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OKAPI:Soteria – For a New Era of Mission Analysis

Frederik Läufer^{a*}, Christopher Kebschull^b, Alessandra Gallucci^c

^a OKAPI:Orbits GmbH, Rebenring 33, Braunschweig, Germany, frederik@okapiorbits.com

^b OKAPI:Orbits GmbH, Rebenring 33, Braunschweig, Germany, christopher@okapiorbits.com

^c ale.gallucci@outlook.com

* Corresponding Author

Abstract

In an increasingly congested space environment, satellites are launched into already crowded regions like the LEO-protected region. Over the past 3 years guidelines and mitigation recommendations have been derived to reduce the risk of creating more space debris. At the same time, the issue has gained increasing importance among policymakers around the globe. This has led to setting regulatory frameworks that changes how the industry operates, to ensure a responsible and long-term use of space. Requirements, like ESA's Space Debris Mitigation Requirements as part of the document ESSB-ST-U-007, the Zero Debris Charter, or NASA's Orbital Debris Mitigation Standard Practices (ODMSP) gain traction as part of broader regulation for space actors, through the US FCC, or the upcoming EU space law. Before launching or providing services to respective economic zones, satellite operators need to comply with said regulations. For a demonstration of the fulfilment of the requirements, documentation is needed showing compliance with respective measures, capabilities, and plans, which require specific expertise on the space debris topic.

To support mission designers and operators, OKAPI:Orbits has developed a new design optimization platform called OKAPI:Soteria. It allows to size and optimize the design of a mission as a response to the new and upcoming needs in space traffic management and space debris mitigation, as well as ensuring mission's compliance with all relevant space debris mitigation requirements. A vast range of analysis can be performed with the tool, going from *Orbital environment analysis* to *Light pollution analysis*. The analyses include assessing the orbital population satellites, or entire constellations, will encounter in each mission phase, its interaction with neighbouring constellations, the number of collision avoidance manoeuvres that can be expected to be performed annually, and, therefore, the required propellant to allocate for those Delta-V needs. Moreover, studies concerning how to best de-orbit the satellite(s) and assessing the magnitude of it are also integrated.

In conclusion, this paper outlines the importance of including Space Traffic Management in the earliest stages of the project, and to involve key operational aspects in the design to optimize key parameters of the mission. An overview of the existing guidelines will be provided, focusing on space debris mitigation requirements. Furthermore, it highlights the importance of considering space debris mitigation requirements to assure compliance with current regulations and to promote a sustainable use of space.

Keywords: Mission Design, Space Debris, Requirements, Regulation, Compliance, Guidelines

Acronyms/Abbreviations

ACPL	Accepted Collision Probability Level
ARES	Assessment of Risk Event Statistics
DAS	Debris Assessment Software
DMF	Debris Mitigation Facility
DRAMA	Debris Risk Assessment and Mitigation Analysis
GEO	Geostationary Orbit
GUI	Graphical User Interface
IADC	Inter-Agency Space Debris Committee
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MIDAS	MASTER (-based) Impact Flux and Damage Assessment Software
LEO	Low Earth Orbit
ODMSP	Orbital Debris Standard Practices
OSCAR	Orbital SpaceCraft Active Removal
ORDEM	Orbital Debris Engineering Model

PROOF	Program for Radar and Optical Observation Forecasting
SARA	Re-entry Survival and Risk Analysis
SDMR	Space Debris Mitigation Requirements
STELA	Semi-analytic Tool for End of Life Analysis software

1. Introduction

For the first 60 years of human spaceflight, mainly two actors (USA and the former Soviet Union / Russia) were the main actors of near-Earth space. Space missions were complex undertakings, funded by a nation state and executed by space agencies together with industry partners. After 30 years the accumulation of space debris became apparent, in LEO and GEO. In the 1990s the IADC (Inter-Agency Space Debris Committee) came together and as part of its activities, studies were performed for the long-term sustainability of space missions resulting in space debris models and ultimately leading to the first derived guidelines for space missions to reduce the creation of space debris. Space agencies committed resources to create tools around these models to simulate and assess the compliance of their missions towards these mostly internal guidelines.

With the increase of commercial activities in space the need for broader applicable guidelines in the form of applied standards and space laws, enforced by nation states towards their space industry, are needed. The tools that are available from the agencies are aimed towards compliance verification of their own missions. Over the past years much work has been performed to maintain and improve these tools alongside the evolving standards. ESA put in place the Debris Mitigation Facility (DMF) projects [1], [2], [3] as part of the Space Safety program to modernize the software stack, focusing on advanced analysis capabilities to verify new requirements.

