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Implementing the Space Sustainability Rating: An Innovative Tool to Foster Long-term Sustainability in Orbit

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Abstract

Given the growing number of government and commercial actors, and planned mega constellations, there is a critical need to consider implementing tools that will incentivise space actors to foster responsible behaviour and implement debris mitigation and remediation measures in order to ensure long-term sustainability of the space environment. Over the past two years, an international and transdisciplinary consortium consisting of the World Economic Forum, Space Enabled Research Group at the Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and BryceTech have been working on the design and development of the Space Sustainability Rating (SSR). The SSR is a tool to assess and recognise missions for sustainable and responsible operations that reduce the potential harm to the orbital environment and impact to 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. These modules include the mission index to estimate the mission's marginal contribution to overall orbital risk; (ii) collision avoidance capabilities; (iii) ability and willingness of the operator to share data on the mission data; (iv) the mission's detectability, identification and tracking; (v) operator's compliance with standards and regulations; and (vi) commitment to use or demonstration of use of on-orbit servicing and external services. This paper provides a third update of the design of the SSR, including an overview of the scoring methodology developed for each of the SSR modules. Prior to the SSR's public launch, the consortium conducted alpha and beta tests of the rating with spacecraft operators in order to gain valuable feedback. This paper presents the methodology of the SSR alpha and beta tests, subsequent feedback, and lessons learnt that have been effectively implemented into the design of the SSR to increase the usability of the rating system.

In late 2020, the World Economic Forum announced a call for applications for the formal management and hosting of the SSR on a permanent basis. As the SSR transitions from design to implementation, this paper further presents the key criteria used to select the SSR administrative organisation (SSR Entity), chosen to work with the consortium on finalising the design of the SSR, and developing a business model to practically and sustainably executing the rating system.

Keywords: Space Sustainability Rating, Space Debris, Space Environment, Long-term Space Sustainability

1. Introduction

In recent years, the global space economy has experienced a transformation with declining costs, and the proliferation of related technology leading to a surge in satellite launches, many of which are conducted by new space enterprises and nations, inevitably increasing the risk of collisions and spurring debates on the safe and sustainable use of vital near-Earth orbits. Over the coming years, thousands of payloads are expected to be launched by the commercial sector alone, adding to approximately 7520 already active satellites in orbit [1]. The orbital environment is a globally shared resource where existing international guidelines steer space actors in their activities. However, these guidelines are not easily enforceable and compliance remains below necessary levels[2]. Guidelines alone are unlikely to sufficiently curtail the creation of new debris in the coming years caused by fundamental shifts in space traffic.

First conceptualised by the World Economic Forum Global Future Council on Space, the Space Sustainability Rating (SSR) is an innovative tool designed to address the challenge of long-term sustainability of the space environment by incentivising actors to design missions compatible with sustainable and responsible operations, and operate missions considering potential harm to the orbital environment and impact on other operators.

Due to the interdisciplinary nature and complexity of defining the term 'sustainability', or even coming to a consensus on what defines sustainable operations, the SSR is designed as a tool to provide quantifiable sustainability metrics, aimed at recognising and supporting actors who adhere to or exceed existing international sustainability guidelines and regulations. As a voluntary rating, the SSR shifts the attitude towards compliance assessment, provides transparency and accountability, and accounts for decisions a space operator can make during the design, operations and end of life phases of a space mission. Since 2019, the design and development of the SSR has been led by an international and transdisciplinary consortia including the World Economic Forum, Space Enabled Research Group at the Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and BryceTech.

Previous papers on the SSR focused on the high-level design and related design decisions. This paper provides an overview of the scoring methodology for each of the SSR modules, and details the aggregation, weighting and tier designations developed for the first iteration of the SSR. Additionally, the paper discusses the outcomes of the SSR alpha and beta tests to evaluate the rigor of the SSR design, feedback from rating applicants, and lessons learnt that have been subsequently implemented into the design of the SSR prior to the SSR being released publicly.

The SSR development process was planned in two phases: a development phase that is now complete and an operational phase to be overseen by a permanent host organisation. In late 2020, the World Economic Forum announced a call for applications from organisations to take on the role of the SSR Administrative Entity to lead and operationalise the SSR, and begin issuing sustainability certifications to mission operators in early 2022. This paper presents the key criteria and process used in the selection of the SSR Entity.

2. SSR Modules and Scoring Methodology

Informed by successful rating systems in other industries, such as the Leadership in Energy and Environmental Design (LEED), a green building certification system developed by the U.S. Green Building Council (USGBC), the SSR is designed as a composite indicator, aggregating and weighing individual indicators (modules) to produce one overall index (rating). Each SSR module consists of an individual point system based on key criteria and information requested from the SSR Applicant. The final result is a numerical rating for a mission that is then associated with a certain SSR Baseline Tier rating (Certified, Silver, Gold, Platinum), as illustrated in **Error! Reference source not found.**.

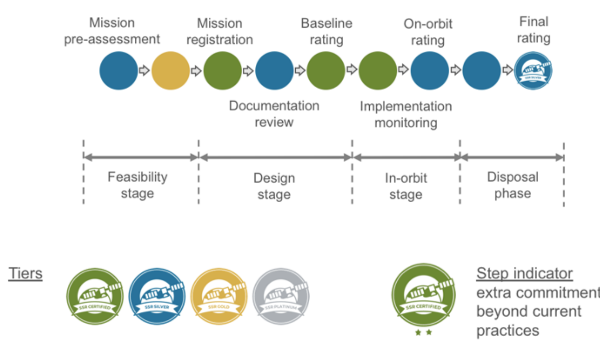

Figure 1 Example of the SSR Baseline Tier awarded at different stages of a mission, and baseline tier designations

