SPACE DEBRIS MITIGATION CHALLENGES FROM DIFFERENT REGULATORY ENTITIES IN THE DESIGN OF NEWSPACE VHR SATELLITES

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ABSTRACT

The Atlantic Constellation represents a joint collaborative effort initiated by Portugal and Spain to develop Earth Observation (EO) satellites operating in Low Earth Orbit (LEO). Within the programme, a set of two initial Very-High Resolution (VHR) satellites are being developed by N3O, the first Portuguese satellite integrator. A partnership with OHB Sweden has been established, the contractor for the platform subsystem. The programme aims to reach optical ground sampling resolution imagery below 50 cm in an extremely agile smallsat platform [2].

The increasing concern with orbital debris and its impact on future space missions has significantly impacted the mission architecture and design of new spacecraft. This concern is well reflected in current regulatory trends followed by ESA and the FCC, where successful disposal no later than five years after mission conclusion is required. The impact of this developing landscape on the design of N3O's first generation of optical VHR satellites (named MARlin for "Muito Alta Resolução, lançamento inicial da N3O" or "Very High Resolution, N3O's initial launch") raises technical challenges in a NewSpace paradigm and demands regulatory breakthroughs in countries with emerging space industries such as Portugal. This article presents an overview on the impacts of these regulations on the design and mission architecture of the MARlin satellite.

Keywords: Space Debris; Casualty Risk; Collision Avoidance Manoeuvres; LEO Protected Region; Very-High Resolution; End-of-life Disposal; Small Satellites; Optical Systems.

1. INTRODUCTION

The MARlin is a 300 kg class small satellite based on OHB Sweden's InnoSat platform and developed under the New Space Portugal Agenda, the organizational body regulating the funding for the programme. InnoSat was first established in 2017 and proven in flight through several missions, such as GMS-T (2021), MATS (2022), ESA's Artic Weather Satellite (2024), GARAI (2024/2025) and ADIS (2025). The MARlin satellite aims to reach sub-50cm ground sampling distance (GSD) from a reference orbit of 540 km, providing imagery in the Panchromatic (PAN) and Red, Green, Blue (RGB) spectral bands using a TDI sensor. The design lifetime of the mission is 7 years, with the possibility to extend further. Being developed in Portugal by N3O and planned to be operated by GEOSAT, MARlin must ensure that all applicable space debris mitigation guidelines are met, including those of the country of launch. These guidelines have had a significant impact on the orbit selection and design of the MARlin satellite during Phase 0/A and B of the project, which also tries to follow previous Earth Observation methodology by established companies such as OHB System [1].

Section 2 starts by giving an overview of the mission and of the key drivers for the design of the satellite. Then, Section 3 discusses the current regulatory landscape of space debris mitigation guidelines, offering insight on those applicable to the project. Sections 4, 5 and 6 provide the relevant analysis to ensure those requirements are being met. Finally, Section 7 concludes on the impacts that space debris mitigation has had on the project, especially due to its NewSpace nature.

2. MISSION ARCHITECTURE

The current baseline for the mission is to place the MARlin satellites in a sun-synchronous (SSO) repeat ground track (RGT) orbit at an altitude between 520 km and 540 km. This altitude selection is partially driven by the end-of-life disposal regulations, which require the satellite to naturally decay within 5 years. Going above 550 km fails to meet this 5-year decay, as addressed later in Section 5. De-orbiting manoeuvres are not possible, since they require the satellite to demonstrate at least 0.9 reliability at end-of-life which is typically not feasible for smallsats. Another advantage of being at (or below) 540 km is that the highly populated 550 km altitude, where the Starlink constellation operates, is avoided. The high number of satellites in this constellation (already over 6750, and more expected in the near future) would likely increase

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

the number of conjunctions during the mission, leading to more complex operations and higher delta-v usage for collision avoidance manoeuvres (CAMs) [3]. Nevertheless, CAMs were a key consideration in the design and sizing of the satellite, as discussed in Section 4.

As a goal, both satellites will be in the same orbital plane throughout the mission, maintaining a Local Time at Ascending / Descending Node (LTAN/LDTN) between 9h-11h and 13h-15h, the optimal range for imagining missions.

