Contribution from SSA data to the definition of a Space Sustainability Rating

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CONFERENCE PAPER

In 2018, the Word Economic Forum issued a call for proposal to develop a so-called “Space Sustainability Rating” to capture the debris risk associated to a mission. Following this call, the European Space Agency, Massachusetts Institute of Technology, University of Texas at Austin, and Bryce Space and Technology have formed a consortium to design a rating able to encourage behaviours that are more responsible by promoting mission designs and operational concepts that are compatible with a stable evolution of the environment. The approach adopted for this initiative is to combine, in a composite indicator, different components, related to both short-and long-term effect, considering the impact on other operators, and on the environment globally. The identified components include a metric of the fragmentation risk associated to an object in orbit, an evaluation of the collision avoidance process adopted by a mission operator, the steps to ease 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. The paper will discuss the direct and indirect contribution coming from Space Situational Awareness (SSA) data in the definition, assessment, and verification of such a rating. The direct contribution refers to how a given mission deals with SSA data and considerations. The evaluation of the aspects related to collision avoidance, detectability, identification, and tracking will be discussed, together with the definition of the levels of data sharing implemented. The rationale behind the proposed classification is to identify and promote actions that are effective in reducing the collision avoidance efforts for other operators and the burden on space surveillance system (e.g. in the case of a launch with multiple similar shaped satellites). Some examples will be presented to answer the questions: What happens to the mission rating if one acquires additional tracking data? And what if one adopts design features to enhance trackability? The indirect contribution refers instead to how SSA data can support the effective adoption and credibility of the proposed rating. For example, the rating will be computed based on operator-provided data (e.g. on the adopted disposal and collision avoidance strategies), so there is operator-provided data (e.g. on the adopted disposal and collision avoidance strategies), so there is an interest in developing reliable approaches to perform independent assessment and validate such inputs. In addition, the current rating formulation requires the number of objects able to trigger a catastrophic collision, the evaluation of the manoeuvre capabilities of an object (also as a proxy of its operational status), the estimation of the relevant properties for lifetime assessment. Finally, the availability of independent data sources will also allow the evaluation of the rating (or at least of some of its components) also for non-participating actors. In this way, a global representation of the level of adoption of mitigation measures can be achieved and the performance of the rating is promoting such measures can be assessed. Therefore, a discussion on the potential sources of the different parameters that are used in the rating evaluation will be presented, discussing their reliability and the availability of independently verifiable data accepted.

1. INTRODUCTION: THE SPACE SUSTAINABILITY RATING (SSR)

The Space Sustainability Rating is an initiative that seeks to foster voluntary action by satellite operators to reduce the risk of space debris, on-orbit collisions, and unsustainable space operations. The concept for the Space Sustainability Rating was conceived by the Global Future Council on Space Technologies of the World Economic Forum [1] through a series of workshops starting. The World Economic Forum held a competitive call for proposals in 2018 and selected a team composed of four organizations to design the Space Sustainability Rating, these organizations include the European Space Agency, Massachusetts Institute of Technology, University of Texas at Austin, and Bryce, Space and Technology. These four organizations formed a consortium with the World Economic Forum to define the technical and programmatic aspects of the Space Sustainability Rating during the period from 2019 through 2021. The Consortium brings expertise in the areas of modeling and evaluating the impact of space debris in Earth orbit, astrodynamics, characterization of space objects, technology policy, space economics and understanding of the role of emerging countries and private actors in the space sector.

The global space community is witnessing a rapid increase in creative business models and new technologies that are leading to plans to launch thousands of satellites into Low Earth Orbit. The number of satellites being proposed is much greater than the historical patterns that have been seen globally to date. While the technology has the potential to bring useful societal services, in areas such as satellite communication and earth observation, there is a growing risk that the capacity of Earth orbit to accommodate such a large set of new space objects safely may be in jeopardy.

The vision for the Space Sustainability Rating 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]. These guidelines highlight the need for state actors overseeing national space activities to pursue approaches such as ensuring they have relevant national regulatory frameworks for outer space activities; actively supervising national space activities; manage equitable use of radio frequency spectrum; register space objects with the United Nations; provide contact information for space operators and information about space objects; improve accuracy of orbital data; promote collection and sharing of space debris monitoring information; practice conjunction assessment; share space weather data; design space objects to foster trackability and debris mitigation; manage re-entry of space objects; manage laser emissions; promote capacity building on sustainable procedures; and support research on space debris reduction. The vision for the Space Sustainability Rating is closely aligned with the Long-Term Sustainability Guidelines that highlight actions that space operators can take during spacecaft design, operation, and end of mission. For example, space operators of launch vehicles and spacecraft can play a key role in providing contact information for personnel that can respond in case there are concerns about potential conjunctions or collisions between space objects (Guideline B.1). Operators can contribute to the pursuit of Guideline B.8 which includes a reminder to choose designs that facilitate trackability a determination of location on orbit, to adopt debris-mitigation guidelines and to share information on the end of life disposal of space objects. Reference [3] provides further discussion of the relationship of the Space Sustainability Rating to the Guidelines for the Long-Term Sustainability of Outer Space Activities.