An actor seeking an SSR will receive a Baseline Tier rating (hereafter referred to as SSR Tiers) based on responses to the SSR questionnaire, which gathers the information required to evaluate each of the SSR modules. The SSR Tier is awarded at different missions phases (i.e. feasibility stage, design stage, in-orbit stage, and disposal phase) as shown in Figure 1. The SSR will be periodically updated to reflect the actual performance over the mission duration that shows whether a mission is becoming more or less sustainable based on the initial planned behaviors attested to by the operator. The final SSR for a mission will be issued at the post-mission disposal phase of the mission, and considers the operator's decisions on the satellite's demise and/or placement of the satellite in decay orbits. This accounts for the mission's actual overall impact on the space environment. In addition to the SSR Tiers, SSR Applicants can earn additional credit in the form of Steps (or bonus scores). Steps exist to recognise operators for good behaviors in emerging areas that are still too new or fluid to be defined in rigid terms and incorporated into the SSR Tiers, such as the on-orbit servicing captured as part of the SSR External Services module, acknowledging that satellite servicing is still in the demonstration phase, and that the not all missions will employ external services. Bonus scores are awarded when an SSR Applicant provides information to specific questions in the SSR questionnaire, or specific SSR modules. Bonus scores are reported separately and do not contribute to the SSR Tier of a mission.

The SSR's modules will be reviewed and revised on a regular basis by the SSR Entity in consultation with the SSR Design Team and Board of Advisors to ensure relevance and adapt to the changes in technologies, the space environment, and international standards. In the first iteration of the SSR, six modules are included in the rating system, with an overarching verification module applied to all modules, namely;

(i) Mission Index (or space traffic footprint);
(ii) Collision Avoidance Capabilities;
(iii) Data Sharing;
(iv) Detectability, Identification, and Tracking;
(v) Application of Standards;
(vi) External Services.

The following section briefly details each of the SSR modules, and respective scoring schemes.

2.1 Prerequisite questions

The purpose of the SSR prerequisite questions is to ascertain if satellite operators requesting a rating meet the minimal level of effort toward sustainability necessary to merit recognition. The SSR prerequisite questions are informed by the Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee [3], and include confirmation of compliance with post-mission disposal guidelines, commitment to employ a space debris mitigation plan and passivation at the end of operations, as well as the commitment to avoid intentional destruction of any space object. These pre-requisite standards are intended to flag irresponsible behavior, but are set low enough to not be exclusionary of emerging actors making a good faith effort towards sustainability but who may not be able to achieve all internationally recognised best practices perfectly.

If one of the prerequisite questions is not answered with strong performance, the overall score of the operator is envisioned be limited to a lower tier level, even if the operator performs well in other aspects of the assessment. For example, one of the prerequisite questions requests the SSR Applicant to confirm if the mission avoids the intentional destruction of any space object. In the case where the Applicant is unable to confirm avoidance of intention harm to other satellites in the space environment, the SSR Applicant will not be eligible to receive a rating, regardless of the mission's performance in the SSR modules. This is in line with the SSR's key objective to encourage sustainable behavior in space, and reward actors who make efforts in the pursuit of long-term sustainability.

In addition, the prerequisite questions ask the operator requesting the SSR evaluation to affirm that it commits to share information and supporting documentation with the SSR Entity (also referred to the SSR Issuer) as required to assess and provide an SSR, and to keep that information up to date.

2.2 Mission Index Module

The mission index is a metric that quantifies the fragmentation risk associated to a mission, which is the likelihood that an object is involved in a fragmentation and the severity of this potential fragmentation measured through the impact on operational satellites [4]. The metric is connected with several aspects of a mission as, for example, the size of the spacecraft, and the orbit where it is operating. The input required for the assessment include mass, cross-sectional area, operational mean altitude and inclination, target disposal trajectory (apogee, perigee), expected disposal success rate, and mitigated collision risk. The value of this metric is computed along the whole mission lifetime (i.e. from feasibility to disposal phase of the mission) to capture the risk reduction associated with the implementation of disposal strategies.

In addition, we also compare the risk associated with the selected disposal and the one corresponding to the IADC-recommended disposal action in the corresponding orbital region (e.g. the 25-year rule in LEO). In particular, two separate scores are compute for a mission: the *absolute* index of the mission (I), intended as the simple evaluation of the risk metric for the mission, and the *relative* value, intended as the ratio between the absolute index I and the one corresponding to the reference mitigation scenario (I_{ref}).

Normalisation

The approach to normalisation for the mission index module is described in detail in [5] and summarised here. For the *absolute* part of the mission index, the normalisation is performed by introducing the concept of environment capacity, that is the number and the type of missions that are compatible with a stable evolution of the environment [6]. This approach is more complex than normalising with a reference mission, but it is also more robust and can capture the evolution of the environment. In particular, the available capacity (i.e. not used by existing missions and space debris) is used as a normalisation factor within the rating and a logarithmic function is applied to translate the normalised index into a value between 0 and 1 that can be integrated with the values coming from the other modules. A similar approach is used also for the relative component of the mission index, where the mapping function to the 0-1 range was selected after a calibration phase based on the analysis of some reference missions with different disposal approaches.

2.3 Collision Avoidance Module

Due to the increasing number of operational satellites and debris in orbit, and limitations of publicly available information on how operators carry out their collision avoidance monitoring and manoeuvres [7], the SSR Collision Avoidance Module recognises efforts taken by the mission operators to evaluate and improve their collision avoidance capabilities. In absence of a perfect space surveillance capability and depending on the operators' capabilities, this module comprises of three categories of actions that can be taken an operator to reduce the risk of accidental collision with debris and among active operators namely;

(i) Orbital State Knowledge (during normal operations);
(ii) Collision Avoidance: Availability to Coordinate; and
(iii) Collision Avoidance: Availability to Coordinate
(iv) Collision Avoidance: Capability to Manoeuvre

[*] Orbital position state knowledge refers to time-indexed position and velocity information, but does not include covariance.

The module further compliments the aspect of risk-reduction related to collision avoidance captured in the mission index [4,8,9], focusing on best practices for which it is more difficult to directly quantify the contribution to orbital risk mitigation.

