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Space Sustainability Rating: Designing a Composite Indicator to Incentivise Satellite Operators to Pursue Long-Term Sustainability of the Space Environment

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Abstract

The Space Sustainability Rating (SSR) was first conceptualised within the World Economic Forum Global Future Council on Space Technologies, and is being designed by an international and transdisciplinary consortia including the World Economic Forum, Space Enabled Research Group at Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and Bryce Space and Technology. With the increasing awareness of the rapidly growing number of objects in space, the implementation of a rating system, such as the SSR, provides an innovative way to address the orbital challenge by incentivising industry to design missions compatible with sustainable and responsible operations, and operate missions considering potential harm to the orbital environment and impact on other operators in addition to mission objectives and service quality. This paper builds upon the SSR concept introduced at the IAC in 2019, and provides in-depth description into the methodology used to design the SSR, based on successful rating systems in other industries such as LEED (green building energy and environmental design). This method seeks to provide a practice tool that governments, satellite operators and insurers can reference. The process also seeks to build capability among emerging space actors as they seek to understand how to design responsible space missions. The SSR is a composite indicator that is a function of the Space Traffic Footprint, measured through a mission index and compared to the so-called Environment Capacity and other measures of the responsibility shown by operator actions. The components of the SSR take into account mission aspects including on-orbit fragmentation risk, collision avoidance capabilities, detectability, identification, trackability, data sharing, on-orbit servicing, collision avoidance, debris mitigation, and adoption of international standards. The paper further explores key questions including; (i) what factors are most important to influence whether an operator seeks to reduce the potential for debris creation, (ii) how can the SSR can contribute to existing mechanisms (eg. UN Long-term Sustainability Guidelines, IADC) in supporting long-term space sustainability, and (iii) how can the SSR educate policy makers regarding manufacturers' and operators' motivations in choosing specific criteria and certifications in designing their mission to achieve a high rating or improve their existing rating.

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

1. Introduction

A central issue in the context of the space environment is that of its long-term sustainability. With the increasing number of space actors and proposed missions, the key to achieving sustainability is by creating, implementing and supporting mechanisms that not only address current demands of the space environment, but can continue to meet the demands of use for future generations. The Space Sustainability Rating (SSR) provides an innovative way to address the orbital challenge by incentivising industry and fostering voluntary action by satellite operators to design missions compatible with sustainable and responsible operations, and operate missions considering potential harm to the orbital environment and impact on other operators in addition to mission objectives and service quality. The SSR was first conceptualised within the World Economic Forum Global Future Council on Space Technologies, and is being designed by an international and transdisciplinary consortia including the World Economic Forum, Space Enabled Research Group at Massachusetts Institute of Technology (MIT) Media Lab, European Space Agency, University of Texas at Austin, and Bryce Space and Technology.

The paper discusses the methodology adopted for the design and development of the SSR. Using a composite indicator approach, different indicators (referred to as nodules) are compiled into a single index (rating).The different SSR modules take into consideration the short- and long-term effect on other operators, and on the environment globally.

2. SSR Design Methodology

While the concept of sustainability is prevalent in the space industry, it is often challenging to define. Sustainability rating systems in other industries have become popular tools to confirm sustainability credentials, offer a comprehensive approach to sustainability, set target points for performance, and recognition when sustainability targets are met [1].

International sustainability rating system's popularity and global scale are admirable aspirations for the SSR. Case studies on several sustainability rating systems were conducted. Due to its success and wide adoption in the green building market, the Leadership in Energy and Environmental Design (LEED) case study is presented in this section, highlighting key aspects that influenced the design methodology of the SSR.

2.1 Analysis of international sustainability rating systems - LEED case study

The creation and success of reliable building-rating and performance measurement systems in other industries such as the Leadership in Energy and Environmental Design (LEED) certification was in response to the emissions and design of the built environment. The U.S. Green Building Council (USGBC) was formed to conceptualise a rating system as demand for standardisation of the green building industry grew and launched the first version of LEED in the late 1990s [2], Version 1.0 was released exclusively to its pilot projects in 1998, and LEED went public with Version 2.0 in March of 2000 [3]. Beginning with rating New Construction and 19 pilot projects [4], LEED grew to its current international operation of six rating systems from Building Design to Sustainable Cities and an Accredited Professional program for each system.

Projects pursuing LEED certification earn points for various green building strategies across several in the planning, construction, and operation phases of a building. Based on the number of points achieved, a project earns one of four LEED rating levels: Certified, Silver, Gold or Platinum. The benchmarks developed by LEED are met by prerequisites first. A project cannot obtain credit without meeting the prerequisites in each category.

LEED considers the lifetime and materials of the whole building, and awards credits for technologies within eight categories of sustainability. There are methods to monitor certified project data throughout the building's operation, allowing users to compare projects across participants. A recertification process for projects ensures the LEED rating is scored according to the latest version. In the past, deadlines to retire an existing version of LEED have shown an increased number of registrants to become LEED certified before the system's scheduled change [5].

Built off the shoulders of LEED, USGBC has also been able to support advocacy efforts to influence policy in the US to reflect green building initiatives [6]. While some rating systems continue to face criticism and challenges to be comprehensive, the adoption, and broad-usage of rating systems such as LEED has helped shape corporate perceptions of sustainability, driven market transformation toward sustainable development, and had a significant impact on the increased adoption and understanding of sustainability metrics, solutions and value proposition within governments, developers, and end-users. In addition to the design aspects outlined above, Table 1 provides an example of aspects of LEED that have influenced the design methodology of the SSR.