While the United Nations guidelines are written to emphasize the perspective of states and government actions, the Space Sustainability Rating emphasizes the actions that can be taken by space operators of satellites, regardless of whether they are government or private actors. The Space Sustainability Rating takes the premise that there is a limit to the capacity of the space environment in Earth Orbit to host the operation of Anthropogenic Space Objects with a level of safety that supports useful operations for all nations who express interest. Building on the premise from the Outer Space Treaty that space is the province of all humankind, part of the rationale to encourage each space operator to behave sustainably is to ensure that all nations who desire to operate in space are safely able to do so. Analysis by the European Space Debris office presents the concept of Environmental Capacity of the Space Environment in Earth's Orbit [4]. The concept of Environmental Capacity notes that there is a historic level of space objects in a given region of Earth's orbit that implies a given level of risk of collisions that could cause destruction or damage to operational satellites. The historic level of space objects also implies a given level of risk that the objects will collide and cause a series of follow on collisions creating new debris, even in absence of any additional space objects being added to that given region of space. The European Space Agency calculates the Environmental Capacity using the MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model to represent the state of the debris environment and estimates the marginal amount of fragmentation risk that is added to a region of space when a new Anthropogenic Space Object is added . Thus, some aspects of the sustainability of space missions do not depend on what a space operator does, but rather on what previous space operators have done in the orbit of that operator. For example, a space operator can choose an orbit in which the Environmental Capacity can handle new space objects without reaching an unacceptable level of risk of collisions or cascading debris creation.

In addition to choosing their orbit, a space operator can make other decisions during the design, operations and end of life phases of a space mission, as noted in the United Nations Long Term Sustainability Guidelines. During the design phase, the space operator can select materials and functional approaches that increase the ability for an observer on Earth to be able to detect, identify and track the satellite, thus contributing to Space Situation Awareness. Designers can consider materials that influence the reflectivity and apparent magnitude for optical tracking; they can also consider dimensions that influence the radar cross section of the spacecraft since many observations from the ground are made by radar systems. Designers of satellites can also consider 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. Designs of space missions can also consider methods to distinguish satellites from other similar satellites, such as those in a constellation of otherwise identical spacecraft. Designers of constellations may consider methods to deploy satellite to reduce uncertainty about which spacecraft is being identified during early operations. Designers also determine the capability of the spacecraft to manoeuvre and deorbit. During the mission operations phase, space operators make decisions that influence the ability of a spacecraft to contribute to the long-term sustainability of outer space. The selection of the orbit is a key decision; as noted previously, if an orbital altitude and inclination is already cluttered with active spacecraft and debris, it may not have the capacity for a new mission. Operators also decide how to manage manoeuvres and collision avoidance during a mission. They make decision about when to manoeuvre and what information to share publicly or with other operators about the behaviour of their spacecraft. For the end of life phase, space operators decide whether to maintain a mission on orbit after the original schedule or to extend for additional service. Operators also decide how and when to deorbit or move the spacecraft to a long-term disposal location if it is not possible to put the spacecraft on a trajectory that move the satellite into the atmosphere for disposal.

With all of these decisions in mind, the Space Sustainability Rating is defined using six Modules that each highlights a set of related decisions faced by space operators. The five Modules include: Mission Index to calculate the Space Traffic Footprint; Collision Avoidance; Data Sharing; Detectability, Identification and Tracking; Application of Standards; and External Services. A rated entity will initially receive a *baseline* rating, which is evaluated during the design phase of a mission and then periodically updated based on actual operator performance during the on-orbit part of the mission. This captures the notion that only once a mission is truly over, is its impact on the space environment known. The rating will score a spec mission to a particular Tier based on the operators' activity to address the sustainability of their mission. In addition, it is also possible to earn credits towards a bonus indicator, which highlights specific steps a mission can take to 'go over and above' the baseline rating towards space sustainability. Examples will be provided later in the paper, where the single modules are discussed more in detail.

Within the six modules, those that relate most closely to Space Situational Awareness include the Mission Index, ; Collision Avoidance; Data Sharing and Detectability, Identification and Tracking. The scope of this paper includes an overview of the assumptions and design of the key Space Situational Awareness (SSA) modules within the SSR to show the close links of the SSR to progress in SSA research and practice.