For each of the categories of action, four different levels are defined, which are associated to different scores:

- Minimum (0 points)
- Low (2 points)
- Medium (3 points)
- High (4 points)

Entities can accumulate points for each of the three category up to the highest level whereby they satisfy all criteria contained in the rubric. If an operator is able to fulfil multiple boxes in a single row, those point values are added. For example, if an actor is able to fulfil the highest level of orbital state knowledge for a mission, the total points they receive will include low (2 points), medium (3 points) and high (4 points), totally a score of 9 points for the entry. Table 1 below details the scoring rubric used for the SSR Collision Avoidance Module.

Table 1 Scoring rubric for the SSR Collision Avoidance Capability module

Orbital State Knowledge	
Minimum (0 points)	Reliance on a third party public SSA provider for state information
Low (2 points)	Operator maintained orbital position* state knowledge of object
Medium (3 points)	Maintain orbital state knowledge of object to < 10 km in any direction Update orbit determination for the operated satellite when a manoeuvre or other event induces a change to its orbit that would cause the operator's state estimation to be worse than the required orbital state knowledge. & Characterise/validate covariance of your orbit determination
High (4 points)	Maintain orbital state knowledge of object to within < 1 km in any direction.

	Update orbit determination for the operated satellite when a manoeuvre or other event induces a change to its orbit that would cause the operator's state estimation to be worse than the required orbital state knowledge. & Characterise/validate covariance of your orbit determination
Collision Avoidance: Availability to Coordinate	
Minimum (0 points)	Not able to coordinate
Low (2 points)	Able to coordinate in response to emergencies (but not necessarily on a routine basis)
Medium (3 points)	Able to coordinate during set hours per day
High (4 points)	Has a system for routine conjunction assessment and 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
Collision Avoidance: Capability to Coordinate	
Minimum (0 points)	Operator has 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
Low (2 points)	Has the capability to be contacted in case of close approach or another high-risk event Operator regularly screens orbits and planned manoeuvres against public catalogues and/or information from SSA sharing organisations and/or third-party SSA providers
Medium (3 points)	Operator is capable of interpreting conjunction data messages and other common formats, to determine risk and generate/screen mitigating manoeuvres Operator has a system for automated routine conjunction assessment
High (4 points)	Has documented procedures for collision screening, assessment, and mitigation Regularly screens operational spacecraft and planned manoeuvres against SSA sharing organisation catalogue
Collision Avoidance: Manoeuvre capability	
None (0 points)	Not able to manoeuvre or affect the spacecraft trajectory
Low (2 points)	Able to deliver a $\Delta v < 1$ cm/s within 6 orbit revolution and/or use of differential drag
Medium (3 points)	Able to deliver a Δv of 1 cm/s within 6 orbital revolutions
High (4 points)	Able to deliver a Δv of 1 cm/s within 1 orbital revolution
Bonus	
Minimum (0 points)	-
Low (2 points)	Maintain orbital state knowledge until spacecraft is placed into a graveyard orbit or is disposed of through atmospheric re-entry
Medium (3 points)	Maintain orbital state knowledge to 10 km until spacecraft is placed into a graveyard orbit or is disposed of through atmospheric re-entry
High (4 points)	Maintain orbital state knowledge to 1 km until spacecraft is placed into a graveyard orbit or is disposed of through atmospheric re-entry

Please note that the scores may continue to be revised as the SSR design matures.

2.4 Data Sharing Module

As the space environment becomes increasingly complex, there is a need for more timely and accurate data sharing practices between actors. In the 2021 'Space Sustainability: Stakeholder Engagement Study', published by the United Nations Office of Outer Space Affairs (UNOOSA), transparency and information sharing were often identified as critical elements to gain trust and build confidence among the space community, with numerous stakeholders reflecting that is was mandatory to build space sustainability practices [10].

In order to incentivise actors to increase their data sharing, and reward actors who are open to sharing data about their missions, the SSR Data Sharing module recognises three categories of data sharing, namely [11]:

(i) Collision Avoidance Coordination Information;
(ii) Satellite Metric Information;

(iii) Satellite Characterisation Information

Table 2 details the scoring rubric for each of the data sharing categories, whereby actors are awarded points for sharing a specific type of data with a certain audience category, including:

(i) SSA Provider(s) who operate SSA databases for use by third parties or provide SSA data products or services to others;
(ii) Upon request by other operators for coordination in response to a high interest event or other specific planned or emergent event;
(iii) Voluntary network(s) of operators/stakeholders such as the Space Data Association that operate a platform to share safety of flight information, with some networks providing additional data verification and validation and/or legal and technical restrictions on the use of shared information; and
(iv) public sharing, whereby the operator ensures the dissemination mechanism makes clear that the information posted is accurate and authoritative information provided by the operator, and where it is clearly stated the operator is committing to keep the information updated and additionally shows the last time the information was updated. Providing information to a third party who hosts and shares such information (e.g. listing a satellite's mass on Wikipedia), would not be sufficient to earn credit under this category.

Table 2 Scoring rubric for SSR Data Sharing Module

Data shared (categorised by contribution to safety)	**SSA Provider(s)**	**Upon request**	**Voluntary network**	**Public**
Collision Avoidance Coordination Information				
Publish + update collision avoidance contact information	10	10	12	12
Publish + update collision avoidance contact time zone/hours of operation	3	3	3	4
Publish + update COLA contact/coordination response time commitments	1	2	2	1
Satellite and Mission Information				
Publish + update satellite ephemeris (including manoeuvres, for LEO: 7 days, MEO/GEO: 14 days into the future). Sharing archived data is encouraged, but not required.	12	8	15	15
Publish + update covariance information	6	5	6	6
Publish + update covariance characterisation/validation	1	2	3	3
Publish + update launch vehicle timing/trajectories (planned and actual)	3	1	1	2
Satellite Characterisation Information				
Publish + update satellite mass	4	3	4	4
Publish + update satellite manoeuvrability (manoeuvrable/non-manoeuvrable)	5	5	6	6
Publish + update satellite manoeuvrability capability	3	2	3	3
Publish + update satellite operational status (operational/non-operational referring to the real-time operational status of the satellite post-launch until disposal)	5	5	6	6
If the satellite uses autonomous systems (systems without a human in the loop) for satellite manoeuvring, publish + update:				
The criteria for when a manoeuvre is triggered	5	3	5	5
Where and with what frequency planned autonomous manoeuvres are reflected in shared SSA information	5	3	5	5
If emergency stop procedures exist to interrupt autonomous procedures in case of malfunction and how another operator should request an emergency stop	2	2	3	3

