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

Tesi di Laurea Magistrale in
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A mio nonno
che mi voleva medico.

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Abstract

The last decade has been characterized by a significant proliferation of large constellations in Low-Earth orbits region. These innovative space infrastructures provide important data and services, such as communications, internet access, Earth observation, but also technologies like GPS, useful for positioning, navigation and timing.

At the same time, the increasing implementation of multi-satellites configurations is rising a critical concern in the long-term sustainability insurance of the outer space.
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 satellite operator delivering ubiquitous 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.

Among OneWeb active participation in national and international actions, Space Sustainability Rating (SSR) project represents an innovative effort in the assessment of the environmental and operational impact of space missions, promoting responsible practices within the space industry.

By exploiting THEMIS, an advanced software developed by Politecnico di Milano and Deimos UK, it is possible to estimate the SSR Mission Index related to constellations according to the probability of collision and explosion of the satellites. The discussion presents the results of the application of the tool to different options for the future OneWeb Generation 2 mission, so that the most promising ones can be identified.

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

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.

Keywords: Sustainability, Constellation, Rating, Light Pollution, Active Debris Removal

Abstract in lingua italiana

L'ultimo decennio è stato caratterizzato da una significativa proliferazione di grandi costellazioni nella regione delle basse orbite terrestri. Queste complesse e innovative infrastrutture spaziali forniscono dati e servizi importanti, come comunicazione, accesso ad Internet, osservazione della Terra, ma anche strumenti tra i quali il GPS, utile al posizionamento, alla navigazione e al cronometraggio.

Allo stesso tempo, la crescente implementazione di configurazioni multi-satellite sta aumentando la preoccupazione nell'assicurare la sostenibilità a lungo termine dello spazio. L'analisi affronta l'argomento approfondendo il livello di impegno verso la sostenibilità spaziale dimostrato da OneWeb, parte del Gruppo Eutelsat e primo operatore satellitare GEO-LEO al mondo che fornisce connettività globale ubiqua. Lo studio si concentra sulle principali iniziative in cui l'azienda è coinvolta e sulla sua adesione al Codice di Condotta della Global Space Operators Association (GSOA).

Tra le attività alle quali OneWeb partecipa in ambito sia nazionale sia internazionale, il progetto di Space Sustainability Rating (SSR) rappresenta uno sforzo innovativo nella valutazione dell'impatto ambientale e operativo delle missioni spaziali, promuovendo pratiche responsabili all'interno del settore.
Sfruttando THEMIS, un avanzato sofware sviluppato dal Politecnico di Milano e Deimos UK, è possibile stimare l'SSR Mission Index relativo alle costellazioni in base alla probabilità di collisione ed esplosione dei satelliti. La discussione presenta i risultati ottenuti dall'applicazione dello strumento per diverse opzioni riguardanti la futura missione OneWeb Generation 2, al fine di caratterizzarne quelle più promettenti.

Nello spirito di promozione della sostenibilità spaziale, una proposta di estensione del sistema di valutazione SSR è inclusa. Vengono esplorate le basi di un indice di inquinamento luminoso, come risposta alla crescente preoccupazione per le emissioni luminose incontrollate causate dalle attività delle costellazioni e il loro impatto sulle osservazioni astronomiche e sull'ambiente terrestre. Per completare, lo sviluppo prevede l'integrazione di un indice per simulare gli effetti di tecnologie di Active Debris Removal (ADR), volto a quantificare gli sforzi per mitigare attivamente i spaziali in disfunzione, l'ostacolo più critico nel garantire la sicurezza e la longevità delle missioni spaziali.

Nell'excursus finale vengono esplorate le implicazioni politiche dell'attuazione delle soluzioni ADR. Poiché la gestione dei detriti spaziali richiede cooperazione e accordi internazionali, la loro rimozione rappresenta non solo sfide tecniche ma anche diplomatiche e geopolitiche, coinvolgendo più nazioni che operano nello spazio. Il successo delle iniziative ADR richiede una collaborazione globale, che solleva interrogativi sulla governance, sulle norme e sul ruolo delle organizzazioni internazionali nella regolamentazione delle attività nello spazio.

Parole chiave: Sostenibilità, Costellazione, Rating, Inquinamento luminoso, Active Debris Removal

Contents

Introduction

0.1. The imperative for sustainable space activities

In people minds, space is often considered the final frontier, a limitless resource to be explored and exploited without restraints, promising boundless possibilities and technological wonders. However, as living in an era defined by unprecedented advancements in space progresses, it has to be faced that human extraterrestrial endeavors are not without consequences.
As the actual age is marked by growing concerns about environmental sustainability on Earth, the paradigm shifts to space domain, focusing on activities and practices. Technological improvement ambitions and growth possibilities extend beyond planet Earth, so long-term ecological, ethical, and economic implications have to be taken into account.

The work seeks to sustain the compelling argument that a sustainable approach to space activities is a necessity in the 21^{st} century. It represents a call to acknowledge the risks and dangers of an increasing and bad-managed space debris situation, as the importance of responsible choices in the mission design.

Space sector is becoming more and more accessible, thanks not only to the fast development of its structures, but also to the significant presence of private realities and international cooperation. This favorable environment promises a prosperous ability to venture into space field. However, this prospective requires that actions beyond Earth are undertaken such that the preservation and the integrity of the celestial bodies and the well-being of future generations are guaranteed.

0.2. The crucial role of space rating systems

The recent developments in the exploration and use of the outer space represent remarkable progress, but also introduce complex challenges, including space debris, regulatory gaps, and the effects of unsustainable practices.
To keep up with the evolution of space sector advancement, the definition of measures that ensure the correct execution of human steps into space environment are required.

Responsible and accountable decision making from space actors can be evaluated through a novel rating approach, that reflects the growing urgency of safeguarding the celestial environment and the global collective interests.
The analysis supports the implementation of space rating systems as effective tools in the maintenance of compliant behaviours, proposing key topics and grading criteria. Following the examples of existing ranking strategies in economic and industrial fields, space rating systems offer a road-map to approach the complexity of space activities with a focus on responsibility, sustainability, and safety. Through the valuation of space operators and the assignment of a score to their missions, the schemes provide objective means for the encouragement and the promotion of responsible behaviors in space.

The most relevant initiative of grading strategy in space sector is the Space Sustainability Rating (SSR) System. The current state of the project is introduced and followed by several considerations on the possibilities of development. The guiding principles and the main scoring methods are presented, as well as the potential benefits to the space industry and the broader international community. The aim of the discussion is to get deeper into a comprehensive understanding of the SSR functioning and to support the necessity of an instrumental tool to foster a culture of responsibility and ethic in space endeavors.

0.3. Literature review

The elaboration of the contents of the analysis was preceded by a significant work of research on the Space Sustainability subject. The wide investigation carried out permits to provide a meaningful picture of the context and a general knowledge of the theme.
This section summarizes the literature review efforts to obtain a preliminary understanding of the topic. The principal reference documents and sources containing the key concepts of the discussion are briefly presented.

The approach to the thematic is conducted by a deep examination of the main notions of Space Sustainability, enclosed in the guidelines [39] and treaties [47] published by UN-OOSA (United Nations Office for Outer Space Affairs) and the Global Satellite Operator Association (GSOA) article [19]. They touch all the fundamental elements regarding Space Sustainability and define the main fields of action. Their review allows the construction and the organisation of the tabular structures reported in Paragraph 1.3.1.

The world of the Space Sustainability Rating System is introduced and later deeply explored by a selection of papers. The papers [46] and [45] give a general overview of the modules and their organization, mentioning the principles and the ideas from which the initiative is originated. More technical reports provide engineering examinations of the numerical characterisation of the index throughout simulation models ([48] and [35]).

At the basis of the concept of the Mission Index, there is the definition of Environmental Consequences of Orbital Breakups (ECOB), as a risk metric exposed in [32] and [36] documents. This measure is strongly linked to the simulation fragmentation events, based on a density approach for debris cloud propagation described by [33] and [30] reports.
A considerable part of the study refers to the implementation of THEMIS software for the computation of the Debris Index. The tool objectives and functioning scheme are exposed in [11], [14]. The papers [13] and [41] help in the understanding of the hidden network of algorithms and simulation models.
The consequent declination in multi-satellites domain, taking the constellation point of view, is approached by the discussions contained in [43] and [42].

The suggestions of SSR Index extensions derive from the recognition of key and critical aspects of the Space Sustainability. The necessity of a Light Pollution Index arises from the examinations of the sky safeguard treated in [24] and [22]. The Brightness Model, developed by Gerardo Littoriano in [37], is exploited as a tool for the prediction of critical light emissions from constellations.
The references [28] and [34] lead most of the consideration on Active Debris Removal contributions to the upgrade of the rating system. The proposal of an ADR Index takes inspiration from the report [8] by Giacomo Borelli, a solid basis from which founds and it is developed a new and predictive tool to be included in the system.

The document [26] supports the final discussion on the technologies political and legal challenges, standing for a unique source of information for the treatment of political aspects of ADR agreements.

0.4. Thesis contributions

The study presented is the result of a collaboration between Politecnico di Milano and OneWeb. The work was born from the company's growing attention, awareness and sensibility towards the adoption of more sustainable space measures and actions. The aim of the dissertation is to emphasize the wide range of possibilities for a private operator in the achievement of fundamental sustainability goals. The SSR initiative, in which OneWeb is involved, is improved through the assessment of the light pollution and the Active Debris Removal impacts on the Index computation. Being OneWeb constellation a reality touched by both the topics, it suits the role of subject of the analysis. Gerardo Littoriano Brightness Model, developed for OneWeb satellites, and the future ELSA-M debris removal mission are good hints for the conduct of the work.

0.5. Thesis outline

The thesis opens with a general introduction to the Space Sustainability topic and the Association of Global Space Operators (GSOA). The preliminary insertion helps to comprehend the tabular structure reflecting OneWeb commitment to Space Sustainability goals and its alignment with GSOA Code of Conduct, reported at the end of Chapter 1.

Chapter 2 is completely dedicated to the Space Sustainability Rating (SSR) initiative. It represents the core of the work, where its functioning and its extensions are deeply analyzed and explored.
THEMIS tool is exploited to evaluate the Debris Index associated to OneWeb Next Generation of satellites, comparing and discussing trade-off design decisions and favourable mission characteristics, according to the software results.
The discussion is followed by the determination of the main key factors useful for the construction of a Light Pollution indicator. This part concludes with the implementation of a brightness model for the execution of light emission predictions, so that projections for not-yet deployed constellation are possible.
The last proposal consists of the introduction of the Active Debris Removal (ADR) contribution in the SSR, thorough the integration of the effects in selected rating modules. It begins with the modelling of a strategy to address ADR impact in the Mission Index profile, according to the structure of THEMIS simulations. Finally, an ad-hoc indicator, that reflects the specificity of the disposal technology adopted, is constructed and applied to the LEO population.

The conclusions and further developments collected in the Chapter 4 are preceded by a concise but comprehensive reflection on the practical bureaucratic and political implications deriving from the implementation of External Services for a private firm such as OneWeb. Chapter 3 aims to summarize useful information to reach a practical formalization of the ADR implementation steps, promoting their maturation in space sector.

1 | OneWeb Approach to Space sustainability

The underlying theme of the discussion is the space sustainability and the available means by which the space community and the space sector can progress in this direction. The exploitation and the use of outer space is a fundamental aspect of human civilization in the 21^{st} century.
As space activities are experiencing an exponential growth, long-term sustainability is now an imperative for space actors. The dynamical and shareable properties of the space, in addition to the proliferation of its inhabitants, require a global effort to guarantee its preservation. The increasing implementation of artificial objects in the Low Earth Orbit (LEO) region and the consequential space debris accumulation constitute a real danger for present and future generations.

The first chapter is committed to properly contextualise the technical proposal later presented, in order to offer an in-depth analysis of the current state of the space sustainability efforts, with a particular focus on the measures that a private space company can pursue nowadays. The object of the evaluation is the well-known subsidiary of the Eutelsat Group, Eutelsat Oneweb, which provides a broadband satellite Internet service in the Low Earth Orbit. The methodology steps include the definition of the level of alignment of the company with the General Space Operators Association (GSOA) Code of Conduct, the definition of the relevant national and international initiatives and the new existing frontiers to address the main sustainability challenges.

1.1. The space sustainability overview

With the words *General Space Sustainability* it is possible to refer to the set of actions that guarantee a responsible and sustainable use of space resources and the assurance of the long-term viability of space activities. There exist a number of key topics and areas of interest belonging to space sector in which the sustainable aspect is crucial.

Space debris mitigation and removal techniques represent a fundamental role in the collision risk reduction in orbit, allowing the removal of inactive objects and protecting valuable assets in space. These measures are essential for several services, such as communications, weather forecasting, Earth observation and navigation. By mitigating space debris, their functionality and availability are safeguarded and constantly ensured.

The Space Traffic Management (STM) and the Collision Avoidance (CA) systems are fundamental instruments to be optimiSed and efficiently updated as the number of satellites and spacecrafts in orbit is increasing. The control of the orbital state of congestion allows to maintain safe specific corridors and ensures the correct execution of the operations.

Looking at the life-cycle of the satellite, both the design and the operations have to be planned to produce the minimum amount of emissions and space debris production. A superficial approach could cause unmotivated space pollution and negative impacts on the space environment. On the other hand, a careful planning ensures an efficient use of the resources, reduces the need for additional launches and limits the carbon emissions associated with the satellite production and deployment.

To complete, also space regulatory frameworks and policies, international cooperation and governance mechanisms have to be oriented towards sustainability goals, as essential connection requirements for more technical aspects.

1.2. The Global Space Operators Association

The Global Satellite Operators Association (GSOA) is a CEO-driven organisation, representing the interests of satellite operators worldwide. Building on the established infrastructure, processes and CEO-driven leadership of Europe, Middle East and Africa Satellite Operators Association (ESOA), GSOA guides operators on topics like spectrum, 5G, space sustainability, and satellite contributions to social and economic development. The mission of GSOA is to provide an unified platform for collaboration among global satellite actors, ensuring missions successes and creating opportunities for policymakers and industry stakeholders to use satellite services.

This goal is achieved by cultivating a conducive political, industrial, and regulatory environment that ensures the availability of satellite services worldwide.

GSOA collaborates with national regulators, governments, standard-setting organisations and regional bodies to ensure the satellite industry's participation in activities across the world and with key global institutions like the International Telecommunications Union (ITU), the World Economic Forum (WEF) and the United Nations (UN).
Members of GSOA, among which OneWeb, have the opportunity to shape the future of the satellite communications industry by participating in a well-organised, operator-driven advocacy organisation.

The GSOA Code of Conduct represents a voluntary set of guidelines for space actors developed by the United Nations Office for Outer Space Affairs (UNOOSA). It aims to promote responsible space activities and enhance the long-term sustainability of outer space.

1.3. OneWeb commitment Table

As the main topic of the study is the Space Sustainability, a preliminary and general understanding of the current state of OneWeb engagement on this issue is required. This involves the examination of the key challenges and threats concerning its achievement and the evaluation of the company efforts and their effectiveness.

As mentioned, among the existing initiatives, the GSOA Code of Conduct is established to promote a responsible behavior in outer space activities and serves as a cornerstone of global space governance. OneWeb, in the role of a satellite-based communication prominent player, takes inspiration from the mentioned guide and participates to a wide range of national and international activities.

The critical analysis is carried on by the construction of a table following a three columns structure. In the first column, all the main relevant space fields in which the company has power to act for the alignment with the Code, are listed. The second and the third columns refer to the elements OneWeb exploits to commit to the sustainability objectives and the possible developing points, respectively.
The classification categories at the basis of the research to define the General Space Sustainability status, are inspired by the concepts collected in a selection of official documents:

- *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

[39];

- *Space Sustainability, The Time to Act is Now*, by ESOA [19];
- *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 [47].

1.3.1. Categories definition and Table characterisation

The level of familiarisation with the GSOA Code of Conduct It reflects the amount of consideration and understanding the private space firm shows with respect to the provisions of the GSOA Code of Conduct and the general guidelines.

Sustainability issues Outreach and Education Engagement It regards promoting awareness and understanding programs of Space Sustainability among employees, stakeholders and the public.

Space Debris Mitigation Measures It evaluates the level of implementation of the available measures to mitigate space debris generation during design, operations and End-of-Life (EOL) phases. This involves taking care of all the possible solutions for satellites to perform controlled re-entry or to adopt de-orbiting strategies in order to avoid long-term space debris.

Space Situational Awareness Enhancement It estimates the amount of participation in the Space Situational Awareness efforts, considering the amount of data shared with international entities and organizations involved in tracking, detecting and predicting the space object movements to avoid collisions and ensure the responsible use of outer space.

Space Operators Coordination It valuates the level of collaboration with other space operators to prevent potential collisions and enhance the safety and the sustainability of space activities. This involves sharing information on planned maneuvers or operational changes that could affect the orbits of the space objects.

Space Objects Registration It considers the alignment to all the defined formal steps behind the identification of space objects, launched by a private space firm, with the appropriate national authority and the update of the registration information, as required by international agreements.

International Space Law Support It assesses the level of commitment to provide the legal framework for space activities, promoting cooperation, preventing conflicts, and fostering space sustainability. It is measured in terms of compliance with treaties and agreements and adherence to the principles and obligations set forth in international space norms.

Policies Review and Update It judges the regular reviewing and updating of policies to ensure that operations remain aligned with the evolving landscape of space activities and regulations. Conducting periodic policy reviews and updates allows the adaptation to new challenges, improving safety measures and maintaining compliance with relevant laws and guidelines.

Industry-wide Collaboration It encourages other private space firms and industry stakeholders to adopt the GSOA Code of Conduct and promote a culture of responsible and sustainable space activities throughout the space sector. This approach fosters a cooperative and supportive environment with other companies and stakeholders that leads to shared knowledge, resources and innovations.

Domain	OneWeb Commitment	Key Insights
Level of familiarization with the GSOA Code of Conduct	*Approach*: Responsible Deployment Qualification and testing programs, Selection of low populated launch and operational orbits, Fault-tolerant constellation configuration *Initiatives*: GSOA Task force on Space sustainability, The Long-Term Sustainability Guidelines (COPUOS)	Internal training, code incorporation in Employee On boarding, regular internal and external communication, acknowledgment statement, periodic review sections, integration into performance evaluation.
Sustainability issues Outreach and Education Engagement	*Approach*: STEM education for schools and universities	Workshops, seminars and training sessions, stakeholder engagement, public awareness campaigns, educational partnerships with institutions.
Space Debris Mitigation Measures	*Approach*: Responsible Disposal (Leave No Trace) High reliability requirement for de-orbit, Five years of decommissioning de-orbiting, Complete passivation possibility, “Designed for demise” satellites, Grappling fixture outfitted satellites *Initiatives*: Debris Mitigation Guidelines from ITU coordination, ISO 24113 (Space systems-space debris mitigation requirements), European Code of Conduct for Space Debris Mitigation, Inter-Agency Space Debris Coordination Committee (IADC), ESA-Zero Debris Charter Initiative	ADR research and investment, monopolistic competition avoidance, space "Breakdown Cover" agreements.

Table 1.1: OneWeb General Space Sustainability status

Domain	**OneWeb Commitment**	**Key Insights**
Space Situational Awareness Enhancement	*Approach*: Reliability metrics before launch and de-orbiting, System-wide basis risk evaluation, No Constellations overlapping, Reliable reflectivity and brightness data *Organizations and collaboration*: United States Space Surveillance Network (SSN), European Space Agency (ESA), Commercial Space Operations Center (ComSpOC), Other National Space Agencies, 18^{th} SPCS and commercial companies *Sensors and Tracking*: GPS/GNSS Receivers, Star Trackers, Inertial Measurement Units (IMUs), Ground-Based Tracking Systems, Onboard Software, Telemetry, Tracking, and Control (TT&C) Systems *Commercial SSA Services use*: Conjunction Assessment, Collision Avoidance Maneuvers, Tracking and Cataloging, Space Debris Monitoring, Anomaly Detection and Resolution *Best Practices*: Standard Data Formats - Common Message Format (CMF) - Consultative Committee for Space Data Systems (CCSDS) data formats, Specific Communication Protocols and channels, Collaborative Initiatives - assessment programs, Orbital Maneuver Planning - Conjunction analysis	Improve investment in sensor technology and tracking systems, integrate data from multiple and various sources, develop data fusion algorithms and software, augment data exchange agreements, invest on collision avoidance and predicting algorithms, improve the accuracy and timeliness of conjunction predictions, conduct periodic reviews of your SSA processes and capabilities to identify areas for improvement, increase presence on international forums.

Table 1.2: OneWeb General Space Sustainability status

Domain	OneWeb Commitment	Key Insights
Space Situational Awareness Enhancement	*International SSA Forums Engagement*: United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Meetings, International Astronautical Congress (IAC), Satellite Industry Association (SIA) Events, Commercial Space Operations Support Working Group (CSOSWG) Meetings, European Space Operations Centre (ESOC) Workshops, "Satellite Orbital Safety Best Practices" form AIAA	
Space Operators Coordination	*Data Sharing Agreements*: JSpCO, Space Data Association, ComSpOC *Communication Protocols*: TCP/IP (Transmission Control Protocol/Internet Protocol), foundational protocol of the internet across networks, UDP (User Datagram Protocol) - low-latency communication, IPsec (Internet Protocol Security), DVB-S2 (Digital Video Broadcasting - Satellite - Second Generation), SFTP (Secure File Transfer Protocol), SNMP (Simple Network Management Protocol) *Conjunction Analysis, Orbit Coordination,* *Collision Avoidance*: Precise satellite position knowledge, Coordination with the 18^{th} SPCS and other operators *International Launches coordination*: Launch Provider Selection (Arianespace, ISRO, SpaceX, Starsem, Rocket Lab), Regulatory Approvals (UK, ITU), Pre-launch conjunction assessment, Launch Services Agreement, Environmental Impact Assessment, Compliance with Space Debris Mitigation Guidelines, Registration Convention, Compliance with International Treaties	Increase the number of formal partnerships, participate in industry and companies associations, open communication channels, engage in multinational projects, develop conflict resolution mechanisms, more investment in networking, augment cross-training and skill exchange, develop a long-term vision and strategy for collaboration.

Table 1.3: OneWeb General Space Sustainability status

Domain	OneWeb Commitment	Key Insights
Space Operators Coordination	*Space Forums and Workshops*: International Astronautical Congress (IAC), Satellite Industry Association (SIA) Events, Space Symposium, ITU Meetings, Satellite Industry Association UK (SIA-UK) Events, International Space Debris Mitigation Conferences *Space Traffic Management*: Independent Operator-Operator (Iriidum, SpaceX, Amazon, etc)	
Space Objects Registration	*National Authority*: UK Space Agency *Information*: pre-launch notification, identification code, orbital parameters from Space-Track *International authority*: UNOOSA	Centralize management with responsible teams, standardize procedures with check-list, forms, and submission guidelines, improve automated tools for data collection, validation, and submission, ensure data security, set univocal communication, establish a comprehensive document management system for storing and organization, periodical review and audit plan.
International Space Law support	*Treaties and Agreements*: Outer Space Treaty, Registration Convention, Space Debris Mitigation Guidelines, ITU Regulations, Astra Carta, EU Space Law, National Licensing and Regulatory Compliance *International Organization Engagement*: United Nations Office for Outer Space Affairs (UNOOSA), International Telecommunication Union (ITU), Inter-Agency Space Debris Coordination Committee (IADC), International Institute of Space Law (IISL), National Space Agencies and Regulatory Authorities Bilateral Agreements and International Treaties	Enlarge company internal and external engagement in policy advocacy, increase discussions and negotiations participation, maximize collaboration with national and international governments, support updating of space law with proposals.