2. SPACE SITUATIONAL AWARENESS AS A KEY CONSIDERATION FOR THE SSR

For the purpose of this paper, "Space Situational Awareness" is defined as the provision of timely and accurate information, data and services regarding the near-Earth space environment and the Anthropogenic Space Objects contained therein. In some analyses the definition of SSA includes information related to asteroids or the direct effects of space weather on satellites, e.g. charging, , but we limit ourselves here to those aspects with a direct impact on the SSR, such as the surveillance and tracking of objects and the long- and short-term prediction of those known anthropogenic objects. One key message of this paper is that Space Situational Awareness is one of several key aspects of space sustainability that the SSR analysis process considers. The Space Sustainability Rating identifies actions that space operators can take to increase the likelihood of maintaining safe and sustainable operators in Earth orbit for both their own missions and the missions of others. Space Operators that take actions to increase their own Space Situational Awareness and the SSA knowledge of the global space community will improve their SSR score.

One of the reasons that the Space Sustainability Rating seeks to emphasize mission aspects related to Space Situational Awareness is that several key challenges remain important within the space community that require more work to overcome. Each of these key challenges is associated with one of the Space Sustainability Rating Modules.

Challenge 1: **Regulatory requirements for space operations and end of life disposal vary around the world.** The team designing the Space Sustainability Rating is drawing from the principles provided by the Guidelines for the Long-Term Sustainability of Outer Space as adopted by the United Nations Committee on the Peaceful Uses of Outer Space. The international space policy regime is built on the foundation of space treaties which have been adopted and domestically ratified by the majority of nations that operate satellites. The space treaties and related international norms and guidelines place the responsibility for regulating space activity at the national level regarding launch, orbit selection and end of life disposal. The International Telecommunications Union provides a globally applied framework to regulate the use of spectrum, and all national frequency regulators participate in the management of spectrum, especially via the World Radio Conferences. For actions taken by space operators unrelated to frequency there is no global coordination mechanism; this is the case for decisions such as choosing the orbital altitude, defining whether or not a spacecraft has the capability to manoeuvre, defining mission lifetime, and selecting the key launch parameters, including launch date, location and trajectory. For these aspects of a mission, individual national governments design their own process to approve launches that are under their national flag or to approve launches in collaboration with multiple launching states. It is common that space mission includes more than one launching state due to collaboration or due to the fact that the launch site, national origin of the launch vehicle and national origin of one or more spacecraft operators can all represent different nations. As can be seen, the international space policy regime can be characterized as decentralized in the sense that national bodies can interpret their responsibilities under the space treaties domestically and design their own method to licence and approve launches and proposed space operations. Given all of this heterogeneity of regulatory regimes to guide non-frequency related decisions by space operators, the space Sustainability Rating cannot simply ask whether space operators meet a minimum standard of behaviour on orbit with regard to orbit selection, technical design of a collision avoidance capability, operational behaviour and end of life disposal. Such a minimum standard has not been universally agreed upon, although the United Nations Guidelines and multiple standards documents do provide useful examples of best practices for reduce space debris and on-orbit collisions. Further, the Space Sustainability Rating seeks to reward space operators who go beyond the minimum expected behaviour and seek to creatively achieve the mission while serving as an exemplar for sustainable space practices. In response to this state of international regulation for on-orbit behaviour by space operators, the Space Sustainability Rating uses a module called the **Mission Index to calculate the Space Traffic Footprint** (Section 3.1) of a mission while accounting for many of the decisions made by a space operator that can be summarized in a computational, physics-based model. As described further in the next section, the Mission Index analysis process allows the SSR team to evaluate they physical impacts that operator decisions have on the space environment and other operators using an analysis process that can be applied consistently for all operators.

Challenge 2: **Data about space mission operations is not available for all stakeholders in a consistent system or format.** There are several key organizations that currently play a role to collect and provide data about the status of operational space missions, especially the United States government, the European Space Agency, the Russian government and several privately organized, voluntary associations of space operators such as the Space Data Association. Many Space Situational Awareness stakeholders use the publicly reported information provided by the United States government with Two Line Elements for Anthropogenic Space Objects. Some space operators publish their own operational status in a format that they select with information such as the location of their spacecraft and information about who to contact in case of concern about a collision. While there are standards bodies and groups such as the Space Safety Association who are advocating for best practices regarding sharing data about operational space missions, there is not globally standard practice or system in place to facilitate the sharing of data among space operators and with other stakeholders such as regulators and insurance providers. The world relies now on a piecemeal set of systems that include a partial set of information about the ownership status, location, operational status and manoeuvre plans for operational space missions. This situation creates uncertainty for space operators and increases the likelihood that potential collisions may not be coordinated effectively. In the current state of affairs, space operators also need to decide how much effort and cost to spend on trying to interpret the complex set of available information, such as the large number of collision alerts that are generated due to uncertainty about the precise location of space objects. With this in mind the Space Sustainability Rating includes the **Data Sharing Module (Section 3.2)** to give credit for satellite operators that make efforts to communicate with relevant stakeholders the information about their own mission that can help regulators, SSA organizations, insurance providers and other operators understand how they are impacted by a give space mission. The Data Sharing module is discussed further below.