Table 1: Example of LEED design considerations considered for the SSR

Design aspects of LEED	Design methodology of SSR
Each new version of LEED incorporates feedback and public comment. This revision process enables LEED to respond to trends and	The SSR consortium have held frequent workshops with stakeholders to provide opportunities for considerable input and

are widely announced to gather a broad audience.	consultation with expert groups
Originally intended for the use of commercial office buildings, early certifications extended to hotels, as well as an environmental center in Annapolis [4]. While the rating could be applied to many existing buildings, it became apparent that the rating system could be altered to accommodate different stages of built environments, eventually expanding to neighborhoods and cities.	The SSR defines a mission as consisting of a single satellite, a satellite and launch vehicle, or larger combinations of these elements. An entity signing up for an SSR evaluation is committing for the entire duration of the planned mission, starting during the design phase and including periodically monitoring as long as the object remains on-orbit. A final rating will be issued at the end-of-life/post-disposal phase of the mission.
The first version of LEED was designed to first be an achievable rating, later introducing more rigor for sustainability, as well as releasing the system for free broadened the reach of LEED.	The first SSR must be simple, enabling industry to grasp the concepts and practices incentivised by the rating.
Well-known structures obtaining LEED certification, such as the Empire State Building, help to boost LEED's reputation, increases the certifications popularity and generates marketing	The SSR encourages stakeholders from industry, government and academia to 'Champion' the SSR by requesting a rating
Built off the shoulders of LEED, USGBC has also been able to support advocacy efforts to influence policy in the US to reflect green building initiatives (Holowka, 2019).	The SSR is aligned with the 2019 Guidelines for the Long-Term Sustainability of Outer Space Activities adopted by the Committee on the Peaceful Uses of Outer Space of the United Nations

2.2 Composite Indicators

Composite indicators have been increasingly recognised as powerful instruments for benchmarking, performance monitoring, policy analysis and public communication in the fields of society, environment and economy [7]. Comprising of individual indicators and weights, a composite indicator acts as an aggregated index representing the relative importance of each indicator [8]. The widespread application and use of composite indicators are attributed to various reasons [9], including: (i) the ability to summarise complex or multi-dimensional issues to support decision-making; (ii) reduce the size of metrics to reveal sufficient information in a succinct manner; (iii) ability to rank entities with respect to complex issues; and (iv) publishing a simplistic presentations and comparisons of performance across entities and their progress over time.

The design of the SSR takes into account decisions a space operator can make during the design, operations and end of life phases of a space mission. Letizia et al. [10] noted that during the design phase, a space operator can select materials and functional approaches that (i) increase the ability for an observer on Earth to be able to detect, identify and track the satellite, thus contributing to Space Situational Awareness; (ii) influence the reflectivity and apparent magnitude for optical tracking. Further design considerations could include:

- Dimensions that influence the radar cross section of the spacecraft since many observations from the ground are made by radar systems;
- Features that make it easier to improve the accuracy of the estimation of satellite location, such as beacons that send a signal to Earth regardless of satellite power status and reflectors that make it easier for spacecraft to be identified or detected;
- Methods to distinguish satellites from other similar satellites, such as those in a constellation of otherwise identical spacecraft;
- methods to deploy satellite(s) to reduce uncertainty about which spacecraft is being identified during early operations; and
- determine the capability of the spacecraft to manoeuvre and deorbit.

During the mission operations phase, space operators have additional key decisions, including:

- Ability of a spacecraft to contribute to the long-term sustainability of outer space;

- Selection of the orbit in case an orbital altitude and inclination is already cluttered with active spacecraft and debris;
- Ability to manage manoeuvres and collision avoidance during a mission;
- Maneuverability and what information to share publicly or with other operators about the behaviour of their spacecraft

For the end of life phase, space operators may consider the following:

- Need/desire to maintain a mission on orbit after the original schedule or to extend for additional service;
- Deorbit or move the spacecraft to a long-term disposal location if it is not possible to put the spacecraft on a trajectory that moves the satellite into the atmosphere for disposal.

Since early 2019, the SSR Consortium has held a series of workshops, bi-lateral meetings, and panel discussions to solicit considerable input and consultation with expert groups and stakeholders representing industry, academia, government, and trade associations. These discussions have served to define using six modules that will be incorporated into the first version of the SSR, highlighting key related decisions faced by space operators in all phases of the mission. The six Modules include: Mission Index to calculate the Space Traffic Footprint; Collision Avoidance; Data Sharing; Detectability, Identification and Tracking; Application of Standards; and External Services. The SSR's modules rely on access to various pieces of factual information and/or analysis, most-often furnished by the satellite operator requesting a rating. Additionally, a seventh and overarching verification module is implemented for operators to demonstrate the quality of the information they share through technical documents, third party verification, or review by national governments.

