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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Integration of Light Pollution and Active Debris Removal Indices in the Space Sustainability Rating

Laurea Magistrale in Space Engineering - Ingegneria Spaziale

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1. Introduction

The last decade has been characterised by a significant proliferation of large constellations in Low Earth Orbits (LEO) region. These innovative space infrastructures provide important data and services for humanity. On the other hand, the increasing implementation of multi-satellites configurations is rising a critical concern in the long-term sustainability insurance of the outer space. The main goal of the study is to support the necessity for a sustainable approach to space activities in the 21^{st} century, especially for what concerns the deployment of complex configurations.

Assessing responsible and accountable decisions from space actors is accomplished through innovative rating approaches, reflecting the growing urgency to safeguard the celestial environment and global collective interests. The Space Sustainability Rating (SSR) system emerges as a powerful initiative. The current state of the approach is introduced and developmental possibilities are proposed and discussed. The discussion contains the basis for the construction of a Light Pollution index and an Active Debris Removal (ADR) indicator to deepen the comprehensive understanding of the SSR functioning, supporting the necessity of an instrumental tool to foster a culture of responsibility and ethics in space endeavors.

2. OneWeb approach to Space sustainability

The analysis faces the topic by delving into the level of commitment towards Space Sustainability exhibited by OneWeb, part of Eutelsat Group and the world's first GEO-LEO constellation for global connectivity. The study focuses on the principal initiatives in which the company is involved and on its adherence to the Global Space Operators Association (GSOA) Code of Conduct.

The critical analysis is carried out by the construction of a tree-columns tabular structure where the main relevant space fields, the solutions adopted and the possible developing points are respectively reported. The study takes inspiration from the following official references:

- *Guidelines for the long-term sustainability of outer space activities of the committee on the peaceful uses of outer space*, by United Nation Office for Outer Space Affairs [8];
- *Space Sustainability, The Time to Act is Now*, by ESOA [4];

- *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*, by United Nation Office for Outer Space Affairs [10].

The subject of the analysis, the English company OneWeb, is critically analysed through a set of domains meaningful from the sustainability point of view:

1. Sustainability issues Outreach and Education Engagement;
2. Space Debris Mitigation Measures;
3. Space Situational Awareness Enhancement;
4. Space Operators Coordination;
5. Space Objects Registration;
6. International Space Law Support;
7. Policies Review and Update;
8. Industry-wide Collaboration.

The study carried out on the level of commitment holds immense value in tracking the overall company. It allows to identify the strength and weakness aspects in a smart and intuitive method. Moreover, if tracked over time, the evolution of the behavior allows to perceive variations and contextualises decision with respect to time-defined situations and conditions.

The applicability of this approach can be extended beyond the specific case of OneWeb company and used as a yardstick for the evaluation of space operators in general. It stands for a precious and intuitive model from which a private enterprises critically places itself among competitors, examining the proper and other state of involvement.

3. The Space Sustainability Rating

Among OneWeb active participation in national and international actions, Space Sustainability Rating (SSR) [9] project represents an innovative effort in the assessment of the environmental and operational impact of space missions, promoting responsible practices within the space industry. It aims to associate missions to an Index which reflects their level of implementation and alignment with sustainable practices. Among the modules, the Mission Index (MI) is computed to estimate the environmental footprint of a space mission.

3.1. THEMIS simulations

THEMIS tool is an algorithm developed by Politecnico di Milano and Deimos UK, whose name stands for "Track the Health of the Environment and Missions in Space" [2]. In analogy with the definition of Environmental Index, the Space Debris mode included in THEMIS software allows the computation of the so called Space Debris Index. The process is based on the profile of the mission, the spacecraft characteristics, the orbit characterisation and other operational aspects, among which collision avoidance manoeuvre efficacy and post mission disposal capabilities and reliability.