Challenge 3: **Space operators have diverse levels of capability to participate in efforts for collision avoidance on orbit.** The growth in popularity and utility of small satellites allows organizations with different levels of expertise, resources and experience to participate in owning and operating satellites. This development has positive implications for new participants in space operations and for governments, universities and companies who seek to establish capability in space technology. There is a diverse set of actors that participate in space operations and a lack of internationally consistent norms for the minimal capabilities of a space operator. Instead, space operators bring different levels of technical capability, different levels of financial resources and different levels of performance expectations to their space operations. Some space missions are operated by commercial companies that offer some level of guarantee that they will provide services to customers. In contrast, some space missions are operated as research or technology demonstrations by universities and government research organizations. Often these types of space operators do not expect to guarantee a specific level of consistency in service or mission duration. These scenarios also influence what type of approach a space operator takes for the topic of collision avoidance. There are several aspects of the actions a space operator might take to participate in on-orbit collision avoidance. First, an operator may invest in resources to track their own space objects and improve their knowledge of the orbital state of their objects. Second, an operator may coordinate with public or private Space Situational Awareness service providers to share orbital state data or participate in analysis to review whether planned manoeuvres appear to increase collision risk. Third, space operators invest in different resources related to participating in coordination regarding potential collisions. The number of people, the level of computational resources and the financial investment that a space operator invests to respond to notice of a potential collision varies widely. There is no standard set of capabilities agreed upon across the international community that sets a requirement for how much space operators must invest in collision avoidance. While this flexibility reduces barriers for new organizations to participate in space operators, it also allows for some operators to make minimal investments in collision avoidance. Meanwhile the physical design of a spacecraft also influences the level to which it can change operations in order to reduce collision risk. The most obvious physical design feature is whether a spacecraft uses propulsion. For the SSR this aspect is accounted for in the Mission Index Module. In addition to the presence or absence of propulsion, other design features that influence collision avoidance include the use of sensors on the spacecraft that include orbital state knowledge (such as beacons, reflectors or GPS receivers) and the operational concept and selection or orbit. The **Collision Avoidance Module (Section 3.3)** within the SSR**,** as described gives space operators credit if they voluntarily choose to make design decisions and invest resources that improve the knowledge of the satellite location and participate in coordinating with other operators as needed.

Challenge 4: **With the current state of the art, space stakeholders are not able to fully characterize and communicate about the presence, identity, operational behaviour and orbital trajectory of Anthropogenic Space Objectives.** While individual space operators may take action to understand and communicate the location of the spacecraft that they operate, there is a wider concern because the population of Anthropogenic Space Objects includes items of a range of sizes and altitudes. Currently, it is not technically feasible for space operators to be fully aware of all the objects in space, including operational spacecraft, debris from previously operated spacecraft and naturally occurring space objects. The **Detection, Identification and Tracking Module (Section 3.4)** of the SSR creates a method to evaluate whether space operators are making decisions that increase the likelihood that space surveillance and tracking systems can observe their spacecraft from the ground. Spacecraft operators can improve the probability that their satellite can be detected by ground-based optical and radar surveillance systems by choosing a combination of spacecraft size, orbit and external materials that improve the reflection of light or radio frequency signals. When spacecraft operators deploy a large number of similar satellites into neighbouring orbital locations, the satellites are likely to be difficult to observe from ground-based systems.

While the Space Sustainability Rating does not fully address the four challenges described above, it does create incentives for space operators to take the actions within their power to work toward either mitigating or reducing these long-term challenges of Space Situational Awareness.

3. SPACE SITUATIONAL AWARENESS ANALYSIS WITHIN THE SSR MODULES

Sections 3.1 to 3.4 disucss the methods used by the SSR to identify and evaluate actions taken by space operators that influence the sustainability of their mission and their contribution to Space Situational Awareness.