Table 1.4: OneWeb General Space Sustainability status

Domain	OneWeb Commitment	Key Insights
Policies review and update	*Global Policies Initiatives*: WEF - A Space Safety Coalition formed by operators, Space Sustainability Rating ("SSR") *Policy Experts Consultation*: ESPI European Space Policy Institute	Advocate for the adoption of sensible, internationally- coordinated space environmental policies into national licensing frameworks, participate in the development of the World Economic Forum's space Sustainability Rating system.
Industry-wide Collaboration	*Industry association*: UK Space Agency *Data Sharing*: pre-launch notification, identification code, orbital parameters *Collaborations*: Gen2 Industry Day, OneEarth, Innovation challenge, AWS (Amazon Web Services) agreement *Consortium, Public-Private Partnerships*: UK government, AIRBUS, AST, Brdy, BT, The Clarus Networks group, Network innovations, speedcast, Bharti Global, SoftBank Group, Hughes Network, Systems, Qualcomm, Grupo Salinas *Contribution to standards*: ITU, European Telecommunications Standards Institute (ETSI), International Organization for Standardization (ISO), ITU-R Working Party 4A (WP 4A), ITU-R Study Group 4 (SG 4), ETSI Technical Committee Satellite Earth Stations and Systems (TC SES), Mobile and Personal Communications by Satellite (TC SES-MPCS), 3rd Generation Partnership Project (3GPP)	Collect and verify carbon footprint for OneWeb, launch partners and supply chain, include carbon footprint guidelines in RFI, engage with World Economic Forum on Space Sustainability Rating, adopt ethical practices in supply chain procurement, develop industry best practices that promote space environmental stewardship and sustainable space activities, establish connectivity in rural and remote areas where it is most lacking, provide rapid response connectivity to areas which require emergency relief.

Table 1.5: OneWeb General Space Sustainability status

1.3.2. Generalisation of the analysis

The study advanced in a schematic approach on OneWeb's commitment to the space sustainability promises important developments and insights for space industry implications.

In principle, it holds immense value in tracking the overall company behaviour evolution over time. Indeed, by investigating its responsible practices and activities, it is possible to obtain indications of the measure of dedication to the main sustainability challenges such as the reduction of space debris, the mitigation of orbital congestion and the minimisation of environmental impacts. The time domain allows to perceive variations and contextualises decision with respect to time-defined situations and conditions.

The structure is expected to evolve in order to dedicate a section to the assignment of the expected and the actually achieved effects to each improvement. This strategy, combined with the time reference, provides a valuable historical record of the progresses. It enables to determine the most efficient and promising aspects to be developed, evolved or matured in response to the ever-changing landscape of space governance and technological advancements. Such longitudinal collection of data is crucial for the assessment of the effectiveness of the selected strategies and specific successful practices are identified to promote sustainability in space.

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.
The categories classifying the areas of action, are common in the space sector. By referring the table to multiple and various cases, the compilation represents a unique reference for the broader space community and a shared road-map for responsible behaviours. 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. The comparison facilitates the identification of strong points and aspects to be improved.

In a rapidly growing and evolving space industry, understanding how competitors navigates the complexities of space sustainability offers beneficial lessons and examples for actors to adopt. The enlargement and the formalisation of the grid methodology becomes a guide in the definition of the private sector engagement with space sustainability. It contributes to a comprehensive understanding of the industry-wide efforts, permitting to identify analogies and discrepancies among different companies and establishing a basis for benchmarking and peer assessment, ultimately driving competition in terms of responsible space practices.

2 | The Space Sustainability Rating

In 2018, the World Economic Forum (WEF) issued a call for proposals to create the Space Sustainability Rating (SSR), a score system reflecting the sustainability of a mission, looking at the debris management and adherence to international guidelines. Subsequently, a consortium comprising the European Space Agency, the MIT, the University of Texas at Austin and Bryce Space and Technology was established to develop a rating system aimed at fostering responsible practices by endorsing mission designs and operational concepts aligned with the stable evolution of the environment.

The goal of the Space Sustainability Rating (SSR) is to stand as motivation for mission operators to formulate operations that align with sustainable practices. It encourages to make decisions taking into account, not only the specific mission primary objectives, but also the potential consequences on fellow operators and the overall debris environment. The rating does not seek to establish a new set of mandatory directives; instead, it aims to acknowledge favorable behaviours such as adherence to mitigation guidelines and initiatives that surpass standard recommendations.

The chosen approach involves the combination of different modules into a composite indicator. These modules encompass distinct facets of space sustainability, considering the impact that missions have on other operators and on the global environment and assessing short-term as well as long-term consequences.

The out-coming indicator includes the sub-indices, described in A.1:

1. The Mission Index (MI);
2. The Detectability, Identification, and Tracking (DIT) module;
3. The Collision Avoidance Capabilities (COLA) module;
4. The Data Sharing (DS) module;
5. The Standards module (ADOS);

6. The External Services (ES) module.

The evaluations of the environmental footprint (MI) and in the DIT score are simulation-based, making use of softwares and algorithms dedicated to the modelling of the performances. The other modules rely on the quantification of inputs provided by applicants through a questionnaire. A seventh module, denoted as Data Verification, is applied across all the categories, depending on the reliability of the information source. The assembly of the comprehensive Index is performed through normalisation and weighting steps, to combine the set of the modules into a unified measure. In addition, a set of answers counts as bonus scores, reported separately as they do not contribute to the baseline rating. The result of the evaluation leads to the categorisations of missions into various tiers, defined with metals.

The power of the instrument is the capability to return values associated to the future behaviour of missions, before their deployment. Candidates and operators can seek the rating prior to launch and, according to the score obtained, adjust features to optimize performances from the sustainability point of view. Moreover, the process refers to the actual context, which undergoes periodic updates. The approach matches the idea that the mission impact is space and time dependent, representing the whole satellite life effects, until the disposal of the object. This awareness leads to the continuous assessment of the index across the various modules, routinely evaluated throughout the mission life cycle.

2.1. THEMIS simulations

2.1.1. Introduction to the software

In the context of space sustainability and the definition of Mission Index as environmental footprint, it is fundamental to recognise a common concept and measure of a mission space impact. The idea is strongly related to the concept of capacity, as the awareness that space orbits can sustain a limited amount of objects that ensure the correct ongoing of the operations. Thus, the definition of an evaluation approach that permits to justify a threshold value of space capacity is consequential.
The effects that already flying missions, but more especially, future satellites are going to introduce in the space environment, is prior for the computation of the rating and a proper delineation of mitigation guidelines.

Starting from these considerations, THEMIS tool [14]is an algorithm developed by Politecnico di Milano and Deimos UK, raised from a project funded by the European Space Agency (ESA). The name of the innovative software stands for "Track the Health of the Environment and Missions in Space" and it is designed to be shared among space community through a Web user Interface.
In analogy with the definition of Environmental Index, the Space Debris mode included in THEMIS tool 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 single mission Debris Index grounds on the assessment of the risk of collisions and explosions during the whole evolution of the mission, associated to their estimated levels of harshness. The approximation is executed in terms of cumulative probability of collision, considering the population of active satellite and simulating the propagation of the generated debris clouds on a set of representative targets.

2.1.2. The Space Debris Index

The background

The Debris Index formulation exploited by THEMIS follows the definition of Environmental Consequences of Orbital Breakups (ECOB) [31]. ECOB is defined as a risk indicator, composed by a probability term p and a severity term e (Eq: 2.1).

$$I = p \cdot e = p_c \cdot e_c + p_e \cdot e_e \tag{2.1}$$

The probability can be declined, depending on the nature of the triggering event, in collision probability p_c and explosion probability p_e. The first term depends on the background population, while the latter reflects the specific object. The severity term e refers to the effects of the object fragmentation on the space environment, respectively e_c and e_e for collisions and explosions.

Equation 2.1 refers to a single time epoch, defined by certain p and e values. In order to account for the whole mission profile, any operative condition is considered. The four terms arranged in the expression are location-depending and defined following a grid approach [18]. It consists of a discretisation technique to define the environment through characteristic Keplerian elements. Their estimations require an accurate modelling of the propagation of the fragments units trajectories. The correct reproduction of the path allows to determine the probability of these fragments to collide with other objects.

For active satellites, the evaluation is performed assuming both the presence and the absence of Collision Avoidance Manoeuvre (CAM) capabilities (Eq. 2.2), where β stands for CAM efficacy, set as a parameter between 0 and 1.

$$I = \beta I_{CAM} + (1 - \beta) I_{no-CAM} \tag{2.2}$$

Computing the index for a single time epoch limits the assessment of the index to a specific condition of the activities. To include all the phases in the indicator, the value of the index is integrated over time (2.3). In the formula, t_0 is the starting epoch of the mission while Δt_{oper} is the duration of the operations. The first integer of the sum refers to the operational life of the satellite. The remaining terms specify the disposal stage, respectively in case of success or failure of the nominal procedures. The reliability index α is the success rate associated to the Post-Mission-Disposal (PMD) solution selected, ranging from 0 to 1. The conventional alternative to the expected PMD is the natural decay, characterised by a probability of occurrence of $(1 - \alpha)$.

$$I = \int_{t_0}^{t_0+\Delta t_{oper}} I dt + \alpha \int_{t_0+\Delta t_{oper}}^{t_{end}} I dt + (1-\alpha) \int_{t_0+\Delta t_{oper}}^{t_f} I dt \tag{2.3}$$

Starling V2.0 [13], developed by Politecnico di Milano, adapts a continuum approach, based on NASA Standard Breakup Model (SBM) [25]. The framework is an efficient tool for the characterisation of fragments' ejection after collisions and explosions. NASA SBM new formulation takes the shape of a probabilistic analysis [17]. From the definition of characteristic length, area-to-mass ratio and ejection velocity, the cumulative density functions are derived. The recognition of the region of interest bounds the area of propagation of the fragmentation such that the appraisal of the density distribution is carried on through a binning discretization.
Once the density state is constructed, the distributions are propagated through the *PlanODyn* propagator [10], applying the method of characteristics to the continuity equations. The expressions of the ordinary differential equations and the impact rate between a debris cloud and a given target are reported in Appendix A.2.

The Index computation

THEMIS tool assesses the impact of a space mission on the space debris environment though the calculation of the Space Debris Index, the equivalent of the Mission Index for SSR nomenclature. The output comes from a set of mission information, including the orbit parameters, the mass and the satellite cross-section, all fundamental for the determination of the risk of fragmentation due to accidental collisions or break-up.

Practically the formulation follows the steps reported in Section 2.1.2, where all the terms present in Section 2.3 are retrieved from the cloud propagation and collision risk estimation in a grid-like approach. The physical characteristics of the object and the mission profile in terms of phases and orbits are inserted by the user and stored in THEMIS database to be later transferred for the computation. The operational orbit data are retrieved from CCSDS (Consultative Committee for Space Data Systems) Orbit Ephemeris Message (OEM) format. The evolution of the mission analysis is provided using the ESA OSCAR tool [9], which allows to select different disposal strategies, such as direct disposal, targeted de-orbit, re-orbit or natural decay, and the propulsion technology design parameters.

THEMIS backend identify the orbital region for the computation of the explosion and collision effect maps. The space domain is divided in Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geosynchronous Orbit (GO), and GEO Transfer Orbit (GTO).

For the LEO category, which is the one of interest of the analysis, a grid in semi-major axis, from 400 km to 2000 km, and inclination, from 0 to 180 *degrees* is implemented [31]. The selected spacial area is discretised in bins, conventionally sized 25 km per 5 *degrees*.

The probability of collision follows the Poisson model, valid for the distribution of gas in the kinetic theory and it is retrieved from the Eq. 2.4, where $N(t)$ is the number of impacts at time t, computed from the integration of the impact rate equation in A.2. The formulated expression shows the dependency of $N(t)$ on the average flux of space debris $\phi(t)$ per m^2 per year, A_c in m^2 and the year of evaluation Δt. The computation makes use of ESA MASTER-8 [16] software tool to obtain the average impact speed of the space debris on a spacecraft, with reference to the debris flux grid.

$$
\begin{aligned}
p_c &= 1 - e^{-N(t)}; \\
p_c &= 1 - e^{-\phi(t) A_c \Delta t}
\end{aligned}
\tag{2.4}
$$

The cumulative probability of explosion is expressed as function of time from the starting epoch, exploiting historical data retrieved from ESA DISCOS database [12]. The classification between payloads and rocket bodies is applied. In Equation 2.5, $S(t)$ is denoted as survival rate, estimated by Kaplan-Meyer static estimator [34], included in Appendix A.3.

$$
p_e = 1 - S(t) \tag{2.5}
$$

The effect factors of collisions e_c and explosions e_e are directly linked to the fragmentation event, as evolution of the cloud of debris and the consequent impact to the population. From [31] considerations, the effects are assumed as the result of the increase in the collision probability for operational satellites, as a measure of the consequences of the fragmentation in orbit. Setting an orbital region, there exists a list of representative targets of the entire population of active objects. The information regarding the operational satellites are extracted from ESA DISCOS [12]. In order to define each i bin properties, the cross-sectional area is computed in a cumulative manner in the grid domain (A_i). The representative target map then is updated depending on the introduction of significant new-entries, especially if large constellations. At this point it is possible to construct the effects maps by simulating for each bin a fragmentation and make it propagate for a set time epoch t_e.

The cumulative probability of collision among the population is retrieved and e defined as Eq. 2.6, where A_{TOT} is the cumulative spacecraft cross section over the 90% of the targets.

$$e = \frac{1}{A_{TOT}} \sum_{i=1}^{N_t} p_c(t_e) A_i \tag{2.6}$$

From this preliminary introduction, all the quantities of Eq. 2.1 are defined, and the calculation of the space debris index is allowed. The out-coming maps are stored and exploited for multiple mission assessments.

The constellation mode

The introduction of large constellations in the near Earth environment implies the placement of a high number of satellites in specific orbital regions and the the risk of occurrence of breakup events. These phenomena can lead to an increase in the background population of inactive and dangerous objects, that make mitigation policies and EOL strategies essential. To improve account for these scenarios, THEMIS software tool includes also the evaluation of the impact of constellations on the space environment.
The simulations allow to investigate the influence of multi-units configurations on the populations of objects already in orbit, especially those active. The consequences are explored in the deployment phase, depending on the strategy adopted, and as a result of the location selected, in terms of semi-major axis and inclination, when fully deployed.

The constellation deployment causes a significant growth in the number of satellites by the introduction of units in a fixed same semi-major axis and inclination region. The work of Muciaccia et al. [43] simulates the introduction of a constellation with characteristics similar to OneWeb one. The deployment is characterised by a satellites placement rate and a map of reference targets. By adding the expected new-entries, the population is updated every year and the maps are regenerated accordingly. The effect of the multiple injections is the disappearance of some reference targets and the appearance of new peaks at the deployed constellation altitude. By going further with the introduction of the satellites in the environment, the maximum peak tends to move towards the orbital region of the constellation and to increase in absolute value.

From the design point of view, not only the number of satellites and their properties matter, but also the constellation location, as the selection of the altitude and inclination combination play an important role. From this awareness, [43] study iterates also on the possible configuration positions. As expected, the fragmentation effects grow in the position of the target represented by the constellation.

Moreover, maps result symmetric with respect to the 90 *degrees* inclination, suggesting that the addition of objects in an area might pose a threat to satellites belonging to the speculate region. Results also show a change in the absolute values, which increases as the orbit inclination decreases, reflecting the higher impact velocity. The review of the outcome stresses the importance of the design definition for the constellation, as the selection of its orbital location poses risk in defined areas.

2.1.3. OneWeb Gen2

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 interpretation of a preliminary simulation of the effects of the introduction of the new set of satellites in the LEO region has the potentiality to drive mission decisions when relevant features, such as the orbital parameters and the units mass, are still not defined.

Once the power and functioning of THEMIS are understood, as the constellations implications recognised, it is relevant that, varying some key features, the differences in the impact on the environment are not negligible.

According to the construction of THEMIS tool and the network of processes behind its operations, the simulations can follow different approaches, depending on the situations to be modelled and tested.

The main significant strategy alternatives are:

1. Performing a change in the background, by modifying the map of targets after an impactful change in the population, and evaluate the index of the actual OneWeb Constellation;

2. Performing a change in the mission characteristics and simulate the introduction of Gen2 to capture the effects on the index.

Option 1 is interesting in the prospective of Starlink next planned launches. The simulation of its deployment permits to determine OneWeb index variation after the introduction of a constellation in a lower orbit.
However, given the proximity and the possibility of action on Gen2 mission, the priority falls on simulation type 2. The evaluation of various options for the Next Generation of satellites are useful to explore the consequences of orbital parameters and satellites distribution and define the most convenient combinations.

The mission scenarios

OneWeb mission analysts are evaluating different options regarding the implementation of the Next Generation of satellites. The figures of merit are the inclination of the planes, the number of planes and the number of units on each orbit. The configurations considered as more prone to be selected 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.

Moreover, the spacecraft physical characteristics are still not set, making the mass value drifting in a range between 150 and 1000 *kg*.

It is important to underline that the final version of the constellation is taking the shape of an hybrid solution between the alternative configurations. In this analysis they are initially decoupled and studied separately to facilitates the computation and reduce the number of merges. Later, in the discussion of the results, the possibilities of combination are accounted and explored.

The main goal behind the modelling of the simulations is to acquire a general overview of the index outcome, iterating on the parameters of interest of the study. In order to define the most convenient combination of the mission features, the strategy is to perform a THEMIS simulation for the lower, the medium and the maximum number of satellites per plane, for both the configurations. Then, as the contribution of each plane is computed, the results are multiplied for minimum, average and maximum number of planes.
The outcome is a database of 18 simulations which allows to identify the most promising combinations for the mission definition (Tab. 2.1 and 2.2). Once these scenarios are environmentally defined, it is possible to estimate the effect of different mass values on the computation of the impact.

Number of planes → **Number of satellites per plane ↓**	12	18	24
12	Simulation 1.1	Simulation 1.2	Simulation 1.3
42	Simulation 1.4	Simulation 1.5	Simulation 1.6
72	Simulation 1.7	Simulation 1.8	Simulation 1.9

Table 2.1: Simulation Combinations for 1200 *km* altitude and 55 *deg* inclination mission configuration.

Number of planes → **Number of satellites per plane ↓**	4	8	12
6	Simulation 2.1	Simulation 2.2	Simulation 2.3
21	Simulation 2.4	Simulation 2.5	Simulation 2.6
36	Simulation 2.7	Simulation 2.8	Simulation 2.9

Table 2.2: Simulation Combinations for 1200 km altitude and 87.9 deg inclination mission configuration.

The input files to be inserted in THEMIS are constructed assuming the mission features collected in Table 2.3. The preliminary simulations are all performed taking $M_{SC} = 150$ kg and a cross sectional area of 2.5404 m^2. For future evaluations, intermediate massive values are going to be selected to valuate the negative effects of a heavier structure. Consequentially, the parameter related to the superficial dimensions of the object is going to be scaled with respect to the mass increment.

Input Data	**Value**
Mass [kg]	150
Body Dimensions [m]	0.48 x 0.52 x 0.52
Solar Panels Dimensions [m]	1.2 x 0.87
Insertion Altitude [km]	450
Operational Altitude [km]	1200
Operational Inclination [deg]	$55 - 87.9$
Constellation lifetime [$years$]	100
Launch year	2025
Launch Duration [$days$]	15
Deployment Duration [$years$]	1
Operations Duration [$years$]	5

Table 2.3: Physical and Operational Input for Gen2 THEMIS simulations.

The software asks for the characterisation of a set of parameters in order to evaluate the level of performance of the spacecraft (Table 2.4). The Collision Avoidance Manoeuvres efficacy is assumed as 0.95, since the capabilities are always ensured until full de-orbit. The Trackability value is an integer number here assigned to 0 as the objects can perform CAM according to the ability to track a debris of size 0.1 m. A high value of 0.99 is considered a valid assumption to reflect the Post-Mission-Disposal reliability in case of constellation configuration.

Input Data	Value
CAM Parameter [-]	0.95
Trackability [-]	0
PMD Reliability Index [-]	0.99

Table 2.4: Input Parameters for Gen2 THEMIS simulations.

The disposal phase is simulated with OSCAR tool from ESA, selecting the *delayed* mode and setting the duration limit to 5 $years$. The End-of-Life phase consists of a transfer to a 1100 km circular orbit and a consequent perigee lowering manoeuvre, reaching an altitude of 250 km. The propulsion unit type has to be declared in order to properly model the trajectories. OneWeb satellites are provided of Electric propulsion units, composed by Xenon Hall-Effect Thrusters (HET), powered by Li-ion batteries.

Simulations results

The altitude of OneWeb Generation 2 of satellite is fixed, as a design choice driven by the intention to occupy a low-crowded region of the space in order to minimise the collision risks for the satellites. Restricting the analysis to orbital considerations, the main focus of the study is accounting the adoption of a lower inclination configuration for the environmental point of view.

During preliminary qualitative comparisons, carried out for the validation of the constellation THEMIS mode, representative configurations are tested to have a general idea of the impact of the orbital parameters selection in the Mission Index outcome.
Looking at the effects of a flatter orbit (Figure 2.1), considering one single satellite orbiting, the Index profile results averagely lower that the curve associated to the original inclination of OneWeb constellation. The reason behind this difference lies behind the properties of LEO satellites population. The map of the targets and the associated debris fluxes (Fig. 2.22), reflecting the distribution of collision probability of the objects, shows that, even though the elevate altitude of the constellation mainly prevents the spacecrafts to occur in catastrophic events, the space below an almost polar orbit presents a significantly higher density of satellites with respect to lower inclinations regions.

The considerations coming from these introductory results are confirmed with the outcomes deriving from the simulations specifically performed for the analysis. It is possible to appreciate the environmental benefits coming from the implementation of a 55 *degree* inclined plane shape.

Figure 2.1 reports the classic behavior of the index during spacecraft mission life-time. The curve presents an initial increment due to the launch and the injection of the satellites in orbit, followed by the execution of the operations. Once the end of operations is achieved, following the Index definition in Eq. 2.3, the object is expected to perform the targeted disposal with a probability of success estimated by the PMD Parameter α. The expected execution of the EOL procedures graphically corresponds to a significant and rapid decrement of the index. The alternative is the abandonment in orbit and the atmospheric natural decay. By considering the other branch rising from the PMD point, it is possible to perceive the long-term consequences of a failure in the planned End-of-Mission strategies. The curves experience a sudden drop and a consecutive stabilization in time.

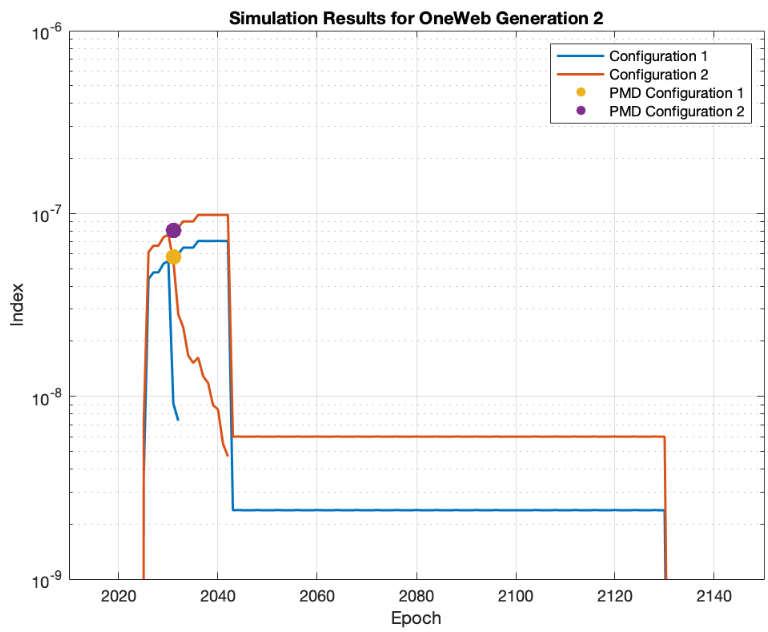

Figure 2.1: Evolution of the Index for a single satellite belonging to the Configurations.

However, these intermediate conclusions have a partial meaning in the discussion. In the description of the mission scenarios in Section 2.1.3, the configurations do not present the same number of satellites per plane, as well as the same number of orbits. Moreover, the low-inclination alternative, which demonstrates a more convenient option from the orbital parameters point of view only, is expected to evolve in a more complex shape, as a thicker network with a higher concentration of units. It is so relevant to estimate the effects of the different coverage solution and distributions techniques in order to draw meaningful conclusions.

The THEMIS simulation input format asks for the characterisation of the deployment strategy adopted, in terms of the final number of satellites per plane and the total duration of the distribution process. The software mechanism makes these design parameters fundamental and definitely impactful when evaluating the environmental footprint of a mission, as they stand for the deployment rate selected for the entire constellation life.

