems requirements for later development phases. In that regard, the THEMIS software tool [13] will be released in 2023 using the framework of the debris index and will allow any operator to compute the debris index of a given mission. In the meantime, additional resources[9] can be used to compute the index of a space mission, and the SSR team can provide other tools[10] to provide a simplified score of the mission index.

2.3. Detectability, Identification and Trackability

The physical attributes of a satellite and the concept of operations affect the ability of sensors located on Earth to detect, identify, and track it. The goals of this second quantitative module of the SSR are to encourage satellite operators to consider how the physical attributes of their satellite design and their operational approach during launch, operations and disposal affect the level of difficulty for observers to detect, identify, and track the satellite. By providing a

[9] Debris index frontend : https://index.sdo.esoc.esa.int
[10] SSR mission index normalization spreadsheet, only provided to SSR applicants.

DOI: 10.13009/EUCASS2023-432

consistent method to analyse a given satellite design and operational concept, this portion of the SSR will provide a standard metric for the comparison of satellite missions in the dimensions of detection, identification and tracking. Also, there is potential for this part of the SSR to encourage development of new ways for satellites to balance the considerations of how to limit their contributions to astronomic light pollution while maintaining their ability to be detected, identified, and tracked when necessary.

The Detectability, Identification and Trackability (DIT) module of the SSR considers the level of ability for observers to detect, identify, and track the mission. The SSR evaluates these aspects of the mission using a software model[11] that simulates a reference ground station network with optical and radar sensors to calculate the probability that a given mission can be detected, identified and tracked, given the mission characteristics. The DIT scoring methodology was developed using case studies of existing space missions that have publicly available information about their physical characteristics and orbits [19]. For the sake of brevity, this work will highlight the main principle and scoring formula for the DIT module, an extensive description of the model definition and validation can be found in [19].

At the date of publication of this work, the DIT module do not comprise the identification part, and is hence composed of three subcomponents, equally weighted to aggregate the score of the module:

$$S_{DIT} = \frac{1}{3} S_{Detectability} + \frac{1}{3} S_{Trackability} + \frac{1}{3} S_{Questionnaire} \qquad \text{Equation 18}$$

The analysis seeks to quantify the Detectability and Trackability of a given residual space object independently of the capabilities of its operator to track the satellite and to reduce the error in estimating the satellite's location. Thus, the analysis considers the perspective of an independent observer that is only working with information available through sensor observations of Anthropogenic Space Objects. Considerations of the level of error for the operator's estimates of satellite location will be considered in the Collision Avoidance section of the SSR. Using primarily simulation, the DIT analyses will start with a set of physical assumptions and initial data requested from the operator. The data requested from the satellite operator partly overlap with the data requested for the Mission Index module which is used in the calculation of the Space Traffic Footprint. The list includes the following:

- Geometric Approximation (rectangular prism, cylinder, or sphere) and dimensions
- Spacecraft face pointing the Nadir direction
- (Optional) Simplified CAD Model – Basic size and geometry
- (Optional) Detailed CAD Model - Complex faceted model (a single diffused facet can be used to average surface irregularities in order to provide an appropriate representation of material surfaces e.g. MLI wrinkling)
- Operational Orbit Parameters (apogee altitude, perigee altitude, inclination, RAAN, argument of perigee, mean anomaly)

A key component of the DIT analysis is the Ground Sensor Network (GSN) capabilities assumed for the model. The ideal GSN for the SSR is one that represents capabilities attainable through commercially procured sensors that are available to countries around the world. The reason for this is that the SSR is intended to use transparent metrics to the extent possible. To accomplish this, the GSN modelled for the SSR is not representative of any specific existing GSN. In particular, the GSN used for these analyses is made up of sensors with capabilities on par with commercially available telescopes and radar systems. The ground sensors are distributed geographically within the simulation in order to give similar coverage to a variety of orbits (Figure 7). More details on the GSN as well as the sensor properties can be found in [19]. The following section will describing the scoring methodology of the three sub-components of the DIT module.