3.1 Mission Index: Calculating the Space Traffic Footprint

The Mission Index is captures the impact of a mission on the environment, its Space Traffic Footprint. In practice, this can be translated into two high-level questions: how detrimental is a mission to its neighbours? And, how likely is this mission to contribute to the Kessler syndrome in the long-term? These two questions try to capture the two dimensions of the disruption that a mission can induce on other operators, e.g. by resulting in an increase in the number of required collision avoidance manoeuvres, and on the environment in general. Several factors contribute in the assessment of the impact of a mission on the environment, such as the orbit where the spacecraft is operating, its size, whether mitigation measures are implemented, etc. In particular, the approach adopted within the SSR is the one described in [4], which is the assessment of the fragmentation risk for a mission, e.g. which is the probability that the spacecraft will fragment (e.g. because of a collision or an explosion) and which is the effect of such fragmentation, measured as the increased collision probability for active satellites.

In [5] several applications of this approach were discussed to show how the proposed formulation allows distinguishing the impact on the environment of choices in the mission architecture (e.g. deploying a constellation at different altitudes) and disposal options (e.g. the adoption of passive disposal devices). A limit of the previous analysis was in the representation of the collision avoidance capabilities, which were simply modelled as present or not. This aspect has been improved in the current formulation that now considers the extent to which the collision risk is mitigated by the adopted collision avoidance strategy, in line with the approach adopted in the ESA DRAMA suite[1]. In particular, the tool ARES [6] assesses the collision risk reduction achieved while considering the level of position uncertainty and the effect of reaction time (i.e. the time between the manoeuvre execution and the predicted encounter). In this way, the formulation now captures the positive effect in terms of risk reduction associated with an improvement of the knowledge of the objects' positions, for example due to the use of a SSA provider with better performance than the baseline, currently set as the uncertainty level in the CDMs issued by the USSTRATCOM.

The Mission Index in itself can be used to compare different missions, but a normalisation approach is needed to include its contribution in a composite indicator such the SSR and make it compatible with the other modules. In past work, an attempt was made to normalise the index value by using a reference value (i.e. the index of the Envisat satellite), under the assumption that this would represent a worst-case scenario. However, this approach has the downside of not being future proof, whereas one of the main motivations behind the adoption of environmental impact assessment is to be able to capture the dynamic evolution of the debris environment [8]. For this reason, the normalisation approach under evaluation for the SSR is based on the concept of environmental capacity [8], i.e. the number and type of missions that are compatible with the long-term stability of the environment. As detailed in [4], long-term simulations of the environment can be used to build a reference scenario with a good level of compliance to space debris mitigation guidelines. This scenario is then compared with the actual use of orbital resources, intended as the sum of the index for all objects in orbit, considering their expected mitigation strategies. Currently post-mission disposal (PMD) plans and their expected success rate are not systematically shared by operators, but thanks to space surveillance data, the activity of a spacecraft can be derived and the evolution of its orbit can be predicted, so the status of the environment can be assessed [9]. In terms of environmental capacity, a share of it is consumed by inactive satellites and rocket bodies, whereas the remaining part can be used for active and new missions. It is this value (the *available capacity*) that can be used to normalise the Mission Index within the SSR to reflect that the criticality of the index of a mission is also related to the global evolution of the environment. Such framework is intrinsically based on monitoring the status of the environment and would benefit from (or even rely on) existing efforts towards more transparency and more consistent monitoring of mission in-orbit activities in relation with licensing aspects [10].

3.2 Data Sharing

Data sharing can improve spaceflight safety through facilitating improved SSA and coordination between operators and for other interested stakeholders such as regulators and insurers. The SSR recognizes these contributions by rewarding operators for sharing various forms of data with different parties. The definition of the SSR ranks operator data sharing actions to difference audiences to highlight which actions have a higher contribution to overall flight safety. For operational flight safety information, operators are required to commit to updating this information in a timely manner to receive credit for sharing. The SSR also includes a Verification process in which space operators

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[1] The DRAMA (Debris Risk Assessment and Mitigation Analysis) tool suite is freely available at https://sdup.esoc.esa.int/drama/.

receive more credit for verification of each module if they invest more resources to provide objective information supoprting their claims of their SSR application.

The SSR definition considers that space operators may share mission data with the following potential stakeholder categories:

- SSA Provider(s)
- Other Operators (upon a request for coordination)
- Voluntary Networks of Operators/Stakeholders
- the Public

Various forms of sharing offer distinct benefit, and so operators can receive points toward their SSR score for each stakeholder category with which they share. For instance, public sharing is desirable because it ensures that all potential users can access needed information. While voluntary networks of operators/stakeholders, such as the Space Data Association, share information in a narrower fashion among their members, they also provide value-added services such as data verification, standardization,

Types of information recognized for sharing include:

1. Contact Information (lists of controlled NORAD IDs or international designators, flight safety contact names, titles, phone numbers, email addresses, languages spoken, time zone and hours of operation, response time guarantees)

   Contact information is critical to coordinate during conjunctions or other high interest events, particularly to avoid uncoordinated collision avoidance manoeuvres. In some cases, coordination can reduce the magnitude of a required manoeuvre or allow the manoeuvre to be performed by a party who will experience less disruption.