While in the same plane, the constellation of two MARlin satellites will be able to achieve daily global access with a half-field of regard of 50º. Phasing both satellites by 180º in true anomaly is key to ensuring the lowest possible revisit times. The current uncertainty surrounding the drop-off orbit and LTAN/LTDN drift throughout the mission may lead to the two satellites being in different planes during the mission. While this somewhat degrades the coverage performance of the constellation, it is possible to optimise the relative phasing of the two satellites to mitigate this issue and achieve daily revisit time at most latitudes.

Two types of mission were considered for MARlin - a decay and a station-keeping mission. The decay mission, being the simplest, means the satellite would perform no altitude maintenance and instead slowly decay throughout its lifetime. To comply with disposal regulation, the satellite could be placed at an initial altitude of 580 km and decay at the rate seen in Fig. 1. While this type of mission would greatly simplify satellite operations, it carries the following disadvantages:

- Varying GSD - as the satellite decays, the GSD (and illumination conditions) will change, which may not be beneficial for certain applications
- Varying coverage performance - the prior rationale assumed a constant altitude throughout the mission for both satellites, which will not occur in this mission type and will lead to a negative impact in coverage

In a station-keeping mission, the satellite performs frequent in-plane manoeuvrers to maintain its altitude within a specific deadband. This mission has the added benefits of a constant GSD throughout its lifetime and optimal coverage performance, with the downside of significantly higher delta-v requirements. When the altitude deadband is reached, the satellite performs a low-thrust in-plane manoeuvre to reach its nominal altitude. Should this manoeuvre exceed one orbit in duration, it must be ensured that the eccentricity is not significantly affected as to maintain frozen conditions.

The key drivers for the size of this deadband are:

- The power budget, specifically the maximum number of thruster orbits possible before sun-bathing is required

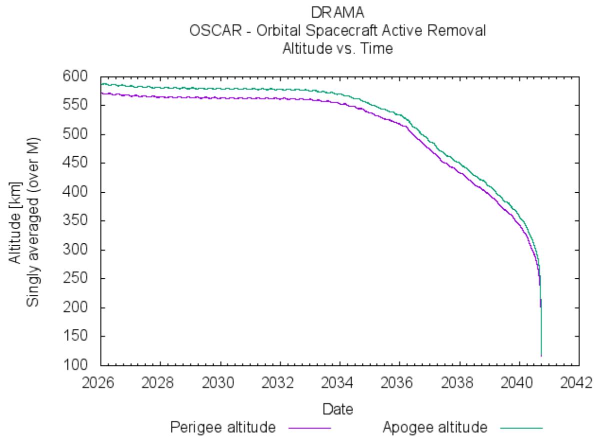


Figure 1: MARlin decay mission option starting at 580 km altitude with re-entry in 2040.

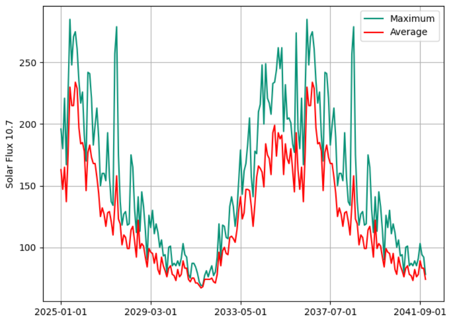
- The impact on the complexity of operations, since a shorter deadband will lead to more frequent but larger manoeuvres
- The availability budget, which should meet the mission's challenging requirement and is highly dependent on the decay rate and thrust of the satellite

For the selected deadband the satellite will need to manoeuvre with varying frequency depending on the environment, specifically the solar activity. In periods of high solar activity the atmosphere expands subjecting the satellite to a higher density and increased drag. The solar activity follows a cycle which repeats roughly every 11 years, making the atmospheric density that the satellite will experience predictable to certain degree. For delta-v sizing, it is common to utilise a standard solar activity cycle such as the ECSS 11-year cycle based on solar cycle 23 [4].

