FROM ANALYSIS TO ACTION: INSIGHTS AND NOVEL TOOL DEVELOPMENT FOR SPACE DEBRIS MITIGATION REPORTS

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ABSTRACT

Space debris presents a significant challenge to the long-term sustainability of space activities. The Independent Safety Office at the European Space Agency (ESA) plays a pivotal role in addressing this issue through the development of standards that promote sustainable space operations via the support and monitoring of their application within ESA. Since 2023, as part of ESA's Zero Debris Approach, ESA has adopted new space debris mitigation requirements [1], which include not only more stringent thresholds, but also novel analyses. For this reason, a new initiative was defined to create reference Space Debris Mitigation Plans and Reports (SDMP and SDMR) for CubeSats and small spacecraft constellations. These reports serve to demonstrate compliance with ESA's Space Debris Mitigation (SDM) requirements [1], complementing the SDM Handbook [2] by providing a structured framework for adherence to the latest standards.

Examples of the requested analyses will be presented alongside the available references and tools, as well as the description of specific developments to address the newly introduced requirements for Dark & Quiet Skies [3]. In particular, a computational pipeline has been developed to efficiently calculate albedo using empirical observational data. This integration provides small satellite developers with realistic and accessible albedo values, ensuring a comprehensive assessment of compliance with brightness standards, while supporting the mitigation of adverse impacts on ground-based astronomy.

Finally, in the preparation of the reference documents, a multi-functional interactive chatbot was also developed. Designed to support seamless compliance with ESA's SDM requirements, this chatbot serves as an intelligent assistant for mission designers and operators. Its capabilities include real-time guidance on ESA standards and requirements, numerical result support for some mission scenarios, and assistance with frequently encountered challenges during compliance verification. In addition, it offers a flexible framework to address evolving needs in mission planning and sustainability, ensuring it remains a versatile and invaluable resource for operators. These features, along with its potential for further expansions, make it an innovative tool in streamlining space debris mitigation efforts, hence fostering sustainable practices in space operations and the adoption of ESA's Zero Debris approach.

Keywords: Space debris, CubeSat, Small Satellite, Space Debris Mitigation Plan (SDMP), Space Debris Mitigation Report (SDMR), European Space Agency (ESA), Dark & Quiet Skies (DQS), Albedo Calculation, Compliance Assessment, Chatbot.

1. INTRODUCTION

1.1. Motivation and Background

The growing congestion of Earth's orbital environment, driven by non-operational satellites, spent rocket stages, and fragmentation debris, continues to raise the risk of collisions and other hazards in space [4]. In response to these challenges, the European Space Agency (ESA) has reinforced its Space Debris Mitigation (SDM) requirements as part of the Zero Debris Approach [1]. These updated standards introduce more stringent criteria across several aspects of mission planning and design.

While these new requirements lay out a robust framework for sustainable operations, applying them in practice is not always straightforward. Some provisions, especially those that call for novel types of analysis, can pose practical difficulties for mission designers and operators.

1.2. Objectives and Scope

To support the transition towards the updated standard, this paper introduces reference templates and tools designed to help missions produce Space Debris Mitigation Plans (SDMPs) and Reports (SDMRs) in line with ESA's latest requirements. The aim is threefold:

- Present the reference SDMP/SDMR documents and

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explain how they help demonstrate compliance with ESA's current SDM standard;

- Highlight two specific tools developed during this work: (i) an albedo calculation pipeline that supports compliance with brightness regulations, and (ii) an interactive chatbot that helps mission developers understand and apply the relevant mitigation requirements;
- Share insights gained during development and propose possible future improvements to support a smoother transition to ESA's Zero Debris standard.

Ultimately, these tools are meant to simplify compliance efforts and reduce ambiguity, especially for missions operating under tight development timelines or limited resources while contributing to a safer and more sustainable orbital environment.