3. Space Sustainability Rating Modules

3.1 Mission Index

The mission index, developed by European Space Agency [11] is an aggregated numerical value that captures the impact of the design and operations of the objects involved in a mission on the space environment, largely based on the mitigation of space debris and its consequences. It further allows for the calculation of the conceptional idea of the space traffic footprint of the mission to quantify the level of harmful physical interference caused by the planned design and mission operations. The SSR Mission Index Module can be quantitatively assessed using a computer simulation that models the behaviour of all space objects, including the proposed new space objects for a specific mission, and incorporates factors such as the spacecraft characteristics, orbital parameters, operational plans and disposal plans in both nominal and contingency cases. The approach adopted by Letizia et al [11], and incorporated into the SSR develop evaluates a mission (single or multiple satellites and launch vehicles), before its launch with respect to existing mitigation guidelines, all well as in respect to what can be accommodated by the environment (e.g. not exceeding a defined risk level), considering objects already in orbits and other planned future missions.

The impact of a mission on the space debris environment is measured using the Environmental Consequences of Orbital Breakups (ECOB) formulation [12]. ECOB is a risk indicator, built from the general expression:

Risk = Probability x Severity,

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. In further detail, p represents the probability of collision with objects large enough to trigger a catastrophic collision, i.e. a collision where enough energy is released that the parent object is destroyed. The availability of collision avoidance capabilities is captured by removing from the computation of the collision probability those objects that are large enough to be tracked with current surveillance systems and can be avoided with collision avoidance manoeuvres.

The term *e* quantifies the effect of the potential fragmentations in terms of the increase in the collision probability for operational satellites. This is done by defining a set of representative objects of the population of operational satellites and computing the collision probability for these objects due to the simulated fragmentations. More details on the approach used to model the probability and the severity terms can be found in [12].

The risk metric so-defined (I) is not computed only at a single epoch, but rather evaluated along the mission profile of an object to the implementation of disposal strategies at the end of mission [11]. In particular, this is done by considering the possible paths of evolution of the trajectory depending on the success rate of the disposal strategy.

It has been shown how the proposed metric, while relying on few high-level parameters, allows capturing the differences among alternative mission architectures, for example considering the adoption of different operational concepts, the deployment of a constellation, and different implementation of disposal strategies [13]. With respect to the formulation applied in previous works [11]- [13], the computation of the collision probability takes into account the reduction of collision probability from trackable objects achieved due to the availability of collision avoidance strategies. In other words, with respect to previous work, the adoption of collision avoidance strategies is no longer treated as binary option (yes/no), but rather with a score (γ) that measures its efficacy. This score depends, among others, on parameters such as the threshold for reaction and lead-time required to implement a collision avoidance manoeuvre. Free tools such as ARES, from the ESA DRAMA suite* [14], are available for this purpose, so that γ is considered an input to ECOB.

The approach defined above provides an absolute evaluation of the impact of a mission on the environment. This means that some mission configurations will always score a higher footprint (e.g. because they introduce in the environment a large total mass) even when they adhere to space debris mitigation guidelines or go beyond them (e.g. by opting for a direct re-entry instead of a re-entry within 25 years). However, one of the aspects that the SSR wants to highlight operators that implement better than required behaviours for what concerns mitigation efforts. In order to capture this aspect, the computed footprint is compared to the one that the same mission would score in a reference scenario. 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):

- LEO: 25-year with 90% PMD,
- MEO: no action,
- GEO: graveyard with 90% PMD.

This evaluation contributes as an additional component to the composite indicator.

3.2 Collision Avoidance

In view of severe fragmentation events, such as that of Fengyun-1C in 2007, the Iridium-33/Cosmos-2251 collision in 2009, and the Briz-M explosions of 2012, concern for the safety of (and risk to) space assets has motivated processes and procedures among mission operators that are part of their routine operations. The SSR Collision Avoidance Module recognises and rewards satellite operators that take actions to improve their ability to identify, respond to, and mitigate collisions, and considers three categories of action by an operator:

Orbital State Knowledge
Cooperative tracking often results in smaller covariances, as do more frequent tracking and improved information about planned satellite manoeuvres (e.g. by characterising the manoeuvre uncertainties). The SSR gives additional credit for better orbit determination, more frequently updated orbit determinations, and better characterised/validated covariance estimation. This could help spur improved orbit determination capabilities, particularly for small satellites that might otherwise lack it.

Collision Avoidance: Availability to Coordinate
The SSR credits operators for maintaining service availability to coordinate with other operators for collision avoidance and the ability and availability to be contacted for collision avoidance purposes.

Collision Avoidance: Capability to Coordinate
The SSR credits operators for maintaining staff with expertise to meaningfully resolve the potential event, namely, the ability to:

(i) Accept and interpret common data formats including conjunction data messages (CDMs) and other Consultative Committee for Space Data Systems (CCSDS) standards;
(ii) Review various sources of SSA information and determine the level of risk posed by a conjunction and whether a manoeuvre is indicated, not-indicated, or if further information is needed;
(iii) Develop manoeuvre plans to mitigate a conjunction, screen manoeuvre plans from other operators for safety;
(iv) Task new non-routine manoeuvres for your satellites and confirm execution.