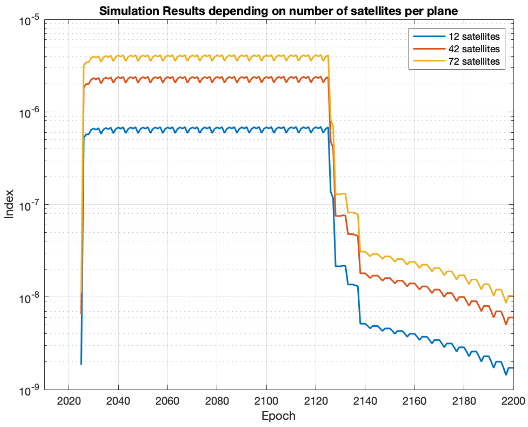

Figure 2.2: 55 *degrees* Configuration Index Representation

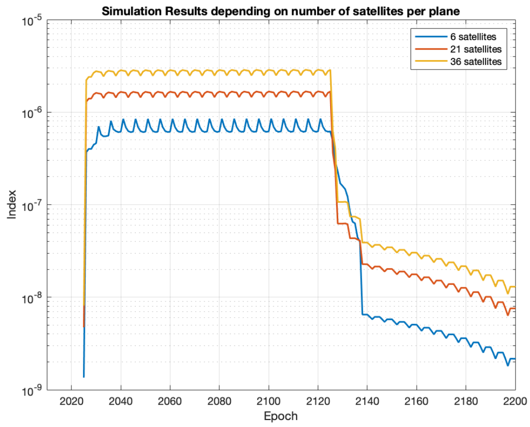

Figure 2.3: 87.9 *degrees* Configuration Index Representation

Figures 2.2 and 2.3 illustrates the index evolution during the 100 *years* mission timeline, considering satellites replacements every 5 *years*. The substitution process is graphically represented by a periodical oscillations, all almost analogue excepting for the $6-satellites$ option for Configuration 2. In this specific case, the waves assume different shapes, with relatively high peaks and subsequent instantaneous decreases. The cause is the low number of planes inhabitants which leads to short and rare phases of satellite deployments and longer periods of low coverage when substituted. There are also discrepancies in the behaviour during the EOL phase, as the solution takes averagely higher values with respect to the more numerous ones. This phenomenon interests 10 *years* after the decommissioning of the constellation, returning inferior during the natural decay.

As expected, setting the deployment duration fixed for all the situations, the magnitude of the environmental impact grows according to the number of units per plane. However, differently from Figure 2.1, the gap between Configuration 1 and Configuration 2 curves decreases, as a consequence of the different number of units. All the lines are around an index value of 10^{-6}, making the comparison less obvious than the single satellite one.

The amount of planes planned for the configurations influences the outcome of the analysis, as the index is multiplied by the number of orbits implemented. These circumstances lead to a necessary overlapping of the curves coming from the simulation referring the 18 combinations described in Tables 2.1 and 2.2.

The out-coming lines permit not only to define the most promising options and less dangerous cases for the space environment, but also to state which factor between inclination, number of satellite per plane and number of plane, weights more in the index definition.

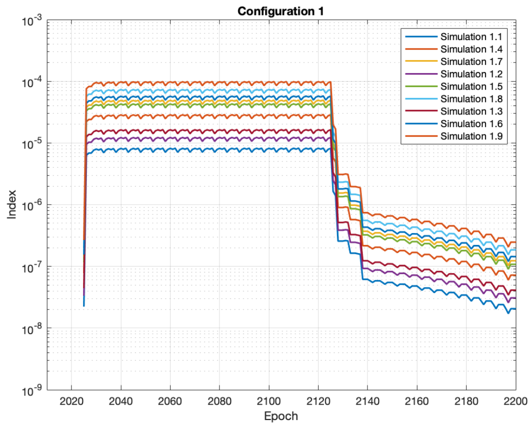

Figure 2.4: 55 *degrees* Configuration Index Representation

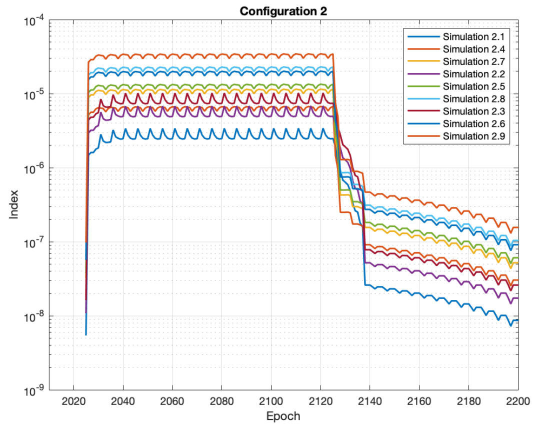

Figure 2.5: 87.9 *degrees* Configuration Index Representation

The results reported in Figures 2.4 and 2.5 are extremely significant, since they confirm that larger constellations, even though placed in flatter planes, turn averagely more impactful that almost-polar solutions with fewer satellites.
The index associated to Configuration 1 in contained in the range between 10^{-5} and 10^{-4}, while the 87.9 *degrees* situation spans half an order of magnitude lower. Anyway, it is possible to notice that a relevant number of combinations from Configuration 1 are still competitive with the more crowded conditions of the 87.9 *degrees* solution. Almost half of the cases fall in the upper range of the Configuration 2 index interval.
During mission design, trade-off decisions on the strategy to be adopted are necessary. Low-inclination configurations, singularly less environmentally concerning, require a higher number of satellites to reach a certain coverage. Numerically it conduces to a greater Mission Index and more prolonged effects over time.

The study conducted until now allows to carry out important conclusions on the effects of key variables in the computation of the Mission Index. The influence of the inclination parameter, the number of units and their spacial distribution are assessed and discussed, also in terms of mission design prospective.
When planning Generation 2 of satellites, OneWeb does not consider the singular implementation of a configuration with respect to the other. The orbital domains are thought to be coupled to improve the coverage requirements.

It translates into the selection of a certain distribution, orbiting on 55 *degrees* inclined planes, flanking a configuration more similar to the previous generation of spacecrafts. It is possible to iterate over all the possible combinations of the constellation strategies in order to obtain a map of the predicted indices profiles. According to the conventional intersections of values assumed by the analysis and explicated by Tables 2.1 and 2.2, the output sample is a collection of 81 lines (Fig. 2.6).

This matching process stands for a valuable reference map for constellation mission analyst and designers. At a true first stage of the project evaluation of the environmental impact, it is possible to consult the differences in the outcomes depending on the features considered and the ranges of values they might assume. Adopting one solution rather than another affects the index up to one order of magnitude.

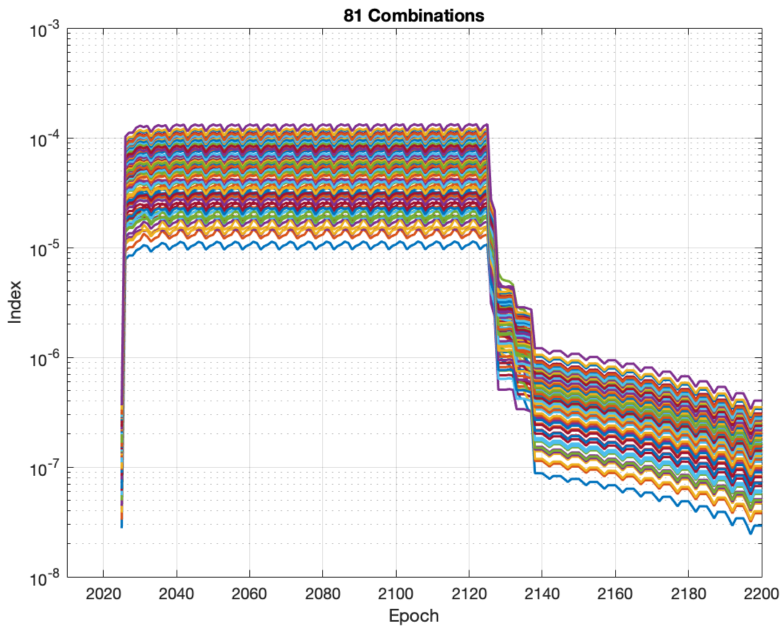

Figure 2.6: Evolution of the Mission Index for the 81 Combinations of Simulations Results.

For simplicity reasons, the sample is reduced to 9 cases, considering the 12 and the 36 satellites per plane configurations for 55 and 87.9 *deg* solutions respectively. Qualitatively, the approach models the adoption of a constellation very similar to the actual one orbiting, coupled with the less impactful low-inclination strategy, in order to improve coverage and performances. The definition of the combinations of the simulations are reported in Table 2.5.

	Simulation 2.7	Simulation 2.8	Simulation 2.9
Simulation 1.1	Combination 1	Combination 2	Combination 3
Simulation 1.2	Combination 4	Combination 5	Combination 6
Simulation 1.3	Combination 7	Combination 8	Combination 9

Table 2.5: Grid of Simulations Coupling for the definition of Configuration Combinations.

The evaluation of the effects of hybrid distributions permits to consider different favorable alternatives for the mission characterisation. From the graphical representation in Figure 2.7, it is noticeable that, when extending the discussion to multiple and differently inclined shell, the association of singularly less convenient cases with other solutions results overall acceptable.
Taking into account a nominal distribution of 4 planes, with 87.9 *degrees* inclination and 36 satellites each, a Configuration 2 with the maximum number of planes hosting 12 units is still a valid option (Combination 7) with respect to most of the other alternatives.

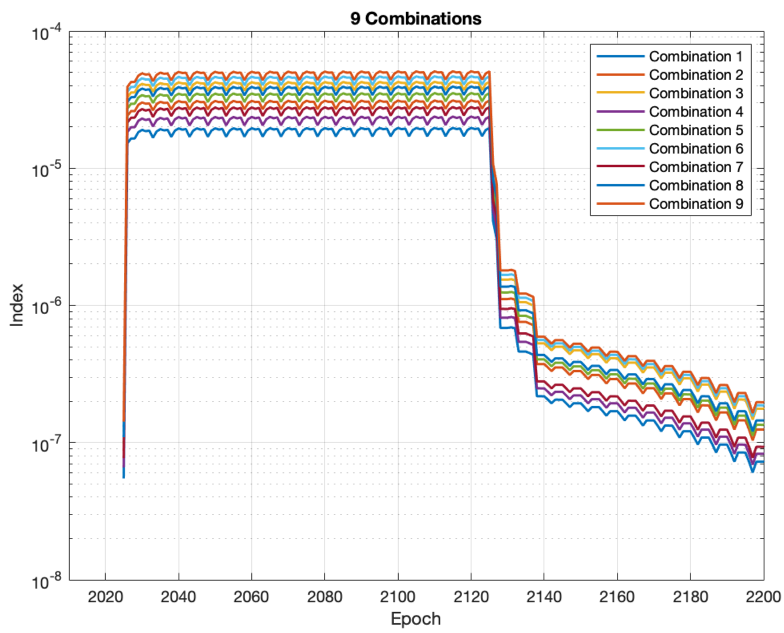

Figure 2.7: Evolution of the Mission Index for the 9 Combinations of Simulations Results of Table 2.5.

Once conclusions from the mission design side are retrieved, iterations on key values of the mass suggest the impact consequences deriving from a more complex structure.
The choice to perform a post-escalation on the satellite characteristics is justified by a logical reflection on the conventional chronological order of the design steps during preliminary planning phases. Usually, depending on the objectives of the mission and the

state of the art of the technologies, the payload and the sub-systems are almost defined in advance with respect to the orbital and distribution parameters discussed before. Anyway, this approach is not mandatory and some posterior adjustments on the mass value might be reasonable from the mission point of view if not procuring excessive negative impacts.

Moreover, with reference to the orbital region selected, there might be additional implications deriving from the specific environment disturbances or coverage requirements that can affect the structure of the spacecraft, leading to succeeding mass variations. These aspects make extremely useful an a-posteriori evaluation of the significance of undesired effects, due to heavier satellites, on the Mission Index. Predictions like these have the power to deviate decisions during design trade-offs.

For these reasons, the next step for the analysis is the evaluation of the mass impacts on the index computation and the power that significantly indirect consequences on the Mission Index might have on design procedures. As Generation 2 of satellites are expected to weight between 150 and 1000 kg, the analysis aims to pursue the evaluation considering spanning values of 400 and 700 kg. Moreover, the estimated cross-sectional area varies with respect to the dimensions of the satellites, according to a correcting coefficient.

2.2. The light pollution index

2.2.1. The context

As already stressed during the discussion, the exponential increase in satellite deployments leads to the imperative of preserving the space environment [51]. Light pollution, stemming from the proliferation of satellites and their illumination, can significantly impact astronomical observations and the celestial environment. The consequences of the reflective phenomena has to be investigated in the Space Sustainability Rating (SSR), so that insights on the responsible strategies for satellite deployment can be addressed to the preservation of the celestial sky.

In the satellite constellations domain, complex configurations such as OneWeb, represent advanced and sophisticated instruments for the connection, navigation and telecommunications services they provide. These multi-units systems are nowadays supplied with new technologies and deployed in orbit to achieve specific mission goals. Their functioning requires hundreds or thousands of mini-satellites orbiting around the Earth, generally in Low Earth Orbits.

It has been noticed that, under certain conditions, these artificial objects result to be visible even to the naked eye. The phenomenon of light pollution deriving from their presence might threatens scientific studies and the researching activities of the astronomical community. In fact, the trace left by satellites result clear and recognisable in measurements, obtaining damaged and deteriorated images [23]. In this regard, it is indispensable to ensure that operations carried by a high number of satellites could provide their services, without significantly affecting the astronomical observations and the sky pureness.

Moreover, the management of the ever-growing population of satellites and the mitigation of the risks associated with space debris, demand innovative solutions. Among the possibilities, the accurate estimation of satellite brightness is a fundamental parameter that underpins collision avoidance, tracking, and overall space sustainability.

The objective of this section is to propose the introduction of a indicator in the SSR Mission Index, related to the level of light pollution footprint due to the implementation of a large constellation in low orbits. A set of figures of merit are presented as aspirant variables on which the rating should be based.
The reflection rises from the analysis of how the constellation features and distribution strategy affects the number of visible objects in a telescopes Field of View (FOV), taking as reference a deep comparison between OneWeb and Starlink constellations. A convention

for threshold magnitude level, based on the altitude of the satellites orbit is proposed and matched with the products of the simulations of satellite Brightness. The model proposed by Gerardo Littoriano [37] is developed and refined in order to precisely predict the apparent magnitudes of satellites and quantify their impact on the sky perception.

This part pursues the objective to take part in the holistic approach to space sustainability assessment, transcending the conventional boundaries of satellite functionality and directly addressing their ecological footprint in the celestial expanse. The module or component, designed to assess light pollution, acts as a critical parameter, enabling mission planners and space agencies to take preventing measures to limit the consequences of their irresponsible endeavors.

2.2.2. The threshold magnitude

In the Astronomy community, there exist few proposals of recommended brightness threshold values for constellation satellites. The brightness emitted by the ensemble of the members of a multi-satellites configuration represents a key indicator when evaluating its contribution on light pollution. In order to preserve the visual appearance of the night sky and limit adverse effects on ground-based observations, the consensus of the astronomical community is to keep any object fainter than the 7^{th} visual magnitude [15]. The methodology adopted by the current analysis, is the limit definition suggested in the SatCon-1 Workshop Report [15]. According to the reference, constellation satellites belonging to LEO should not overcome a threshold visual magnitude which depends on their orbital altitude h. The definition of satellites apparent magnitude implies that the lower the value the brighter the object. From this consideration and the awareness that lower units are more prone to represent a bias for the measurements, the limit scale is arranged and contextualised with respect to LEO maximum altitude $h_0 = 2000\ km$ (2.7).

$$M_t(h) = 7.0 + 2.5 \cdot log_{10}\left(\frac{h_0}{h}\right) \tag{2.7}$$

The recommended brightness limits are computed for a selection of currently orbiting constellation satellites in Table 2.6.
Comparisons between mission observations and threshold values are not enough as these measure of recommended is an indicative reference and other contributors influencing the level of light pollution due to a constellation have to be taken into account. Satellites distributions configurations and the spanning between planes and spacecrafts are strictly related to the number of visible satellites above ground-based observers.

Constellation	Number	Altitude $[km]$	Threshold Magnitude
SpaceX Starlink 340	7518	340	8.9239
SpaceX Starlink 550	1600	550	8.4017
SpaceX Starlink 1150	2800	1150	7.6008
OneWeb	648	1200	7.5546
Amazon 590	784	590	8.3254
Amazon 610	1296	610	8.2893
Amazon 630	1156	630	8.2542
Sat Revolution	1024	350	8.8924
China CASC	320	1100	7.6491
China LuckyStar	156	1000	7.7526
China Commsat	800	600	8.3072
China Xinwei	32	600	8.3072
India AstroTech	600	1400	7.3873
Boing	2956	1030	7.7205
LeoSat	108	1423	7.3696
Samsung	4700	2000	7
Yaliny	135	600	8.3072
Telesat LEO	117	1000	7.7526
Iridium	66	780	8.0223

Table 2.6: Constellation characteristics and recommended brightness magnitude values.

In addition, the point of view of the analysis is still prior to effective operation, pursuing a pre-evaluation tool. In this sense a method based on post-launch measurements is not effective.

By accounting for the constellation characteristics, it is possible to build a composite light pollution indicator that consider the configuration features and the estimated values of apparent magnitude before deployment. Predictions on the amount of brightness emitted define if the constellation is prone to overcome the limits imposed by astronomic community and verify the alignment to guidelines.

2.2.3. An overview on constellations

The constellations reported in Table 2.6 compose a list of multi-satellites mission architectures, based operator websites and official documents submitted to the Federal Communications Commission (FCC) [22]. It portrays a representative sample of a variety of configurations characterised by a large number of satellites, rather than an exact illustration of the operative or close to be launched objects. The population is a valid reference of measurements for the scaling of the study results.

For simplification reasons, each constellation is assumed to have the satellites uniformly distributed in circular orbits, with the same altitude and the same inclination. The units are grouped in a series of orbital planes whose nodes cover uniformly the line of the equator. The inclinations of the constellations of interest range from 42 to 80 *degrees*.

In the first steps the analysis facilitates the computations by modeling the satellites distribution as uniform over the Earth surface. However, it is intuitive to suppose that low inclination constellation distributions causes a shortage of satellites in the polar regions and an increase of units at latitudes close to the inclination of the constellation. This factor will be taken into account in the next part of the study (Section 2.2.4).
The preliminary neglection of this phenomenon leads to an overestimation of the number of satellites above the equatorial and low-latitude regions, and a consequent underestimation at latitudes close to the orbital inclination. Since the majority of the large professional telescopes are located at low latitudes, the results are conservative in terms of evaluation of the impact, so the simplification is initially accepted.

The first step consists in the computation of the number of satellites above the horizon of a general observatory, so at a distance of $z = 90$ *degrees* from the Zenith. For this analysis also the limit elevation of $z = 60$ *degrees* is considered as it corresponds to the upper values of FOV of most of the astronomical observations performed. The results reflect what are denoted as satellites in range, so the objects present over an observatory, independently of their illumination.
The condition of visibility of a satellite above the horizon can be expressed in terms of the orbital position angle γ, as $\gamma < \gamma_0$ (Eq. 2.8). R_{Earth} is the radius of the Earth, h is the altitude of the satellite above the Earth. The value of γ_0 can be computed for each constellation of Table 2.6. The computation passages include the estimation of the spherical cap area above the angular distance z. Then, the number of satellites expected in the focus is derived as the ratio of the cap area to the area of the sphere. The equations are reported in B.1, leading to Eq. 2.9.

$$\gamma_0 = arcos\left(\frac{R_{Earth}}{R_{Earth} + h}\right) \tag{2.8}$$

$$N = \frac{N_{cons}}{2}\left(1 - cos\left(z - arcsin\left(\frac{R_{Earth}}{R_{Earth} + h} sinz\right)\right)\right) \tag{2.9}$$

The graphical representation returns the number of constellations satellites in range over the observatory, depending on the elevation (Fig. 2.8), defined as $90 - z$ *degrees*, with z angular distance from Zenith.
To account for any arbitrary constellation altitude, the fraction of objects in range with respect to the whole constellation units, is shown in Figure 2.9. From the plot, it is possible to notice that the percentages in range goes from 2 to 12 , with a significant drop at 15 *degrees*, reaching $0.5 - 3$ at 30 *degrees*, spanning $250 - 2000$ *km* altitudes.

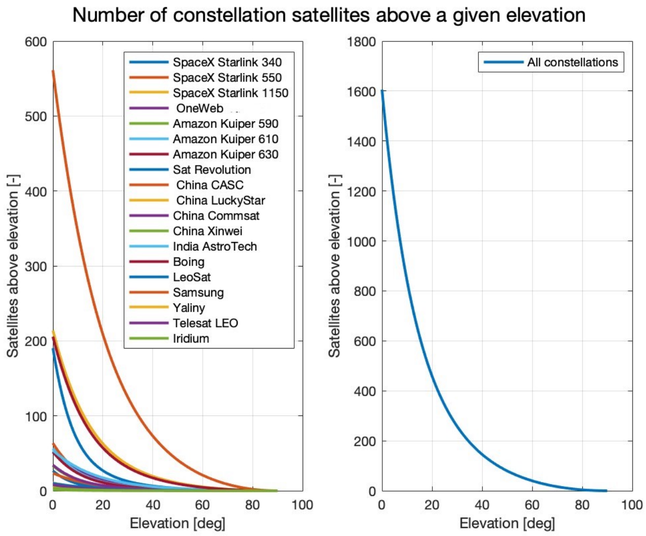

Figure 2.8: Number of satellites of the constellation above a given elevation.

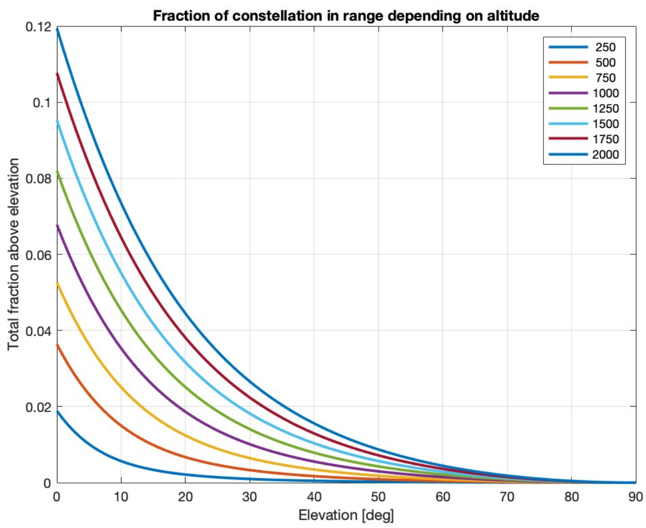

Figure 2.9: Fraction of constellation in range depending on Elevation and Altitude.