Other forms of data sharing (Bonus)				
Radio-frequency Information to support interference avoidance/mitigation/geolocation	1	4	3	3
Spacecraft anomaly information	1	2	3	4
Other datasets to support government/academic research†	3	3	3	4
APIs or other means for automatic machine to machine access to above information.‡	1	1	2	2

Please note that the scores may continue to be revised as the SSR design matures.

2.5 Detectability, Identification and Tracking

Based on the physical and operational characteristics of the satellite during launch, operations and disposal, the Detection, Identification and Tracking (DIT) module of the SSR considers the level of ability for observers to detect, identify, and track the mission [12, 13]. The SSR evaluates these aspects of the mission using a software model 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 were developed using case studies of existing space missions that have publicly available information about their physical characteristics and orbits. Key aspects considered in the design of the DIT module is described in Table 3.

Table 3 Description of the detection, identification, and tracking aspects applied to the SSR DIT Module

Module Aspects	Description
Detection Probability that a space object can be detected from a reference set of ground-based sensors	Geometric approximation of the satellite and the orbital information are used to estimate the satellite's average visual magnitude from an optical sensor and probability of detection by a radar sensors.
Identification§ Probability that a naïve observer can identify that the object as one of the objects in a known catalogue, using only information that is independently measured	Distinguishing features of the satellite (radar cross-section, dimensions, altitude, angular momentum, and visual magnitude) are used to quantify the ease of identifying the satellite. This score is calculated by referencing ASTRIAGraph [14], a tool to support Anthropogenic Space Objects (ASOs) visualisation and tracking by combining data from multiple SSA.
Tracking Probability that a naïve observer can effectively predict when an identified object will return to the field of regard of a network of sensors, based only on information that is independently measured	Orbital information and simulated sensor network are used to calculate the average length of an access opportunity where the satellite can be observed by a sensor, the average interval of time between opportunities, and an approximation of what percentage of the orbit can be observed.
Questionnaire Questions to qualitatively evaluate the actions taken by the operator to increase Detectability, Identifiability and Trackability of the satellite	Ability to track the resident space objects operated? • Operator depends on Space-track or other third party public SSA providers (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)

† Examples might include (but are not limited to) non-lethal impact data, inferred atmospheric drag, and/or manoeuvre information.

‡ Points are per totally compliant data category (Collision Avoidance Coordination Information, Satellite Metric Information, Satellite Characterisation Information), so total score for automatic access is three times these values.

§ Identification aspect of the SSR module is not currently included in the first iteration of the SSR

Questionnaire (cont.)	Ability to provide verifiable photometric/radiometric characterisation data on the satellite to the SSR evaluator • Radiometric Data (average/max/min RCS) (2 point) • Photometric Data (average/max/min Visual Magnitude) (2 points)

Applicants applying for an SSR are required to provide the following inputs on the characteristic information and planned orbital information for the satellite for the DIT module:

- Required:
  - Geometric approximation and dimensions (rectangular prism, cylinder, or sphere);
- Requested:
  - CAD model (Basic size and geometry);
  - Detailed CAD model (Complex faceted model, i.e.>1000 faces, with material details);
  - Operational Orbit Parameters;
  - Nominal requirements for satellite Attitude/Pointing during primary mission;
  - The number of satellites in the mission and the deployment process from the launch vehicle;
  - Qualitative description of the early operational stages to reach the operational orbit

Normalisation

For the Detectability and Tracking aspects of the DIT module, the normalisation is carried out by defining performance tiers for each of the metric, as detailed in [5].

Each of the four DIT Module Aspects (Detection, Identification, Tracking, and the Questionnaire) are equally weighted to form the overall DIT module score.

2.6 Application of Standards

As part of the SSR, mission operators are evaluated on mandatory or voluntary adoption of internationally recognised design and operations standards that have been applied to the mission in efforts toward safe and sustainable operation in the space environment. The Design and Operations Standards module of the SSR consists of a questionnaire whereby applicants are awarded for mandatory adoption (points gained that impact the SSR Tier) and voluntary adoption (bonus scores that impact the SSR Steps). The scoring methodology used in the module aims to find a balance between discouraging the selection of looser regulatory regimes and recognising beyond-than-required behaviours [5].

The SSR Design and Operations Standards modules considers the adoption and/or tailoring of the following:

- Space debris mitigation guidelines (e.g. IADC);
- UN COPUOS Long-Term Sustainability guidelines;
- Space debris mitigation standards or verifiable laws (e.g. ISO, FSOA);
- Standardised operational products (e.g. CCSDS);
- In case of close proximity or rendezvous operations: relevant safety standard (e.g. CONFERS).

Additional questions in the module also request information from the SSR applicant regarding;

(i) The release of debris in orbit from the satellite or launcher;
(ii) Probability of explosion;
(iii) Ability of the satellite to be passivated after its operational lifetime;
(iv) Use of disposal orbit after end of operations for spacecraft and launch vehicle upper stage;
(v) commit to registering/has registered your payload and associated objects with the United Nations Committee on the Peaceful Uses of Outer Space's Register of Objects Launched into Outer Space.