3.3 Data Sharing

Long-term sustainability of the safe environment presents an opportunity for international cooperation towards mutually beneficial goals. As noted in conference room paper at the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) sixty-second session in June 2019 [15], satellite operators need a complete picture of the environment around them to make decisions confidently. Sharing of space object data from a variety of sources, transparency in data sharing, and improved confidence in the accuracy of data

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* Available for download at https://sdup.esoc.esa.int/drama/

will serve to build trust. The SSR Data Sharing Module addresses the information satellite and launch vehicle operators could share with other operators and stakeholders, and the contribution of such sharing to ensuring sustainability and safety in space. The implementation of the data sharing module supports recommendations to find ways to incentivise and facilitate this sharing and develop mechanisms and standards for sharing data on space events.

Potential forms of data sharing are divided into three categories:

- Collision Avoidance Coordination Information

Currently, many, if not most, high-risk conjunctions involving active satellites controlled by different operators are resolved via manual communication between the involved operators. There is an operational need to be able to reliably reach the contact associated with a given object to ensure the operator is aware of the conjunction and so any necessary collision avoidance manoeuvres can be planned and coordinated.

- Satellite Metric Information

Launch information helps operators avoid problematic overlaps. Operational status information helps operators determine whether coordination is possible or necessary. Ephemeris information improves SSA, as operator orbit determination is often better than non-cooperative estimates. Covariance information helps determine if satellite position information is decision-quality or if more information is required.

- Satellite Characterisation Information

Satellite mass and size provided to receive a SSR and used as part of the footprint calculations, will not necessarily be released publicly. Knowing accurate mass and size information for operational satellites can help increase the fidelity of orbit propagation and conjunction assessments by third parties.

  - Autonomous systems (subset of Satellite Characterisation Information)

With the introduction of autonomous collision avoidance algorithms, having public information about their concepts of operation will be important for these systems to be designed to avoid feedback loops between systems that lead to unsafe behaviour. This is highly important in certain orbital regimes and will grow more important as such systems become more widespread.

The SSR Data Sharing module includes both publication and update requirements, i.e. operators must commit and follow through on keeping the relevant form of data up-to-date in addition to sharing it to receive SSR credit. The specific update cadence depends on form of data, but unless specifically specified, should be reasonable to support common operational uses of that information.

Additionally, the SSR recognises operations who share a given type of information with particular stakeholders. To achieve credit for sharing a specific type of data with a certain stakeholder category, the SSR applicant should generally make the specific form of data available to entities in that particular category on a reasonable and non-discriminatory basis, but does not need to proactively demonstrate that every potential possible entity in a category has the capability to receive their data (e.g. making data available in a commonly used data format is enough, even if a subset of potentially users have systems that do not support that format). Examples of stakeholders include:

SSA Provider(s)
Many entities operate SSA databases for use by third parties or provide SSA data products or services to others. Some of these entities are governmental, others are operated as non-profits or in academia, and some are for profit entities.

Other operators upon request for coordination
Another operator may make a request for coordination to an SSR applicant in response to a high interest event or other specific planned or emergent event. Operators may be willing to share information with other entities with a credible need to know in response to such an event.

Voluntary network of operators/stakeholders
Various organisations, including the Space Data Association, exist as venues to share safety of flight information, with some providing additional data verification and validation and/or legal and technical restrictions on the use of shared information.

Public
In order to earn credit for sharing with the public, the operator must maintain and provide the relevant source of information. Having provided the 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.

3.4 Detectability, Identification and Tracking

The SSR Detectability, Identification and Tracking (DIT) Module encourages satellite operators to consider how the physical attributes of their satellite design and their operational approach during launch, operations and disposal affect level of difficulty for observers to detect, identify, and track the satellite. By providing a consistent method to analyze a given satellite design and operational concept, the SSR DIT module will provide a standardized metric for the comparison of satellite missions in the dimensions of detection, identification and tracking.

The SSR Consortium is creating a new computational model that considers the theoretical performance of optical and radar ground-based sensors that observe Anthropogenic Space Objects (ASO). The computational model uses information provided by spacecraft operators to simulate the actual orbit of a single or multi-spacecraft mission. The model assumes that there is a ground-based observing system that does not have information about the name, orbit or trajectory of the spacecraft. The computational model assumes a reference set of optical telescopes (with apertures of .5 meters), UHF surveillance radars and tracking radars that are tuned to observe several sizes and altitudes of satellites. The Reference Observer Network is defined with observation capabilities that are in the midrange of capabilities, when comparing current government and commercial ground-based sensors of ASOs. The Reference Observer Network is located in fictitious ground station locations that provide uniform geographic coverage across Earth's land masses.

- Using a newly designed 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.

- Key definitions that drive the analysis include:
  - Detection: This definition considers the scenario in which a space surveillance system using optical and radar sensors to observe ASOs 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 uniformed case, the Detection analysis asks the likelihood that the spacecraft of 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 ASO, 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.

  - Identification: For this analysis, Identification refers to the process in which an observer who does not have a priori information about the name, ownership, range and size of spacecraft, uses information gained through physical observations to gradually specify how difficult it is for an uninformed observer to uniquely distinguish a given spacecraft from others using only measurable or inferred characteristics independent of coordination with a spacecraft operator to complete the identification process. In practice, it is very difficult to distinguish a spacecraft from others, thus the analysis shows the difficulty by calculating the angular momentum for a spacecraft and identifying a group of satellites that are found to be in a mathematical cluster based on angular momentum. The smaller the cluster, the easier it will be to identify the spacecraft.

  - Tracking: 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 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 improves the prediction for when the spacecraft will pass within the field of regard again.