The THEMIS tool front-end interface will be addressed to external users and will allow the analysis of the mission impact in predictive manners. As OneWeb Generation 2 Constellation is close to be deployed, this type of analysis is fundamental in order to assess the impact of the space mission on the space environment.

The configurations considered to be tested are:

- 12 to 24 planes at 1200 km altitude and 55 deg inclination, with 12 to 72 satellites on each plane;
- 4 to 12 planes at 1200 km and 87.9 deg inclination, with 6 to 36 satellites on each plane.

18 combinations of the number of planes and number of units per orbit are selected to be simulated (Tables 1 and 2).

Planes → **Sat \ plane ↓**	12	18	24
12	Sim. 1.1	Sim. 1.2	Sim. 1.3
42	Sim. 1.4	Sim. 1.5	Sim. 1.6
72	Sim. 1.7	Sim. 1.8	Sim. 1.9

Table 1: 55 deg inclination simulations.

Planes → **Sat \ plane ↓**	4	8	12
6	Sim. 2.1	Sim. 2.2	Sim. 2.3
21	Sim. 2.4	Sim. 2.5	Sim. 1.6
36	Sim. 2.7	Sim. 2.8	Sim. 2.9

Table 2: 87.9 deg inclination simulations.

Figures 1 and 2 shows the results of the index evolution during the constellation life-time respectively for the 55 deg inclination Configuration and 87.9 *deg* inclination Configuration. The overlapping of the results permits to declare the most promising solutions.

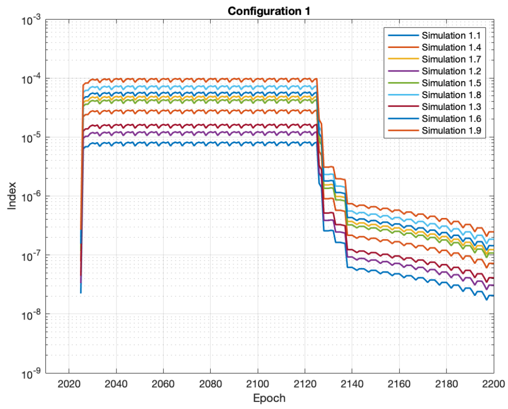

Figure 1: 55 *deg* inclination Index evolution.

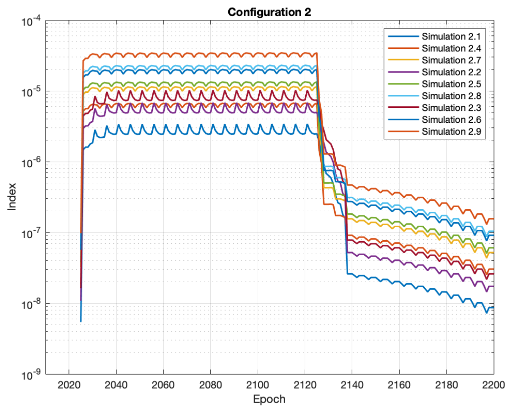

Figure 2: 87.9 *deg* inclination Index evolution.

The study goes beyond the separated estimations of the indicator values, made by Andrea Muciaccia, but characterises the implementation of multiple shells by combining the configurations. The approach tests the model of the coupling between the most similar representation of OneWeb constellation with the less crowded,so less impactful, case of the 55 *deg* strategy (Tab. 3). The results deriving from the matching strategies in Figure 3 opens promising alternatives in the mission design definition.

	Sim. 2.7	Sim. 2.8	Sim. 2.9
Sim. 1.1	Comb. 1	Comb. 2	Comb. 3
Sim. 1.2	Comb. 4	Comb. 5	Comb. 6
Sim. 1.3	Comb. 7	Comb. 8	Comb. 9

Table 3: Grid of simulations coupling for the definition of combinations.