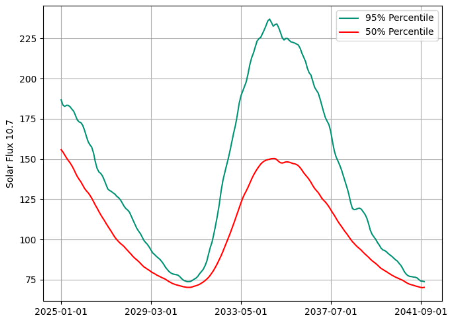
At N3O, a prediction of the solar activity from NASA's Marshall Space Flight Center (MSFC) is used during early mission analysis [5], as per the ESA guidelines for delta-v computation [6]. MSFC provides the 5%, 50% and 95% percentile prediction for the future solar activity, which should be used according to the mission phase.

During nominal operations for sizing of station-keeping, the 95% is the worst-case due to increased drag. For the end-of-life (EoL) disposal, the 50% should be used instead. A comparison between these two set-ups (ECSS vs MSFC) is seen in Fig. 2, plotting the F10.7 solar flux index up to the expected end of the mission (the Ap index is also used in the atmospheric model but not shown here). The MSFC solar activity prediction is seen to be overall lower than the ECSS one, resulting in decreased delta-v requirements but in longer EoL disposal time.

It is worth mentioning that, during the project, some opportunities for enhanced guidance from the relevant regulatory entities have been observed regarding which assumptions should be taken for each mission phase to en-



(a) Extended ECSS solar cycle 23, maximum and average values



(b) Extended MSFC solar cycle prediction (July 2024), 95% and 50% percentile values

Figure 2: Overview of the solar activity cycles used in N3O mission analysis

sure compliance with the guidelines. While ESA provides documentation on the form of ECSS and guidelines, the same was not observed from the regulatory entities - which may be partially due to the relative novelty of the space sector in Portugal. For now, ECSS such as ECSS-E-ST-10-04C [4] are being applied in the project to ensure best practices.

In summary, one of the major driving constraints for the mission architecture definition was the end-of-life disposal (Section 5) regulation.

3. SPACE DEBRIS MITIGATION

Space debris mitigation (SDM) comprises a series of actions that tackle, among other topics, the release of debris, break-ups, disposal, and re-entry. To comply with current guidelines, various mitigation actions are included in the mission design, ranging from collision avoidance and disposal manoeuvres to passivation strategies and the assessment of the casualty risk.

Adopting these mitigation actions to their full extent in small satellite missions can place significant constraints on the resulting performance and mission scope unless significant schedule and cost impacts can be accommodated - with the latter case often not being a possibility in the current commercial landscape.

3.1. Regulatory Landscape

Challenges in the implementation of SDM guidelines may start with discovering which ones apply. Although the design and analysis of these mitigation actions for each mission are under the probe of every regulatory entity, not all of them treat this subject equally, both in extent and thoroughness.

For the MARlin satellites, the response to critical topics within these regulations is under preparation such that differences in the requirements amongst distinct licensing authorities will not heavily impact the concept of operations and overall configuration in future stages. This is achieved by considering guidelines from the national authorities – in Portugal, the national communications and space activities authority is ANACOM –, and from the country of a potential launch provider – Federal Aviation Administration (FAA) in the United States or ESA in Europe.

For both ANACOM and alternative European launch providers, ESA requirements are expected to represent the strictest set of mitigation measures, acting as an appropriate reference in case of uncertainty. Beyond a significant number of normative references, the following standards either from or adopted by ESA can be highlighted:

- ESSB-ST-U-007 - ESA Space Debris Mitigation Requirements (30/10/2023)
- ESSB-ST-U-004 - ESA Re-entry Safety Requirements (04/12/2017)
- ECSS-U-AS-10C - Adoption Notice of ISO 24113 (09/02/2024)
- ISO 24113:2019 - Space debris mitigation requirements (05/2023)

This set of documents is quite extensive in its scope and includes validation and verification requirements that must be followed for proof of compliance.