2. DEVELOPING REFERENCE SDMP/SDMR

ESA's updated Space Debris Mitigation Requirements cover a broad range of mission design considerations, making clear, mission-specific documentation essential for consistent and efficient compliance. In parallel with the latest updates to the Space Debris Mitigation Handbook [2], new reference versions of the Space Debris Mitigation Plan (SDMP) and the Space Debris Mitigation Report (SDMR) have been developed. These templates aim to guide mission developers through the revised standard and ease the often time-consuming task of demonstrating compliance.

2.1. Motivation for Reference Documents

Each reference template provides the following:

- **Structured Layout:** Each section corresponds to a specific branch of requirements in ESSB-ST-U-007 [1], providing a ready-made framework for presenting key analyses (e.g., orbital lifetime, collision risk) and compliance planning.
- **Concrete Examples:** Sample tables, text fragments, and verification methods illustrate how to document compliance with every relevant provision, reducing ambiguity for first-time satellite operators.
- **Scalability Across Mission Types:** While initial templates focus on specific mission classes, additional references will be introduced over time to cover a wider range of spacecraft designs and operational scenarios.

2.2. Availability and Future Updates

These reference documents will be available through ESA's official channels, offering a consistent approach to compliance while remaining adaptable to different mission needs. As new mission profiles emerge, additional templates will be released to reflect their specific constraints and operating conditions always within the same structured framework inspired by the Zero Debris Approach.

Over time, this growing set of reference documents will give developers a reliable starting point for their compliance work, while encouraging more uniform application of ESA's SDM requirements across the industry.

3. IDENTIFYING COMPLIANCE GAPS

ESA's revised Space Debris Mitigation (SDM) requirements offer a solid and comprehensive framework, but translating them into mission-level compliance makes the user encounter some challenges. While developing the updated SDMP/SDMR reference documents, two key issues were faced.

3.1. Absence of a Standardized Method for Albedo Estimation

New visibility requirements, introduced under initiatives like Dark & Quiet Skies [3], require missions to assess their apparent brightness and, where needed, apply mitigation strategies. A central parameter in this evaluation is albedo, the proportion of sunlight reflected by the spacecraft. This parameter depends on several factors: surface materials, geometry, attitude, and more.

Estimating albedo accurately is a complex and often costly task. It requires either dedicated simulations or detailed material and geometry characterizations, which are not always feasible, especially for small missions with limited budgets or early-stage designs. As a result, many developers either rely on rough assumptions or omit the analysis altogether, which can lead to inaccurate brightness assessments or overly conservative sizing of mitigation measures. To support these missions, a pipeline was developed to provide realistic, mission-specific albedo values based on in-orbit brightness observations.

3.2. Complexity in Navigating Interrelated SDM Requirements

Another challenge lies in the complexity of the requirements themselves. The latest ESA standard introduces a growing number of interrelated requirements, and navigating them is far from straightforward. Many requirements depend on several factors at once, such as orbital altitude, propulsion capability, or mission duration, making compliance highly context-dependent.

This can be particularly overwhelming in the early design phases, when mission parameters are still evolving. A change to one subsystem can have ripple effects across several requirements, each with its own thresholds and verification conditions, and this may lead to a cascading effect as it can affect other related requirements. Without a systematic way to navigate these dependencies, compliance assessments can become time consuming, lead to inconsistencies in the design or omission of critical constraints.

To address this, an interactive compliance chatbot was developed. It helps developers navigate the standard by mapping requirements to mission parameters and automating common verification tasks, making the process more intuitive and efficient.

4. ALBEDO ANALYSIS FOR "DARK & QUIET SKIES"

As discussed in Section 3.1, deriving realistic albedo values is not trivial, especially given the lack of standardized methods and the variability in existing observational datasets. To address this gap, a computational pipeline was developed to estimate albedo values by combining real brightness observations with mission-specific data. This approach offers satellite operators a practical way to generate consistent, reliable estimates improving the transparency and credibility of their compliance assessments.

4.1. Data Sources and Preprocessing

The albedo estimation pipeline is based on two data sources, correlated using each satellite's NORAD ID:

1. **Satellite brightness observations:**, obtained from a public tracking database. Each observation includes:
    - Observed magnitude, indicating the apparent brightness of the satellite.
    - Distance between the observer and the satellite.
    - Phase angle, which accounts for the Sun-satellite-observer geometry.
2. **Cross-sectional area:**, retrieved from the catalog DISCOSweb (Database and Information System Characterising Objects in Space). A web interface that provides publicly accessible metadata on space objects, including geometry, launch information, and status.