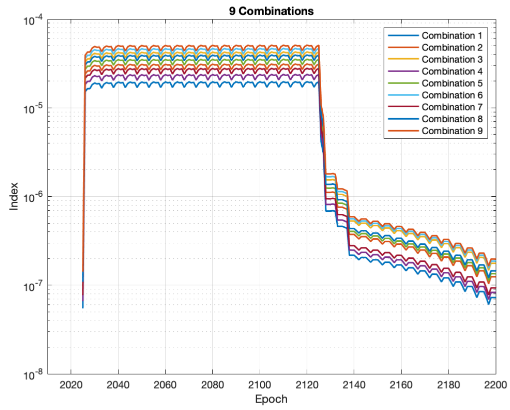

Figure 3: Combinations Index evolution.

3.2. The light pollution index

In the spirit of advancing Space Sustainability, a proposal of extent of the Space Sustainability Rating (SSR) system to a Light Pollution Index is included. The concept rises from the growing concern of uncontrolled light emissions caused by constellation activities and their impact on astronomical observations and Earth's environment.

The indicator is expected to depend on the number of satellites illuminated over an observatory and the definition of a reference Threshold Magnitude, inspired by the guidelines of the Astronomical community [3]. The limit is scaled on LEO population, taking $h_0 = 2000\ km$ the maximum altitude value in Equation 1, where h is the altitude of the constellation.

$$M_t(h) = 7.0 + 2.5 \cdot log_{10}\left(\frac{h_0}{h}\right) \qquad (1)$$

Assuming a uniform distribution, the first variable depends on the number of satellites constituting the constellation, its altitude and the observatory Field of View (FOV). A sample of constellations is analysed and the number of illuminated objects estimated taking as reference $z = 90$ and $z = 60$ *degrees* of FOV (Fig. 4).

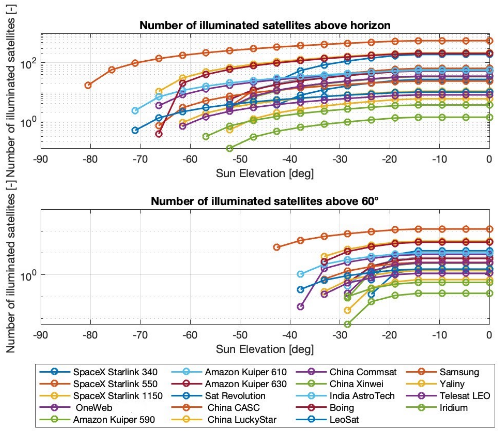

Figure 4: Number of satellites in range above the horizon or above zenithal distance $z = 60$ *degrees* illuminated by the Sun, as a function of the Sun's elevation.

The influence of the inclination in introduced by comparing Starlink constellation to OneWeb one, respectively inclined of 53 and 87.9 *degrees*, with reference to the latitude of the MMT Observatory [6]. As noticeable from Figure 5, satellites do not distribute uniformly over the Earth, so a density correcting factor in introduced in the computation of the illuminated spacecrafts. A first attempt of indicator is modelled integrating the logarithmic curves over one day and calculating the number of light measured units above the Brightness limits during the 11^{th} July 2023 in Table 4. The threshold are 8.9239 and 8.4017 for Starlink 340 and 550 shells and 7.5546 for OneWeb. IF and BTRF stand for Illuminate Fraction and Brighter than Reference Fraction.

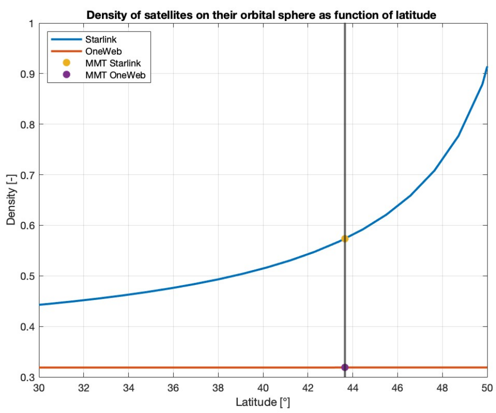

Figure 5: Density of Starlink and OneWeb satellites on their orbital sphere as a function of latitude.