   Various directories for contact information exist, including through the Space Data Association and space-track.org. The SSR recognizes sharing a broad set of relevant information, and provides an additional incentive for keeping this information up to date.

2. Ephemeris (launch and orbital, covariance, covariance characterization/validation)

   Sharing and fusion of ephemeris data from multiple sources can improve state knowledge. Frequently owner/operators have better ephemeris data than can be acquired from non-cooperative tracking. Several companies make their ephemeris data publicly available on the web, and others share their data with other operators via the SDA or space-track.org. Some operators consider ephemeris information to be commercially sensitive or proprietary. Covariance information is helpful, especially for smaller objects, but needs to be realistic to be useful. Due to the lack of standardized covariance calculation methodologies, the SSR recognizes operators willing to disclose information about their covariance characterization/validation methodologies while recognizing that many operators will not be willing to disclose significant information about their flight dynamics.

3. Characterization Data (manoeuvrability, operational status, mass, maximum dimension)

   Manoeuvrability information is helpful to determine potential future states for objects when another operator involved in a conjunction cannot be contacted, and to help determine which operator (if any) should move to mitigate a conjunction. The SSR asks for maximum capable 24hr displacement to include relevant capabilities for spacecraft making use of differential drag for manoeuvrability or potential novel propulsion techniques. Operational status is useful for similar reasons but is potentially very sensitive for operators who have not publicly disclosed impairments to satellite health. Mass information is helpful as a proxy for collision consequence severity. Maximum dimensions are used for some collision assessment techniques.

   Binary manoeuvrability and operational status information is available for some objects through space-track.org for entities that have signed SSA sharing agreements with USSTRATCOM. The European Space Agency publishes mass and dimensional estimates for many space objects through its Database and

Information System Characterising Objects in Space (DISCOS) service[2]. A limited number of operators provide operational status information publicly.

4. Autonomous Manoeuvre System Disclosures (trigger criteria, update frequency in any shared SSA information, and emergency stop procedures)

   As more operators operationalize autonomous collision avoidance capabilities, it is important that there is coordination to prevent inadvertent emergent behaviour as they interact with one another or satellites flying on more manual processes. These disclosures are intended to facilitate such coordination with other operators, while recognizing that details of the autonomy implementation may be considered proprietary by some operators.
   To the best knowledge of the authors, only one operator has deployed a system for autonomous collision avoidance. In the future, more of such systems may be present, with the potential need for coordination among these different autonomous collision avoidance systems.

5. Other Forms of Voluntary Data Sharing (detailed radiofrequency information sharing to support interference avoidance/ mitigation/geolocation, spacecraft anomaly information sharing, other data sets to support government or academic research)

   This category recognizes that operators have several other forms of data sharing that could benefit other operators or categories of space stakeholders, but that are considered outside the core focus of the SSR. This category is designed to provide bonus recognition to operators who disclose such information in a way that provides benefit to other stakeholders, but is written more flexibly to accommodate different possibilities. Limited sharing already exists in most of these domains, but tends to be on a more case-by-case basis. Examples of other forms of data sharing might include atmospheric drag information and non-lethal impact data to support model development.

3.3 Collision Avoidance

This category recognizes operators for investing in particular capabilities that contribute to collision avoidance. Three categories are recognized, with a rubric of four possible levels of performance per category.

1. Orbital State Knowledge

   The better an operator's knowledge about its spacecraft trajectories, the better it can coordinate with others to avoid potential collisions. This category rewards operators for maintaining orbital state knowledge to certain threshold error values, as well as updating their orbit determinations in a timely manner.

2. Collision Avoidance Availability to Coordinate

   This item recognizes the importance of operator ability to response to emergent conditions and coordination requests in a timely manner. It gives credit to operators for greater availability to coordinate, especially those with staffing 24 hours per day.

3. Collision Avoidance Capability to Coordinate

   This category acknowledges operators for possessing conjunction screening and assessment capabilities, screening against an SSA sharing organization catalogue, being able to interpret conjunction data messages, knowing how to generate and screen mitigating manoeuvres, and implementing documented procedures for each of these tasks to reduce human error. This can either be performed in-house, or through procuring the services of a relevant third-party.

3.4 Detection, Identification and Tracking

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[2] Available at https://discosweb.esoc.esa.int/

The Detection, Identification and Tracking Module within the Space Sustainability Rating evaluates how operator decisions about mission design, spacecraft design and spacecraft operations influence the probability that observers on the Earth will effectively Detect, Track and Identify the spacecraft for a given mission. For this analysis, the following definitions are used to consider the observation of spacecraft from Earth.