Table 2 below shows a simplified list of the assumptions, inputs, outputs, and operator actions relevant to the DIT analysis.

Table 2 Chart of Assumptions, Inputs, Outputs for DIT analysis

	Detectability	Identification	Trackability
Assumptions	Assumed Characteristics of Anthropogenic Space Objects: Lambertian Sphere (Ideal matte surface), Cylindrical Prism or Rectangular Prism Perfectly diffuse Albedo = 0.2 to 0.3 Ground Sensor Network Capabilities (discussed below) Ideal Viewing Conditions (Solar light reflecting while satellite passes over the ground sensor which is in shadow)		
Inputs	•The physical dimensions of the spacecraft •Geometric approximation •the number of satellites deployment process from the launch vehicle •Mass •Cross sectional area •Operational Mean altitude •Operational Inclination •Target End of Life apogee •Target End of Life perigee •A qualitative description of the early operational stages to reach the operational orbit		
Outputs	Visual Magnitude Likelihood of Detection of the Spacecraft	Categorization of Spacecraft as Low, Medium or High Difficulty to identify	Likelihood of Correctly Predicting Orbital Evolution

Detectability

As one example, the following section provides additional information about the detectability analysis created for the first iteration of the SSR. This work has two components: optical detection and radar detection. At a high level, an optical detection occurs when light (typically sunlight) reflects off an ASO, is captured by the aperture, and is then focused onto the sensor which translates the incoming photonic intensity into an electrical signal that can be recorded and converted into useful data. The size of the aperture in an optical system determines the amount of light that can be captured. The larger the aperture, the greater the amount of light the system can capture. In optics, the limiting magnitude is a visual magnitude value that corresponds to the dimmest brightness value that a given aperture size can effectively capture. Successful optical detection occurs when enough light is reflected off the detected object to be picked up by a sensor as a signal rather than noise. In this analysis, the limiting magnitudes of three differently sized optical apertures are used as cutoffs between minimally detectable ASOs, more detectable ASOs, and very detectable ASOs. The base cutoff for an ASO to be considered optically detectable is set at an average visual magnitude of 16, the limiting magnitude of a 0.5m aperture optical telescope. The mid-tier cutoff for optical detection is set at an average visual magnitude of 10. This represents the approximate limiting magnitude of 50mm binoculars, which were selected because binoculars represent one of the first practical steps up in optical technology between the naked eye and a 0.5m telescope. At the top end of the DIT Optical Detection rating scheme, the cutoff value is set at an average visual magnitude of 6. This value was chosen because it is the approximate limiting magnitude of the naked eye, and if an object is optically detectable without any additional optical equipment then it will certainly be easy to detect with any practical optics currently in use.

The optical detectability analysis starts with manual input of the ASO and mission data from the questionnaire into the automating MATLAB script. From there, the script outputs the data relevant to optical analysis to STK where the satellite model is placed into its intended orbit. Once in simulated orbit, the Electro-Optical/InfraRed (EOIR) toolkit in STK is utilized to simulate the sensor response to the visual light reflected off the surfaces of the model. As noted above, the EOIR model accounts for several sources of error. This sensor response is then output to MATLAB in the form of irradiance values, which are then used to calculate a visual magnitude value for the ASO. This visual magnitude estimate is then compared to a set of criteria based on the limiting magnitudes of different optical sensor sizes. The second portion of the detectability analysis pertains to ASO detection by radar systems. When it comes to merely detecting an object with a given radar system, there are two dominant factors that influence detection. The first factor is the radar cross-section (RCS) of the target object. ASOs with larger RCSs reflect more of the transmitted signal back towards the ground, making it more likely that the receiver antenna will detect the return signal and consequently the ASO itself. The second factor is the range between the object and the radar system components. As radar signals travel away from the transmission antennae, they attenuate as more and more of the signal is absorbed and reflected by air molecules between the sensor and target. This means that the signal that reaches a distant ASO will be weaker, leading to a weaker return signal that then experiences the same attenuation process on its return trip to the receiver. As a result, objects become more difficult to detect by radar as the distance between them and the radar system increases.

For the SSR, the radar detectability analysis assumes a generic UHF (ultra-high frequency) surveillance radar system as the observer system. A surveillance-style radar is assumed for detection to represent an uninformed observer that is merely looking for any ASO. In practice, surveillance radars constantly send out radar pulses at generically set frequencies to attempt to detect objects in space, which is the focus of the Detectability analyses. Once an ASO is detected, radar tracking techniques are used to increase confidence and accuracy in the observer's understanding of the RSO. These tracking techniques are covered in the Identification & Tracking portion of the analysis later in this document. To estimate the difficulty associated with detecting a given ASO via radar, the SSR first uses the geometric information it has on the object to estimate its average RCS at a few chosen frequencies across the UHF frequency band. Then these RCS estimates are used in conjunction with the ASO's orbital information to estimate the likelihood of detection for that ASO.