	IF	BTRF	TOTAL
Starlink	0.3771	0.9195	1.2966
OneWeb	0.1634	0.6410	0.8044

Table 4: Constellation light score.

The second part of the estimation wants to be substituted by an a-priori evaluation. Instead of referring to on-going measurements of constellations already deployed, the analysis aims to returns predictions on the light emissions. The Brightness Model designed by Gerardo Littoriano [7] is developed with the addition of a model of atmospheric extinction (Pickering Model in Equation 2, where λ is the phase angle) and further validated with observation from MMT Observatory.

$$X = \frac{1}{sin(\lambda) + \frac{244}{165+47\lambda^{1.1}}} \quad (2)$$

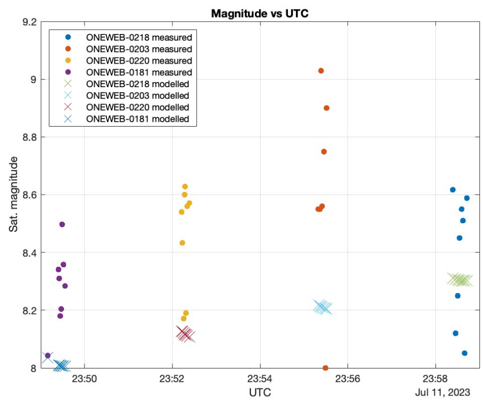

Figure 6: Comparison between modelled and measured magnitudes.

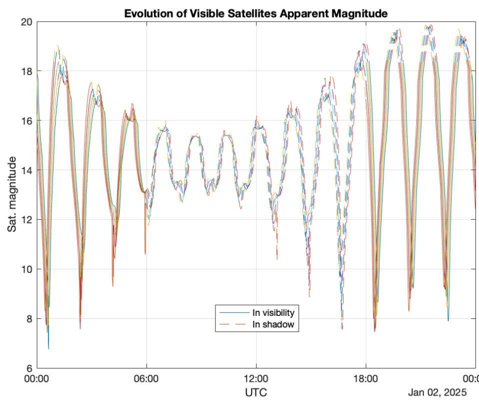

Figure 7: Projection of Gen2 apparent magnitude during the 1^{st} January 2025.

After checking that the advanced tool returns the data coming from real measurements as showed in Figure 6, it is exploited to predict the behavior of the apparent magnitudes of Gen2 OneWeb satellites spanned according to Simulation 1.9 (Tab. 1). The evolution of the brightness during the 1^{st} of January 2025 is reported in Figure 7.

3.3. The ADR Index

To complete, the upgrades provide the integration of an Active Debris Removal (ADR) Index, aimed to quantify the efforts to actively remove space in-active objects, one of the most critical aspects in ensuring the safety and longevity of space missions. According to the recent developments and successes of mission leading the validation and demonstration of Active Debris Removal technologies, their application as Post-Mission-Disposal solutions is always more probable and realistic, especially for LEO objects. What makes the discussion even more interesting is the imminent opportunity for OneWeb to demonstrate the effectiveness of a debris removal technology with ELSA-M mission in 2024.

3.4. THEMIS extension

A simple case of ADR implementation is considered, where a service vehicle (SV) is employed to remove a non-operational spacecraft (SC). By analysing the tree of possible failures during a removal operation (Fig. 8) and estimating the success rates of Rendez-Vous and Re-Entry, the computation of the Index according to THEMIS functioning is possible.

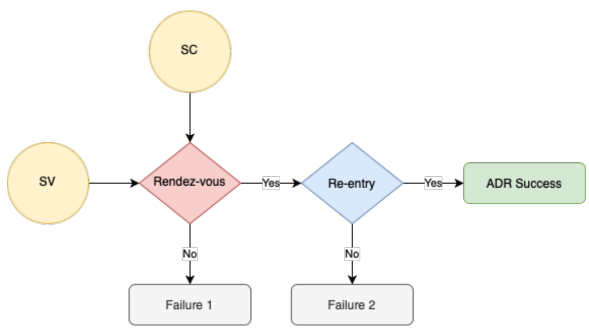

Figure 8: Failure Tree.