By merging these datasets, each brightness observation is matched with its spacecraft characteristics for subsequent computations.

4.2. Filtering for CubeSats

Since the analysis is focused, in this case, on CubeSats, a filtering condition is applied: only satellites with an average cross-sectional area $\text{Avg}_X \leq 0.15\,\text{m}^2$ are retained. This criterion ensures that the dataset represents a population of CubeSats typically from 1U to 3U). Entries with missing or invalid data are also discarded.

4.3. Albedo Computation Process: Lambertian Reflection Model

The estimation of albedo follows a Lambertian reflection model, which assumes that the satellite surface reflects light diffusely rather than specularly. The albedo calculation relies on observational data, specifically the apparent magnitude recorded for a given satellite, its topocentric distance, and the phase angle at the time of observation.

The first step in the process is calculating the observed irradiance of the satellite, E_{Sat}, which is computed based on its apparent magnitude relative to the Sun. This relationship is expressed as:

$$\frac{E_{\text{Sat}}}{E_{\text{Sun}}} = 10^{\frac{m_{\text{Sun}} - m_{\text{Sat}}}{2.5}}. \tag{1}$$

where m_{Sun} is the apparent magnitude of the Sun and m_{Sat} is the recorded satellite brightness. The observed irradiance is then linked to the satellite's reflectivity function, f_{r}, using the Lambertian model:

$$f_{\text{r}} = \rho \cdot \frac{A}{\pi} \cdot \frac{1 + \cos(\theta)}{2}. \tag{2}$$

where ρ represents the geometric albedo, A is the cross-sectional area, and θ is the phase angle. Since irradiance decreases with the square of the topocentric distance R, it follows that:

$$E_{\text{Sat}} = \frac{f_{\text{r}}}{R^2}. \tag{3}$$

By substituting the reflectance function into this equation and solving for albedo:

$$\rho = \frac{E_{\text{Sat}} \cdot R^2 \cdot \pi}{A \cdot \left(\frac{1+\cos(\theta)}{2}\right)}. \tag{4}$$

4.4. Results and Statistical Analysis

The following key statistical measures were obtained:

- Mean albedo: ≈ 0.2287
- Median albedo: ≈ 0.1666
- Standard deviation: ≈ 0.1796

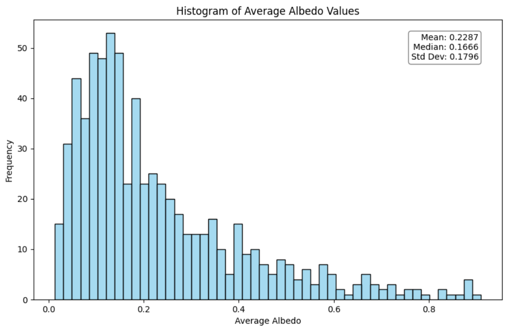

Figure 1. Histogram of derived albedo values for analysed satellites.

The computed median albedo of 0.1666 provides a practical reference for CubeSat missions evaluating their brightness against Dark & Quiet Skies recommendations. By incorporating real-world observational data, this approach offers a more realistic and accessible solution for evaluating brightness impacts.

5. CHATBOT DEVELOPMENT: MANAGING PARAMETERS AND SUBSYSTEMS FOR COMPLIANCE

As discussed in Section 3.2, understanding how different mission parameters interact with ESA's requirements can be challenging, especially given the number of interrelated requirements. To address this issue, a structured dependency matrix was created and embedded within an interactive chatbot. This combination provides mission developers with a practical tool to navigate ESA's mitigation standard more efficiently and consistently, particularly during early design phases.

5.1. Dependency Matrix Development

The dependency matrix maps key mission parameters and subsystems, extracted from documents such as ESSB-ST-U-007, ESSB-HB-U-002, and the SDMP/SDMR, to the specific requirements they influence. Each row corresponds to a parameter (e.g., altitude, propulsion, power system), and each column to an ESA requirement. Then, inside the table, the relevant cells contain each a short justifications that explain the link between eachother.