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 cutoffs 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. According to AGI, the company that owns and develops the STK software used for the analysis, a detection event with a probability of detection over 50% can generally be considered a successful detection. In order to differentiate ASOs that barely make the minimal detectability cutoff from those that handily exceed it, the Radar Detectability employs two additional cutoffs at 70% and 90% probability of detection. The rationale behind the 90% cutoff is to set a golden standard for what the DIT analysis can consider very detectable. In practice, it is likely that most, if not all, of the ASOs that fall into this top tier will be large. This is due merely to the fact that larger objects have a greater ability to reflect radar waves back towards the Earth. The 70% cutoff was set to bridge the gap between the minimally detectable and the very detectable to give ASOs that exceed the minimum detectability standard by a 20% margin of probability the ability to earn a slightly higher score in the DIT module.

3.5 Application of Standards

The adoption of internationally endorsed standards in the space domain has been identified as a clear path towards ensuring compatibility in understanding between operators among themselves, and between an operator and the space environment which is being used. As such, as part of the SSR emphasis is placed on the adoption of standardisation concept in design and operations where possible. It is however recognised that design and operation standard can have regional differences while trying to achieve the goal of extended space sustainability. It is intended that the SSR Application of Standards Module will be updated between SSR versions.

3.6 External Services

Innovations taking place in the area of close proximity operations have the potential to improve space sustainability and as such are of interest. The external services module considers a wide range of activities and identifies classes of action that satellite operators can take to make their mission more amenable to receive external services or to increase the probability of successful external services such as fixing, improving, and reviving satellites and refers to any work to refuel, repair, replace, or augment a satellite in space. Additionally, it accounts for design features that ensure or improve the detectability, trackability and identifiability of satellites in non-cooperative situations such as a low-power beacon or reflector.

The application of external services can be widely different for individual mission concepts, and as such the SSR does not assume that all operators will invest in external services, and in some cases such as low altitude orbits or small satellites, external services are not deemed necessary. Additionally, external services technology is evolving in 'real-time', often after missions are launched. A significant number of contemporary external service cases are satellites that were not designed to be serviced (non-cooperative satellites). It is expected that this will likely continue for the next 1-2 years. Given the relatively low level of quality of knowledge on these different external services features, the first iteration of the SSR will weight all external services features equally. the external services module provides bonus scores (steps) for missions where the investment in external services capabilities are appropriate, with scope for re-evaluation in later versions as verification, validation and successful demonstration of external services capabilities are proven.

Third-party organisations such as NASA's Satellite Servicing Projects Division (SSPD) [16] and ESA's Clean Space Office [17] have begun independent assessment, verification and validation of external services features through their own testing, particularly design choices, e.g. grapple fixtures. These verification tools or evidence of self-validation and verification will be necessary for in the external services module.

On-Orbit Servicing (OOS) of satellites takes into consideration life-extension and upgradability as technology evolves, as well as the employment of external end-of-life disposal strategy. The utilisation of OOS, either through the operator's actions or payment of an external service will allow the operator to gain SSR bonus credit, pending the mission complies with current regulatory standards. As external services is a fairly new technology, the risks of failure are higher and non-trivial until consistent successful demonstration of these capabilities are proven. It is envisioned that future iterations of the SSR will account for technological demonstration of these services.

In addition to external service market maturity and technology adoption, legislative and policy drivers will also impact market adoption and should be monitored closely. The SSR will assess if the operating team are complying with standards developed and proposed by international groups e.g. Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) [18] Table 3 below highlight key categories within the SSR External Services Module during design and prelaunch, on-obit phases of a mission.

Table 3: Summary of the SSR external services module

Category	Description
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 use it.	Installing of OOS features in preparation to create a fail-safe option. Examples include visual fiducials, grapple fixtures, mechanical features, grasp features, and items to make it easier to track the object in case of radio failures such as beacons
Commitment to use or demonstration of use of On Orbit Servicing	Employment of OOS capabilities Included in quantitative model, including risk of failure Accounts for the action in line with the mission timeline (before use it is a proposed action; later it is a verified action)
	External end-of-life removal service Included in quantitative model, including risk of failure
Utilising OOS in line with current standards (refer to 'Application of Design & Operation Standards')	Consideration of standards and practices for commercial satellite servicing e.g. CONFERS

3.7 *Verification*

As previously stated, an over-arching verification module is implemented in the SSR design to allow satellite mission owners to provide information to confirm that their responses to the SSR questionnaire is high quality.. A satellite mission owner can choose to verify their responses by providing related technical documents; providing materials from official filings about the mission submitted to a regulatory body; by providing technical documents generated by a third party or by providing evidence of a review of their documents by an independent technical expert. A verification weighting will be attached to inputs provided by the operator to both reflect the SSR issuer's confidence that its assessment of the operator or system's conformance with various SSR requirements is accurate and to incentivise entities to provide better verified data as part of their submission. It is noted that verification may not be appropriate/necessary across all mission types and SSR modules.

3.8 *Excluded SSR Modules*

Upon careful consideration and discussions with stakeholders, a number of modules have been purposely excluded in the first iteration of the SSR design. In many cases, the exclusion of these modules in the SSR is primarily to simplify the development of the SRR through a focus on the physical space environment, and it is envisioned that these modules be will considered in future SSR revisions. A short description on each of the excluded modules in the current SSR version is provided below.