It is important to take in mind that satellites are visible because of the reflected sunlight. Therefore, in order to result observable, a satellite must be both in range and illuminated by the Sun. The fraction of visible satellites that are illuminated by the star varies with its position with respect to the local horizon. When the Sun is above or on the local horizon, all the satellites in the range are illuminated. The trend of fraction of irradiated satellites can be defined as in Eq. 2.10, and it is expected to decrease as the light source passes beyond the horizon, until reaching the zero value. The decrement is approximated as a linear drop with respect to the Sun's elevation above the horizon a_{sun}. The model exposed in [22] is demonstrated to be valid in LEO domain, following the linear relationship reported in Eq. 2.11.

$$f_{illuminated} = \frac{A_{illuminated}}{A_{tot}} \tag{2.10}$$

$$\begin{cases} f_{illuminated} = 1 \qquad if \quad a_{sun} \geq 0 & (2.11a) \\ f_{illuminated} = 1 - \dfrac{a_{sun}}{a(z_{max})} \quad if \quad 0 \geq a_{sun} \geq a(z_{max}) & (2.11b) \\ f_{illuminated} = 0 \qquad if \quad a_{sun} \leq a(z_{max}) & (2.11c) \end{cases}$$

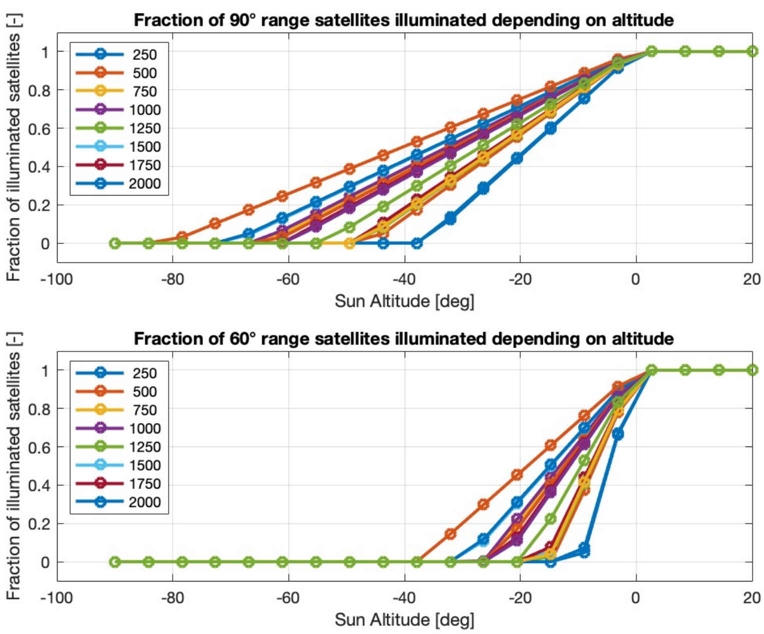

Figure 2.10: Fraction of the satellites in range and illuminated by the Sun as a function of the Sun's elevation above the horizon, considering different altitudes.

In the Figure 2.10, it is possible to evaluate the percentage of illuminated units, depending on their altitude value, as the Sun elevation varies. Respecting the expectations, as the cone of analysis reduces from $z = 90$ to $z = 60$ *degrees*, the minimum Sun elevation required by the satellites to be illuminated increases. Fig. 2.11 refers to the number of units in logarithmic scale. It is useful to recall that, for the preliminary consideration of uniform distributions, the results can be generalised to any observatory while the linear approximation introduced in Eq. 2.11 restricts the validity to satellites in low orbits.

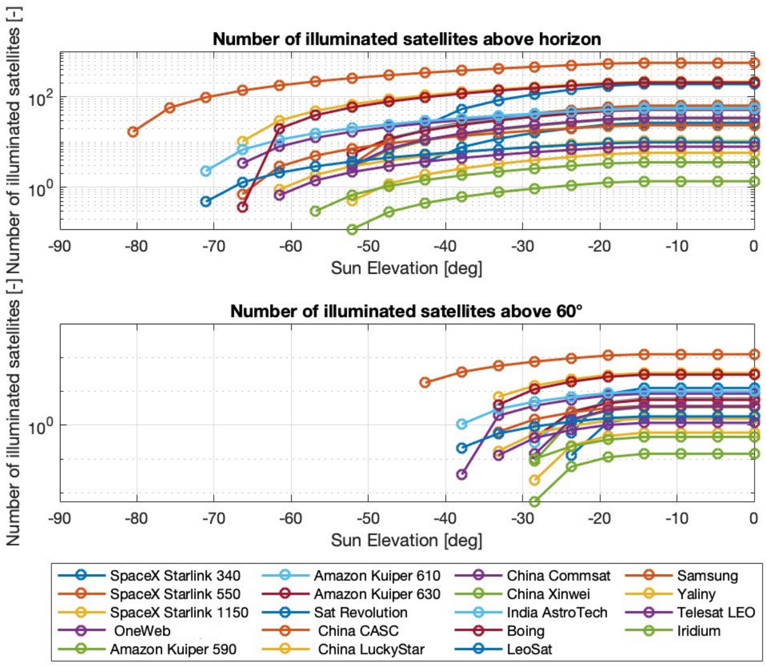

Figure 2.11: Number of satellites in range above the horizon or above zenithal distance $z = 60$ *degrees* illuminated by the Sun, as a function of the Sun's elevation.

2.2.4. OneWeb vs Starlink

In this section, the dependencies on the latitude of the observer location to the satellites distributions are introduced, in order to understand the local effects due to the presence of the constellation is assessed.

The analysis is restricted to Starlink and OneWeb constellations. The comparison takes into account a set of three orbital regions, which correspond to 340 and 550 *km* Starlink shells and OneWeb Gen1 (Tab. 2.6, second, third and fifth rows). The constellation selection is justified by the relevant differences they present in the value of altitude, in the number of configuration units deployed and, equally important, in the planes inclination.

Starlink satellites lean towards $i_{SL} = 53\ degrees$, while OneWeb satellites respect $i_{OW} = 87.9\ degrees$ of inclination.

It seems intuitive that satellites, belonging to low inclination orbits, tend to spend different times in space regions above the Earth, as their latitude varies. On the other hand, when planes are close to a polar inclination, the spacecrafts distribution results more uniform. This phenomenon is confirmed by Figure 2.12, where the function of the density of satellites on their orbital sphere is depicted with respect to the latitude lat (Eq. 2.12).

$$\begin{aligned} density_{SL}(lat) &= \frac{1}{\pi}\frac{cos(lat)}{\sqrt{sin^2(i_{SL}) - sin^2(lat)}}; \quad with - i_{SL} \leq lat \leq i_{SL} \\ density_{OW}(lat) &= \frac{1}{\pi}\frac{cos(lat)}{\sqrt{sin^2(i_{OW}) - sin^2(lat)}}; \quad with - i_{OW} \leq lat \leq i_{OW} \end{aligned} \tag{2.12}$$

Taking as reference location the 9-channel Mini-MegaTORTORA (MMT-9) observatory latitude [27], which provides the measurements of satellites magnitudes for the analysis, its value is around 43 $degrees$ and the difference in density is not negligible.
The latitude at which observations are made affects the time spent over the telescope, so the number of satellites in the FOV and consequentially the amount of disturbances induced.

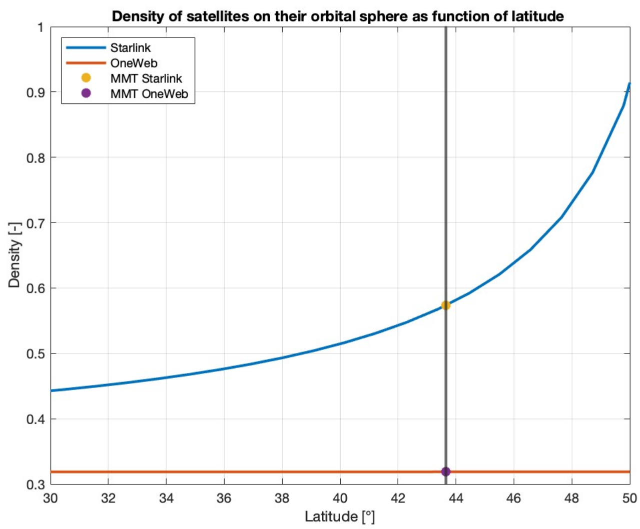

Figure 2.12: Density of Starlink and OneWeb satellites on their orbital sphere as a function of latitude.

For observatories located between -30 and 30 $degrees$, the inclination influence is less impactful and the density factor can be omitted in the computation. It is confirmed by the short distance between the curves in Fig. 2.12.

All the steps reported in the previous section are performed, taking as reference a telescope FOV of 30 *degrees*, as the average between the maximum range and the common sensitivity of the tool [27]. This assumption leads to the visibility considerations in Table 2.7.
The introduction of the density function is enclosed in the computation of the number of visible satellites by a multiplier $CF = \frac{density_j}{density_{90}}$, with $j = SL, OW$, respectively for Starlink and OneWeb, and referred to the uniform case of polar orbit. The resulting fractions and number of visible units are reported in Figures 2.13 and 2.14.

Constellation	**Horizon visibility** γ_0 $[deg]$	**FOV visibility** γ $[deg]$
SpaceX Starlink 340	-18.31	-3.32
SpaceX Starlink 550	-22.99	-5.19
OneWeb	-32.69	-10.23

Table 2.7: Constellation conditions of visibility above horizon, $z = 90$ *degrees* and in the FOV range $z = 30$ *degrees*.

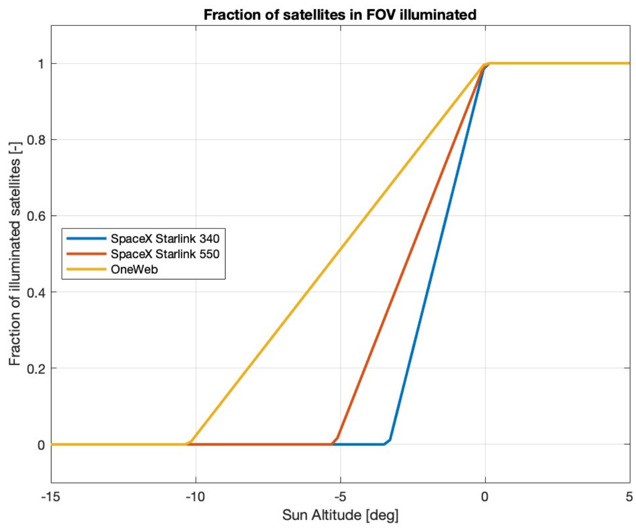

Figure 2.13: Fraction of OneWeb and Starlink satellites in FOV range and illuminated by the Sun as a function of the Sun's elevation.

The objective of the analysis is to supply a numerical indicator which measures the impact of the presence of these light-reflecting units in the sky. In order to discard the Sun altitude variation, it is possible to perform the evaluation in a unit time of one day, by the integration of the curves in Figure 2.14.

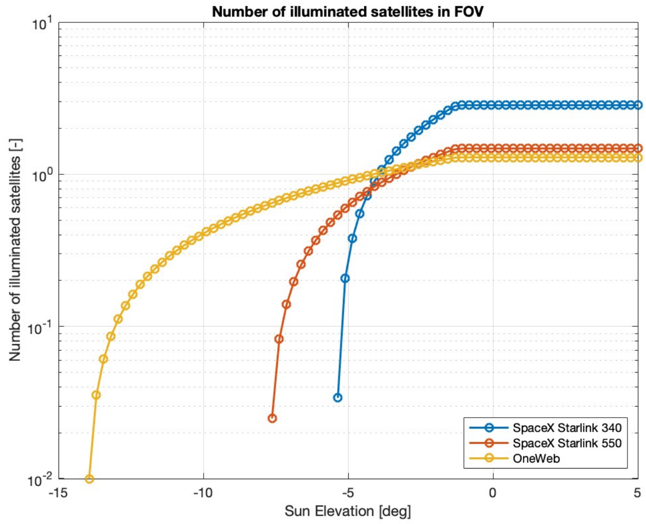

Figure 2.14: Number of OneWeb and Starlink satellites in FOV illuminated by the Sun, as a function of the Sun's elevation.

As daily measurements of the satellites magnitudes are provided in [40], it is reasonable to have also an hint of the number of observations output above the recommended magnitude threshold suggested by the astronomy community (Section2.2.2). The information dated back on the 11^{th} July of this year are considered. By iterating on the values of the standard magnitudes and comparing with the results of Tab. 2.6, the fractions of Brighter-Than-Recommended (BTR) spacecrafts are retrieved.
In Table 2.8, the daily fraction of illuminated satellites, coming from the integration, are divided by 100 for comparison reasons. The partial contribution of both the Starlink shells are summed up to return an overall measure of the constellation impact. The total score voice summarises the fractions into a numerical Index, considering them equally without the application of ad-hoc weights.

Constellation	**Illuminated fraction**	**BTR fraction**	**Total Score**
SpaceX Starlink	0.3771	0.9195	1.2966
OneWeb	0.1634	0.6410	0.8044

Table 2.8: Light Pollution constellation indicators for Starlink and OneWeb.

The first part of the work flow suits a prediction approach. Starting form the mission features, if improvements in the light pollution footprint are desired, it is possible to consider alternative design options. Assuming the inclination value of 53 *degrees* for Gen2 configuration modifies the fraction of illuminated satellites, reaching the considerable value of 0.2939.

However, it is important to recall that the whole discussion is based on the specific position and measurements of MMT observer. The generalisation implies rather the selection of conventional coordinates for reference observations or the evaluation of multiple measurements coming from different sources. For a preliminary study, the Russian astronomical observatory [27] suits the analysis since it is able to capture the inclination effects on the spacecrafts visibility and represents one of the main public sources of satellites apparent magnitude.

Since the Space Sustainability Rating aims to return the impact of a mission before its launch, so that undesirable secondary effects on the environment can be avoided, the latter part of the analysis based on a posteriori observations of operative satellites, is replaced by a priori predictions of magnitudes. In this regard, a valid model of satellite brightness computation gets in the game.

2.2.5. Brightness Model implementation

The last considerations on the Light Pollution Index exploit the results of Littoriano [37]. The reference paper proposes and validates an advanced three-dimensional brightness model for spacecrafts. The validation is enhanced by the comparison to a data-set of observations provided by "GAL Hassin" astronomical observatory, nestled in Isnello, near Palermo [2]. The model magnitude predictions are performed and compared to different measurement campaigns, spanning the years 2020 to 2021.

The construction of an efficient brightness model for spacecraft light emission evaluation represents a crucial concept in space operations. An effective simulation helps in understanding and predicting how space objects reflect, emit, or scatter radiation.
When dealing with constellations, spacecrafts might appear as tiny points of light in the sky. Comprehending their brightness allows ground-based and space-based tracking systems to locate and track the spacecrafts accurately. This is vital for mission control, tracking and navigation. Moreover it can facilitate the determination of the amount of power needed for communication signals and the influence of distance, antenna size, and orientation factors in connection. In congested regions of space, such as LEO, an accurate knowledge of satellites brightness is crucial for collision avoidance and space debris identification and monitoring. Finally, scientific missions based on remote sensing and observation instruments, need to be capable of understanding and predicting light emissions from space objects so that astronomers and scientists can identify any interference with data form observations.

As predictable by any attempt of conversion from real world to models, some deviations and peaks are noticeable. The main objective of this section is to quantitatively evaluate the deviations between brightness estimations and observatory measurements, taking as reference a sample with different characteristics from the "GAL Hassin" one, in order to further validate the simulation tool. The results deriving from the adaption of the model and a new set of data are compared and discussed.
The correct functioning of the predictions permits to explicitly incorporate the magnitude threshold indicator in the environmental index calculation, in advance with respect to the constellation deployment and the consequent observations. This approach represent a further attempt to pursue the general goal of space sustainability, exploring the consequences of light pollution on SSR rating system.

The observations

The measures and the observations of reference are retrieved from a database of measurements made by a 9-channel Mini-MegaTORTORA (MMT-9) wide-field monitoring system with high temporal resolution, belonging to Kazan Federal University [27]. It is located in Russia at 43.64972 *degrees* latitude and 41.43139 *degrees* longitude. The Field of View of the instrument in estimated from the features of the telescope. The value assumed is 30 *degrees*, which is the average between the maximum range and the sensitivity of the tool.
In order to further validate the model and refer the output to the same observer location of the previous sections, a set of observations carried out on the 11^{th} July of 2023 are selected [40]. The analysis sample is composed by four OneWeb satellites, each one characterised by eight measures of magnitude. As noticeable from the Table 2.9, the available data for the objects are very close in time, representing a first difference from the information provided by "GAL Hassin" astronomical observatory. Secondly, the sheets report information of the phase angle rather than on the elevation of the satellites, imposing a different strategy for the checks on orbital mechanics.

The adaptation of the model

The main features of the Brightness Model exposed in [37] are reported in Appendix B.
The OneWeb spacecraft physical model introduced is maintained and adapted for a new set of computations. According to the assumptions, the satellite is approximated to a six-face prism, provided with solar arrays and antennae, considered as 2D-planes. The reflectance values are taken as $\rho_j = 0.3$, $j = 1, ...6$ for the main body panels, $\rho_{SA} = 0.01$ and $\rho_{Ant} = 0.65$, for the appendices.

Satellite	**UTC**	**Phase** $[deg]$	**Magnitude**
ONEWEB-0218	23:58:23.597000	66.914	8.617
	23:58:27.397000	65.902	8.120
	23:58:30.297000	65.127	8.250
	23:58:32.797000	64.458	8.450
	23:58:35.697000	63.680	8.550
	23:58:37.397000	63.223	8.510
	23:58:39.797000	62.578	8.051
	23:58:42.797000	61.770	8.588
ONEWEB-0203	23:55:19.497000	68.320	8.550
	23:55:21.696000	67.724	8.550
	23:55:23.397000	67.263	9.029
	23:55:24.797000	66.882	8.560
	23:55:27.297000	66.202	8.749
	23:55:29.397000	65.629	8.000
	23:55:30.897000	65.219	8.900
	23:55:30.897000	65.219	8.900
ONEWEB-0220	23:52:12.696000	70.112	8.540
	23:52:13.597000	69.865	8.433
	23:52:15.496000	69.343	8.171
	23:52:16.796000	68.984	8.600
	23:52:17.296000	68.846	8.628
	23:52:18.596000	68.488	8.190
	23:52:20.296000	68.017	8.560
	23:52:23.298000	67.185	8.571
ONEWEB-0181	23:49:09.497000	71.262	8.043
	23:49:24.197000	67.129	8.341
	23:49:25.197000	66.846	8.310
	23:49:26.597000	66.448	8.180
	23:49:27.997000	66.051	8.204
	23:49:29.197000	65.709	8.497
	23:49:30.997000	65.197	8.358
	23:49:33.197000	64.570	8.284

Table 2.9: Observations data from campaign of 11^{th} July 2023 [40]

The dimensions are approximated to a 1x1x1 m solid, provided by 2x1.5 m solar panels and an antenna of 0.15 m radius.

As already mentioned, the observer is located at $lat_M = 43.64972$ *degrees* latitude and $lon_M = 41.43139$ *degrees* longitude and the observation sample composed by four spacecrafts, measured eight times in a time span of 1 *minute*.
The Two-Lines Elements (TLE) information associated to the satellites of interest are retrieved from *CelestTrack database* [1]. As it can be noticed from the data shown in

Table 2.10, the orbital parameters are collected from the day after the measurements, the 12^{th} July 2023. The latter is taken as starting time for simulations, implying a backward propagation of the initial Keplerian elements. The reason is due to the proximity to the observations hour and a higher compliance to the constellation nominal inclination.

Satellite	TLE
ONEWEB-0218	1 48214U 21031E 23193.57944428 -.00000162 00000+0 -47026-3 0 9999 2 48214 87.9047 142.7622 0001445 118.8233 241.3042 13.145008191 07725
ONEWEB-0203	1 48235U 21031AB 23193.57733729 -.00000917 00000+0 -25076-2 0 9990 2 48235 87.9049 142.7790 0001823 72.4654 287.6675 13.145049751 07629
ONEWEB-0220	1 48232U 21031Y 23193.57521011 -.00000263 00000+0 -74272-3 0 9993 2 48232 87.9055 142.7935 0002345 89.6106 270.5292 13.145011271 07752
ONEWEB-0181	1 48230U 21031W 23193.57309153 -.00000161 00000+0 -46793-3 0 9996 2 48230 87.9052 142.8282 0001975 85.8257 274.3099 13.144998821 07599

Table 2.10: TLE of 12^{th} July 2023 [1]

For each object belonging to the sample, the passages reported in Appendix B are executed so that the magnitudes deriving by the application of the model are collected. The orbital mechanical reference noted by the observatory sheets is the phase angle (Eq. 2.13).

$$\lambda = acos(-\frac{\vec{r_o} \cdot \hat{n_s}}{\|\vec{r_o}\|}) \tag{2.13}$$

It measures the angular distance between the Sun, the satellite and the observer. In order to verify the consistency of the observations, the quantity is retrieved from the vectors obtained from the propagation to be compared with the ones reported by the observatory. To recall, $\hat{n_s} = \frac{\vec{r_{SC,Sun}}}{\|\vec{r_{SC,Sun}}\|}$ is the versor referred to the position vector of the spacecraft from the Sun, while $\vec{r_o}$ is the relative position vector of the satellite with respect to the observation position (Appendix B).

In this updated version, the computation of the magnitude is refined by the inclusion of the effects due to the atmospheric extinction. The phenomenon consists of the loss of starlight in passing through the Earth's atmosphere. The cause is due mainly to the light scattering caused by molecules of nitrogen and oxygen. The amount of atmospheric extinction can be assumed proportional to the air-mass, so the measure of the amount of air along the line of sight when observing a star or other celestial source from below Earth's atmosphere [21]. The most recent model of atmospheric extinction factor is proposed by Pickering in [44] and defined by Equation 2.14.

$$X = \frac{1}{sin(\lambda) + \frac{244}{165+47\lambda^{1.1}}} \tag{2.14}$$

The correction is applied as additional contribution to the computation of the total apparent magnitude of the satellite.

Validation results

The satellite phase angle, as already mentioned, is exploited to understand the consistency of the analysis from the orbital mechanics point of view. Indeed, by comparing the angular distance derived from the integration vectors and the observed one, the quality of the orbital model is assessed. In Fig. 2.15 it is possible to appreciate that the satellite evolution is coherent in trend with the observations, even if the modelled angles, represented by circles, do not perfectly match the observation results, signed with crosses.

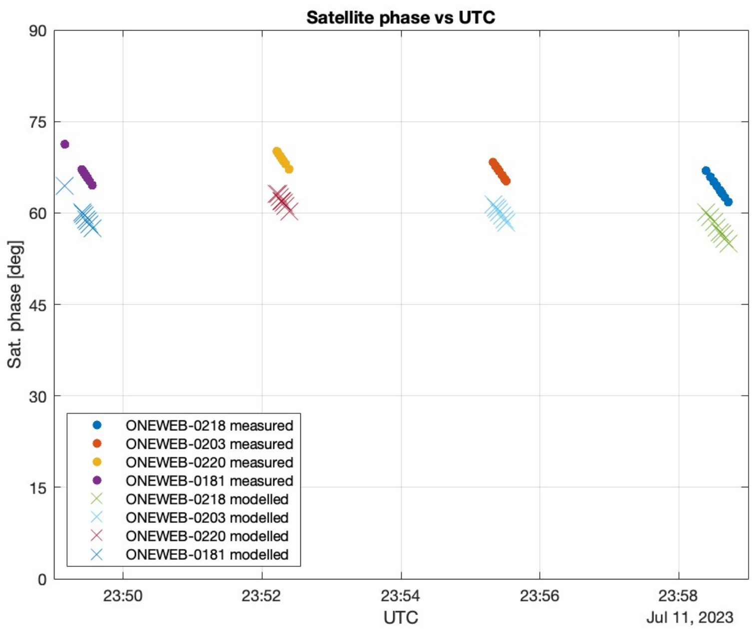

Figure 2.15: Representation of the values of phase angle λ for measurements and model estimations.

The divergence, which results constant and equal to 6 *degrees* might be the caused by the orbital model selected, which results not sufficiently precise for the set of TLE available. Moreover, the use of Keplerian elements closer to the time of measurement would improve the coherence of the results with respect to the observatory. The inaccuracy is not negligible but it does not compromise the validity of the magnitude simulation, as the output belongs to the observations ranges. In order to increase the accuracy of the phase angles checks, the integration can adopt a faster time-step, getting closer to the value of time reported in the TLE. Anyway, for the support of the analysis, the increase in the computational time is excessive for global qualitative considerations on the tool.

Looking at the computed magnitudes in Figure 2.16, the model with the addition of atmospheric effects, results one more time a valid simulation of the mean brightness value of an object. The validation approach carried out by Littoriano [37] addresses a time-distributed sample of measurements, for a higher number of objects, composed by few and more spanned observations.
The situation here reflects multiple and time-close data, allowing to extend the validity of the model even to measurements of the same object in a short period of time, of the order of 1 *minute*. This capability is useful considering that, brightness values coming from the observatory, which are represented as dots (Fig. 2.16), even if spanned by seconds, cover a relatively wide range of values. *ONEWEB-0203* presents the highest difference between the maximum value and the lowest one, separated by 1 point magnitude.