The simulation of an ADR implementation in performed though the aggregation of 3 simulation, contracted to return all the phases branches in case of failure occurrence.

The evolution of the Index is represented in Figure 9. From the Post-Mission-Disposal (PMD) point it is possible to recognise the Index evolution in case of:

1. Failure 1: The Rendez-Vous fails but the SV succeeds the Re-Entry;
2. Failure 2: Both SC and SV fail at h_{op} after the Rendez-Vous;
3. ADR success.

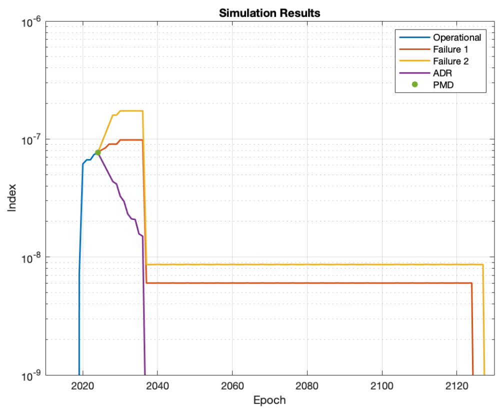

Figure 9: Evolution of the Index in case of ADR implementation.

3.5. The ADR External Service Index

ADR consists of one of the most representative application of external support, in parallel with re-fueling proceedings. The SSR External Service module extension intents to attribute more value to missions that are predisposed and compliant to the Active Debris Removal disposal selected. The output of the evaluation, I_{ADR}, has its roots in a previous proposal of ranking framework for ADR missions candidates [1].

The update proposed is composed by of a partial integration and adaption of the indices resulted from the reference, expanding the set of parameters in order to account to any aspect of Space Sustainability.

The discussion derives from the awareness that the involvement of an Active Debris Removal service has to be rated from different points of view, each one embodied by a numerical indicator:

- I_{env} represents the mission environmental impact in the debris context;
- I_{ec} depicts the economic value associated to the mission orbital region;
- I_{op} is a measure of the attitude state of the satellite, in relation to the removal opera-

tions;

- I_{IOS} embodies the level of performance offered by the ADR technology selected, composed by I_{scal} and I_{rel}, and its own impact on the environment, I_{envIOS}.

All the contributors to the final index are assembled in Equation 3. The rating system is based on a weighting (ω_{env}, ω_{ec}, ω_{op}, ω_{IOS}) and scaling (PI) approach.

$$I_{ADR} = (\omega_{env}I_{env} + \omega_{ec}I_{ec} + \omega_{op}I_{op} + \omega_{IOS}I_{IOS})PI;$$
$$I_{IOS} = -I_{envIOS} + I_{scal} + I_{rel} + 1 \tag{3}$$

The analysis goal is the investigation of the set of sub-indices in the region of interest, which spans from 400 to 2000 km. The principal information of the population belonging to this space area, are extracted from *UCS Database* [11].
Once the specific definition of the terms is achieved, the final assembly of the Index is computed for active and passive satellites, classifying between the categories. Figures 9 and 10 show the objects which return higher values of the ADR Index. The study of the domain of active satellites stands for a valid alarm for operators whose missions are near to End-of-Life. The frequent extension of operation and the quick replacement of satellites imply a regular update of the debris situation. On the other hand, the passive satellites ranking is an efficient drive for international collaboration, acting as a strategic tool for the adoption of important mitigation measures in the space environment and for the prevention of further impactful effects.