For U.S. launches, the FAA is responsible for regulating launch vehicle activities and any payloads that are not regulated by the Federal Communications Commission (FCC) are subject to a Payload Review [7], as identified by SpaceX [8]. This review, in the form of a document, confirms if the owner or operator collected the necessary licenses and if its launch or reentry does not pose a risk. The required information includes the expected life span of the payload and its planned disposal. The FAA does not indicate any specific requirements for the disposal or any other space debris mitigation topics in the context of the Payload Review. However, SpaceX informs that it supports FCC's guidelines for disposal up to 5 years after the mission ends [8] and a statement of compliance with this guideline is commonly requested. Nonetheless, no detailed analysis or any robust proof of compliance is requested by SpaceX in its licensing process with U.S. authorities.

This disparity in the verification of requirements can lead to vast inequality between missions, depending on the acting regulatory entities. For instance, assuming that licensing bodies of various European countries do not have the capacity or intention to enforce ESA guidelines, missions based on those countries may decide to steer away from emerging European launch service providers and launch from the U.S. or other territories with more relaxed regulations to lower risks of non-compliance and overall effort. Thus, while not discarding that the exponential rise of launched satellites and space debris poses various concerns, unifying and simplifying the SDM guidelines across the world should be a pressing concern, particularly for regions such as Europe where the strictest set of requirements is enforced.

Despite the differences in their application, it is worth noting that there is a converging trend on this matter, which may fuel the needed homogenization of requirements across different countries. For example, the FCC guidelines for disposal [9] - a 5-year window at EoL with a probability of success of 0.9 – are in harmony with ESA standards, as well as the requirements for the casualty risk threshold. Furthermore, the Orbital Debris Mitigation Standard Practices from the U.S. Government, another commonly referenced document for operations in the USA, is also harmonized with ESA standards, under the influence of the Inter-Agency Space Debris Coordination Committee (IADC). Even within the U.S., the FAA typically follows guidelines created by other U.S. federal agencies and, with the increased concern with space debris, there may be an approximation between its demands and the full scope of the current FCC requirements.

A positive example of a global initiative on this subject is the Zero Debris Charter, which sets a series of goals for a commitment to space safety and sustainability. This declaration started by ESA, which is collecting significant support from various countries and companies, is accompanied by the Zero Debris Booklet, which defines critical technological developments needed to achieve the charter's requirements. These collaborative efforts are still non-binding agreements and transposing them to broadly accepted regulatory frameworks is the necessary step to achieve true global cohesion.

The details regarding which standards apply to the MARlin satellites are under clarification as the licensing process progresses, in parallel with the final definition of the launch provider – nonetheless, both Europe and the USA are pioneers in Space debris mitigation and the strictest rules are assumed at this stage. Space debris mitigation practices described in the referenced ESA standards are expected to be met in the development and operation of the MARlin satellites. This is corroborated by the inclusion of these strategies and analysis at an early design stage, exerting influence on the concept of operations, the satellite configuration, and various technical trade-offs.

4. COLLISION AVOIDANCE

As mentioned in Section 2, the selection of the operational altitude was done with collision avoidance in mind, which has somewhat mitigated the issue. Nevertheless, CAMs remain a key design and sizing driver. Firstly, it impacted the selection of the propulsion system, which should provide sufficient thrust to perform a CAM in relatively short notice. It also impacted the delta-v sizing, where the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool can be used to estimate the number of collision avoidance manoeuvres during the satellite lifetime. This analysis is shown in Fig. 3 for different Annual Collision Probability Levels (ACPL), which quantify the risk of a collision occurring. An ACPL of 10^{-4} is a commonly used value and yields under one collision avoidance manoeuvre for an altitude of 540 km, assuming a 1.6-meter sphere representative of the satellite in a deployed configuration. Despite this result, a conservative safety margin was imposed to account for the evolving space debris population, resulting in a baseline of 5 CAMs per year.

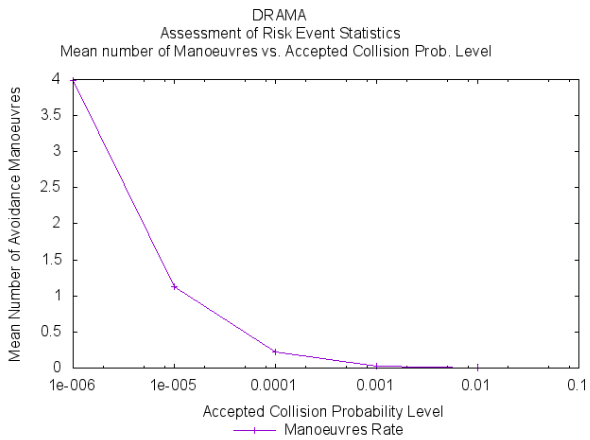


Figure 3: DRAMA Ares run for MARlin, showing the mean number of CAM for different ACPL values.