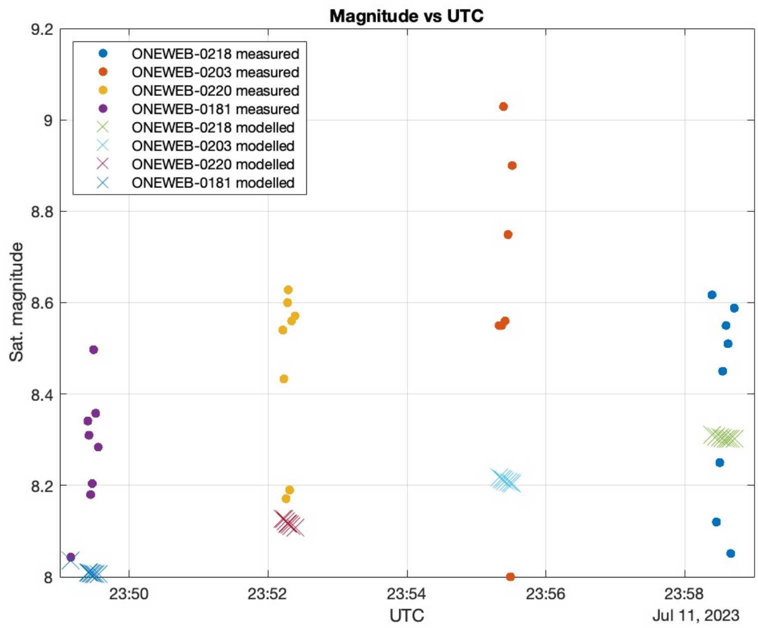

Figure 2.16: Representation of apparent magnitude values for measurements and model estimations.

The success of the validation is also supported by the computation of the statistical quantities of the outputs distribution. The differences between MMT observations and the modeled magnitudes present a mean value of the of $\mu = 0.3322$ and a standard deviation of $\sigma = 0.1895$.

It is possible to appreciate that the simulation confirms the alignment of OneWeb satellites belonging to the sample of the analysis to the guidelines suggested by astronomical community, resulting fainter that the threshold magnitude value related to 1200 km altitude of 7.5546.

The tool can be exploited to predict the brightness behavior of satellites before their full-deployment, avoiding configurations which would lead to an excessive amount of disturbances in the sky environment. By inserting the tool with a realistic and good TLE set of elements, it is possible to have an idea of the quantity of light emitted by the configuration and prevent any unwanted consequence.

2.2.6. The construction of the Constellation Brightness Predictor

The already required input for the Mission Index evaluation comprehends the set of information useful for the estimation of a valuable Light Pollution Index. The definition on the overall configuration features and the specific satellites properties are fundamental data in the computation.
The results coming from the analysis suggest the introduction of an additional algorithm to the module, to stand for the brightness related sustainability criteria for the evaluation of large constellations. The inclusion of this aspect returns a more complete overview of the environmental impact of a multi-satellite mission, whose deployment effects interest a wide variety of fields.

The availability of an instrument capable of predicting the amount of light that objects are going to emit, allows the operator and the space community to get a clue of these quantities. Regarding the evolving of new guidelines associated to the protection of the skies, the same tool stands for a warning signal in case of the overcoming of shared thresholds.

The validation of the upgraded model carried out in the study represents a good starting point for the construction of an advanced tool. The diffusion and the further use of the implement promises the requirements and the level of qualification to become a reference for the definition of light configurations and light mitigation measures for the Space community. It is reasonable to model a Light Pollution Index which refers to the results coming from the Constellation Brightness Predictor (CBP) tool, based on the estimation of the apparent magnitude of a sample of illuminated satellites.

The simulation is thought to base on the assumption of a dummy observatory, whose local and technical features are chosen according to critical and conservative approaches. The reference values of observatory latitude, longitude and Field of View are set in order to capture the influence of the inclination and of the co-presence of unites in the sky.
From the comparison between OneWeb constellation and Starlink, it is stated that the position of the observer affects significantly the fraction of illuminated satellites in the space above the observatory location. Applying the density factor permits to margin the high inclination constellations, and accurately considers dis-homogeneous distributions of satellites. As already argued, the observatory characteristics of the Russian telescope adopted for the analysis plus its unique public source of data, makes the candidate a valid option to represent an efficient guide for the generalization.
The comparison with respect to the limit suggested by Astronomical community is allowed when the propagation of a reliable TLE of the satellites orbital parameters is possible to determine their orientations in space. The mapping of the apparent magnitude values during one day indicates the alignment with respect of the light emission guidelines.

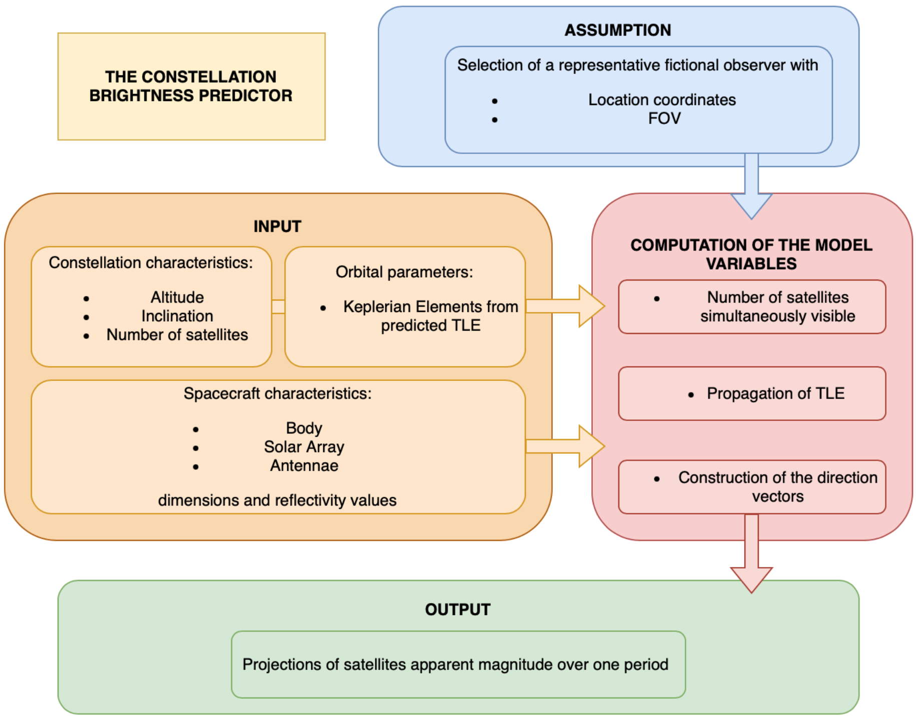

Figure 2.17: Building blocks for the construction of the Constellation Brightness Predictor.

A first attempt to collect all the logical steps behind the evaluation of the brightness of a future constellation mission is reported in Figure 2.17. As already discussed, the structure origins from the establishment of a conventional observer, whose location and technical features are sensible to the influence of the constellation inclination in its distribution behavior. The information required to the operator are the generic characteristics of the configuration, the specific properties of the spacecrafts and an orbital motion reference. From the available data it is possible to describe the coverage provided by the units over the Earth, propagate the satellites orbits according to their spacial density and retrieve all the vectorial quantities necessary to compute the apparent magnitude.

The methodology is applied to estimate the brightness behavior of the next Generation of OneWeb satellites. The simulation performed takes into account the usual physical features of the original spacecrafts (Tab. 2.3) and the observations source context already presented during the analysis [27].
The case tested is the most crowded combination of 55 *degrees* configuration, corresponding to Simulation 9 in Table 2.1. It refers to 24 planes, characterised by 72 satellites each, with a total of 1728 units. This restricted set of preliminary information allows to compute the maximum number of simultaneously illuminated satellites in range n_{ill}, which indicates also the number of orbital propagations to perform.
The Keplerian elements of reference for the motion definition are constructed to return a basic path on which the positions related to the other sample objects are scaled. Discarding the nominal values of inclination and eccentricity, the number of revolution k is set to 13.1245 in order to return a semi-major axis of 7578 km. The initial angular coordinates are conventionally set as zeros for the first integration.
The Right Ascension of the Ascending Node (RAAN) Ω and the Mean Anomaly M are then updated to modify the initial state for the orbital propagation according to the spacial distribution of the satellites. The Right Ascension of the Ascending Node follows a spanning dictated by the number of planes N_{planes}. The Mean Anomalies definition depends on the number of satellites per plane N_{sats} (Eq. 2.15). The starting epoch is chosen as the midnight of the 1^{st} January of 2025.

$$\begin{aligned} \Omega_{j+1} &= \Omega_j + \frac{180}{N_{planes}} \quad j = 1, .., n_{ill} \\ M_{j+1} &= M_j + \frac{360}{N_{sats}} \quad j = 1, .., n_{ill} \end{aligned} \tag{2.15}$$

The computational steps follow the passages exposed in Section 2.2.5, with the improvements and modifications introduced by the adaption of the model.

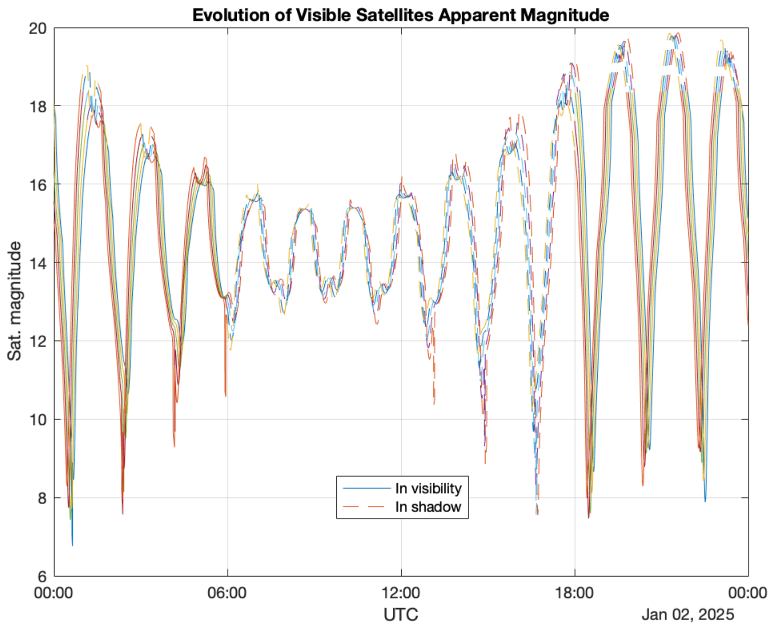

Figure 2.18: Evaluation of the apparent magnitude curves of $n_{ill} = 5$ OneWeb Gen2 satellites during the 1^{st} January 2025.

In Figure 2.18 it is possible to observe the amount of light emission referring to the representative sample of OneWeb Gen2 satellites in one day. The curves classify between the intervals in which the satellites are visible and the phases in which they are in shadow. This property depends on the position of the sun with respect to the observation point horizon, as discussed in Section 2.2.3.
From this graphical representation it is possible to obtain the range of values that a constellation brightness might assume. It is worth to recall the strong predisposition the strategy has to be generalised, standing for a useful tool to be exploited for reliable prediction measurements. As it is constructed, some conclusions on the effects of the spacecraft dimensions and the constellation characteristics can be already estimated and discussed in advance.

Possible improvements interest the extension of the computation to a variety of satellites structures, without limiting the analysis to the conventional shape of main body plus appendices assumed for OneWeb satellites. Moreover the kind of shell configuration adopted by the design can be taken into account. The definition of the starting coordinates for the satellites propagation might appear different in case of Walker Star or Walker Delta-type constellations.

2.3. ADR Index

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. In this regard, the evaluation of the benefits and criticalities deriving from their performances is fundamental to be included in the Rating System.

As part of OneWeb commitment to space sustainability and environmental commitment, the company is actively working with governments and industry on the establishment of ADR services. Behind the primary objective of reduction of the amount of space debris in Low Orbit Region, the goal is to minimise the de-orbit cost per satellite. The employment of external satellites for removals under multi-operators agreements seems a promising solution. In collective programs, a plurality of operators, organisations or agencies cooperate to concentrate financial and technological efforts and design a common facility. The initiatives are enforced by means of supportive joint funds, research partnerships, governments' grants and incentives, international agreements and industry consortia.

The main requirement for service providers to answer to the request of collective projects is the multiple objects retrieval capability on a single mission. This strategy implies a significant decrement in the per-satellite removal cost, appealing more attractive to commercial operators. Secondly, the maximisation of the scalability of the ADR vehicle in servicing candidate targets, is a strong condition for the optimisation of the operations. LEO orbits ranges from 400 to 2000 km altitude, and are populated by satellites of different sizes, shapes and mass properties. The opportunity of technology reuse, component modularity, and interface standardisation dramatically reduces the costs and the complexity of the marketplace.

This last awareness leads OneWeb to commit itself in the equipment of the constellation units of mechanical features that facilitate capture and retrieval operation. The satellites are provided of a lightweight, compact and minimally intrusive docking plate, mechanically secured to the main structure. This characteristic makes OneWeb a strong candidate in future removal practices. Furthermore, over the last years, the company has collaborated with Altius Space Machines on advanced grappling techniques for the standardisation of a versatile capture interface for on-orbit servicing [52].

2.3.1. ELSA-M mission

What makes the discussion on Active Debris Removal more interesting is the imminent opportunity for OneWeb to demonstrate the effectiveness of a debris removal technology, set to take place in 2024. The mission is expected to exploit ELSA-M, a service vehicle which offers a real-world test case to better characterise the main ADR concepts, technologies, and strategies.

The redundant approach adopted by the constellation design makes the loss of a single satellite not critical. A failure-tolerant configuration is intended to continue functioning even if individual units experience failures. However, when a satellite of the constellation becomes non-operational, it is still valuable to remove it to maintain optimal performance and reliability and reduce the collision risk associated. Active debris removal allows for the execution of the disposal of such units and their replacement with functioning ones. This ensures that the constellation remains always fully operational.

This is the case of the broadband satellites SL41, which failed after a software issue right at the end of the orbit raise. The unit represents a good opportunity to test the level of performance of ELSA-M, as it presents the main requirements to be a valid target for the removal activity.

The idea was born from the partnership with Astroscale, a debris-removal startup, under European Space Agency (ESA) Sunrise program. The initiative grants a funding of 15 million euros which enables to complete the service vehicle design, up to the satellite pre-integration phase. The majority of OneWeb satellites have magnetic docking plates that are compatible with ELSA-M's capture mechanism. The preliminary mission by Astroscale, ELSA-D, or End-of-Life Services by Astroscale-Demonstration, released and re-captured a tiny LEO satellite with the same methodology, validating its performances in orbit. The success of the operations paves the way for ELSA-M implementation.

ELSA-M service is capable of removing multiple failed satellites in a single mission. It is designed to undertake sequential debris captures and re-entries, expanding the re-usability capability and reducing the cost of the service. Its reliability is built on a heritage pathway from ELSA-D, that ensures safe and robust operations, assuring the safety of the client, with trustful and passively safe trajectories, fail-safe multi-level control authority, passive and active aborts, high-fidelity ground-based simulation and operator training, and a cyber-secure service with authentication and encryption. The spacecraft is prevented by an optimised propulsion unit, with both chemical and electric components so that precise docking maneuvers and efficient orbital transferring can be performed.

ELSA-M is expected to be efficient also in advanced rendez-vous and docking phases, including difficult tumbling capture, which is particularly relevant for failed clients. The operations involve, after its launch, the search and the approach of the client, a fly-around inspection, and the execution of a capturing maneuver to dock with the target. Finally, the chaser bring the client to a low drop-off altitude for uncontrolled re-entry [7].

2.3.2. THEMIS extent to ADR

As already mentioned in the introduction to the SSR, the Mission Index (MI) module is strongly related to the simulations performed by the THEMIS software. The more recent version of the tool successfully achieves the ability to assess the environmental footprint of a multi-satellites mission but still lacks of an ADR option for Post-Mission scenarios. In order to account for this eventuality, the debris index of a mission that makes use of an Active Debris Removal, is estimated as a sum of the contributions of fabricated sub-missions, each one associated to a different scenario for the life of the satellite.

A simple case of ADR implementation is considered, where a service vehicle (SV) is employed to remove a non-operational spacecraft (SC). The input required are:

- M_{SC}, the mass of the target;
- M_{SV}, the mass of the chaser;
- h_{op} and i_{op}, the operational orbital parameters.

The goal of THEMIS remains the assessment of the operator mission impact, adopting the service client point of view. According to Eq. 2.3, the index considers the success rate of the Post-Mission-Disposal with respect to the abandon of the SC at h_{op}, and the consequent natural decay. The SV is planned to be directly launched and inserted at the specific operational altitude, where Rendez-Vous (RV) and Re-Entry (RE) procedures are performed.

The attempt implies that all scenarios are included in the index computation. A Tree Approach analysis is adopted to graphically represents all the possible failures. With reference to the conditions depicted, the negative events that might occur are:

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

The schematic illustration of the chances is reported in Figure 2.19. These scenarios have a probability of happening represented by the Rendez-Vous success rate α_{RV} and the Re-Entry success rate α_{RE}, whose values are significant a-priori assumptions.

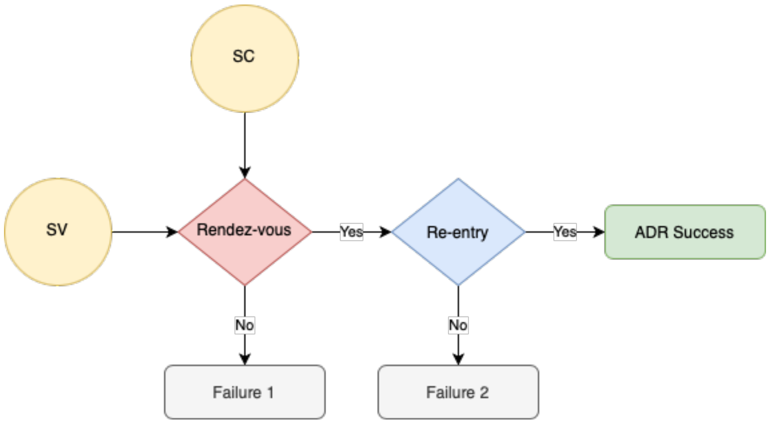

Figure 2.19: The failure tree related to a first attempt of analysis.

From the previous considerations, the expression of the impact on the environment for the mission, considering the ADR service as Post-Mission Disposal (PMD) strategy, takes the form of the sum of four integrals in Equation 2.16.

$$\begin{aligned}
I = &\int_{t_0}^{t_0+\Delta t_{oper}} I(h_{oper}, i_{oper}, M_{SC})dt \\
&+ (1-\alpha_{RV}) \int_{t_0+\Delta t_{oper}}^{t_{f1}} I(h_{oper}, i_{oper}, M_{SC})dt \\
&+ \alpha_{RV}(1-\alpha_{RE}) \int_{t_0+\Delta t_{oper}}^{t_{f2}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt \\
&+ \alpha_{RV}\alpha_{RE} \int_{t_0+\Delta t_{oper}}^{t_{end}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt
\end{aligned} \tag{2.16}$$

To recall, the index is propagated along all the different phases of the mission to properly reflect its impact. According to the discussion already conducted in Section 2.1, the first integer refers to the mission risk indicator from the launch to the end of operations $t_0 + \Delta t_{oper}$. The remaining integers account for the PMD phase and are respectively related to Failure 1, Failure 2 and the success of ADR operations.

The current software input format still does not provide the possibility to insert the key parameters of the ADR to differentiate the cases. As a first approximation of the output, under the suggestion of Equation 2.16, the risk indicator is obtained considering separately the blocks as isolated missions.
The operational part is computed until the Post-Mission phase, taking the same parameters of the original mission simulation. If the Rendez-Vous fails but SV re-enters, the mission satellite is expected to naturally decay. As the service is still operative and independent from the target, it does not represent any additional contribution to the en-

vironmental impact. Also in this case the integer depends on the mass of the spacecraft only. The remaining simulations refer to the failure of both SV and SC and the complete success of the totality of the planned EOL operations respectively. The mass of the external object plays a role in the computation, collected by the mass parameter estimated as the sum of the objects $M = M_{SC} + M_{SV}$.
The Active Debris Removal PMD success rate is $\alpha = \alpha_{RV}\alpha_{RE}$. The probability of failure of the Rendez-Vous phase is $\alpha = (1 - \alpha_{RV})$, whereas criticalities in the Re-Entry phase are $\alpha = \alpha_{RV}(1 - \alpha_{RE})$ likely to occur.

Construction of the input files

Before executing the assembly of the index contributors, some assumptions and considerations are carried on. The computation follows the conventional pattern of Eq. 2.3, assuming for each case a different mass, a specific cross sectional area and a PMD success rate. The simulation need to be characterised by the reliability parameter for Collision Avoidance Maneuvers, assumed as 0.95, and the Trackability index, flagged with the value 0, for all the models (Tab. 2.11).

The operational phase and the Failure 1 simulation are retrieved from the same input file, as they are based on the SC object mass only. α_{RV} is the corresponding PMD index, with 0.9 a valid value. The branch corresponding to the success of the RV, underlined in red in Eq. 2.17, is discarded. This assumption permits to account for the natural decay only. Once the evolution of the index is retrieved, the parts of the profile corresponding to the operational phase and the failure of the Rendez-Vous are determined.

$$\begin{aligned} I_1 = &\int_{t_0}^{t_0+\Delta t_{oper}} I(h_{oper}, i_{oper}, M_{SC})dt \\ &+ (1 - \alpha_{RV}) \int_{t_0+\Delta t_{oper}}^{t_f} I(h_{oper}, i_{oper}, M_{SC})dt \\ &+ \alpha_{RV} \int_{t_0+\Delta t_{oper}}^{t_{end}} I(h_{oper}, i_{oper}, M_{SC})dt \end{aligned} \tag{2.17}$$

The alternative disposal options are simulated neglecting the operational part, and considering a dummy spacecraft that collects the contributions of both the objects. ELSA-M is assumed to have a mass of $M_{SV} = 175\ kg$, and 0.660x0.664x1.100 m dimensions, taking as reference the information available of the predecessor [6]. The lacking addends of Eq. 2.16 can be obtained by building the expressions such that the specific coefficients are obtained.

Simulation 2 permits to return the integer related to Failure 2. Assuming α_{RV} and α_{RE} equal to 0.9, the probability of success of the Post-Mission phase is set as $(1-\alpha_{RV}+\alpha_{RE}\alpha_{RV})=0.91$, such that the natural decay of the SC and SV is simulated (Eq. 2.18). Same considerations for Simulation 3, where the success of Re-Entry phase is generated through the multiplication of the reliability factors (Eq. 2.19).

$$
\begin{aligned}
I_2 = & \int_{t_0}^{t_0+\Delta t_{oper}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt \\
& + \alpha_{RV}(1-\alpha_{RE}) \int_{t_0+\Delta t_{oper}}^{t_f} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt \\
& + (1-\alpha_{RV}+\alpha_{RE}\alpha_{RV}) \int_{t_0+\Delta t_{oper}}^{t_{end}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt
\end{aligned} \tag{2.18}
$$

$$
\begin{aligned}
I_3 = & \int_{t_0}^{t_0+\Delta t_{oper}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt \\
& + (1-\alpha_{RV}\alpha_{RE}) \int_{t_0+\Delta t_{oper}}^{t_f} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt \\
& + \alpha_{RE}\alpha_{RV} \int_{t_0+\Delta t_{oper}}^{t_{end}} I(h_{oper}, i_{oper}, M_{SC}, M_{SV})dt
\end{aligned} \tag{2.19}
$$

The key parameters characterising the simulation are collected in Table 2.11. Once the input files corresponding to the profiles of the missions described are created, the index value along all the phases can be computed, discarding the ramifications which do not belong to the mission design.

Input Data	**Sim. 1**	**Sim. 2**	**Sim. 3**
Mass $[kg]$	150	325	325
Cross sectional area $[m^2]$	2.5404	3.216	3.216
CAM Parameter [-]	0.95	0.95	0.95
Trackability [-]	0	0	0
PMD Reliability Index [-]	0.9	0.91	0.81

Table 2.11: Physical and Operational Input for OneWeb ADR THEMIS simulations.

Simulations results

The methodology modelled leads to the construction of multiple input files, each one thought to return at least one of the index profiles composing Eq. 2.16.
The main difference from the conventional implementation of the software is the presence of an additional branch from the date of disposal to represent the ADR strategy.

The extra component is the consequence of the existence of one more possible scenario for the evolution of the operations, which is reflected by an addend to the original expression 2.3. Since more than one actor participates to the Removal and Re-Entry phases, the mission profile results more complex if accounting for all the eventualities.