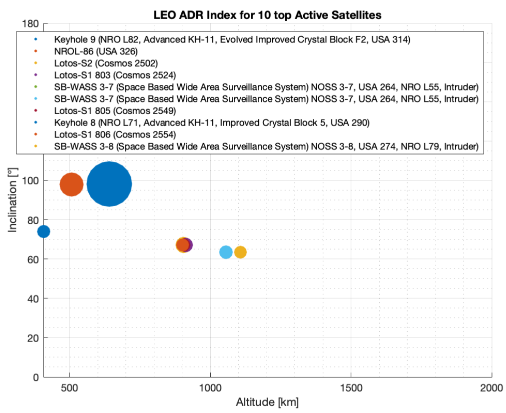

Figure 10: Graphical representation of the top 10 ranked active satellites for ADR removal.

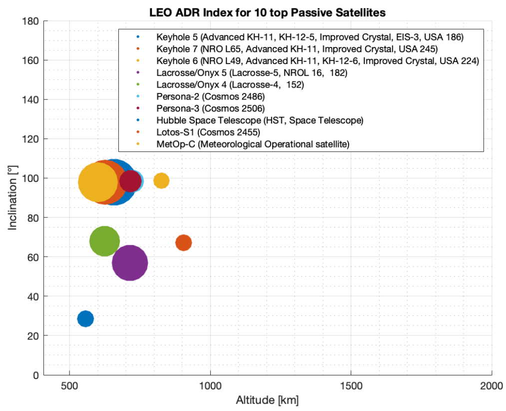

Figure 11: Graphical representation of the top 10 ranked passive satellites for ADR removal.

4. Political excursus on ADR challenges

In the final excursus, the political implications of ADR implementation are explored. Since the management of space debris necessitates international cooperation and agreements, their removals represent not only technical challenges but also diplomatic and geopolitical ones, as it involves multiple space-faring nations. The success of ADR initiatives requires global collaboration, raising questions about governance, norms, and the role of international organizations in regulating activities in space.
The Active Debris Removal service regulation method that is suited to be adopted by OneWeb takes inspiration from the Aerospace Corporation proposed model, described by Tyler A. Way and Josef S. Koller as the Contractual and permission-based framework [5]. The solution grounds on a couple of fundamental and necessary requirements. At the basis of the agreement, the presence of the consent between the debris owner and the ADR service provider is mandatory. To align different law sources, the document is coupled with a legally binding contract that incorporates domestic laws and international obligations.

5. Conclusions

The work exposed aims to explore the critical aspects of the Space Sustainability, starting from a company point of view, switching to a proposal of integration of Light Pollution and Active Debris Removal Indices into the comprehen-

sive Space Sustainability Rating framework, and concluding with a practical presentation of the ADR agreement requirements. The discussion follows the natural evolution of the questions that a company investigates when approaching challenges but also opportunities, related to the sustainable use of outer space.
By delving into the OneWeb Commitment, the pioneering initiatives designed to foster responsible practices in space operations are defined. The tabular analysis applied for the case study is adaptable to any company belonging to the space sector. This property allows to register both strategies and resulting outcomes in a schematic and univocal approach.
The awareness of the impacts of the light pollution in Astronomy and Space sectors underscores an investigation on the effects of the deployment of large constellations for a proper regulation of artificial light emissions. By incorporating light pollution index considerations into the Space Sustainability Rating framework, an holistic approach to preserve the night sky and reduce energy waste in space is adopted.
The study aims to the generalization of a methodology suitable to stand for a practical preliminary instrument to estimate the brightness behavior of a mission and prevent dangerous configurations.
Exploiting the increasing propensity in the use of Active Debris Removal solutions for the reduction of space debris, the analysis proposes its inclusion by modelling the effects in the Index computation. The THEMIS simulation-based approach is developed to define the required steps to integrate the Post-Mission-Disposal option in the algorithm.
Finally the presented version of the External Service model, focused on the ranking of missions from the removal operations point of view, has the ambition to stand for an additional contributor in the Index evaluation and a formal support for the clean-up of orbital debris.

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