Another key challenge of collision avoidance is the lack of pre-established procedures in the event of a conjunction. Currently, most operators work on a case-by-case basis where contact is established to the operator of the incoming satellite and a joint decision is taken on who should perform the CAM. While this solution works, there are no rules/guidelines to facilitate the decision of who should manoeuvre. Working towards the standardisation of the process, a list of potential criteria is provided here:

- Available delta-v - where the satellite with the most left over fuel would perform the manoeuvre

- Thrust capability - where the satellite with the highest relative thrust would perform the manoeuvre for faster avoidance
- Large constellations - operators with a very high number of satellites could be advised to implement (near) autonomous CAMs and notifications for the incoming satellite's operator
- Mission Type - where scientific missions of high importance could take priority, and the incoming satellite should manoeuvre
- Mission Cost - where high cost missions would again take priority over small or mass produced satellites
- Years in Flight - where the satellite's elapsed time in orbit would influence the decision

There is a long process ahead to ensure standardisation of this process, which could begin by coordination efforts with satellite operators in Europe and the U.S.

5. END-OF-LIFE DISPOSAL

A critical part of space debris mitigation is a satellite's end-of-life disposal operations, which should ensure it does not pose a risk to other operational satellites in LEO. This section addresses this in the context of the MARlin, ensuring that, after passivation, the satellite will re-enter the atmosphere within a specific amount of time to mitigate debris in orbit.

5.1. Requirements

The recently updated FCC [9] and ESA [11] rules for satellite de-orbiting has significantly impacted all satellites in the LEO region. While before 25 years were allowed for re-entry and subsequent disposal, the rapidly increasing population of space debris and awareness regarding this issue has motivated the change to only 5 years. Additionally, this constraint must be ensured with a 0.9 reliability at EoL.

The way that the spacecraft re-enters at end of life may be divided into two categories. The first, a **controlled re-entry** is characterised by the satellite performing a re-entry burn, decreasing the perigee altitude significantly and allowing for control of the landing zone of the resultant debris. By selecting a zone with low population density, the casualty risk of the spacecraft's re-entry is significantly decreased. In addition, this strategy is most common for satellites which employ chemical propulsion methods, as these provide higher thrust allowing for the perigee altitude to be accurately controlled. Additional approaches other than using chemical propulsions are possible, such as that of the Starlink constellation, which even though primarily relies on natural decay, combines this with attitude slews aimed at changing the drag area of the satellite down to very low altitudes of ≈ 125 km. This control of the drag area allows the targeting a landing zone in the ocean, significantly decreasing the casualty risk [3]. The use of this method still requires the necessary reliability to be demonstrated.

The 0.9 reliability requisite raises an issue for smallsats in the context of NewSpace; the accelerated timescales, frequent usage of off-the-shelf components and compromises on subsystem redundancy make it very challenging to achieve. Such is case with the MARlin satellite. Additionally, the high delta-v requirements for the mission have led to the choice of electric propulsion (EP) as opposed to chemical, not allowing for fine perigee control and preventing controlled re-entry. An additional benefit of EP is the usage of gaseous propellant instead of liquid - the latter leads to sloshing inside the propellant tank, increasing the duration of the satellite's settling time when imagining after a slew. Although anti-sloshing propellant tanks are available, these would represent a delta cost and schedule for the project.

The combination of electric propulsion and low reliability at EoL leads an alternative type of re-entry being necessary. The **uncontrolled re-entry** does not make use of a high-thrust disposal manoeuvre but instead relies on either atmospheric drag - natural decay - or a long duration low-thrust manoeuvre - manoeuvred decay - to progressively lower its altitude. Even though this re-entry type does not require any propellant, it has the downside of increasing the casualty risk since a particular landing zone cannot be selected. Once again, the low reliability at EoL prevents the usage of electric propulsion to lower the satellite's altitude, making natural decay the only viable option for MARlin.