To align the much need space debris mitigation requirements (SDMR) verification process with the design and manufacturing pace of commercial companies, the Soteria platform has been developed around the existing DMF tooling with the aim of simplification and scalability.

2. Space Debris Mitigation Requirements

As part of the IADC, which is constituted of 13 members: Agenzia Spaziale Italiana (ASI), Centre National d'Études Spatiales (CNES), China National Space Administration (CNSA), Canadian Space Agency (CSA), German Aerospace Center (DLR), European Space Agency (ESA), Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), Korea Aerospace Research Institute (KARI), National Aeronautics and Space Administration (NASA), State Space Corporation ROSCOSMOS, State Space Agency of Ukraine (SSAU), and UK Space Agency the first mitigation guidelines have been derived and formulated to be part of the Space Debris Mitigation Guidelines, released in 2007. It was compiled based on work performed during the 1990s and early 2000s [4].

Multiple standards and practices have been developed, including the ISO 24113 standard, on which ESA's ESSB-ST-U-007 [5], and JAXA Space Debris Mitigation Standard (JSDMS) [6] build, the French Space Operations Act (FSOA) [7], and the US Government's Orbital Debris Mitigation Standard Practices (ODMSP) [8]. They contain requirements and mitigation measures for satellite & mission designers, as well as satellite operators to be taken during the design and operational phases.

All of them contain definitions for example protected regions (LEO & GEO) as well as requirements to ensure a limitation of the orbital lifetime after end of mission (e.g. “5-year rule”, “25-year rule”), limit the probability of accidental collision, and to reduce the on-ground casualty risk from a re-entering satellite. The wording is different in all documents but aimed at similar outcomes applicable for spacecraft and launchers:

- ESSB-HB-007 / ISO 24113:2023 requirements structured into the subclauses:
 - Space debris release restriction,
 - Avoiding break-ups in Earth orbit,
 - Disposal,
 - Re-entry,
 - Dark and quiet skies,
 - Lunar orbits
- U.S. Government Orbital Debris Standard Practices (ODMSP) objectives:
 - Objective 1: Control of Debris released during normal operations,
 - Objective 2: Minimizing Debris generated by accidental explosions,
 - Objective 3: Selection of safe flight profile and operational configuration,
 - Objective 4: Post mission disposal of space structures
 - Objective 5: Clarification and additional standard practices for certain classes of space operations,

- French Space Operations Act (FSOA) contains articles, of which the following correspond to:
 - Article 20 on launch and re-entry risks, and Article 44 for casualty risk,
 - Article 21.1: Avoiding release of launcher elements into orbit,
 - Article 21.2: Ensure re-entry safety of launch MROs,
 - Article 21.5: Protected region clearance – LEO,
 - Article 21.6: Protected region clearance – GEO,
 - Article 40.1: Avoiding release of MRO,
 - Article 40.4: Protected region clearance – LEO,
 - Article 40.5: Protected region clearance – GEO.

Alongside the requirements documents are available that provide descriptions the assessment of compliance, as included in NASA-STD-8719.14C, which aligns with the ODMSP of 2019 [9] and ESA's ESSB-ST-U-007 [5]. The latter includes newly derived requirements based on the Dark and Quiet Skies for Science and Society - Report and recommendations as well as for space operations on Lunar orbits, limiting space debris creation, promoting space traffic coordination and proper disposal of spacecraft or launch vehicle.

3. Available Tools

Accompanying the documents, agencies make available tools to verify compliance with these requirements. ESA provides its MASTER & DRAMA tool suite, CNES makes available STELA and NASA ORDEM & DAS.

3.1 MASTER

ESA created the Meteoroid And Space debris Terrestrial Environment Reference (MASTER) in the beginning of the 1990s to better understand the near-Earth environment, focusing on meteoroids and space debris. The first beta version available from 1995 [10]. It describes the statistical population, that discriminates the debris sources (launch and mission related objects, explosion and collision fragments, solid rocket motor slag etc.) into bins and derives the debris flux (in $1/(m^2a)$) and spatial density (in $1/km^3$). It provides a flux browser to process and visualize the data for different orbital regimes. The latest version is MASTER-8, released in 2019 [10].