The comparison between the successful execution of the Post-Mission Disposal selected and the alternative natural decay is not obvious. It is reasonable to doubt the efficiency of the Active Removal if the consequences due to the malfunctioning of the capture system are not proportional to the benefits deriving.

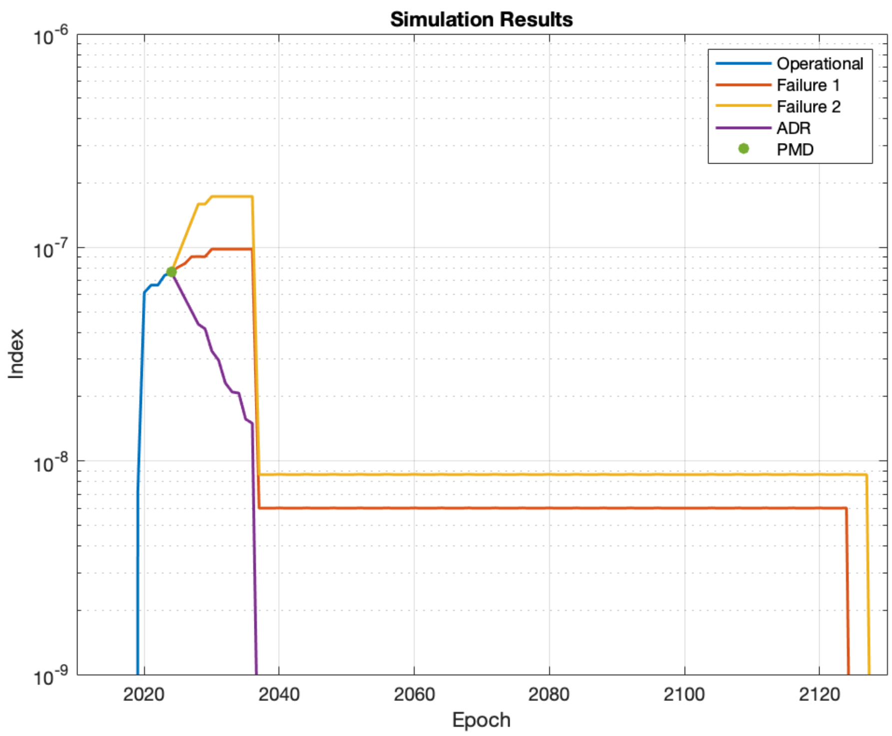

Figure 2.20: Evolution of the mission Index considering the adoption of an ADR solution for Post-Mission-Disposal.

Figure 2.20 shows the outcome of the analysis. The curve composed by the operational ramification and the Failure 1 option illustrates the index evolution of a spacecraft launched, injected, employed and then abandoned to its orbit. The trend respects the intuitive behavior of the associated environmental impact on the debris population, with maximum values and increments and oscillations and initial PMD phase, and the later stabilization during disposal.

Failure 2 refers to the effects on the overall mission due to the chaser mistakes in the steps to be performed for the removal. In case of unsuccessful Re-Entry for both the satellites,

the coupling of the objects natural decays gives a higher value of the index with respect to the previous scenario. Not only the average indicator measure is over the standard curve, but also the conclusion of the Re-Entry is postponed.
The correct execution of the Removal operations and the correct Re-Entry are graphically represented by the purple curve, labeled with *ADR*. The profile exhibits the quick and effective End-of-Life procedure by assuming lower values than the operational ones, with a significant drop and a definitive annulment of the overall environmental impacts in a briefer time.

The convenience of the ADR technology adoption for defunct satellites with respect to their natural decay is logically predictable. An Active Removal by an External Service is a valid disposal alternative for the decommissioning of a failed or off-powered spacecraft, unable to carry out all the tasks required for the targeted EOL strategy.
Anyway, the negative implications resulting from the risk of a more impactful atmospheric de-orbit have to be taken into account.

From Graph 2.20, it is possible to compare the indicator curve related to the satellite natural decay and the failure of the capture (Failure 2). The potential of the mitigation measure of interest is demonstrated by the evaluation of the magnitude displacement between the two lines. Applying an appropriate margin to the Rendez-Vous and Re-Entry reliability indices, underestimating their successive rates to 0.9 in the study for conservative reasons, the worst case scenario has an impact on the environment analogue to the abandonment of the target in space. The difference indeed can be considered negligible, keeping in mind that the risk associated to the total loss of the objects is approximated as 0.09%.

It is relevant to underline that the primary goal of the discussion is to formulate and report the logical and the computational passages to be integrated in the software in order to account for Active Debris Removal solutions. The post-processing assembly of the results is adaptable to be included in the algorithm. The inclusion of ADR technologies in the analysis permits the achievement of a more complex and comprehensive description of the mission scenarios.
Moreover, the output is not limited to practical objectives but numerically validates and promotes the adoption of active mitigation measures in the space debris management. The qualitative considerations on the numerical results allow to appreciate the efficiency of the method and can be exploited to encourage the exploitation of these innovative measures in the administration of the in-active satellites population.

Further considerations

It is important to underline that the analysis carried out is a first attempt to quantify the effects of the ADR on the Mission Index as defined today. The tool can be improved including an additional part to the code to obtain the whole profile with one single computation and the related input format asking for the extra parameter required for the evaluation. To better define the Removal phases and obtain a more detailed description of the scenarios, an intermediate step could be increasing the complexity of the operations, taking into consideration more eventualities. The result is the enlargement of the tree, thus the length of the integers sum.

The SV can be imagined to be launched and injected at an insertion altitude h_{ins}, from where it performs a relocation at an altitude h_{RV}. The case reflects the realistic situation in which the service travels in a reference orbit, agreed by multiple clients, and, on request of a specific target, it reaches the related altitude, which belongs to the range of operational heights. The procedures are followed by a Rendez-Vous manoeuvre and Re-Entry de-orbiting. The comparison, in this case, is referred to the conventional disposal strategy, characterized by an uncontrolled Re-Entry.

For OneWeb case it consists of a transfer to a 1100 km circular orbit, a perigee lowering to 250 km and an atmospheric re-entry in 5 years, with a PMD success rate of 0.99.

From the Tree Analysis approach, seven failure branches are identified:

1. Both SC and SV fail to relocate and remain in their initial orbit;
2. SC fails the relocation and SV fails the Re-Entry;
3. SC fails the relocation but SV performs the Re-Entry;
4. SC relocates but SV fails the relocation;
5. Both SC and SV relocate but Rendez-Vous and Re-Entry fail;
6. Both SC and SV relocate, Rendez-Vous fails but SV re-enters;
7. Both SC and SV relocate but Re-Entry fails.

The description is characterised by an additional success rate, which refers to the relocation phase α_{RL}, for both the objects SC and SV, and the SV specific PMD index in case of nominal disposal α_{SV}, which would represent the new set of additional data for THEMIS software. A value of 0.95 can be considered reasonable for the first three parameters, while the service vehicle has a percentage of nominal disposal success comparable to the spacecraft one of 99%.

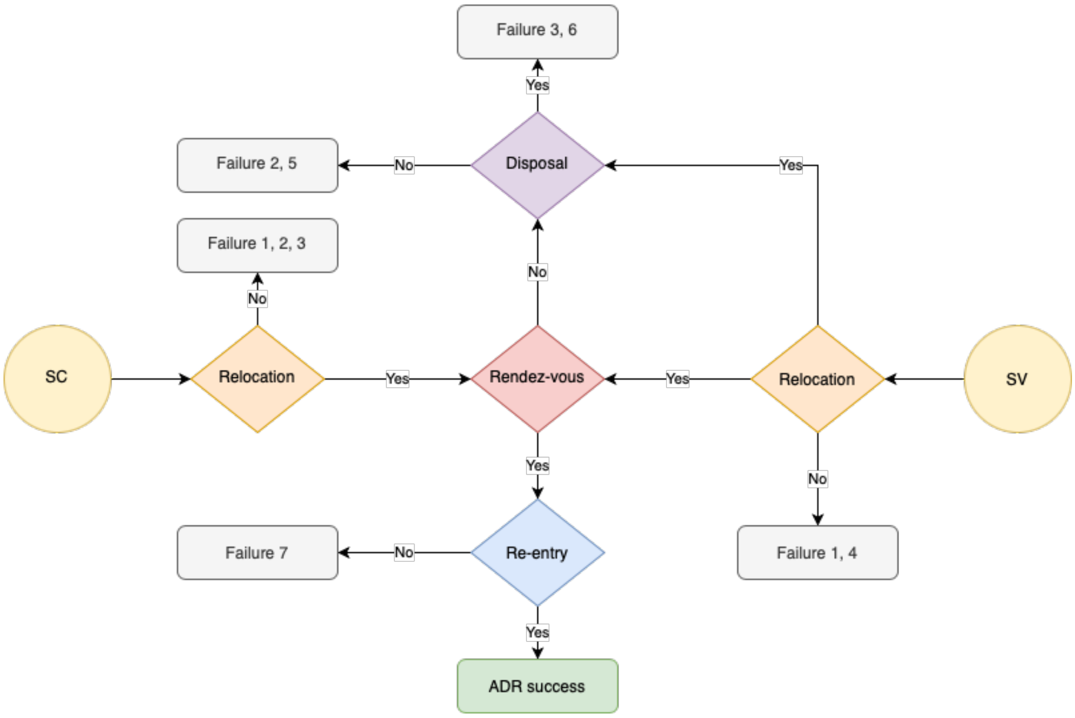

Figure 2.21: The failure tree related to a higher level of complexity analysis.

From the diagram 2.21 it is possible to deduce that, once the spacecraft reaches the Rendez-Vous altitude, it looses the capability to perform maneuvers. It is presumable the strong dependency of the index evaluation on the altitude selected to perform the Rendez-Vous manoeuvre. This awareness leads to stress the importance of the selection of this operational parameter, which can determine the convenience of the strategy with respect to the nominal case.

The refined analysis of the tree of failures suggests that the Index expression, resulting from the scheme, is formed by 9 addend integers. Following the same approach adopted for the simpler case, the estimation requires the construction of 8 input files in order to obtain all the contributors to the expression. For simplicity reasons, the passages are theoretically modelled but omitted in the discussion, even though definitely achievable through the assembly of a set of relevant input files and the consequent interpretation of the out-coming branches.

The digression wants to demonstrate that more complex or different Active Debris Removal strategies can be modelled through THEMIS tool, according to the chronological order of the operational steps and their probability of success. The next development would be the automatic introduction of several functionalities in the software in order to account for multiple End-of-Mission solutions.

2.3.3. CAC and DIT questionnaires extents

The introduction of an Active Debris Removal solution in the Space Sustainability Rating System would affect not only the simulation-based modules, but also the questions-based ones. As previously introduced by the illustration of the grading method, in the compiling phase, the operators are asked to submit a set of qualitative information. Depending on the level of advance demonstrated, the mission acquires a defined score in the module of interest.

Supposing the possibility to exploit an external object to assist the spacecraft in collision avoidance management, alternatively to the nominal self-maneuvering, implies additional points to the overall mission. Indeed, in case of unavailability, passivation or malfunctioning, the ADR service states as a temporary or permanent solution for the task. Depending on the level of capabilities offered by the technology adopted, the attribution of the points is defined in the Table 2.12.

Minimum (0 points)	No availability of collision avoidance alternative service
Low (2 points)	Possibility of request of external collision avoidance service in extreme cases
Medium (3 points)	Moderate external service manoeuvres capabilities, limited availability to perform collision avoidance support
High (4 points)	Advances external service manoeuvres capabilities, constant availability to perform collision avoidance support

Table 2.12: Collision Avoidance: ES Manoeuvre capabilities Bonus.

Moreover, the Detectability, Identification and Trackability (DIT) module is updated to reflect the capacity of the chaser to identify, detect and track the object to be removed. Points are directly proportional to the level of detail of the information, spanning from cooperative to uncooperative procedures (Tab. 2.13).

Low (0 points)	Not able to perform DIT procedures - impossible capture of the object
Medium (2 points)	Able to perform DIT procedures - possibility of cooperative capture only
High (3 points)	Able to perform DIT procedures - possibility of both cooperative and uncooperative captures

Table 2.13: Detection, Identification and Tracking: ES Bonus.

2.3.4. The ADR External Service Index

Starting from the definition of External Service (ES) module, it delineates the actual domain in which the involvement of an Active Debris Removal strategy plays a crucial role. ADR consists of one of the most representative application of external support, in parallel with re-fueling proceedings. In the recent years, due to the servicing technologies stead progress, the high interest and the market readiness, On Orbit Servicing (OOS) sector is experiencing an important growth. The trend is sustained by the increasingly common use by operators to equip cooperative satellites with tools and technologies able to differentiate and enlarge removal mission operations.

The ES module extension intents to attribute more value to missions that are predisposed and compliant to the Active Debris Removal disposal selected. In the perspective of maintaining the focus of the analysis on the global environmental impact, the contribution of the service space footprint is added, as its specific level of performance offered.
The output of the evaluation, I_{ADR}, has its roots in a previous proposal of ranking framework for ADR missions candidates [8]. In the paper, a quantitative measure is formulated to rank LEO space mission objects, according to their physical and orbital characteristics.

The extension proposed consists of a partial integration and adaption of the indices resulted from [8], expanding the set of parameters in order to account to any aspect of Space Sustainability. In this way, the approach switches from an a-posteriori evaluation of active satellites, to a a-priori prediction of the benefits of Active Removals in the space environment. The framework developed stands for a practical support in the design of multiple-target active debris removal missions, guiding the definition of the preliminary requirements in LEO region.

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 operations;
- 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 Eq. 2.20. The rating system is based on a weighting (ω_{env}, ω_{ec}, ω_{op}, ω_{IOS}) and scaling (PI) approach. 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* [50].

$$\begin{aligned} I_{ADR} &= (\omega_{env} I_{env} + \omega_{ec} I_{ec} + \omega_{op} I_{op} + \omega_{IOS} I_{IOS}) PI; \\ I_{IOS} &= -I_{envIOS} + I_{scal} + I_{rel} + 1 \end{aligned} \tag{2.20}$$

The Environmental Term

The environmental contribution to the ADR Index I_{env} assesses the criticality of the mission considering the spacecraft as an inactive satellite in its orbital context.
The rating is based on the evaluation of the potential benefits and advantages arising from its removal. In order to numerically determine this quantity, a valid method is the estimation of the number of fragments that would be created in case of collision occurrence. Anselmo and Pardini papers [3], [4] and [5] propose a factor based on the product between the probability of a catastrophic collision and the number of secondary fragments produced. As this probability P_c is directly proportional to the debris flux encountered by the object ϕ and the spacecraft mass and orbital life, M and *life*, the environmental term takes the equation form of 2.21.

$$\begin{aligned} P_c &\approx \Phi \cdot M \cdot life(h) \\ N_f &\approx M^{0.75} \\ I_{env} &= P_c \cdot N_f = \left(\frac{\Phi}{\Phi_0}\right)\left(\frac{M}{M_0}\right)^{1.75}\left(\frac{life}{life_0}\right) \end{aligned} \tag{2.21}$$

N_f expresses the number of fragments generated from the catastrophic collision, based on the NASA break-up model [25].
The debris flux in LEO region ϕ is computed by MASTER-8 [16] and extracted from grid distribution. The data were provided courtesy of Borelli et al. [8]. The data are available as a $2D$ *Matlab* structure in mean altitudes and inclinations variables, restricted to objects grater than 10 cm (Fig. 2.22). The reference dimensional size is the agreed threshold which defines a catastrophic collision, characterized by an impact energy of 40 $\frac{J}{g}$. Mean altitude is assumed as the mean value between elliptical perigee and apogee [50], as LEO orbits are generally almost circular.

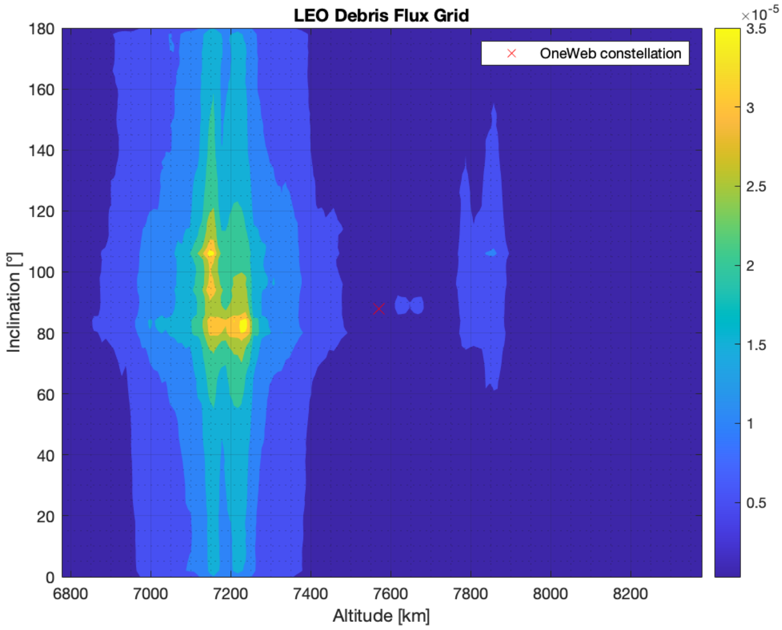

Figure 2.22: Debris flux grid in LEO computed with the MASTER-8 model considering objects greater than 10 cm. [8]

The orbital lifetime, as suggested by [5], is computed through a 7^{th} grade interpolation model of the altitude h (2.22).

$$
\begin{aligned}
&c_1 = -4.7205e^{-17}; \quad c_2 = 1.6537e^{-13};\\
&c_3 = -2.2755e^{-10}; \quad c_4 = 1.6294e^{-7};\\
&c_5 = -6.557e^{-5}; \quad c_6 = 0.014788;\\
&c_7 = -1.6937; \quad c_8 = 75.839;\\
&life(h) = c_1 h^7 + c_2 h^6 + c_3 h^5 + c_4 h^4 + c_5 h^3 + c_6 h^2 + c_7 h + c_8
\end{aligned}
\tag{2.22}
$$

Finally, the rating scale is obtained through a normalization step based on a reference satellite of mass $M_0 = 1000\ kg$, orbiting at 800 km altitude with an inclination of 98.5 *degrees*.

According to the fractions, this convention leads to higher values of environmental index for satellites representing a greater risk to the near-Earth debris environment. The procedure is applied to all the objects belonging to LEO region and most dangerous cases are reported in Figure 2.23. The high ranked spacecrafts are generally characterized by a significant mass and belong to quite busy orbital slots. OneWeb related Index is also reported in the map, and estimated as the contribution of all the constellation members by multiplying the single satellite score for the total number of units. Even though it consists of almost 650 satellites, the environmental impact is significantly inferior to several mono-satellites situations. From the flux grid 2.22 it is noticeable that the 1200 km altitude region is less debris crowded that lower orbits.

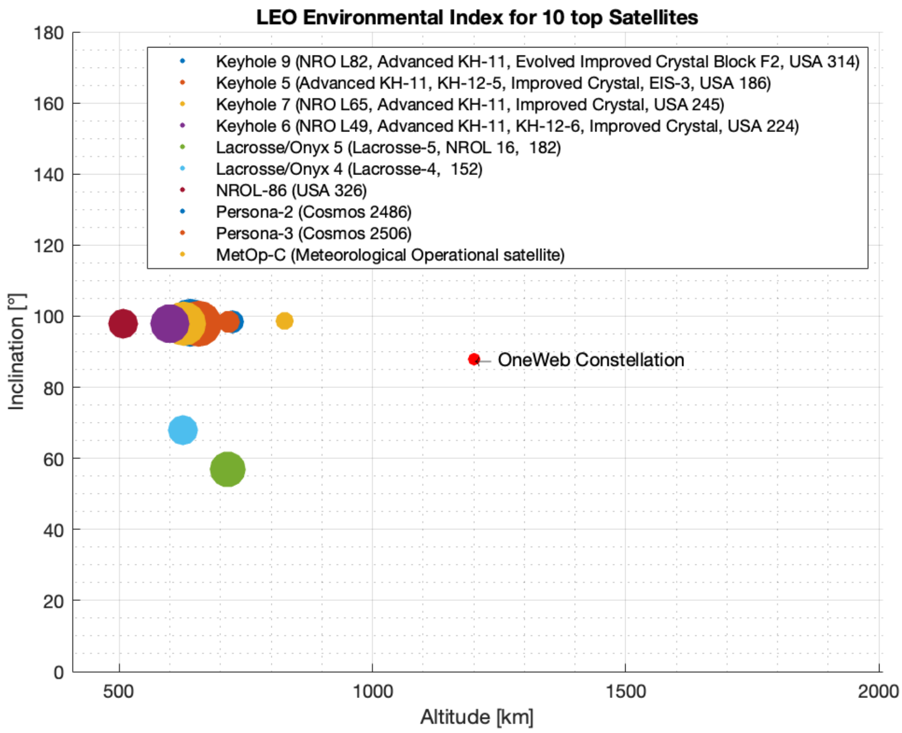

Figure 2.23: Spacial representation of the Environmental Index top 10 ranked Satellites in LEO region.

The Economical Term

The Environmental Index does not include any economic consideration on the possible advantages deriving from the removal of an object in a high-valued orbital slot. An additional figure has to directly assess the economic benefits in the prospective of the sustainable exploitation of space resources.

The characterisation of this measure is based on the definition of economic resource value. It allows to quantify an area by attributing a value to each altitude-inclination combination. The selected method returns a valid relative representation of the economic value for a range of LEO orbital regions, without aiming to obtain any absolute economic estimation of the orbital slot. The strategy roots on the computation of the cumulative insured value of satellites belonging to a specific orbital bin.

The insured value of the satellites, present in each spacial unit, is estimated considering the relationship proposed by [29]. The main assumptions behind this formulation is that the totality of active satellite population is covered by insurance and the satellites value depends on their masses.

$$I_{iv} = \sum_{j \in (\Delta a, \Delta i)} 52253 \left(M_j z_j\right)^{0.9843} \tag{2.23}$$

In Equation 2.23, M_j is the satellite mass in kg belonging to the specific unit. z_j is a correcting factor proposed by the current study which scales the population according to the class of the mission. As depicted in Table 2.14, to each category reported in *UCS Dataset* [50], a score is associated. The methodology allows to get a wider distribution of the values, validated by an increase of the variance from $\sigma = 3.938$ to $\sigma = 3.948$.

Class	**Score** z
Communications	5
Earth/Space Observations	4
Satellite Positioning and Surveillance	3
Technology Development/Demonstration	2
Unknown	1

Table 2.14: Class scaling factors.

The insured value is computed for each bin belonging to LEO region, defined spanning discretization of 50 km altitude (Δa) and 2 deg inclination (Δi). The Economic Index is finally obtained from the normalization to the parameters referred to the 800 km altitude and 98.5 deg inclination bin, and then translated to a logarithmic scale (Eq. 2.24).

$$I_{ec} = log_{10} \left(\frac{I_{iv}}{I_{iv0}} \right) + 10 \tag{2.24}$$

As for the first term introduced, the output returns higher value of I_{ec} for greater economical resource values of the orbital bins. It is so possible to graphically represent a map of the bin values in the region of analysis. In order to compare this second sub-index with the environmental one, the results are multiplied by a factor of 10^{-1}.
From the Figure 2.24, the orbital bin in which OneWeb constellation falls is economically high valued, denoted with colors associated to numbers around the unit.

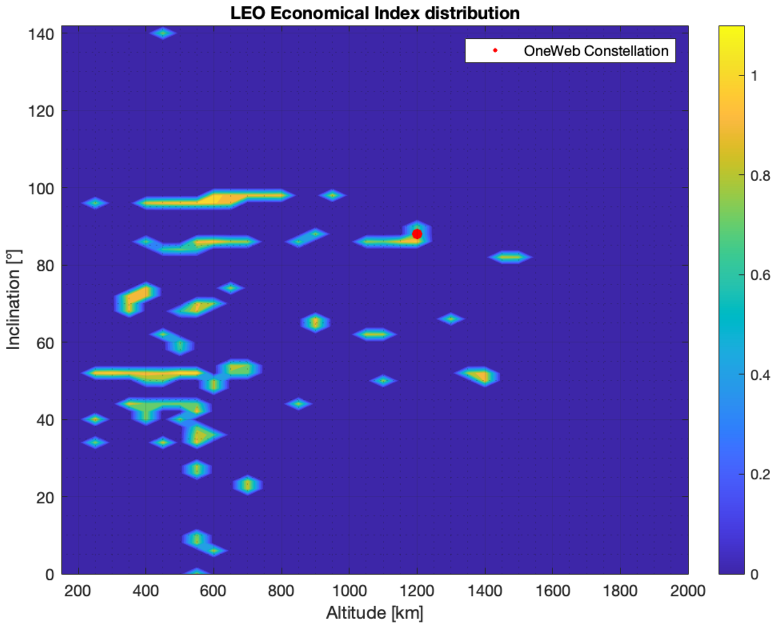

Figure 2.24: Spacial representation of the distribution of the Economical Index in LEO region.