[11] Systems Tool Kit (STK), from AGI, "EOIR" and "Radar" modules

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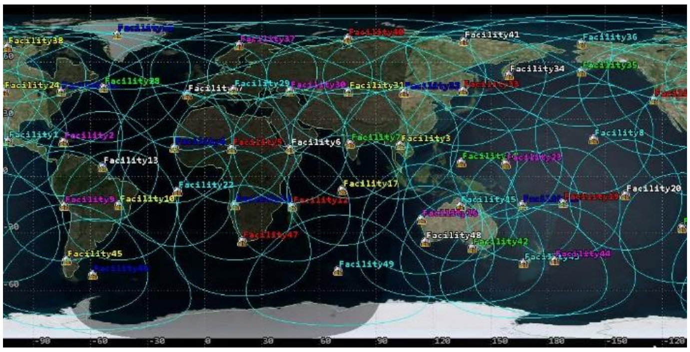

Figure 7: Generic Ground Sensor Network used in the Trackability analysis [19]

2.3.1. Detectability

This definition considers the scenario in which a space surveillance system using optical and radar sensors to observe Anthropogenic Space Objects is monitoring for spacecraft without having a specific list of objects and without a priori knowledge of the size, altitude or orbital characteristics of spacecraft. For this uninformed case, the Detection analysis asks the likelihood that a spacecraft in a given orbit can be detected separately by optical telescopes and surveillance radars. The Detectability of a set of mission spacecraft is therefore defined as the likelihood that the optical telescope and surveillance radar system will observe an Anthropogenic Space Object, subject to sources of error from the sensors, from signal loss as it propagates through the atmosphere and from illumination constraints due to the geometry of the sun, spacecraft and sensor.

The detectability analysis of the SSR has two components: optical detection and radar detection. These represent the two most predominant methods for gathering data on satellites and other anthropogenic space objects (ASOs). These two portions of the analysis are represented in Figure 8. The goal of each of these analyses is to estimate how difficult it will be to detect a proposed ASO using each method individually and then translate that difficulty into a scorable metric for the SSR.

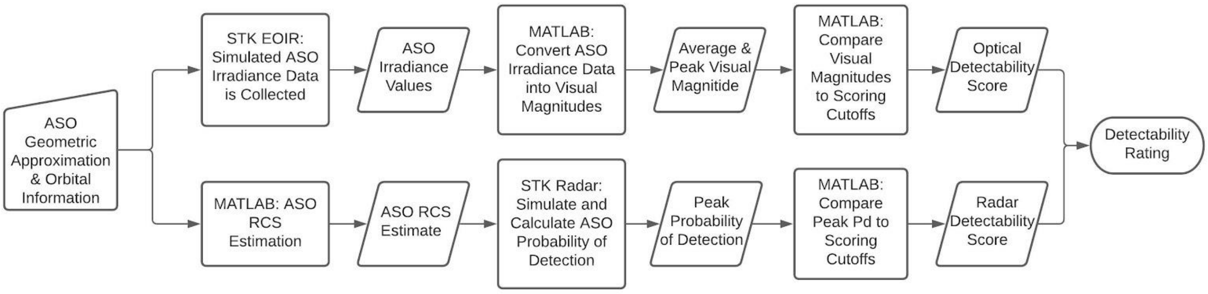

Figure 8: Detectability analysis flowchart [19] (RCS refers to Radar Cross Section, Pd refers to Probability of Detection)

<u>Detectability scoring cutoff:</u>

a. <u>Optical detectability:</u> The optical detectability testing employs a binary scoring method with one threshold between detectability. This threshold is set at a visual magnitude of 15, which represents the limiting magnitude of an optically idealized 0.25m telescope. In this context, optically idealized means that the telescope itself does not introduce any error into the optical detection process. In practice, imperfections in the lenses, mirrors, and electronics of optical sensors lower the limiting magnitude of the overall optical system. This means that the scoring cut-off of 15th visual magnitude between "Detectable" and "Not Detectable" corresponds to an idealized 0.25m telescope as well as a non-idealized 0.3m-0.5m telescope. Telescopes of this class were selected for the lowest cut-off based in-part on the work done at the Air Force Research Lab on "Raven automated small telescope systems". This study explored and validated the concept of using commercially available telescopes of size less than < 0.5m for satellite observation and tracking. If an ASO meets the 15th magnitude cut-off, it receives a score of 1, and if it does not meet the cut-off it receives a score of 0.5 for the Optical portion of the Detectability Score.