3.2 DRAMA

Based on the insight that the MASTER population can give on the space debris environment a companion software suite has been developed called DRAMA (Debris Risk Assessment and Mitigation Analysis). Its purpose is to support satellite and mission designers to assess the effectiveness of debris mitigation strategies, calculate the statistical risk posed by debris on the spacecraft and caused by the re-entry on ground. For this purpose, the following analysis modules are available as part of DRAMA [11]:

- ARES (**A**ssessment of **R**isk **E**vent **S**tatistics), assesses collision event statistics between operational spacecraft and the trackable object population. It can calculate the mean conjunction avoidance manoeuvres and the associated fuel consumption.
- MIDAS (**M**ASTER-based **I**mpact **F**lux and **D**amage **A**ssessment), performs damage analysis on defined surfaces in space. The MASTER population is used to derive the flux on the surfaces and estimate the number of impacts, probability of collision. By using ballistic limit equations (BLE) associated with those surfaces the number and probability of penetration can also be assessed.
- OSCAR (**O**rbital **S**pacecraft **A**ctive **R**emoval), is able to estimate the remaining orbital lifetime of space objects and also derive the delta-V needed to reach a target orbit. OSCAR supports various means of disposal, including chemical and electrical propulsion systems, electrodynamic tethers and drag augmentation systems.
- CROC (**C**ross **S**ection of **C**omplex **B**odies) allows to model a satellite using 3D primitives. It can then compute the cross-sectional area of the structure from various aspect angles and
- SARA (**R**e-entry **S**urvival and **R**isk **A**nalysis) can compute the re-entry trajectory of a space object through Earth's atmosphere to the ground. Based on the fragments that survive and their trajectories, it calculates the risk for the on-ground human population.

The first DRAMA version 1.0 has been developed from the early 2000s. DRAMA 2.0 followed in 2014 with upgrades to all analysis modules except SARA and a new graphical user interface [12]. Its latest iteration (DRAMA 3.1.1) became available in November 2024. The DRAMA 3 iterations added a more complex re-entry analysis and minor updates to the other analysis modules and user interface [11] [13].

In DRAMA 4.0, which is currently being developed, MASTER and DRAMA are combined in a common framework. The aim of the development is to simplify the input definition from the tool-centric approach of previous DRAMA and MASTER versions to a mission-centric approach. Users of DRAMA must define their mission and satellite for every analysis module separately. However, in many cases the different analysis modules need to use the same input in a slightly different way. DRAMA 4.0 lets users define multiple satellites and mission phases. It also allows parametric analyses with slightly different settings. As a new feature DRAMA 4.0 introduces workflows to perform compliance checks for ESSB, FSOA, and ODMSP requirements.

3.3 ORDEM

The Orbital Debris Engineering Model (ORDEM) has been developed by NASA and is currently available in version 3.2. Like MASTER it has been created to describe the near-Earth environment and has similar functionalities. However, both follow different modelling philosophies. The underlying populations describing the environment show similarities and agreement where data coverage of objects on orbit is good [14]. ORDEM and MASTER can estimate the collision flux, which is the object flux on surfaces of space missions and other objects. The flux as output of the model is used to compute the collision probability over the mission lifetime.

3.4 DAS

The Debris Assessment Software (DAS) is available alongside ORDEM and provided by NASA with the purpose to assess a space missions compliance with NASA requirements for reduction of space debris. The orbital debris assessment (ODA) is supported by DAS and defined in NASA Technical Standard 8719.14 [9]. DAS and DRAMA are created for the same purpose and offer similar functionalities. While DRAMA is a tool suite bundling different analysis modules (ARES, MIDAS, OSCAR, CROC, SARA) in the backend, DAS offers these functionalities in one software package executable, including a graphical user interface. DAS provides multiple analysis modes, including

- Orbit evolution analysis, which propagates and visualizes altitude over time and also estimates the orbit lifetime, including a LEO dwell time.
- Post mission disposal manoeuvres and manoeuvres to storage orbits, visualized with plots showing multiple altitudes over time with contours of delta-vs.
- Cross-sectional area calculations as inputs for the analyses.
- Re-entry survivability analysis, that allows the definitions of objects and materials and generates as an output table containing demise altitude, casualty area and kinetic energy for reach object.

The requirements assessment yields a compliance indicator for each requirement and covers debris passing through LEO dwell times, debris passing near GEO, a collision probability estimation for multiple objects and an estimation of post mission disposal failures, identification of critical surfaces, including probabilities of penetration.