<u>Re-Entry:</u> From a space debris mitigation point of view, the end of life disposal of spacecraft through atmospheric re-entry is generally the preferred form of post-mission disposal as it does not leave debris on-orbit. On one hand, non-destructive re-entries by means of capsule or other thermally protected vehicles are generally prohibitively expensive. On the other hand, there is a potential risk to those on the ground, in the air, and at sea from collision with any objects that survive re-entry. Similarly, re-entering objects can deplete stratospheric ozone, increasing UV radiation exposure for humans on the ground, and contaminate land and water if hydrazine or other toxic materials survive re-entry. Proper de-orbit

procedures, spacecraft design for demise, and modelling can help quantify and minimise these risks. The exclusion of re-entry in the SSR beta description is primarily to simplify development of the SRR through a focus on the physical space environment. This is a category that may be added in future SSR revisions, particularly with respect to managing aggregate risk from planned large constellations and a significant increase in the number of on-orbit and re-entering spacecraft.

Spectrum: Satellite operators use spectrum for spacecraft telemetry, command and control, and to deliver payload data or perform communication services. Radiofrequency interference degrades mission performance and may cause safety hazards by preventing communication with a spacecraft or through denying a user access to critical safety-related spacecraft services. A future SSR module could encourage spectrum information sharing and designs that make efficient use of spectrum, minimise interference for others, and facilitate interference geolocation, identification and mitigation (e.g. Carrier ID). This item is excluded from the initial SSR formulation for several reasons. First, interference tends to be a short-run, reversible event, (unless it is sufficiently bad to cause accidents or permanent losses). Second, regulation and norms in this area are fairly complex and well-developed already without SSR incentivisation. Third, properly addressing spectrum would be a highly complex task, potentially involving deep access into company proprietary information, and significantly delay the initial SSR beta concept.

Economic Aspects: The field of economics devotes significant consideration to the allocation of scarce resources. While Earth's orbit is a finite and scarce resource, allocation to date has been done largely on a first-come basis, with states pursuing missions as they see fit (or authorising such missions by commercial entities) unless conflicting with the ITU regulations on spectrum use. Resulting debris has generally been treated as a mission consequence rather than a long-term or indefinite allocation of that scarce resource. It is conceivable that a future SSR module could reward operators for allocations that optimise use of finite orbital resources, perhaps using the same four criteria of "rational, equitable, efficient and economical use" identified by the ITU to guide its mission. Consideration of operational financial resources and insurability could also play a role in assessment of the ability of an operator to conduct appropriate remediation in the event of an accident or other major off-nominal behaviour. This potential module is excluded due to insufficient consideration and international consensus to guide the development of a potential economic module.

Impact on Astronomical Observations: Certain satellites may reflect significant light in a manner that interferes with and/or saturates astronomical instruments on the ground. This concern is most significant for low altitude constellations with large areas of highly reflective surfaces oriented to reflect light towards the Earth. Potential mitigation techniques include adjustments to satellite surface coatings and coordination and sharing of predictive ephemerides with astronomical observers to facilitate sensor masking. This concern is not addressed in the Detectability, Identification, and Trackability module, as greater detectability is important for all satellites from an overall space safety point of view, while only a limited number of satellites and mission concepts raise these issues. These concerns can and should be addressed by operator/astronomer coordination on an as necessary basis.

Broader Forms of Sustainability: The term sustainability is used in a variety of terrestrial contexts to refer to a broad set of considerations including supply chain sourcing and renewability, environmental emissions, and labour practices that can apply to the resource utilisation and manufacture of space objects. One significant distillation of this concept is the set of 17 specific goals and associated targets identified in the United Nations Sustainable Development Goals. The current SSR beta version does not address these broader topics, including the launch vehicle's methods of propulsion to obtain orbit, and is focused specifically on the physical space environment.

4. Space Sustainability Rating Scoring Methodology

The SSR is formulated as a combined score based on the evaluation of individual modules where the individual aspects of space sustainability are covered. The SSR is constructed in such a way that the information required to obtain the rating is available to operators or owners of space missions without the need to disclose proprietary or confidential information to the rating issuer. As an example, a spacecraft 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.

Baseline Score: Tiers

A rated entity will receive a baseline rating that will describe the different Tier awarded to a mission at a particular point in time. The rating is periodically updated based on actual operator performance during the on-orbit part of the mission. At regular points during the operational lifetime of the mission, the mission will be evaluated again to take into account information that becomes available later in the mission lifecycle, such as the objects deployed during launch and the final operational orbit. This captures the notion that only once a mission is truly over, is its impact on the space environment known. An entity signing up for an SSR evaluation is committing for the entire duration of the planned mission, starting during the design phase and including periodically monitoring as long as the object remains on-orbit. The final SSR for a mission will be issues at the end of life of the mission, after the disposal phase has been completed.

When a mission is awarded a rating at any point during their lifecycle, that rating will be valid for a given time frame before it needs to be re-assesed. Absence of communications between the operator and SSR issuer during the on-orbit implementation, combined with transparent reporting on space surveillance data, could thus lead to a dilution of the rating under the on-orbit entry.

Bonus Score: Steps

During each evaluation, it is possible to earn additional credit towards a bonus indicator, which highlights certain steps a mission can take to 'go over and above' the baseline rating towards space sustainability. Various questions, as well as certain entire modules, count towards this bonus. Bonuses are reported separately and do not contribute to the baseline rating of a requesting entity.