2.7 External Services Module

With satellite servicing technologies steadily progressing over recent decades a growing interest and market readiness have emerged for on-orbit satellite servicing (OOS) and cooperative satellites specifically equipped with the tools and technologies needed to extend satellites' lifespans. The SSR external services module considers a wide range of activities aimed at recognising actions taken by that satellite operators to employ external services or to increase the probability of successful external servicing, and are classified into four categories of actions, including [11]:

(i) On-orbit features
(ii) Standardised interfaces
(iii) Life extension services
(iv) Use of external ADR (beyond compliance)

Table 4 details the four categories of actions in the external services modules during the different phases of a mission.

Table 4 Scoring rubric for SSR External Services module

Category	Description	Example
On-orbit feature (0.5 Bonus points)	Operators can take actions during the design and pre-launch phase to make it easier to have their mission serviced in the future. This does not imply that they will definitely use OOS.	Installing of OOS features in preparation to create a fail-safe option for satellite repair, refuelling or disposal. Examples include visual fiducials, grapple fixtures, mechanical features, grasp features etc.
Standardised interfaces (0.5 Bonus points)	Utilising OOS in line with current standards developed and proposed by international groups e.g. Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)	Employment of OOS capabilities that include standardised interfaces
Life extension services (0.5 Bonus points)	Commitment to use or demonstration of use of On Orbit Servicing	External end-of-life removal service
Use of external Active Debris Removal (beyond compliance) (0.5 Bonus points)	Commitment to use or demonstration of use of On Orbit Servicing	Use of external Active Debris Removal but still complies with 25 year deorbit rule

Please note that the scores may continue to be revised as the SSR design matures.

Noting that many of the OOS features are still in the demonstration phase, and that the not all missions will employ external services (low altitude orbit or small satellites), the first iteration of the SSR's external services module will award bonus scores for missions only, and will be weighted equally. A total of 0.5 bonus points will be awarded for missions that meet the requirements for each category. It is envisioned that with the verification, validation and successful demonstration of external services capabilities continue, scope for re-evaluation of points in this module will be considered.

2.8 Verification Assessment

A verification assessment module is applied to all six previous modules of the SSR in order to confirm that the SSR applicant's input is accurate and reflects confidence from the SSR Entity that the input and data provided is accurate. The SSR Entity is not responsible for conducting an in-depth review to confirm the accuracy or technical credibility of information provided by an applicant (although it reserves the right to investigate submissions for accuracy/credibility and adjust ratings accordingly). Instead, the credibility of applicant-provided information will be assessed based on the levels of verification listed in Table 5 as demonstrated in documentation submitted by the applicant.

Table 5 Different levels of verification assessments defined in the SSR

Corrective Factor	Verification Assessment Level
0.5	**Assertion by Applicant** Affirmative statement by the applicant is provided, without supporting documentation
0.6	**Assertion with Technical Documentation** Supporting technical documentation on the mission design is disclosed to the SSR Entity
0.8	**Public Release of Technical Documentation** Supporting technical documentation is submitted to a government or non-profit available for public review
1	**Authority** An independent technical review or the confirmation of the compliance by a third-party technical expert is provided

Points awarded through either data inputs and/or questionnaire responses in the six modules outlined above will be multiplied by the corrective factor corresponding to the verification assessment level selected by the SSR applicant. Section 3.2 provides a example of the impact of the verification assessment on the SSR Tier scores of a sample mission.

2.9 Weighting and Aggregation

During the scoring process, the total number of points earned by the entity in a given module are divided by the total possible points. The normalised point total is an input to the full SSR calculation, and results in a score between 0 (low) and 1 (high and the best achievable score). This normalisation procedure is relevant for all SSR modules, excluding the Mission Index and Detection, Identification and Tracking modules as described in Section 2.2 and Section 2.5 respectively

In order to assign the SSR Tier level of mission, the normalised scores from individual modules are aggregated into a single SSR score, as described in [5]. Each of the six SSR modules is assigned a weighting factor in the form of a percentage based on alpha and beta testing of the SSR. Certain modules are considered more substantial in the context of long-term space sustainability than others and therefore make up a higher portion of the overall SSR Tier score. The SSR modules carry weighting factors classified as high (50%), medium (15%) and low (5%) contribution to the SSR Tier level, as follows:

- **High** (50% contribution to the SSR Tier)
  - Mission index module
- **Medium** (15% contribution to the SSR Tier)
  - Collision Avoidance Processes
  - Data Sharing
  - Detection, Identification, Tracking
- **Low** (5% contribution to the SSR Tier)
  - Design and Standards Application
  - External Services (constituting bonus points only)

The weighting factors presented in this paper continue to be assessed, with on-going analysis based on further beta testing.

3. Alpha and Beta Testing

The alpha and beta testing phase of the development was conducted to provide an opportunity for the consortium to test and calibrate the SSR prior to public registration. The aim of the alpha and beta testing was to engage with stakeholders to help improve aspects of the SSR. These include ensuring clarity and precision in the questionnaire, and minimising the burden associated with completing the questionnaire and required documentation verification, and identifying challenges and/or loopholes. Importantly, both alpha and beta tests were used to inform the weighting for each module of the SSR and the SSR Tier categories.

Alpha tests were conducted by the SSR consortium members, namely ESA and MIT on respective missions from each organisations, followed by beta testing by external operators. A select group of partners were invited to conduct the first beta testing of the SSR to ensure the model correctly took into account diverse criteria from the variety of missions that are already operational or are set to launch. Airbus evaluated two earth observation missions to identify the differences in SSR tiers based on improved compliance. Planet evaluated a constellation mission based on different orbital altitudes and generations.

3.1 SSR Tier categories

Based on the outcomes of the alpha and beta testing, the SSR Tier designations were categorised as the following:

<u>Certified:</u> The mission meets the pre-requisite requirements to apply for an SSR. The SSR applicant demonstrates willingness to increase mission's sustainability. Current sustainable practices need to be incorporated into the mission.

<u>Silver:</u> The mission incorporates current sustainability practices with areas to improve upon. The SSR applicant demonstrates consideration for the orbital environment in design and operation of mission.

<u>Gold:</u> The SSR applicant demonstrates currently accepted best practices for sustainability in all aspects of the mission. The mission has minimal impacts on the orbital environment beyond the necessary use.