3.4 STELA

In line with the FSOA, CNES developed the Semi-analytic Tool for End of Life Analysis software (STELA) [15]. Its purpose is to allow the user to assess the compliance with the requirements stated in the FSOA for its four main criteria:

- C1: Lifetime under 25 years,
- C2: No LEO crossing within 100 years,
- C3: No GEO crossing between 1 and 100 years,
- C4: No GEO crossing within 100 years.

STELA contains a propagator that can be configured with advanced parameters. Simulations are running in an iterative manner. In line with ORDEM and DRAMA, it also provides a helper to determine the mean cross sections aimed at drag and reflectivity areas using complex definitions of bodies based on shapes and dimensions of their surfaces. The compliance output is given in a report summary, showing the thresholds for compliance or non-compliance supported by plots.

4. Soteria Mission Design Platform

The Soteria mission design platform is aimed at simplifying the verification process with an easy-to-use graphical user interface that allows for the definition of mission phases and different satellite configurations with their respective parameters as part of projects. The user can select space debris mitigation requirements to check compliance with running the respective analysis, including the use cases:

- Orbit environment analysis,
- Satellite failure impact analysis,
- Conjunction analysis,
- Collision avoidance strategies,
- De-orbiting strategies,
- Re-entry analysis,
- Debris impact analysis, and
- Light pollution analysis.

In a manual approach the analysis requires setting up a toolchain that needs to run iteratively. The Soteria platform uses workflows based on the DRAMA 4.0 software to produce the results and processes them further aligned the needed values for the verification. Documents are produced for the user to understand the reasoning and use it as input for their obligations towards authorities. In the following the conjunction analysis and collision avoidance strategies analysis are discussed, followed by the debris impact and de-orbiting analysis.

Conjunction Analysis

With the simulation of the space debris environment that a spacecraft will face within its lifetime, it is possible to estimate the expected number of manoeuvres required to avoid potential collisions. The analysis will cover the following requirements:

- Collision risk management for proximity operations and formation flying ESSB 5.3.3.4 b, c, d and
- Collision with large objects during orbital lifetime: ODSMP 3.1.

As a result, the most suitable Accepted Collision Probability Level (ACPL) is determined as well as the required delta-V. The ACPL determines when conjunction risk requires a manoeuvre. The following Figure 1 shows the relationship between the ACPL, and the number of manoeuvres expected for a mission phase, while providing a recommended ACPL in accordance with ESA ESSB-ST-U-007 guidelines.

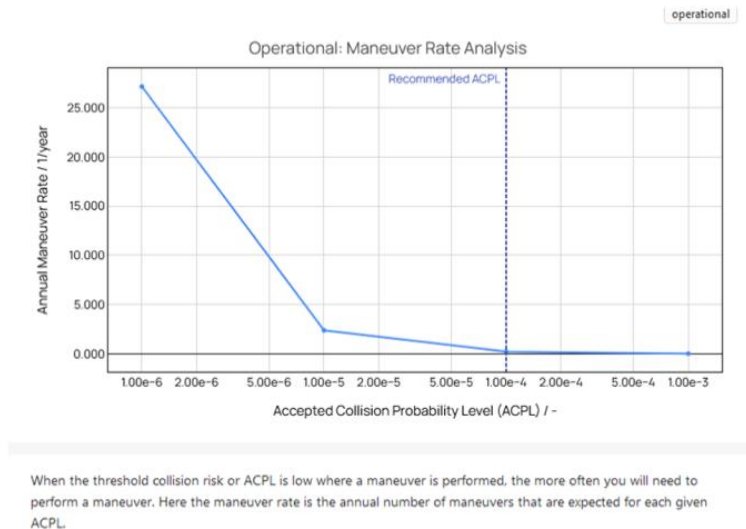


Figure 1 Screenshot showing Soteria conjunction analysis manoeuvre rate plot for the operational (nominal) mission phase.

The collision risk with different objects will be evaluated. This includes the collision probability with:

- objects larger than 1 cm,
- meteoroids and debris between 1 mm and 1 cm.

Based on the mission phase, the expected number of collision warnings and avoidance manoeuvres for single satellites and the entire constellation will be estimated. The iterative and parametric approach regards the number of revolutions before a conjunction event the avoidance manoeuvre should be performed. The necessary parameters for the mission phases will be provided by the user. An example of a typical mission profile might be:

1. The deployment orbit for up to 30 days.
2. The nominal operational orbit for up to 7 years,
3. The PMD (Post Mission Disposal) orbit until the re-entry of the spacecraft into Earth's atmosphere.