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b. Radar detectability: In radar analysis, a detection event occurs when the returning radar signal from the detected object is strong enough to be distinguished from the background noise with a certain level of confidence. For the DIT Radar Detection analysis, there are three cut-offs set to delineate between ASOs that are minimally detectable, ones that should be easier to detect, and ones that should be nearly guaranteed to be detected. A detection event with a probability of detection, as defined in the STK software, over 50% is considered a successful detection[12]. In order to differentiate ASOs that barely make the minimal detectability cut-off from those that handily exceed it, the Radar Detectability employs one additional cut-off at 75%. If an ASO meets the 50% threshold it receives a Radar score of 0.5, if it meets the 75% threshold it receives a Radar score of 1, otherwise it receives a Radar score of 0.

Table 6 summarizes the scoring cutoffs of the Detectability analysis of the SSR for both the optical and radar detectability

Table 6: Detectability Scoring thresholds [6],[19]

Sub-components	Metrics	Scoring thresholds		
		0	0.5	1
Optical Detectability score ($S_{Detectabiltity_{optical}}$)	Visual Magnitude		<15	>15
Radar Detectability score ($S_{Detectabiltity_{radar}}$)	Probability of Radar detection	<50%	50-75%	>75%

The overall Detectability score is a finally a combination of the Optical contribution and the Radar contribution. Thus, Detectability is evaluated as:

$$S_{Detectability} = 0.5 \times S_{Detectabiltity_{optical}} + 0.5 \times S_{Detectabiltity_{radar}} \quad \text{Equation 19}$$

2.3.2. Trackability

For this analysis, Tracking refers to the process in which an observer has already detected and identified a spacecraft and next seeks to monitor and predict the evolution of the orbit of the spacecraft over time. The Tracking analysis asks how difficult it is for an observer who is not the satellite operator to perform the tracking function. In this case, the assumption is that the satellite tracker has information about the name, owner and instantaneous location of a satellite at a specific time, however, the observer does not have full knowledge of the orbital parameters. In this situation, the uncertainty of the tracking information increases when the access times are shorter for a ground station to observe a spacecraft. Thus, the trackability analysis computes access times as a figure of merit to estimate the level of uncertainty in the tracking process. More frequent overpasses of a ground-based network of telescopes and radars improve the prediction for when the spacecraft will pass within the field of regard again.

In the final portion of the analysis, the SSR assesses the trackability of a satellite by analyzing the level of certainty with which an independent observer can estimate the future evolution of the orbit of a spacecraft. This stage assumes that an observer uses the reference optical observation system and a tracking radar system that is tuned to the appropriate parameters to observe an object of the given size and range (as identified in the Detectability analysis). The analysis calculates the future predicted periods in which the Detected space object will overfly the telescopes and radars in the ground sensor network. The analysis calculates the level of uncertainty for the estimates of future overpasses. The higher the uncertainty in the future orbital trajectory estimates, the lower the trackability score.

[12] (https://help.agi.com/stk/11.0.1/Content/training/StartRadar.htm).

DOI: 10.13009/EUCASS2023-432

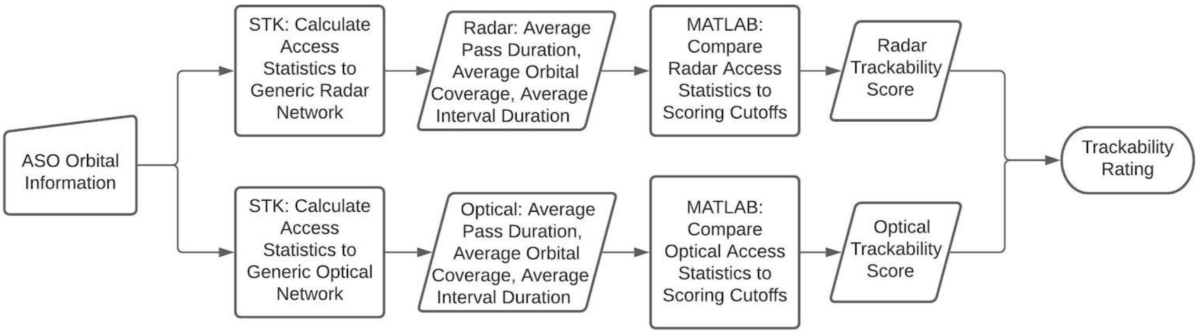

Figure 9: Trackability analysis flowchart

<u>Trackability scoring cutoff:</u>

In order to provide an empirical basis for selecting scoring cut-offs, TLEs of approximatively 3200 active satellites were extracted from Celestrak[13]. These satellites were then run through the trackability analysis to produce distributions to help identify trends in the pass duration, orbital coverage, and interval duration metrics. The cut-offs described below were defined through a combination of information from literature on the topic and from observations of the empirical data produced for ~3200 active missions.