<u>Platinum:</u> The mission incorporates innovative methods for improving the orbital environment that go beyond common best practices. The SSR applicant demonstrates sustainable practices that enhance sustainability outcomes across all aspects of the mission.

3.2 Example SSR Mission Evaluations

The following sections presents examples of SSR evaluated missions performed during the alpha and beta tests. Names and details of the missions have been excluded to preserve confidentiality of the mission operators, until such a time that the operators choose to make their SSR public. Figure 2 presents the results of alpha and beta tests on a range of missions, and details the normalised scores for each SSR module, and subsequent SSR Tier.

<u>*Comparison of LEO vs GEO missions*</u>

CubeSat missions have low associated risk, as shown by reaching 0.4 weighted score in the mission index module.

However their inability to manoeuvre, lack of collision avoidance capabilities, and inability to easily be detected or tracked due to their size result in low weighted in the collision avoidance and DIT modules. A GEO mission (GEOSat) SSR evaluation showed that the same weighted score in the mission index module. In comparison to the CubeSat missions, the GEO mission scored higher in the collision avoidance, data sharing, and DIT modules reflecting the fact that the GEO operator shared ephemerides and other data to facilitate coordination, and benefited from a reduced risk in the Mission Index metric with respect to LEO missions.

Comparison of Earth Observation missions

A comparative study of three Earth Observations (EO) missions was conducted to determine the impact of operators' design choices, such as satellite size and end-of-life (EOL), on the final SSR Tier rating. The three mission scenarios evaluated, namely:

(i) A default example (EO #1): an EO mission in a Sun-synchronous orbit in a non-naturally compliant altitude such that a manoeuvre is required to meet the 25-year rule at the End-of-Life of the mission (EO #1);
(ii) The default mission with the disposal phase was reduced from 25 to 5 years (EO #2); and
(iii) The default mission whereby the size of the spacecraft is doubled (EO #3).

EO #2 receives an improved assessment for in the mission index module when the disposal phase was reduced from 25 to 5 years, highlighting the ability of the mission index module to capture the decreased impact of the mission on the space environment, largely based on the mitigation of space debris and its consequences. EO #3 simulates an EO mission whereby the size of the satellite is double that of EO #1. The impact of the increased size of the satellite results in a higher associated fragmentation risk, and therefore reduced weighted score in the SSR mission index module when compared to the EO #1 and EO #2 mission scenarios [5].

Comparison of LEO constellation missions

Finally, a comparative evaluation of a large constellation mission at high altitude (LCH) and low altitude in LEO (LCL) was conducted to study the impact of operational altitude of the satellites on the SSR. Neither the LCH or LCL spacecraft are naturally compliant with the 25-year rule. LCH's satellite post-mission disposal probability is assumed to be 95%, while LCL's is assumed to be 90%. LCL scores better due to a lower level of intrinsic risk associated with the lower altitude, even with a lower post-mission disposal success rate.

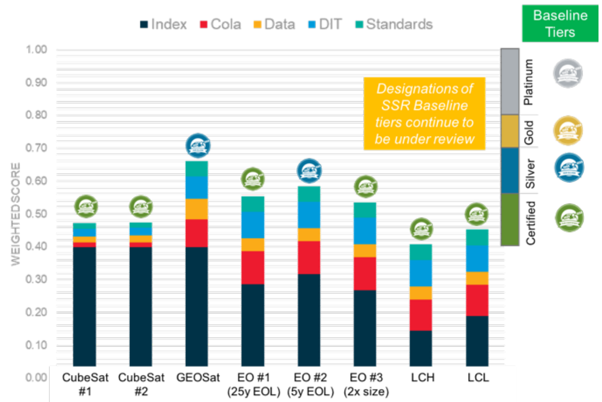

Figure 2 Example of alpha and beta testing of missions and SSR Tier designation

Optimisation studies

Based on the initial alpha and beta tests, optimisation studies were conducted to determine how changes to collision avoidance and/or data sharing of missions could impact the overall SSR Tier scores, as shown in Figure 3. In the mission scenarios evaluated, no changes were made to the satellite mission design (i.e. mass, size, number of satellites in a constellation). This results in no changes to the mission index and DIT modules of the SSR between the default and optimised mission scenarios.

Mission A represents a fleet of satellites (<10) in LEO, and achieved a Silver SSR Tier rating in the default scenario. In order to improve its sustainability and SSR score, the hypothetical operator then makes changes to its behaviours for the collision avoidance module. By increasing its Orbital State Knowledge and Availability to Coordinate from medium (3 points), as represented in the Mission A default scenario, to high (4 points), as represented in the Mission A optimised scenario, it increases its overall SSR from 0.63 to 0.67, edging closer to reaching the SSR Gold tier.

The Mission B example extends the optimisation study further. Representing a fleet of earth observations satellites (<5), Mission B achieved a Silver SSR Tier rating in the default scenario. By updating Mission B's data sharing to include sharing specific types of data upon request by other operators (for coordination in response to a high interest event or other specific planned or emergent event), it achieves significant increases in the SSR data module, allowing Mission B's optimised scenario to move from a Silver tier score of 0.62 to a SSR Gold tier score of 0.72.