The relevant collision flux is evaluated based on the latest available space debris population. The collision probability is computed for several different configurations of the satellite, considering different debris sizes, presented and assessed graphically. Figure 2 shows the resulting annual delta-v budgets required for spacecraft, based on the chosen ACPL. The outputs will provide an analysis of the collision flux (1/m²/duration) on objects in the orbits of interest as well as the collision probability for different configurations of the satellites (%/year and %/mission lifetime), both for single satellite missions and full constellations. Additionally, the results will include an analysis of the debris flux characteristics, in terms of statistics over different impactor sizes, impact directions etc. A definition of the ACPL and its consequences on the mission parameters, namely the number of expected collision warnings, number of collision avoidance manoeuvre, their impact on the reduced risk and spent fuel in each mission phase.

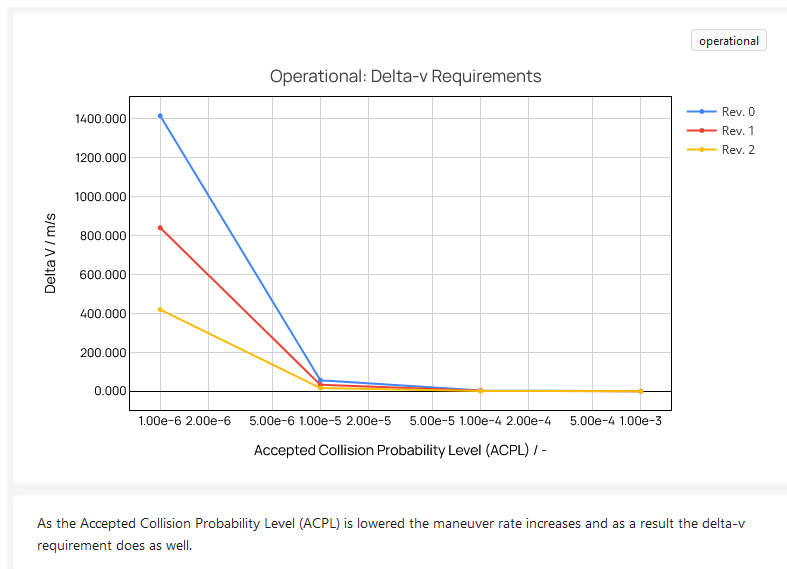
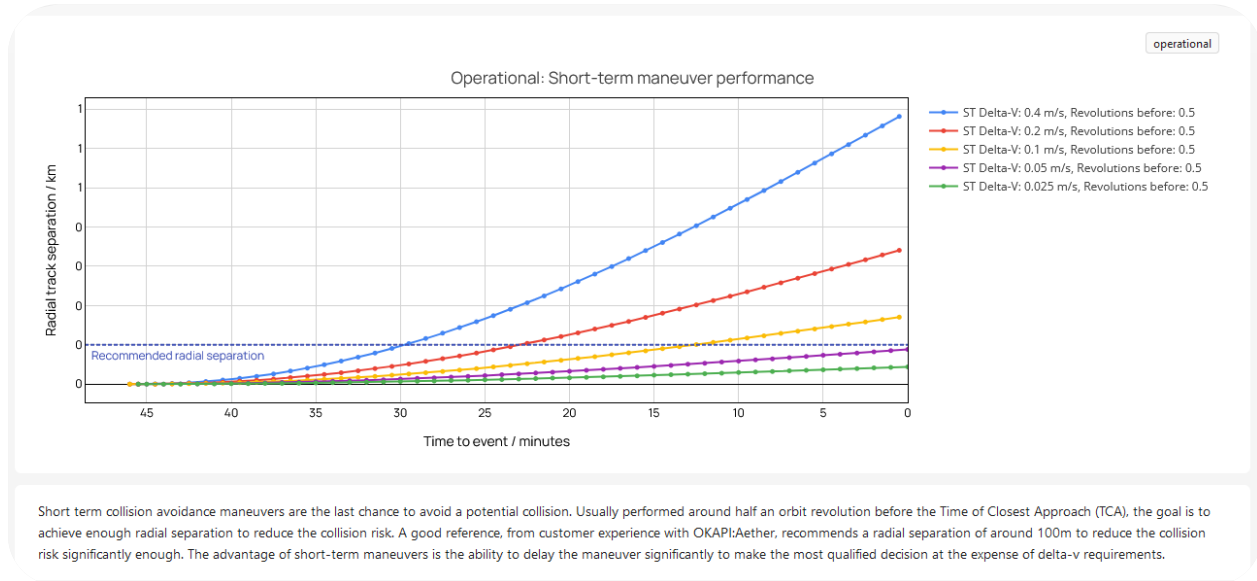