Scoring for the Trackability analysis is broken down into three components with two sub scores for each. The first component is based on the ASO's average pass duration, with scoring cut-offs at 120s (.25), 180s (.5 pts), and 400s (1 pts). The second component is based on the ASO's average orbital coverage, with scoring cut-offs at 10% (.25 pts), 25% (.5 pts), and 60% (1 pt). The third component is based on the ASO's average interval duration, with scoring cut-offs at 12hrs (.5 pts) and 6hrs (1 pt). The total score for trackability is calculated for both the optical and radar components, and the scoring cutoffs for the three metrics are summarized in Table 7.

$$S_{Trackability_{optical,radar}} = \frac{1}{3} Pass\ Duration + \frac{1}{3} Orbital\ Coverage + \frac{1}{3} Interval\ Duration \quad \text{Equation 20}$$

Table 7: Trackability scoring thresholds [6], [19]

Metrics (computed for both optical and radar)	**Scoring thresholds**			
	0	0.25	0.5	1
Pass duration	<120"	120-180"	180-400"	>400"
Orbital coverage	<10%	10-25%	25-60%	>60%
Interval duration	>12h		12h-6h	<6h

The best achieved score between optical and radar trackability is used as the Trackability score in order to reflect that after a successful detection, one trackability method would be used over the other based on performance.

$$S_{Trackability} = \max\left(S_{Trackability_{optical}}; S_{Trackability_{radar}}\right) \quad \text{Equation 21}$$

2.3.3. <u>DIT Questionnaire</u>

The final component of the DIT analysis is an additional qualitative score derived from an operator's responses to the questionnaire. Certain aspects of the DIT processes cannot be quantitatively assessed at this time, so the questionnaire

[13] https://celestrak.org

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includes a few questions that evaluate the performance of the operator in the areas of satellite characterization and tracking. The questions are the following ones:

Do you track the resident space objects you operate?

- Operator depends on Space-track, other third party public SSA providers, or is tracking the RSO by its own means. (1 point)
- Operator or contracted SSA Service Provider identifies and maintains custody of operated satellites within 14 days of deployment and thereafter. (2 points)
- Operator or contracted SSA Service Provider identifies and maintains custody of operated satellite within one day of deployment and thereafter. (3 points)

(Bonus) Provide verifiable photometric/radiometric characterisation data on the satellite to the SSR evaluator.

- Radiometric Data (average/max/min RCS) (2 bonus points)
- Photometric Data (average/max/min Visual Magnitude) (2 bonus points)

The aggregation of the questionnaire part of the DIT module follows the same procedure as the qualitative module, dividing the points earned by the total number of points available.

3. Conclusion

The Space Sustainability Rating (SSR) offers a unique and comprehensive tool that allows to capture various aspects of space sustainability practises into a single score output. Such analysis, while holding a great significance for satellite operators as it allows them to evaluate their missions' compliance with best practices, additionally provides valuable insights on areas of improvement, accompanied by specific recommendations issued based on the rating outcomes. The importance of such a rating scheme also extends to regulators and space agencies seeking to promote the widespread adoption of sustainability best practices within their jurisdiction.

To maintain the credibility of any rating scheme, it is crucial to adopt a transparent approach in its methodology. While previous work has extensively detailed the rationale behind most modules and their specific criteria, this research paper presents an updated guide to the Space Sustainability Rating. It focuses on describing the scoring methodology of qualitative modules and places emphasis on the quantitative modules. Detailed explanations of the Mission Index and Detectability, Identification, and Trackability modules are provided, along with a list of key references to aid in understanding specific concepts.

While this work aims to serve as a comprehensive reference for comprehending the Space Sustainability Rating's methodology and concepts, future endeavours will revolve around developing tools that enable satellite operators to evaluate their missions against the defined metrics through an automated computation process. A significant step towards this objective will be the anticipated release of the THEMIS software in 2023, which will facilitate the computation of the debris index for space missions. Overall, this paper lays the foundation for a deeper understanding of the SSR, while also paving the way for future advancements that will enhance the practicality and accessibility of this rating system for the space industry.

DOI: 10.13009/EUCASS2023-432

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