Due to the novelty of some of the bonus categories, bonus items are often less defined and rely more heavily on operator self-assessment versus verification of a particular well-defined behaviour. Various SSR modules treat bonuses differently, such as the SSR External Services module which entirely consists of bonuses for both the baseline and on-orbit scoring evaluations. Additionally, the Application of Design & Operation Standards module provides bonuses for standards voluntarily adopted by operators in excess of national requirements, and the Data Sharing module includes a bonus relating to data sharing for purposes other than collision avoidance. Figure 1 shows an illustrative example of SSR Tiers and Step indicators inspired by the LEED classification system

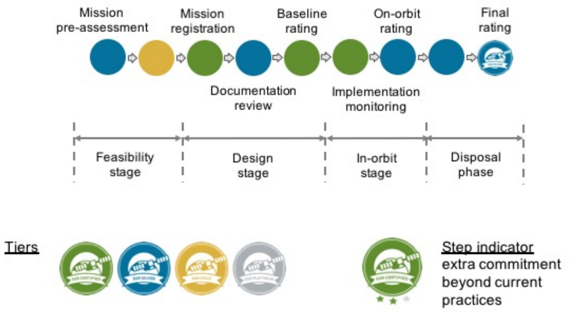

Figure 1. Example of SSR Tiers and Step indicators at different mission phases

5. Mechanism to support long-term sustainability

Over the past year, the SSR consortium have held a number of events and workshops that bringing together stakeholders to review and provide feedback on the development of the SSR. This paper highlights key factors on what drives operators to consider long-term sustainability of the space environment, and the role that the SSR would play as a voluntary positive incentive. Notable mentions include:

- Financial and economic incentives that could impact insurance premiums, and therefore potentially reducing costs,
- Support for current and potential regulations that create an even playing field among space actors,
- Altered procurement processes, such as selecting higher-rated launchers,
- Potentially lead to more positive customer and public perception, acting as a competitive advantage and greater prestige,
- Used in marketing and environmental, social and governance-style corporate reporting.

In addition, the SSR wants to shift the attitude towards compliance assessment and highlight good behaviour, instead of focusing on shaming bad behaviours. Operations in space are quite transparent and, for example, it is possible to detect which satellites are manoeuvring at the end of life and compile statistics of compliance rates [19] or lists of the most dangerous objects [20]. However, these efforts have been only partially effective in triggering an improvement in the compliance rates. Initiatives such as the SSR can contribute by put in the spotlight responsible operators, which can serve as positive examples of technological and operational solutions that have been successful in terms of debris mitigation.

Over the past year, the space industry has supported the introduction and implementation of the SSR. In October 2019, the Satellite Industry Association (SIA) announced the release of a set of Principles of Space Safety [21], drafted to help protect freedom of use and long-term access to space. Included in the principles, SIA noted, "Consistent with these principles, the UN guidelines and other best practices, SIA member companies seek to demonstrate best practices for the sustainability of space, to create positive incentives for participation by all space stakeholders. SIA supports rating systems that assess and reward space safety practices of satellite stakeholders globally." In April 2020, the Federal Communications Commission (FCC) of the United States released a Fact Sheet on Mitigation of Orbital Debris in the New Space Age, a revision of the FCC's orbital debris mitigation rules [22]. The FCC's factsheet specifically mentioned "…organizations such as the World Economic Forum's Global Future Council on Space Technologies are working toward other approaches to space debris, for example, a "Space Sustainability Rating" that would provide a score representing a mission's sustainability as it relates to debris mitigation and alignment with international guidelines."

6. Conclusion

The paper provides a detailed description of the design and development methodology undertaken to create the SSR. Designed as a composite indicator, the SSR evaluates a mission on six modules which include a metric of the on-orbit fragmentation risk, an evaluation of the collision avoidance process adopted by a mission operator, the detectability, identification, and tracking of the mission, the level of data sharing implemented, the adoption of international standards related to debris mitigation measures, and the readiness of a mission with respect to on-orbit servicing. An additional overarching module is implemented to verify the information provided by the entity requesting a rating without the need to disclose proprietary or confidential information. These modules have been incorporated into the design of the first iteration of the SSR after extensive consultation with stakeholders representing government, industry and academia, with suggestions of additional modules that can be included in future versions of the SSR. The evaluation of individual modules where the individual aspects of space sustainability are covered are combined to provide the SSR for a mission. Details of the SSR scoring formation in the form of Baseline (Tiers) and Bonus (Steps) at different phases of a mission are presented.

The implementation of the SSR is also closely aligned with, and contributes to existing policy and regulatory mechanisms such as the 2019 Guidelines for the Long-Term Sustainability of Outer Space Activities adopted by the Committee on the Peaceful Uses of Outer Space of the United Nations and the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, highlighting actions that space operators can take during spacecraft design, operation, and end of mission for the long-term sustainability of the space environment. Key factors on what influences operator to reduce the potential for debris creation are summarized based on input derived from a series of workshops and meetings with stakeholders.

The SSR itself is envisaged as a regularly revised scoring system, to adapt to the evolutions in the space environment as well as best practices and standards. Work is currently underway on the scoring and weighting of individual modules, drawing from successful rating systems in other industries, as well as alpha and beta tests of missions to evaluate the rigor of the SSR design, receive direct feedback, and make changes accordingly before the SSR is made public. Modules where changes are likely between SSR versions are also being identified. Additionally, work is also being doing on the science of branding and considers how different types of rating impact reactions in the space sector.

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