Figure 2 Screenshot showing delta-v requirements for different ACPLs in the Soteria GUI

Collision avoidance strategies

As an extension to the conjunction analysis, the impact of different collision avoidance strategies on the delivered service is analysed, namely the long-term and short-term strategies. Where a long-term strategy implies an early decision, which can also be combined with station keeping manoeuvres and thus saves propellant, the short-term strategy allows longer evaluation of the event, with a chance of improving probabilities. However, in the case of a late manoeuvre decision the fuel needed to achieve radial separation will be greater and the possible impact on the availability of the payload, because of the size of the manoeuvre, must be considered. Figure 3 shows the output of the short-term manoeuvre strategy analysis, where a recommended radial separation is highlighted. The different burn durations can be evaluated to determine whether they achieve the necessary radial separation. Furthermore, with the rising popularity of electric propulsion and its often-inherent limited thrust and duty-cycle, collision avoidance strategies need to be tailored to overcome these limitations.



Short term collision avoidance maneuvers are the last chance to avoid a potential collision. Usually performed around half an orbit revolution before the Time of Closest Approach (TCA), the goal is to achieve enough radial separation to reduce the collision risk. A good reference, from customer experience with OKAPI:Aether, recommends a radial separation of around 100m to reduce the collision risk significantly enough. The advantage of short-term maneuvers is the ability to delay the maneuver significantly to make the most qualified decision at the expense of delta-v requirements.

Figure 3 Screenshot showing the radial separation for short-term manoeuvre strategy.

Based on collision warning scenarios, avoidance manoeuvre capabilities will be tested. The thrust and uncertainties at the time of manoeuvre start will be evaluated. The impact of uncertainties in the thrust and the initial state vectors are evaluated for a range of epochs before the event. For each different thrust duration, level, and direction the differences in the resulting trajectories are analysed to determine their impact on collision avoidance scenarios.

The sensitivity toward operational decision like the targeted collision probability and minimum radial distance as result of a manoeuvre will be analysed to select the most suitable propulsion system and its settings as well as the favourable avoidance strategy based on the capabilities of the thruster.

Debris impact analysis

For the objects in space that are not trackable due to their smaller size, an analysis to assess the impact and penetration between these objects and the spacecraft can be conducted. The effects of such events on different components of the satellites will be investigated. This includes the number of impacts, as well as the expected direction with respect to the in-flight direction. A 3D model of the satellite will be defined with a focus on the surfaces of interest e.g. solar panels or satellite bus, it will consider different the different materials and components. The impact flux for each necessary surface will be determined, followed by a penetration probability analysis using ballistic limit equations and relevant population models.

The risk of debris penetrating the satellite bus, and their sensitive components will be conducted. Providing insight into which surfaces are exposed to the highest risk and would benefit from extra shielding. The degradation of solar panel over the operational mission phase will be calculated. In addition, to optimize the design and reduce the risk of penetration and damage of critical component, suggestions on orbit optimization and material choices will be provided. The compliances with the requirements focused on "Accidental break-up caused by a collision " will be assessed, which include:

- Collision risk assessment during design: ESSB 5.3.3.1 and
- Collision with small debris during mission operations: ODMSP 3.2.

De-orbiting strategies

By considering the evolving solar activity in the long-term period, the geomagnetic activity, satellite configuration and attitude, the best disposal option will be evaluated. Different simulations will be conducted, by varying the relevant parameters such as solar weather forecast represented in Figure 4.

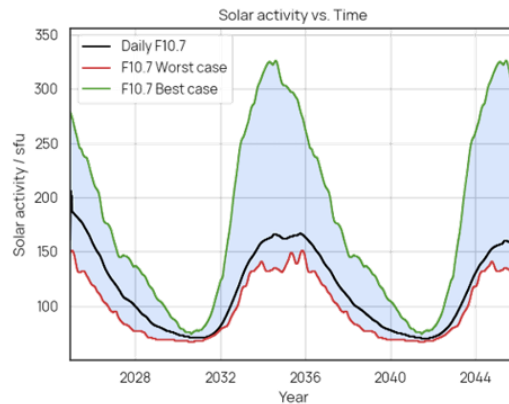


Figure 4 Solar weather forecast including best- and worst-case confidence intervals.