5.2. Integration into an Interactive Chatbot

While the matrix provided a complete picture of these dependencies, its static format limited its usability. To improve it, the matrix was integrated into an interactive chatbot. The goal was to make it easier for users to access and understand the requirements that applied to their mission, without needing to manually trace each dependency. The chatbot then allows users to input a parameter or subsystem and receive a list of corresponding requirements, along with concise explanations of how each one applies. This approach transforms a dense dataset into a tool that can support real-time decision-making during compliance assessments.

5.3. Full Development of the Chatbot

What began as a basic prototype has since evolved into a more capable tool. This shift was driven by the need for greater interactivity and adaptability. Its main features now include:

Parameter and Subsystem Query: As explained above, when a user inputs a mission parameter or subsystem, the chatbot retrieves all ESA requirements influenced by the input along with detailed justifications.

Requirement Identifier Lookup: Users can input a specific ESA requirement identifier to obtain the text of the requirement from the standard, including its context, description, and any associated notes.

Brightness Calculation Assistance: The chatbot also includes a step-by-step brightness calculator. By entering the values of altitude and cross-sectional area, users can estimate apparent magnitude under worst-case conditions.

5.4. User Interaction and Data Management

The chatbot operates on a structured backend that enables efficient querying and response generation. It draws from two main datasets: one containing the parameter-to-requirement mappings and another with detailed descriptions of each ESA requirement. When a user submits a query, the chatbot processes it by identifying the intent, standardizing terms through synonym mapping, and retrieving the relevant information. This setup allows for flexible, accurate interactions and ensures that the tool remains usable even when input terminology varies across users.

5.5. Significance and Future Developments

Looking ahead, future developments may focus on expanding the range of supported queries and improving natural language understanding. Integrating real-time data from ESA systems and enhancing the brightness calculation module with more advanced modeling could further improve the tool's accuracy and relevance. As the SDM standard continues to evolve, the chatbot's flexible structure ensures it can grow with it.

6. CONCLUSIONS

Working with ESA's updated Space Debris Mitigation (SDM) requirements has made it clear that while the new standard is comprehensive, applying it in practice still comes with challenges, especially for missions with limited time or resources. The goal of this work was to support that process by developing tools that are not only technically correct, but actually helpful for the people using them.

The reference SDMP and SDMR templates were built to make compliance more straightforward and less ambiguous. By structuring the documents around the standard itself and including concrete examples, they aim to reduce uncertainty, especially for developers navigating the process for the first time.

A notable challenge was the lack of a consistent approach to albedo estimation. To address that, a computational pipeline was developed, integrating real brightness observations with mission-specific data. This approach helps mission designers produce reliable albedo values and ensure they meet visibility constraints under the Dark & Quiet Skies initiative.

Meanwhile, coping with overlapping SDM requirements also posed challenges, especially as missions move through different design phases. The interactive chatbot offers a direct response to this issue, allowing developers to query requirements in real time and receive straightforward guidance tailored to their parameters.

Each of these tools were developed with the goal of easing requirement integration into the development process. Although a necessary first step, these tools are currently at a rudimentary stage and have a large capacity for enhancement. As these tools improve to incorporate more efficient models and additional missions types, they must continue to align with ESA's Zero Debris goals.

Looking ahead, there are several areas where this work will continue to evolve. For the reference documents, upcoming efforts will focus on adapting the templates to support a wider range of mission types. On the albedo side, future versions of the pipeline could incorporate additional observational data and improve the reflectivity model to better account for diverse surface properties. As for the chatbot, the next step would be to connect it with live mission data, automate parts of the compliance verification process and expanding the chatbot's scope to include deeper compliance checks. Additionally, the possibility of testing the chatbot in real mission scenarios would provide valuable feedback and help refine it based on actual user needs and behavior.

By continuing to refine these solutions, we move closer to a future where meeting SDM standards is not just a regulatory box to check, but a seamless part of building and operating responsible missions in space.

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