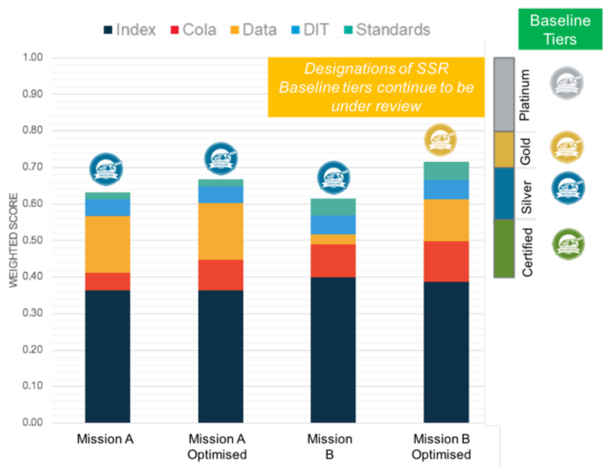

Figure 3 Example missions showcasing SSR Tier improvements based on changes to module inputs

Further studies during the alpha and beta testing phase of the SSR studied the weightings assigned to the verification assessment module of the SSR, as shown in Figure 4 below. Mission X was evaluated whereby all inputs were held consistent, except for the verification assessment applied to the inputs. As described in Section 2.8, inputs where the mission operator is able to inputs that are reviewed by an independent technical review or the confirmation of the compliance by a third-party technical expert (Authority) will receive a higher verification assessment compared to if the same data only were to only be verified by assertion by the applicant (Assertion by Applicant).

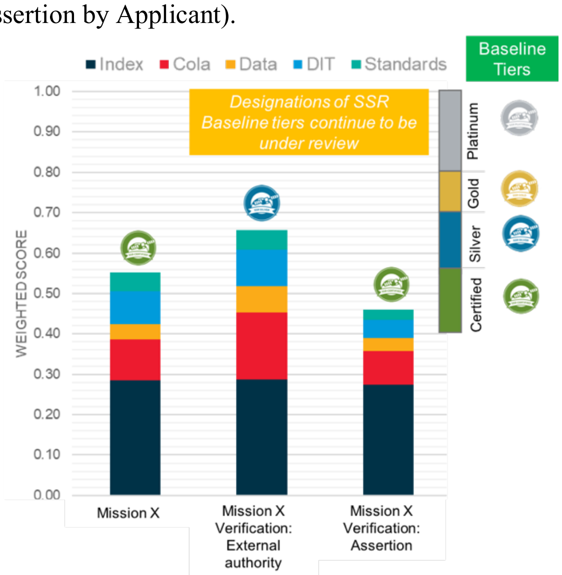

Figure 4 Example missions demonstrating changes to the SSR Tiers based on verification of inputs

3.3 Feedback from SSR beta testing

SSR beta testers provided valuable feedback, and a summary of the key observations and subsequent implementation of revisions in the first iteration of the SSR are detailed in Table 6 below.

Table 6 Summary of key feedback notes from beta testing, and subsequent implementation in the SSR design

Beta testing feedback	Implementation in the SSR design
Satellite operators and manufacturers design their missions in response to the constraints and needs of their end users and the physics of their orbit. This leads to different options for how to pursue a high SSR score, with operators suggesting that more flexibility in the SSR modules including orbital selection, data sharing, collision avoidance, and number of spacecraft.	The SSR and its modules are envisioned to be periodically updated, based upon technology updates, the status of the space environment, and updates to long-term space sustainability regulations. As described in [11], while a number of modules were excluded in the first iteration of the SSR, these will be analysed for inclusion in future iterations of the SSR. On-going discussions are being conducted by the SSR Consortium with actors on how much flexibility is required in the data sharing or collision avoidance modules.
Some satellite operators consider whether to extend the life of a satellite or replace it with a newer model. Understanding the sustainability impacts of life extension decisions requires a life-cycle approach that considers the launch, spacecraft reliability, technology maturity and changes in the orbit.	The SSR modules account for the design decisions made and updated by the operator at all phases of a mission, including end-of life. The mission index module and External services account for decisions in the event that the operator decides to extend the life of the mission.
Beta testers encouraged the SSR team to clearly communicate to operators what actions influenced their score and what actions they can take to improve it.	As shown in Section 3.2, the SSR consortium and host entity will strive to consult with SSR applicants on actions that can be taken during all phases of the mission to increase their overall SSR Tier score.

Beta testers noted that decisions are made about key mission features that influence the SSR at specific points in the design and operations phase. For example, an orbital altitude is selected early in the design phase and it may not be feasible to change it; this may imply that the operator will need to consider other SSR modules to improve their score such as data sharing, collision avoidance or detectability.	As the SSR Tier of a mission will be updated periodically, any changes during in-orbit operations or end-of-life decisions made by the operator (e.g. increased data sharing, or earlier disposal at the end of operational life of a mission) after launch will be reflected in the updated SSR Tier. The final SSR Tier of the mission will only be assigned after the disposal phase of the mission.
Beta testers requested that verification assessment of public release of technical documentation should also include the availability of data via public information sharing, a public API (application programming interface), or an API that would be provided to a requestor, upon request.	The SSR verification assessment as well as SSR data sharing module is designed to account for a number of categories of information sharing that allow the SSR Entity to be confident in the inputs received by the operator while not disclosing proprietary information regarding the mission. Data can be shared via an API rating than hosting a particular website, on the condition that there is an associated query-builder for less-technical users.
Do you plan to have at the end an Excel sheet that provides directly an assessment of the final rating? The interest would be to see rapidly what improvements in design/operations are useful to perform a better final score.	Some of the modules rely on computations that cannot be embedded into an Excel file. Our recommendation is for the hosting agency to setup a web-based interface to allow operators to compute the rating also outside/before a formal submission exactly to be able to assess how different actions/decision would affect the final score.

4. Selection of SSR Administrative Entity

Following the initial alpha and beta testing of the SSR, in late 2020, the World Economic Forum began its search for an entity or a consortium of entities willing to take over the management and day-to-day operations of the SSR. The selected entity was envisioned to be international in nature, impartial, trusted by actors in the sector, and with appropriate resources to ensure initial roll out. The selected SSR Administrative Entity would be responsible for three types of activities, namely:

(i) issuing SSRs to missions submitted by satellite operators for evaluation;
(ii) pursuing campaigns to raise awareness about the SSR to the space community; and
(iii) working with the SSR Advisory Group[**] and the SSR Consortium[††] to maintain and update the SSR technical definition as needed.

4.1 Selection process

The selection of the SSR Administrative Entity was conducted in a two-step process, as detailed in Table 7 below.