Detection: This definition considers the scenario in which a ground-based surveillance system using optical and radar sensors to observe Anthropogenic Space Objectives is naively 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 probability that the spacecraft of a given orbit can be detected separately by optical telescopes and surveillance radars. The radars are assumed to be an Ultra High Frequency (UHF) System that is not tuned for observation of a specific range or size of objective. Instead, the radar returns observations of any space objects that pass within its field of regard. The Detectability of a set of mission spacecraft is therefore defined as the probability that the optical telescope and surveillance radar system will observe, subject to sources of error from the sensors and from signal loss as it transfers through the atmosphere.

Identification: For this analysis, Identification refers to the process in which a naïve observer who does not have a priori information about the name, ownership, range and size of spacecraft, uses information gained through physical observations from earth to gradually specify that a specific object observed from ground-based sensors is observed repeatedly and that it can be identified as an object with a specific name, orbit and owner. This analysis asks how difficult it is for a naïve observer to uniquely distinguish a given spacecraft from others using only observable characteristics independent of coordination with a spacecraft operator to complete the identification process.

Tracking: For this analysis, Tracking refers to the process in which a ground-based observer has already detected and identified a spacecraft and next seeks to monitor and predict 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 use information obtained independently from the 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, but does not have full knowledge of the orbital parameters. In this situation, the tracking analysis considers the probability that a tracker can continue to observe the spacecraft for a mission over time, while distinguishing among similar spacecraft within a mission constellation and gradually improving the prediction for when the spacecraft will pass within the field of regard of the ground-based optical and radar sensors.

To evaluate the Detectability, Identifiability and Trackability of a spacecraft mission for the purpose of providing an SSR score, the SSR team is creating a new computational model that considers the theoretical performance of optical and radar ground-based sensors that observe Anthropogenic Space Objects. 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 ranging from .25 to .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 Anthropogenic Space Objects.

The Detectability Analysis simulates the spacecraft passing over optical sensors and surveillance radars. The computational model calculates the period of time that the spacecraft pass through the field of regard of the sensors, estimates sources of error from the sensors and loss of signal in the atmosphere and calculates a probability of detection. The Identification Analysis, performs several steps by assuming that the ground-based observer does not know the identity of the spacecraft but is working to estimate whether the object is part of a catalogue of known space objects. Thus, the observer is gradually using the list and the information obtained from the observation to estimate how many objects on the list of known space objects could be the newly observed objects. The more objects that the naive observer can eliminate from consideration, the higher the probability of detection for the mission spacecraft. The analysis assumes that the observer is gradually collecting information over multiple passes regarding the visual magnitude (from optical observation), range and approximate size (from the radar observations), the angular momentum vector and the patterns of illumination that provide qualitative information about the spacecraft (such as indications that the spacecraft may be tumbling). The output of the Identification Analysis is a probability of identification when compared to a known catalogue of space objects.

The Tracking Analysis assumes that a ground-based operator has identified an Anthropogenic Space Object as a unique entity, but does not have the orbital parameters from the spacecraft operator. Thus, they are using information obtained in independently (approximate size, altitude and instantaneous angular momentum) and seeking to predict the orbital trajectory and estimate future overpasses of the spacecraft for the observation network of telescopes and radar sensors. The output of this analysis is a probability that the uniformed observer will be able to repeatedly estimate when the spacecraft will pass overhead using information obtained independently and that the observer can distinguish the spacecraft from other similar spacecraft that may have similar orbital characteristics. Work on the DIT Module is ongoing and more detail will be shared in future publications.

4. HOW WILL SSA PROGRESS SUPPORT THE SUCCESS OF THE SSR?

As can already be established from the previous section, the core architecture of the Space Sustainability Rating includes not only how well an operator *intends* to behave in orbit but also to ensures those statements are verifiable once in orbit. This captures the need for a transparent evaluation and communication on how an individual mission contributes to the notion of a sustainable environment and to avoid the so called "tragedy of the commons" when it comes to the space environment. Since the beginning of the space era, the build-up of civilian SSA capabilities has been largely driven by the need to keep tab on one's own objects during the active parts of the mission, e.g. to schedule commanding and downlink activities. From a military perspective, there was also the need to create visibility and intelligence on the behaviour of objects belong to potential adversaries. The common minimal intersection of this is reflected in the minimal input required to comply with the UN registration conventions: A name and description of a launched object with an operational orbit [11]. However, since the turn of the millennia, there has been an ongoing change in users and stakeholders, and the services derived from SSA data driven by the need to perform collision avoidance operations in an increasingly congested environment. At least since the Cosmos – Iridium collision in 2009, the global trend has been established towards increased accuracy of space surveillance products, and the commercial availability of such products. The SSR is enabled in this landscape, where the position of missions can be independently verified and their behaviour transparently monitored.