The Operational term

The operational term to the Active Debris Removal reflects challenges that the capture and removal phases submit to satellites. In order to simplify the quantification of the sub-index, a mechanical rigid capture is simulated. The technology presents one of the highest maturity and feasibility level. The requirements associated to this removal approach are assumed to depend on the target physical and dynamical properties only, neglecting any influence from the environment. The spacecraft attitude motion determines the tumbling state, which is a weighty factor in the attachment stage.
The grade of mobility is estimated through the amount of synchronisation acceleration required by the service to align with the satellite. The mass variable reflects the mechanisms and the propellant needs constraints for the de-orbit. The Operability Index is so defined as a the product between impact functions (Eq. 2.25).

$$I_{op} = \left(\frac{a_{s0}(L,\omega_f)}{a_s(L,\omega_f)}\right)\left(\frac{M_0 - M}{M_0}\right) \tag{2.25}$$

The term $a_s(L,\omega_f)$ symbolises the chaser acceleration necessary for the full synchronisation with the target. The function is constructed on the estimation of the effort required to balance the rotating target centrifugal acceleration. This idea is supported by simulations that implement fly-around control, varying station keeping distances and target attitude states, reported in the reference paper [8]. The simplified formulation of Equation 2.26 returns a satisfactory output with respect to the simulated results.

$$a_s(L, \omega_f) = L\omega_f^2; \quad \omega_f = \frac{\omega_a}{3\frac{deg}{s}} \tag{2.26}$$

- L is denoted as safe distance. Setting a conventional threshold of 1000 kg between small and large satellites, an average density of $\rho_1 = 200\ \frac{kg}{m^3}$ is assumed for the first category, while $\rho_2 = 30\ \frac{kg}{m^3}$ is valid for biggest objects. The safe length is computed as the diameter of the spacecraft, approximated as a sphere of mass M, extracted from *UCS Dataset* [50], and density ρ_j depending on its classification;
- ω_f term is computed from the apparent angular rate data. Light curve data from MMT ground observations [40] are useful to analyse the attitude state of each debris object. For the objects labelled as *"Aperiodic"*, the angular acceleration is taken as $\omega_a = 1\ \frac{deg}{s}$. On the other hand, the remaining satellites and the objects with no available light curve data are referred to $\omega_a = 3\ \frac{deg}{s}$.

In Eq. 2.25, the specific function associated to the mission is placed at the denominator, which implies an higher value of I_{op} for low-tumbling objects. The mass affects the index with a linear inverse proportionality, so that the largest masses are considered more problematic for the capture. The normalisation applied is to a mass of 10 *tons*, an angular velocity of $\omega_a = 3\ \frac{deg}{s}$ and a safe length of $L = 2\ m$.

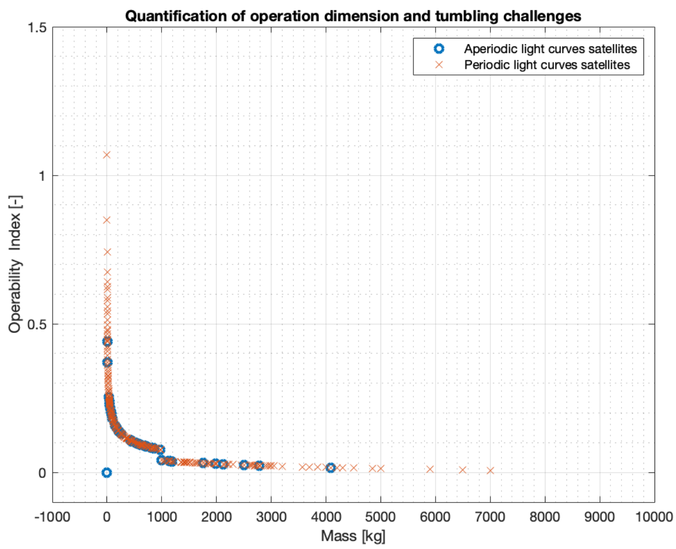

Figure 2.25: Graphical representation of Operational Index with respect to satellite mass.

Figure 2.25 shows the trend of the indicator considering different spacecrafts masses. Behind this decrement behavior, there is the strong assumption that massive objects are more complex to be removed. Inserting the effects of the shape factor, accounting for the presence of appendices that represent an obstacle to the capture, generates a more accurate study. This preliminary analysis results a sufficiently accurate measure for the rating of compliance in operations between chaser and target.

The In-Orbit Service term

As mentioned in Section 2.3.4, the intention of the SSR is to stand for an efficient tool for the preliminary evaluation of missions. The point of view of the analysis is precedent to the launch of the spacecraft and sustainability decisions, taken by operators, are quantified and measured on prediction basis.

In this regard, it is fundamental to forecast the implementation of active mitigation measures to define and promote convenient and sustainable behaviors. Tracing the effects of multiple ADR options permits, in phase of design, to establish the most opportune disposal strategy, depending on the specific mission characteristics. It is worth to remark that same considerations can take the opposite direction. Operations might be planned to exploit a determined service and, to result the most suitable as possible to the external intervention, modifications on mission characteristic can be made.

Back to the definition of In-Orbit Service Index 2.20, I_{IOS} contains all the information regarding the specific ADR solution selected in the mission design. The contributors to the indicator expression are the terms defined as:

- The Environmental index associated to the service vehicle at the target operational orbit, I_{envIOS};
- The Scalability index related to the extensibility of the service operations, I_{scal};
- The Reliability index reflecting the level of robustness of the technology, I_{scal};

Looking at OneWeb removal opportunity planned for 2024, it is interesting to apply and simulate ELSA-M performances to LEO population. The outcome of the analysis has the ambition to represent a solid reference in case of collaborative agreements, permitting the identification of analogies and strengths among potential clients. The list of partial contributors and the figures of merit are collected in Table 2.15. For each of the IOS terms, the key input and the respective declination for ELSA-M are determined.

Term	Input Parameters	ELSA-M Assumptions
I_{envIOS}	Operational altitude h_{op} Operational inclination i_{op} Service mass M_{SV}	$h_{op} = h_{target}$ $i_{op} = i_{target}$ $M_{ELSA-M} = 175\ kg$
I_{scal}	Altitude range Δh Inclination range Δi Mass range ΔM Removal Rate per year R Hohmann transfer from Parking orbit h_{par} and i_{par}	$\Delta h = 200\ km$ $\Delta i = 1\ deg$ $\Delta M = \pm 15\%\ M_{target}$ $RATE = 1\ \frac{obj}{year}$ $h_{par} = 400\ km$ $i_{par} = i_{target}$
I_{rel}	Rendez-Vous Success Rate α_{RV} Re-Entry Success Rate α_{RE} Technology TRL	$\alpha_{RV} = 0.9$ $\alpha_{RE} = 0.9$ $TRL = 7$

Table 2.15: Characterization of the In-Orbit Service Index Input Parameters and ELSA-M data.

The service Environmental index I_{envIOS} is modelled at the target orbit to account the impact of the chaser on the spacecraft debris context. The mass value and the TRL level are extracted from ELSA-D data-sheets [6].
During the attribution of the remaining variable values, some assumptions are made. ELSA-M vehicle is expected to be able to vary its operational range between a span of 400 km and 2 deg. The propulsion sizing procedure is based on the target dimension and margined by the 15% of its mass. It supposes the extension of the operations to objects weighting in that interval. ELSA-M performances are predicted to guarantee 1 removal per year. From the operational point of view, its insertion takes place at a parking orbit at 400 km, from which the transfer is simulated as an Hohmann trajectory to the target orbit. Finally, the confidence of the ADR solution is measured in terms of reliability indices for the Rendez-Vous and Re-Entry, which are taken as 0.9 for both the phases.

The study hypotheses the application of ELSA-M technology to all the candidate targets belonging to LEO. Computationally, the environmental impact of the In-Orbit Service follows the steps described in the Paragraph 2.3.4, setting the mass as M_{ELSA-M} and iterating on all the altitude-inclination combinations of the population.

The scaling term I_{scal} depends on the amount of similar objects in the target neighborhood, scaled with the annual $RATE$, and the propulsion effort to reach the region.
From the altitude, inclination and mass ranges, the operational areas around each candidate of the population are delineated and the number of feasible targets N_{multi} is retrieved.

$$N_{multi} = \sum_{j} (h_j \in \|h_{target} \pm \Delta h\|) \wedge (i_j \in \|i_{target} \pm \Delta i\|) \wedge (M_j \in \|M_{target} \pm \Delta M\|)$$

The scalability of the service includes a function that permits to evaluate the proportionality between the propulsive requirements and the number of probable removals. The relation is introduced by the impulse ΔV, estimated as the expense required by the service to reach the target. The transfer is simulated as an Hohmann trajectory connecting the parking orbit to the final altitude. This model imposes the inclination of the parking orbit equal to the target one. The quantity $\frac{\Delta V_0 - \Delta V}{\Delta V_0}$ decreases as function of the propulsion effort, penalizing the most demanding situations. ΔV_0 is obtained computing the impulse requirements necessary to reach the maximum altitude of 2000 km.
In order to compare the scaling term to the other contributors, the number of similar objects is normalized by 3000, corresponding to the LEO density circa (2.27).

$$I_{scal} = \left(\frac{N_{multi}}{3000}\right) RATE \left(\frac{\Delta V_0 - \Delta V}{\Delta V_0}\right) \tag{2.27}$$

As THEMIS tool suggests, every measure adopted for the Post-Mission Disposal phase carries a certain level of uncertainty from the feasibility point of view. Active Debris Removal technologies are solutions which still require time to be fully developed and validated. For this reason, in this study, not only the probabilities of success of the operations are considered, but also the level of TRL referred to the specific mechanism selected is present in the Equation 2.28.

$$I_{rel} = \alpha_{RV} \alpha_{RE} \frac{TRL}{9} \tag{2.28}$$

The formal implementation of the rating needs the agreement of a common grading method to evaluate the state of the art of the ADR alternatives. The study adopts the Technology Readiness Level estimation proposed by [38], reported as aggregate score (Table 2.16). The demonstrations and validation steps are experiencing progresses and advances, especially for what concerns mechanical and magnetic captures, which are detectable from 2019. However, if scaled, the classification still represents a good reference for a post deeper diversification of the alternatives.

ADR method	Aggregate Score
Collective	1.7
Laser-based methods	1.3
Ion beam shepherd-based methods	1.75
Tether-based methods	2
Sail-based methods	1.7
Satellite-based method	1.5
Unconventional method	1.8
Dynamical system-based method	2

Table 2.16: Technological Readiness Level of the Active Debris Removal methods [38].

Once all the contributions to the I_{IOS} are defined, the evaluation of the total score is performed, according to the signs expressed in Equation 2.20.
Maintaining the usual operator point of view, the trends presented in Figure 2.26 are a valid starting point for examinations. The values of the In-Orbit Service Index is graphically represented with respect to the orbital parameters.
From the images, altitudes around 500 km and 1200 km appear more prone to the exploitation of ADR solutions, presenting a positive indicator value. It is not a coincidence if realities such as Starlink and OneWeb are realistically considering such options. Intermediate altitudes of the order or 800 km instead badly suit the solution, showing not only lower values but also lower densities. Since the whole interval of inclination is able to return positive numbers and almost equally distributed, this variable is less stringent as measuring meter for the removal.

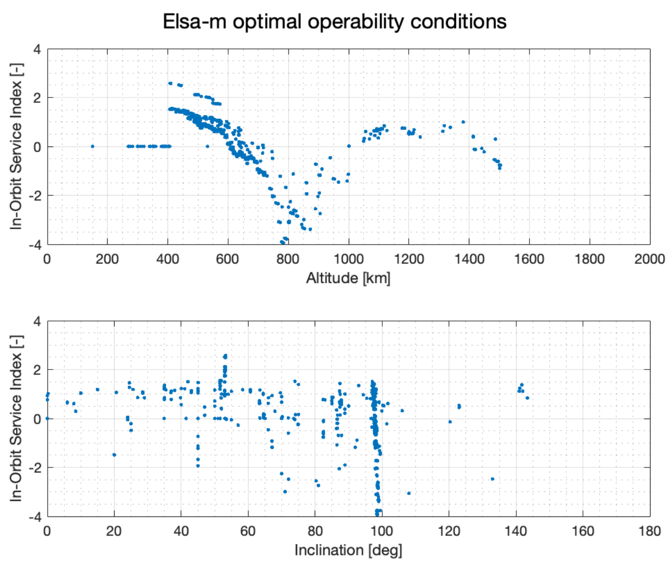

Figure 2.26: Representation of the In-Orbit Index.

Keeping in mind the variety of possibilities for developments and optimization, the maps have the power to constitute a strong initial reference for the evaluation of the adaptability of a mission to an ADR Post-Mission operation. Optimal orbital slots and sharing partners can be identified for collaboration purposes.

Results interpretation and possible improvements

The assembling of the sub-indices described into the comprehensive I_{ADR} provides weighting and scaling strategies.

The multiplier factors are selected to differentiate the levels of relative importance. The environmental and service terms are considered prior to economical and operability aspects. From this statement, the weights are imposed as $\omega_{env} = \omega_{IOS} = \frac{1}{3}$, while $\omega_{ec} = \omega_{op} = \frac{1}{6}$.

The Proximity Index PI is implemented to classify the population between operative objects, so called active satellites, and the ones which have passed the expected End-of-Life time. This information is retrieved by adding to the launch date from *UCS Dataset* [50], the expected lifetime. The spacecrafts not reporting the information of interest are supposed to guarantee the operations for 10 years.
Then, for both the categories, the Proximity Index is constructed such that missions which take precedence in the use of Active Debris solutions are rewarded amplifying their indicators. They consist of old past missions, whose end dates are further from today, and missions closer to disposal. This classification is obtained by computing the time distances $diff_A$ and $diff_P$, respectively for active and passive satellites (Eq. 2.29), and then scaling the ADR Index with the factors expressed in Equation 2.30.

$$diff_A = t_{EOL} - today; \quad diff_P = today - t_{EOL} \tag{2.29}$$

$$PI_A = \frac{max(diff_A) - diff_A}{max(diff_A)} t_{EOL}; \quad PI_P = \frac{max(diff_P)}{max(diff_P) - diff_P} t_{EOL} \tag{2.30}$$

At this point, all the ingredients necessary for the computation of the general Active Debris Removal Indicator are available and LEO inhabitants can be ranked regarding their predisposition to the specific PMD solution and their compliance to the service.

The particularity of the current analysis is the fundamental introduction of the chaser impact on the environment and the level of performance offered. The intention is to look at the results with the prospective of Space Sustainability interpretations, and the potential of preliminary prediction of the effects of Active Removals.

Figures 2.27 and 2.28 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 (Tab. 2.17).

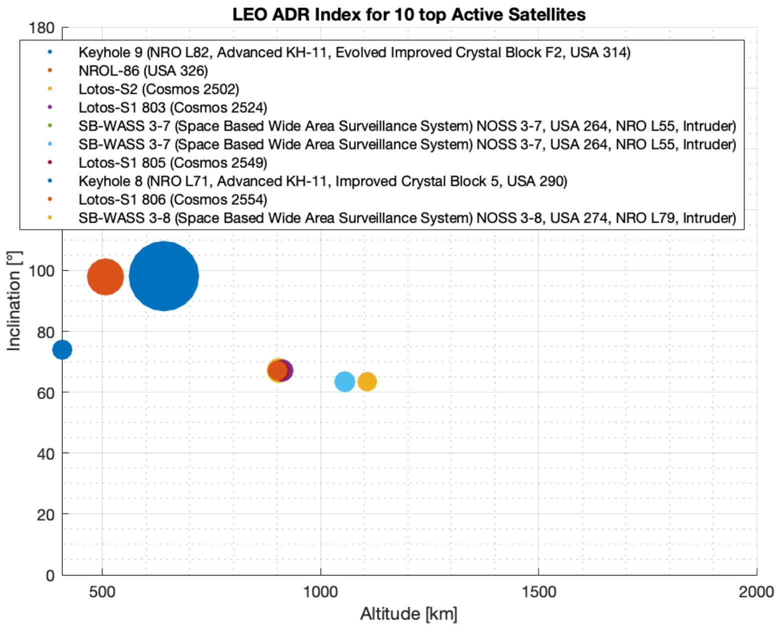

Figure 2.27: Graphical representation of the top 10 ranked active satellites for ADR removal.

Satellite	Semi-major axis $[km]$	Inclination $[deg]$	Mass $[kg]$	I_{ADR} $[-]$
Keyhole 9	641	98.2	20000	22.5698
NROL-86	507.5	97.89	20000	6.29422
Lotos-S2	905.5	67.15	5000	2.91222
Lotos-S1	912	67.1	5000	2.30056
SB-WASS 3-7	1056.5	63.4	6500	2.04423
SB-WASS 3-7	1056.5	63.4	6500	2.04423
Lotos-S1 805	905	67.1	5000	1.99814
Keyhole 8	407	74	18000	1.89125
Lotos-S1 806	902	67.1	5000	1.8187
SB-WASS 3-8	1106.5	63.4	6500	1.78296

Table 2.17: Top 10 Active satellites for ADR Index.

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 (Tab.2.18).

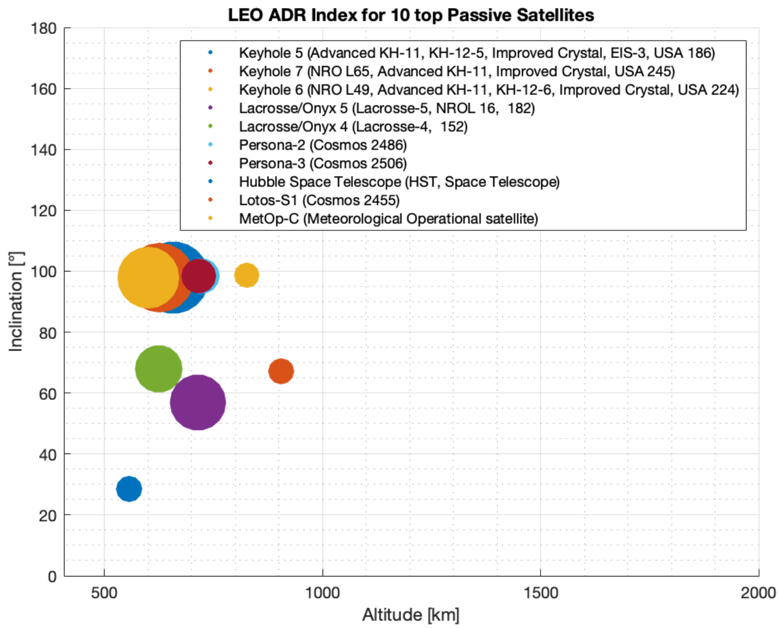

Figure 2.28: Graphical representation of the top 10 ranked passive satellites for ADR removal.

Satellite	**Semi-major axis** $[km]$	**Inclination** $[deg]$	**Mass** $[kg]$	I_{ADR} $[-]$
Keyhole 5	657	97.9	18000	23.8162
Keyhole 7	627	97.8	18000	22.0095
Keyhole 62	600	97.8	18000	17.3633
Lacrossa/Onyx 5	714.5	57.01	14500	14.4037
Lacrossa/Onyx 4	625	68	14500	10.2886
Persona-2	723.5	98.3	7000	5.75697
Persona-3	715.5	98.5	7000	5.5277
Hubble Space Telescope	557	28.5	11110	3.14773
Lotos-S1	902	67.1	5000	3.08546
MetOp-C	827	98.7	4084	2.91496

Table 2.18: Top 10 Passive satellites for ADR Index.

Recalling the general goal of the Rating System, a space operator belonging to both private and national sectors has the possibility to justify and measure the impact of mission design decisions depending on the output of the analysis.

The future and planned collection of a wide range of scenarios allows the establishment of industry benchmarks, facilitating and formalizing the comparison. The proposed predefined set of sustainability metrics for Active Debris Removal has to be improved and extended as the boundaries of the technological frontiers are widening.

The achieved outcome database permits the development of Key Performance Indices (KPIs), related to Active Debris Removal and Sustainability, including more precise estimations of the number of debris objects removed, the reduction in the collision risks and the percentage of operable orbital slots. A conclusive refinement is addressed to different domains, less technical, but equally determinant. Since the collaboration factor plays a crucial role in the realization of Removal Initiatives, measuring the amount of partnership engagements and economically grading the level of investment in ADR technologies affects the rate of the mission. These final considerations are intended to be projected in terms of time, tracking the evolution of both the parameters and the outputs over time, to assess space operators progresses and contextualize their sustainability efforts.

3 | Political excursus on ADR challenges

The technical challenges interesting the implementation, the demonstration and the validation of Active Debris Removal technologies are certainly one of the main reasons this alternative is not yet frequent among disposal strategy. The intentional capture and removal of defunct and non-operational objects hide multiple challenges in the mechanism and devices design as in the operations definition.

However, the implementation of ADR initiatives is slowed by the profound political implications that extend beyond the boundaries of the planet Earth. The political significance of ADR in the space debris management is evident if the complex web of international agreements, national interests and the evolving dynamics of space governance are considered. Behind the functioning of this mitigation measure, it is necessary that nations and organisations collaborate so that the global challenge of space debris is effectively fulfilled. Collaboration means that the allocation of responsibilities, the development of ADR technologies and the formulation of regulations for debris removal are achieved through official diplomatic negotiations. The political implications extend also to issues of space security, sustainability and access. Disagreements over satellites priority to ADR, technology sharing and financial burdens directly influence geopolitical relationships and have far-reaching consequences on international space cooperation.

In this context, the conclusion of the study delves into the pressing necessity of Active Debris Removal in space debris management and explores the political implications associated with the development and the implementation of ADR initiatives. Moreover, some considerations on the responsible definitions and the requirements formalization, deriving from the adoption of an External Service from OneWeb, are analysed.

3.1. Political key aspects

One of the most tricky aspects for Active Debris Removal missions is the transferring of ownership during these cleaning processes. The challenges involve mainly the identification of responsibility. Whenever a target has to be removed, it is necessary to determine the entity or the organization responsible for the debris production. This step implies clarifying the nation, the company or the organization that is originally accountable for the defunct object. The identification passage is crucial, since it sets the stage for various legal and practical considerations regarding the removal operations but also the ultimate fate of the object.
The concept of "space salvage" interests the recovery and removal of space debris by an external entity, which is similar to the concept of salvage operations for shipwrecks. This type of actions has implications for international space law, which is the legal framework that governs activities in outer space. It is therefore essential to understand the relationship between space salvage and international space law to facilitate the agreement of a common legal pattern.

In addition, in the domain of space activities, the question of liability for damages caused by space debris is an ever-present concern. As underlined by the collision risks associated, space debris poses an increasing danger to operational satellites, space stations, and even crewed missions. International treaties and agreements, such as the Outer Space Treaty and the Liability Convention, lay down a framework for resolving disputes and determining liability for space activities. However, the evolving nature of space operations and the emergence of ADR missions have added layers of complexity to these issues. International community is grappling with the challenge of addressing liability for space debris incidents as the actions have to result in adhering to the principles and obligations set forth in international space treaties.

3.2. Contractual and permission-based approach

The ADR 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* [26].

3.2.1. The background and fundamental principles

The reference approach is based on several international agreements and conventions. The Article VI of the *Outer Space Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* [47], sets the international responsibilities for space activities, which include ADR operations.

Principles of ownership and damage management, that are addressable to the implementation of such technologies, are discussed respectively in the Registration and Liability Conventions. Finally, all the aspects related to the attribution and control of licenses are considered in the national domain of interest, so treated by the *UK Space Industry Act* [20].