Table 7 Details of the two-step selection process including key information requested by applicants

Description	Requested Information
Call for Letters of Intent for any entity (or consortium of entities) that would be interested in the formal management and hosting	• If and how the entity was already involved on the topic of space sustainability • Entity's vision and reason for wanting to take on the management of the SSR • Reasoning and evidence for the entity to be the best fit for the SSR management • Details of resources (human, financial, etc.) available to

** The SSR Advisory Group consists of independent and multi-stakeholder group of experts selected by the World Economic Forum to advise and provide high-level guidance

†† The SSR Consortium consists of the organisations selected by the World Economic Forum to design and develop the SSR, and consist of World Economic Forum, Space Enabled Research Group at Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and BryceTech.

of the Space Sustainability Rating starting in 2021 on a permanent basis	manage the first 2 years of the SSR roles and responsibilities that you propose for the entity or entities that will participate in managing the SSR under the vision you propose. • Details of the core lead/team be assigned to the SSR, transition and launch?
Extended Letter of Intent which included addition clarification questions regarding resources, budgets, technical partnerships, and visions for the operating structure of the SSR	• Details of technical expertise to support the on-going work of the SSR to ensure it stays current (beyond input from the Advisory Group), including overall technical capability to cover SSR management, updates and future expansion • Confirmation and further details of the necessary budget to cover up to the first 2 years of hand-over and roll-out of the SSR • Further details on resources (e.g. full or part time employees) to support the hand-over and roll-out of the SSR in the first two years • Suggested operating structure • Details of potential partners (if applicable) • Evidence of ability to coordinate with space operators globally and leverage influence within the space sector.

4.2 Key selection criteria

Upon receiving the extended letters of intent, applications were reviewed and rated based on the following criteria:

- Technical Qualifications
- Resource Allocation
- Objectivity/ Neutral status
- Risk to long-term management (highest mark
- Possible integration (partnership) with other partners
- Strength of proposal and plan proposed

4.3 Selected SSR Entity

Based on the accumulated scores for the selection criteria provided in Section 5.2, the [EPFL] EPFL (École polytechnique fédérale de Lausanne) Space Center, known as eSpace, was selected as the host SSR entity, tasked with implementing the SSR as an operational rating system in preparation for its roll-out.

The EPFL Space Center (eSpace) is an interdisciplinary hub, working with students, academic institutions, international space agencies and industry partners, with an overall mission to promote space related research and education at EPFL. eSpace achieves its mission through three key areas:

- Education
- Fundamental research
- Innovative development projects

eSpace is currently focused on the research initiative on Sustainable Space Logistics, which includes missions such as removal of space debris and technologies such as Relative Navigation and Space Robotics, demonstrated by the partnership with eSpace's commercial spin-off ClearSpace SA, due to launch its first space debris removal mission in 2025. The centre boasts a team of experts with a wide range of industry and academic experience, and benefits from close collaborations with research laboratories and institutes at EPFL.

eSpace will undergo a transition phase with the SSR consortium on finalising the development of the SSR and the business model, and take ownership and management of the SSR in the first half of 2021. The selected entity accepts to take up the rating in its current, document-based form (as per finished work of the consortium) and not make any changes without prior consent of the consortium. Once launched, there are expected to be annual reviews (or extraordinary amendments per new policy, technology or environmental events) with the help of the broader Advisory Group to ensure the rating stays relevant, unbiased and true to its goal of motivating actors to go above and beyond in exhibiting sustainable behaviour in relation to orbital debris mitigation. Addition modules or expansion of SSR should also be considered per input from the Advisory Group. Following the transition, the SSR Consortium will join the SSR Advisory Group, together with the representative of the selected entity and the new Advisory Group will continue forward to ensure future sustainable operations and continued development of the SSR.

5. Conclusion

As the challenge of orbital debris is set to grow, current and future missions face an increasing risk of possible collisions. The SSR provides an innovative way of addressing the orbital challenge by encouraging responsible behaviour in space through increasing the transparency of organisations' debris mitigation efforts by;

(i) offering recognition of sustainable actions and decisions taken by actors, thereby encouraging better behaviours by operators;
(ii) simplifying the assessment of and quantifying sustainability metric to draw a clear comparison between missions; and
(iii) helping to recognise and spread new behaviours/best practices for sustainability more nimbly than national regulation.

The paper provides a detailed description of the scoring methodology used for the SSR. Namely, the SSR transforms information provided by the SSR applicant through a questionnaire and supporting documentation into scores for various modules. These module scores are then composited to produce a single rating and corresponding SSR Tier rating and bonus scores which represent a mission's space sustainability. The SSR design was validated through beta testing with stakeholders from industry. These Beta testers volunteered to evaluate their missions using the SSR to help improve the rating system, identify the level of difficulty in completing the questionnaire and required documentation verification, and uncover challenges with proposed SSR module inputs. The alpha and beta testing phase of the SSR development was critical in defining the SSR module weighting factors and SSR Rier definitions. Select results of the alpha and beta tests are presented in the paper, as well as an analysis of how different modules or inputs can impact the SSR Tier awarded to missions. Furthermore, the paper presents the subsequent beta testing feedback, and details lessons learnt that have been effectively implemented into the design of the SSR to increase the usability of the rating system.

The SSR's modules and scoring methodology were design on the principles of pproviding an objective, quantitative and metric based tool to assess sustainability, while remaining technology and design neutral, with scores tied to the contribution to overall orbital risk. Additionally, the transparency behind the SSR design allow SSR Applicants to easily understand and interpret their respective SSR evaluations, encouraging operators to reflect on improvements to their mission and respective SSR.

By voluntarily taking part in the rating, satellite operators will share a single point of reference externally describing their mission's level of sustainability. Making their aggregate score publicly available, these actors will increase transparency and place emphasis on their debris mitigation approach, without disclosing any mission-sensitive or proprietary information. The rating may also act as a differentiator and trigger positive outcomes (e.g. impacting insurance cost or funding conditions), incentivising other stakeholders to improve their behaviour.

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