There are essentially two ways in which SSA data contributes to the definition, assessment, and verification of the SSR: Direct and Indirect. In the direct way, the SSR modules are set-up to capture how missions deal with the available SSA, or self-generated, datasets to achieve sustainability. This boils down to two major considerations designers and operators can make when they are putting together their mission. On one hand, there are those actions that effectively reduce the collision avoidance efforts for other operators and, on the other hand, there are the actions that reduce the burden on space surveillance systems. This first one is addressed in Sections 3.2 and 3.3, via the assessment of an operator's knowledge on its orbital state and what to do with this knowledge in particular. The SSR will incentivise those mission which reduced the positional uncertainty to a minimum, e.g. by employing state of the art orbit determination technologies, and manage to share this information effectively when involved in close approaches with others [12]. This targets a reduction in collision avoidance manoeuvres by means of standardised exchange against understood and known risks. An improvement in orbital state knowledge over a baseline SSA solution can be achieved by increasing the operator's own capability, e.g. publishing GNSS based orbit determination with small uncertainty (i.e. the so-called covariances), or by employing dedicated tracking and monitoring solutions as available on the commercial SSA market. Operators earn additional recognition when such a capability can be maintained after the normal operations of the mission are over, and the object is left to drift in space uncontrolled. Taking care of your own object and exchanging data is just one side of the sustainability problem. Even when these steps cannot be improved over the current baseline for SSA products, an operator or mission designer can still take steps to ensure the mission fits well with available SSA solution, as such ensured the mission has a solid baseline for determining on orbit interactions. This is the content of Section 3.4, where improved detection and tracking is seen as a must-have solution in view of the ever further evolving miniaturisation of space systems to the points where they are no longer visible from an SSA perspective or are visible but with poor orbital solutions. Both detection and identification of space objects remain technical challenges. Detection is a concern because space objects can't be tracked create a background risk for others in the same way as the majority of space debris does. The timeline between first detection and systematic detection is crucial, as this can mean the difference between life and death for some payload. Improvements in these aspects beyond the current day norm would thus be contributing toward a higher tier SSR score for a mission. The risk that a mission itself becomes involved in collision is accounted for quantitatively as part of Section 3.1.

As already laid out in the previous section, the SSR is based on operator-provided data (e.g. on the adopted disposal and collision avoidance strategies) in order to compute the rating already prior to launch. The indirect contribution from the SSA community to the SSR in the future will be found in the development of reliable approaches to perform independent assessments aimed at validating such operator provided inputs once the mission is on orbit and award a final rating. Input to the SSR are designed with these aspects in mind, but SSA products that provide a reliable and independent answer to effectively determine baseline collision risks in orbit are still in its infancy. Notwithstanding these limitation, more straightforward question such as “did a mission dispose as planned” or “is a manoeuvre capability present” are relatively easy to verify independently. The continuous monitoring of a mission by an SSR-issuer would thus serve as an incentive to remain true to a sustainable operations baseline once on orbit and enable a transparent communication in case of deviations from the baseline plan. Unexplained deviations from the submitted SSR baseline plan could thus lead to a dilution of the final rating. Finally, given sample values determined from the on-orbit population with independent SSA intelligence on certain objects, a majority of the scoring for any object on-orbit could be done automatically. This would allow missions with an emphasis on sustainability, i.e. those requesting an SSR, to be compared against their peers, even if the latter ones do not explicitly request to be rated. This underlines the SSR’s commitment to transparent operations.

5. WHAT CAN SATELITE OPERATORS DO TO CONTRIBUTE TO THE SSR?

Section 2 discussed actions that space operators can take to improve their scores in the Space Sustainability Rating and to contribute to long term efforts to reduce the four key challenges to space sustainability that were introduced in this paper. Space operators can also take several steps to support the initiative to have a globally adopted Space Sustainability Rating. First, space operators can learn about the definition of the Space Sustainability Rating develop plans to move from lower SSR performance to higher performance. Second, space operators can coordinate with their national regulators for space activity to explore mechanisms for the government to adopt definitions similar to the SSR in their process to review and approve launches and frequency applications. Third, space operators can participate in voluntary organizations that share space data, provide training for new space operators on space sustainability and create standards for spacecraft design and operations. Finally, space operators can participate in technology research efforts that aim to innovate new systems to improve Space Situational Awareness, such as methods for SSA data sharing and management, methods for tracking Anthropogenic Space Objects and methods for operating constellations or satellites in congested orbits that reduce collision risk. Along with other space stakeholders, satellite and launch vehicle operators can play a leadership role to establish norms of behaviour that help ensure the long-term sustainability of outer space, starting with Earth Orit.

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