First a forecast of the solar activity in the long-term will be conducted following standardized methods. The atmospheric density and consequently, the atmospheric drag acting on the satellite, will be studied to analyse orbital decay, leading to scenarios including a faster or slower de-orbit, and relevant thrusters’ considerations. The 3D model of the satellite will be created to ensure the most accurate analysis, by including different attitudes and more accurate cross sections. Best-case and worst-case scenarios for disposal will be analysed, allowing for the selection among best options, focusing on saving propellant and being compliant with disposal regulations. Each scenario will be provided with an overview of the duration of the disposal, delta-v requirements, and propellant savings.

Furthermore, the following Space Debris Mitigation requirements will be checked:

- General Earth orbit clearance: ESSB 5.4.2.1
- LEO protected region clearance: ESSB 5.4.2.3
- Post mission disposal of space structures: ODMSP 4.1
- When terminating the operation of a space system in LEO: JAXA 3.4.3
- Control and return to Earth of a space object or group of coordinated space objects: FR 3
- Object passing through the LEO region: IADC 5.3.2

Compliance

Following all analysis a compliance verification summary is compiled. It gives insight into the analysis results and their impact on the requirements. Figure 5 shows an example of compliance page and the reasoning behind the compliance results. This allows the user to gain insight why their mission might not be compliant and how to change the configurations to achieve compliance.

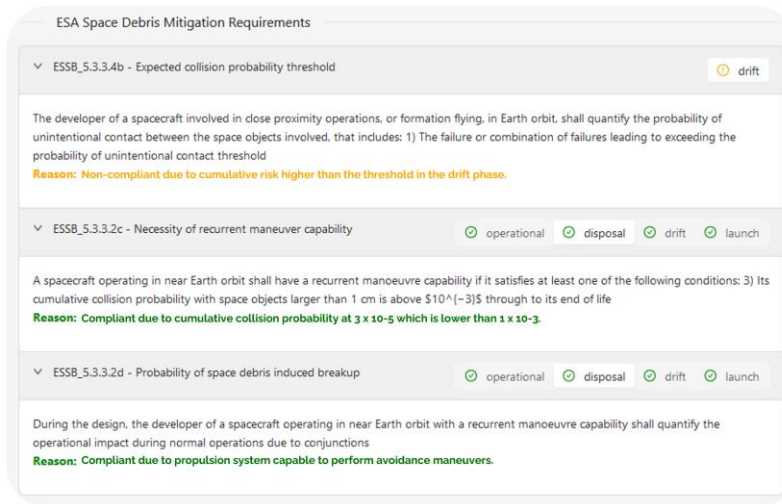


Figure 5 Screenshot of Soteria's compliance page.

6. Conclusion

Mission designers and satellite manufacturers are facing a diverse landscape of quickly evolving space debris mitigation guidelines and standards: the ISO 24113 standard, on which ESA's ESSB-ST-U-007 [5], and JAXA Space Debris Mitigation Standard (JSDMS) [6] build, the French Space Operations Act (FSOA) [7], and the US Government's Orbital Debris Mitigation Standard Practices (ODMSP) [8]. These cover topics including requirements for spacecraft reliability, space debris release restriction, avoiding break-ups, disposal at end of life, re-entry, and newly added the dark and quiet skies and lunar orbits. The verification of these requirements can be achieved using mission analysis tools made available from space agencies, e.g. STELA from CNES, ORDEM and DAS from NASA and DRAMA and MASTER from ESA. Each bring their own models and capabilities. These have been developed over the past 30 years and are aimed at the compliance of their own agencies space missions.

The Soteria mission design platform has been designed for commercial space actors with the need for quick and scalable iterations on their mission design. Using the established ESA tool suite, a SaaS approach has been chosen moving the needed compute power for the simulations to the cloud, allowing for quick iterations of the mission design, while remaining compliant with the requirements. The second priority of the platform is an educational part. The user interface presents the results of the analyses related to the requirement assessment with explanatory text. The information helps understand the requirements and iterate the design of the space mission accordingly.

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