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.

Even though they represent a solid basis for the establishment of a formal pact, the realization still hides potential prohibiting factors that could affect or worry the stipulation. When it comes to agreements between debris owners and service providers in space active debris removal (ADR), the areas of export practices, liability definition and ownership are particularly crucial.

3.2.2. Main political challenges

Space technologies, including those involved in active debris removal, have serious national security implications. Governments and private companies have to follow the export procedures for sensitive devices, as well as knowledge information, when delivering to other countries, in the complex network of sector of allies or actors with divergent geopolitical interests.

Several international agreements and treaties already govern the export of space objects and the compliance with these regulations is fundamental to avoid conflicts and ensure the adherence of ADR activities to global norms.

Space activities in general and specifically ADR operations are guided by international space law. Determining the liability in the event of accidents, collisions, or damage during debris removal operations is still a complex issue, both in the definition of responsibilities and consequences.

At the basis of ADR implementation there are maneuvers and movements in space, and the risk of accidents or unintended consequences is inherent. Defining liability ensures that parties are aware of the potential risks and have mechanisms in place to handle, manage and compensate any damages that may occur.

In the prospective of collaborative programs, space debris include satellites or parts owned by different countries. Determining ownership is fundamental, especially when dealing with debris from multiple sources, since national interests and the protection of space assets influence negotiations on ownership rights.
Moreover, as technology advances, the interest in salvaging and utilising space debris for various purposes increases significantly and ownership rights become the valid criteria in determining the figures who have the right to salvage and exploit these materials.

3.2.3. The Contract and official documents characteristics

To respond to any eventual uncertainty related to the adoption of an Active Debris Removal, the document goal is to formalise the engagement requirements between the parts, in a sufficiently exhaustive and global way. There are several indispensable characteristics to be properly stated in order to represent an official and common reference.

ADR Service Adopted and Re-Entry Mechanism The selected ADR service and re-entry mechanism impact the level of safety of the operation and compliance with space regulations. The formal definition of the strategy ensures the complete parties understanding and agreement on the methods used, reducing the risk of accidents and environmental impact.

Retention of Debris Ownership Determining the ownership of debris post-removal is crucial for legal clarity, helping and facilitating the avoidance of disputes over ownership rights. The transparency ensures that the debris is appropriately managed and used, taking into account national interests and legal obligations.

Liability Issues Clearly defining liability in the contract helps managing and allocating risks appropriately. This includes responsibility for potential damages, accidents, or any other issues that may arise during the ADR process and provides a legal framework for handling unforeseen events.

Licensing Responsibilities ADR operations require licenses and approvals from regulatory bodies. The responsibilities in the contract ensure all necessary permits obtainment, reducing the risk of legal complications and ensuring compliance with space regulations.

Technical Data Exchanged Technical data and information exchanged between parties are accompanied by the clarification of the scope and terms of this data exchange to conduct the operation smoothly, with all actors having access to the necessary information for success.

Export and ITAR Control Issues ADR activities involve technologies subject to export controls like ITAR. Addressing export control issues in the contract ensures that all parties are aware of and comply with relevant regulations, preventing legal complications and potential sanctions.

Intellectual Property Transfers A clear understanding of how intellectual property rights are handled encourages innovation, since contributors are appropriately rewarded and that innovations can be used for the benefit of all parties involved.

Messaging and Public Communication Responsibilities Public perception influences the success of ADR operations. Clearly defining messaging and public communication responsibilities helps managing public expectations, address concerns and maintain transparency, contributing to the overall success and reputation of the operation.

Bilateral Memorandum of Understanding (MOU) in Case of Multiple States In case of multiple states involvement, ADR requires coordination and collaboration established by a bilateral MOU. It is a framework for cooperation which defines the roles and responsibilities of each state, guaranteeing that the operation is conducted efficiently and in accordance with the objectives of all participating states. In other words, MOU is a formal deal between states determining the liability and its extent, between the ADR provider, the debris owner and the launching states. The Memorandum takes into account the individual domestic regulatory regimes governing ADR operations, improving the similarity to provide consistent operational rules, without significant regulatory discrepancies.

The topics discussed in the MOU document are:

- Authorization and licensing responsibilities;
- Registration responsibilities;
- Technical data exchanged;
- Liability issues;
- Ownership transfers;
- Transparent messaging responsibilities.

3.3. OneWeb study case

3.3.1. Responsibilities assessment

As mentioned in the previous part of the discussion, the main requirement for a clear and transparent formalisation of a contract is the assessment of the responsible actors to each phases or aspect involving ADR. This passage is fundamental under many sides, beyond clarity and understanding. A thorough assessment of tasks and obligations allows identifying potential risks and liabilities associated with each party role. This enables the implementation of risk mitigation measures, reducing the likelihood of accidents, damages or legal issues during the ADR process. The definition of responsibilities ensures that all parties comply with the terms and conditions outlined in the contract. This compliance is essential to maintain the integrity of the contractual agreement and preventing disputes or breaches. A single and shared view of the situation facilitates communication and coordination among the actors, crucial for the success of a collaborative ADR effort, particularly when dealing with multiple entities or states.

Exploiting the imminent occasion of UK Space agency to invest on Active Debris Removal market and offer an efficient mitigation measure for debris management, the study aims to define the main ADR aspects and assign to each one a responsible figure. The Table 3.1 lists the main characters involved in the operations and the related task. Ofcom or the Office of Communications is the United Kingdom's communications regulator. It is an independent regulatory authority that oversees various aspects of the communications industry in the UK. Ofcom's responsibilities include broadcasting regulation, telecommunications regulation and spectrum management.

ADR operation aspects	UK Responsible
Launch and re-entry	UK Space Agency
Remote sensing system	OneWeb
Radio frequency spectrum use	Ofcom
Insurance requirements	OneWeb

Table 3.1: List of defined Responsible for ADR activities in case of OneWeb implementation.

For what concerns the responsibilities assessment, a long-term solution could be the establishment of a centralised regulatory entity to license ADR activities in the commercial sector.

3.3.2. Response to the main political challenges

In the adoption of an Active Debris Removal service, OneWeb, as private space company, has alternatives depending on the solution selected. The national strategy implies the hiring of a UK domestic entity remover. This allows that debris removal operations occur within a single state responsibility, limiting the challenges deriving from external deals. In the prospective of collaboration, international debris service solution, characterised by involvement of more than one nation, is a probable option.

In the Table 3.2 , the most significant and concerning political and legal obstacles are extracted from the considerations carried out above and summarised. For each challenge, a proposal of solving measure, offered by the implementation of the political model described, is reported.
In the tabular structure, in parallel with the already known and discussed challenges of liability, ownership and export control, more implications are considered.

The expression *space debris* is often used broadly to refer to defunct satellites, off rocket stages, fragments from disintegration, and other non-functional, human-made objects in orbit around Earth. Anyway a specific and universally accepted legal definition does not exist, since the rapid evolution of space activities and the complexity of the issue.
In addition, the perception of Anti-SATellite (ASAT) weapons usage in the context of Active Debris Removal (ADR) roots in the possible dual-use nature of the technology. Anti-satellite weapons have the potential to serve for defensive purposes, such as protecting against hostile actions in space, but also for offensive actions, including the destruction of satellites. The perception of ADR being used for ASAT weapons could raise concerns about the borders between international cooperation and militarization and questions about global security and stability.

ADR Political-Legal Challenge	**Framework approach**
Lack of legal definition of space debris	Deal based on consent and permission through binding contracts, designed on a case-by-case basis
ADR perception of anti-satellite (ASAT) weapons usage	Launching state express consent to operations and constant communication with space community
Liability protection from accidents	Private companies purchase liability insurance to indemnify the government for liability of space activities
Ownership transfer	Not required, the ownership of the space debris remains to the original owner and control is managed by the contact agreement
Export control of technical information	Definition of thresholds depending on the ADR technology

Table 3.2: Responses of the framework to the main ADR challenges.

4 | Conclusions and future developments

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 comprehensive 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 main initiatives to foster responsible practices in space operations are identified. The analysis aims to validate their potential and to shape the future of space activities, promoting cooperation and mitigating the risks associated with orbital debris. 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. If recorded and time contextualised, the map of the improvements achieved by responsible actions and the application of the GSOA Code of Conduct is constructed. The consulting of the structure allows a post-evaluation to define the most effective actions and the most promising directions to conduct.
The study converts from a current-state analysis to a time-contextualised evolution of the benefits. In this regard, a set of numerical variables reflecting achievements in space sustainability has to be determined and monitored over time in order to obtain trends and correlations.

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 generalisation of a methodology suitable to stand for a practical preliminary instrument to estimate the brightness behavior of a mission and prevent dangerous configurations. The future steps prevent the application of the strategy to different and various situations in order to collect a representative sample of profiles of satellites magnitudes and coherently construct a rating system.

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 its 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. The intention is to extend the tool to the post-processing managing of the results in a singular Debris Index run.
Finally the presented version of the External Service model, focused on the ranking of missions from the removal operations point of view, aiming to stand for an additional contributor in the Index evaluation and a formal support for the clean-up of orbital debris. The next advance is planned to be the performance of the simulations for a wide range of ADR technologies, iterating on their characteristics and the operability capabilities. In parallel to their development and implementation, the goal is to create a reliable database for the selection of the disposal options for operators.

It is essential to identify the potential future prospective that a comprehensive definition of the SSR Index represents in the realm of space sustainability. The future holds immense promise for a more sustainable and responsible approach to outer space and the scope of the work is to serve as a foundation for further developments in this critical field. The SSR Index not only highlights its current practical and efficient significance, but also underscores the imperative to align space progress with a meticulous evaluation of sustainability. This study supports the cause standing as a cornerstone, emphasising the necessity for a qualified assessment of the environmental impact and long-term viability of space activities. By coupling technological advancements with particular lens on sustainability, the solid groundwork for a future where progress in outer space is harmonized with the preservation of the cosmic environment, is lied down. The findings presented provide a launching pad for further developments, guiding the trajectory of space exploration towards a more conscientious and enduring future.

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A | Appendix A

A.1. SSR modules description

The Mission Index The Mission Index is a risk metric that quantifies the probability of fragmentation associated to a specific mission. It is defined as the product between the likelihood that an object gets involved in a fragmentation event and the severity of this potential occurrence, measured through the estimation of the effects of the impact on operational satellites [32].
The output refers to all the participants to the operations, that certainly includes the spacecraft functional unit, but also the launch vehicle and mission related objects aimed at providing a specific service. The risk metric is computed considering the contribution from all the objects planned by the original mission design. The estimation of the impact depends on the satellite physical and operational characteristics:

- Mass;
- Cross-sectional area;
- Operational mean altitude;
- Operational inclination;
- Target disposal trajectory;
- Expected disposal success rate;
- Mitigated collision risk.

In order to asses the general environmental impact of the mission, the value of the Index is computed along the whole lifetime. The sum of phase contributions guarantees to capture the risk reduction associated to the implementation or the failure of the disposal strategy. The expected disposal success rate distinguishes between the correct evolution of the End-of-Life, and the alternative recommended disposal action of the orbital region. For the mission life cycle, the environmental features and the background debris population are considered.

The Collision Avoidance Capabilities Module There exists many strategies a mission can choose to operate in a congested environment. The module focuses on the operational aspect of collision avoidance, evaluating the operators capabilities to identify, respond to and mitigate collisions. The questions are related to the level of orbital state knowledge, depending on accuracy, updated frequency, covariance characterisation, the availability to coordinate and the capability to coordinate, based on the presence of established procedures to handle conjunctions alerts.

The Data Sharing Module The section evaluates the amount of information an operator is willing to share and the range of sharing adopted through a matrix approach. Points are assigned according to different combinations and the consequences on the contribution to space flight safety of the shared information. Data considered are collision avoidance coordination information, satellite metric information and satellite characterisation information. To each type of data, the SSR user has to provide the audience that can achieve the specific information. The entities can belong to SSA Provider(s), operators upon request for coordination, voluntary network of operators/stakeholders and public.

Application of Design & Operation Standards Module The strong assumption behind this module is the recognition of the importance of guidelines and to ensure a common understanding of mitigation actions. The questions are classified between mandatory and voluntary measures, giving bonus scores. The questionnaire is constructed in such a way that looser regulatory regimes are discouraged while beyond-than-required behaviours are prized. The guidelines and standards which guide the rating are:

- Space debris mitigation guidelines;
- Long-Term Sustainability guidelines;
- Space debris mitigation standards and laws;
- Standardised operational products;
- Relevant safety standard, in case of close proximity or rendez-vous operations.

The External Services Module The last module takes into account the predisposition to adopt external services for life extension or removal, with the score contributing to the bonus component of the rating. The activities and classes of operations that are considered are all actions that can be carried out to increase the amenability and to make use of In-Orbit Service (IOS). This option is implemented for fixing, improving and reviving satellites but also refueling, repairing, replacing and removing spacecrafts. Four specific categories of actions are defined:

- IOS features during design and pre-launch phases;
- Standardised IOS features during operations;
- Life extension service;
- Active removal.

A.2. The density distribution function

The density distribution mentioned in 2.1.2 is propagated with reference to the method of characteristics to the continuity equations [49]. At the basis there is the conversion from a partial differential equation to a system of differential equations (A.1).

$$\begin{cases} \dfrac{d\mathbf{y}}{dt} = \mathbf{F} & \text{(A.1a)} \\ \dfrac{dn_x}{dt} = -n_x \nabla_y \cdot \mathbf{F} & \text{(A.1b)} \end{cases}$$

In the system, $\mathbf{F}$ represents the force field, $\mathbf{y}$ is the phase space variables while n_x the phase space density.
The impact rate, called η, characterizing the interaction between a debris cloud and a target object, is retrieved through the fragment flux against the target cross section, A_c. From the Keplerian elements expression of the density $n_{\alpha,\beta}$, defined by α and β, respectively (a, e, i) and (Ω, ω, f), the impact computation is reported in Equation A.2.

$$\eta = A_c \int \int \int_{\mathbb{R}^3} \sum_{k=1}^{4} \frac{n_{\alpha,\beta}(\alpha, \beta^{(k)})}{\| det J^{(k)}_{r \to \beta} \|} \| v_T - v(\alpha, \beta^{(k)}) \| d\alpha \tag{A.2}$$

A.3. The explosion probability indicators

The survival rate and the explosion probability are evaluated by the use of the Kaplan-Meyer, reported in Equation A.3.

$$S(t) = \prod_{t_i < t} (1 - \frac{d_i}{n_i})) \tag{A.3}$$

B | Appendix B

B.1. Number of satellites above a cap

h_z is defined as the height of the zenithal cap, characterized by the position of the satellite at its angular distance from Zenith z (Fig. B.1). The satellites orbits at an altitude of $R_{sat} = R_{sat} + h$.

$$h_z = (R_{Earth} + h)\left(1 - cos\left(z - arcsin\left(\frac{R_{Earth}}{R_{Earth} + h} sinz\right)\right)\right) \tag{B.1}$$

The spacial region identified as the spherical cap above z is computed by Eq. B.2, while the total area of the sphere containing the constellation satellites is expressed by B.3.

$$A_{vis} = 2\pi \left(R_{Earth} + h\right) h_z \tag{B.2}$$

$$A_{tot} = 4\pi \left(R_{Earth} + h\right)^2 \tag{B.3}$$

The number of satellites present in the spherical cap corresponding to z is retrieved by the preceding quantities in Equation B.4.

$$\begin{aligned} N &= N_{cons}\frac{A_{vis}}{A_{tot}} \\ N &= N_{cons}\frac{h_z}{2\left(R_{Earth} + h\right)} \\ N &= N_{cons}\left(1 - cos\left(z - asin\left(\frac{R_{Earth}}{R_{Earth} + h} sinz\right)\right)\right) \end{aligned} \tag{B.4}$$

B.2. The Brightness Model

The apparent magnitude is defined as the brightness of a celestial object, expressed by means of a physical quantity, called visual magnitude. Its measure depends on F, the radiant flux density perceived by the observer eyes, and F_0, referred to the radiation

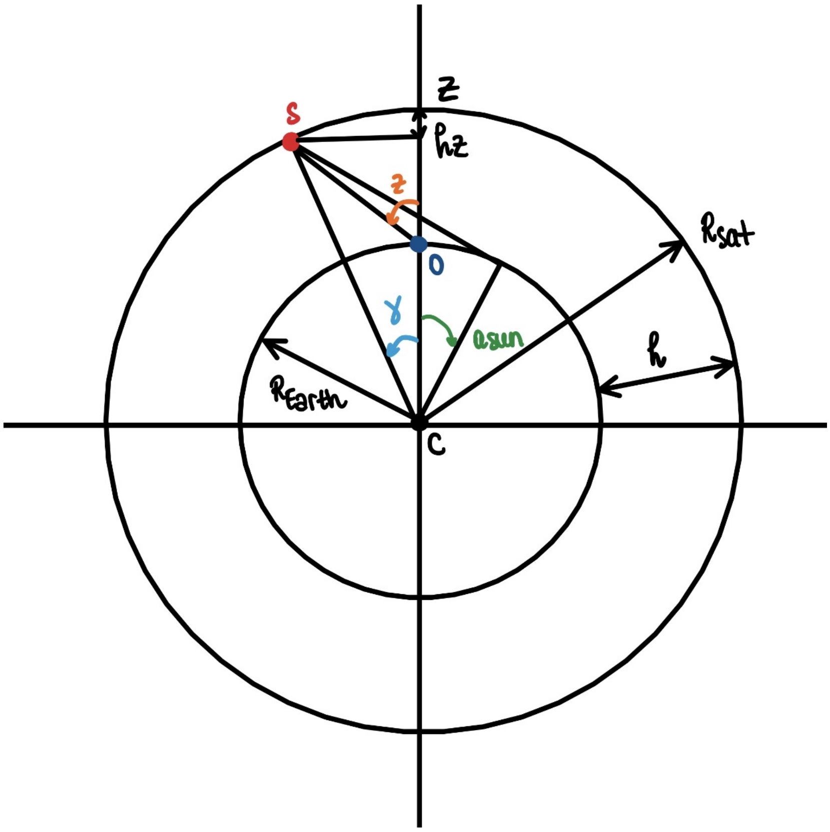

Figure B.1: Graphical representation of vectors and angles for the computation of visible satellites.

coming from the Sun (B.5). The lower the value the brighter the object.

$$m = -26.74 - 2.5log_{10}(\frac{F}{F_0}) \tag{B.5}$$

Photometry applied to planar surface is characterized by the dependence on the attitude of the object. The relative orientation between the source and the observer is fundamental. As the plane attitude plays a fundamental role in the reflection of the incident radiation, its photometric quantities are function of the incident and viewing angles θ_i and θ_r. The integration over the surface of the object is based on the normal vector to the surface, pointing towards a constant direction. The general expression for the elementary radiant intensity given by a certain elementary area dA is given in Equation B.6, where the angles θ_r and ϕ_r are the polar coordinates with respect to a certain point over the surface and $cos(\theta_r)dA$, the projection of the infinitesimal area onto the direction of the observer. For a plane, the angles between the surface's normal and the source and observer directions are constant, so can be extracted from the integral. Taking as reference the Lambert's plane, properly selected as valid rule for the model, the Bidirectional Reflectance Distribution

Function (BRDF) is a constant value (Eq. B.7).

$$dI = L(\theta_r, \phi_r)cos(\theta_r)dA \tag{B.6}$$

$$I(\theta_r, \phi_r) = F_0 \frac{\rho dA}{\pi} cos(\theta_i)cos(\theta_r) \tag{B.7}$$

The consequent radiant flux density and its related visual magnitude can be computed as represented in Equation B.8.

$$\begin{aligned} F(\theta_r, \phi_r) &= F_0 \frac{\rho dA}{\pi r^i} cos(\theta_i)cos(\theta_r); \\ m &= -26.74 - 2.5log_{10}(\frac{\rho dA}{\pi r^i} cos(\theta_i)cos(\theta_r)) \end{aligned} \tag{B.8}$$

The model is extended to three dimensional objects. The body of the spacecraft can be assumed as a prisms composed by six faces, each of them characterised by a normal vector to the surface $\hat{n_j}$, $j = 1, ...6$. At this point, for the j^{th} normal direction, the incidence and viewing angles can be computed and referred to both the sunshine and the Earth-shine contributions. In the Equations B.9 and B.10, $\rho^{(j)}$ and $A^{(j)}$, are the reflectances and surfaces areas.

$$\begin{cases} F^{(j)}_{SC,Sun} = F_0 \dfrac{\rho^{(j)} A^{(j)}}{\pi \|\vec{r_o}\|^2} cos(\theta^{(j)}_i)cos(\theta^{(j)}_r) & \text{(B.9a)} \\ cos(\theta^{(j)}_i) = \dfrac{\hat{n_j} \cdot r_{SC,Sun}^{\rightarrow}}{\|r_{SC,Sun}^{\rightarrow}\|} & \text{(B.9b)} \\ cos(\theta^{(j)}_r) = -\dfrac{\hat{n_j} \cdot \vec{r_o}}{\|\vec{r_o}\|} & \text{(B.9c)} \end{cases}$$

$$\begin{cases} F_E = \dfrac{2}{3} A_E \dfrac{R_E^2 F_0}{\pi \|\vec{r_o}\|^2} (sin\alpha_E + (\pi - \alpha_E)cos(\alpha_E)) & \text{(B.10a)} \\ F^{(j)}_{SC,E} = F_E \dfrac{\rho^{(j)} A^{(j)}}{\pi \|\vec{r_o}\|^2} cos(\theta^{(j)}_{i,E})cos(\theta^{(j)}_r) & \text{(B.10b)} \\ cos(\theta^{(j)}_{i,E}) = -\dfrac{\hat{n_j} \cdot \vec{r}}{\|\vec{r}\|} & \text{(B.10c)} \\ cos(\theta^{(j)}_r) = -\dfrac{\hat{n_j} \cdot \vec{r_o}}{\|\vec{r_o}\|} & \text{(B.10d)} \end{cases}$$

Equation B.9 refers to the sunshine while Equation B.10 refers to the Earth-shine. In the expressions, $r_{SC,Sun}^{\rightarrow}$ is the vector describing the location of the Sun with respect to the spacecraft. It is calculated from $r_{Sun}^{\rightarrow}$, extracted by using *planetEphemeris* function

on Matlab, and $\vec{r}$ the radial vector linking the satellite with the Earth Centered Inertial (ECI) reference frame, as $\vec{r_{SC,Sun}} = \vec{r_{Sun}} - \vec{r}$.
The site position vector $\vec{r_c}$, reflecting the observer location, depends on its specific longitude and latitude, and computed through *lla2eci* Matlab function. The relative position vector of the satellite with respect to the observation position is obtained as vectorial relationship $\vec{r_o} = \vec{r} - \vec{r_c}$.
A_E is the Earth's albedo mean value of 0.37, while the Earth phase angle (Eq. B.11) is defined as the angle between the Sun's position with respect to the Earth ($\vec{r_{Sun}}$) and the satellite orbital location ($\vec{r}$). $\theta_{i,E}$ represents the incidence angle, as the angular distance between the Earth position with respect to the satellite and the normal direction to the panel.

$$\alpha_E = acos(\frac{\vec{r} \cdot \vec{r_{Sun}}}{\|\vec{r}\|\|\vec{r_{Sun}}\|}) \tag{B.11}$$

Solar arrays and antennae respect the 2D-planar model. The first are assumed Sun-pointing, mounted on the spacecraft by means of 3D joints. The solar array normal vector points towards the direction of the Sun $\hat{n_{SA}} = \frac{\vec{r_{SC,Sun}}}{\|\vec{r_{SC,Sun}}\|}$.
Same considerations for the antenna contribution, They are modelled to be generically oriented in the space. In this analysis the nominal-operative case is taken into account, so observer-pointing $\hat{n_{Ant}} = -\frac{\vec{r_o}}{\|\vec{r_o}\|}$.
The photometric quantities are computed by following the steps shown in Equations B.9 and B.10. Finally, the visual magnitude of the complex 3D prism-solar panel can be estimated as in Equation B.12

$$m = -26.74 - 2.5log_{10}(\frac{\sum_{j=1}^{6} F_{SC,Sun}^{(j)} + F_{SC,E}^{(j)}}{F_0}) \tag{B.12}$$

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