5.2. Assumptions on Decay Time

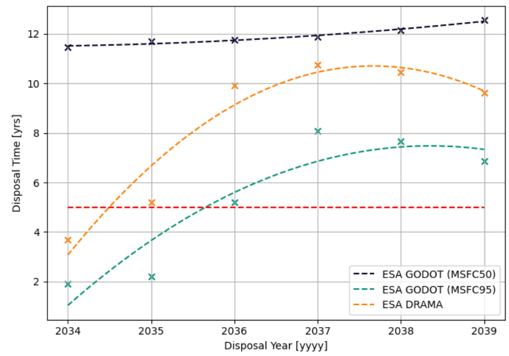
The low atmospheric density in order of $10^{-13} kg/m^3$ creates challenges in meeting the 5-year de-orbiting rule. Compliance with the requirement is highly dependent on the assumptions made both for the solar activity, influencing atmospheric drag and solar radiation pressure (SRP), and for the spacecraft parameters. As mentioned in Section 3.1, guidance on these assumptions is sometimes not given or conflictory between different regulatory entities. In Phase 0/A of the project, the guidelines from ESA have served as a baseline. Specifically, the most up-to-date guidelines for computation of the delta-v and propellant mass budgets [6] have resulted in the following assumptions being used:

- Atmospheric Model - NRLMSISE-00, as recommended in [4].
- Solar Activity - as described in Section 2, the MSFC 50% percentile is used in ESA GODOT, while the sample ECSS cycle is used in ESA DRAMA.

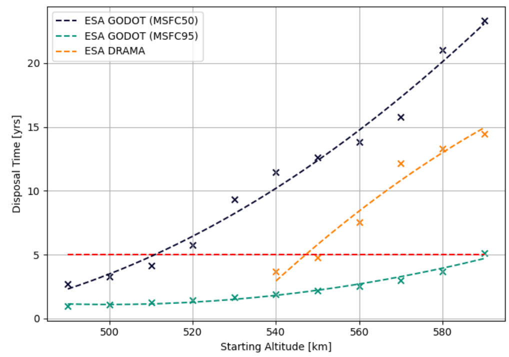
- Spacecraft Mass - 280 kg, current project baseline value.
- Spacecraft Drag Area - 2.3 m^2, estimated using the CROC module in ESA DRAMA, assuming a randomly tumbling satellite.
- Spacecraft Drag Coefficient - 2.2, as per guidelines for the worst-case EoL disposal value; a drag coefficient of 2.45 was also obtained from a Direct Simulation Monte Carlo tool at 500 km altitude.
- Spacecraft SRP Area - 2.3 m^2, also assuming a randomly tumbling satellite.
- Spacecraft Reflectivity Coefficient - 1.2, a commonly taken value for early design.

5.3. Decay Analysis and Results

N3O makes use of both DRAMA - ESA's tool for compliance analysis with space debris mitigation standards - and GODOT - ESOC's astrodynamics library - for general mission analysis and in this case, to study compliance with the disposal regulations.



(a) Starting disposal year vs disposal duration for the MARlin, comparing ECSS sample cycle in DRAMA with MSFC in GODOT for a 540 km altitude



(b) Starting altitude vs disposal duration for the MARlin, comparing ECSS sample cycle in DRAMA with MSFC in GODOT for a 2034 disposal date

Figure 4: EoL disposal parametric results for the disposal year and starting altitude for DRAMA and GODOT

DRAMA allows for collision avoidance estimation (ARES), collision impact damage (MIDAS), EoL disposal studies (OSCAR), projected area estimation (CROC) and re-entry casualty risk estimation (SARA). For the context of compliance with the disposal regulation, the OSCAR module is used in combination with the ECSS sample solar cycle seen in Fig. 2 (a), the recommended method. The decay analysis is performed for several dates around the end of the mission. The results are presented in Fig. 4 and show how orbits above 550 km are not compliant with the 5-year rule at the nominal lifetime under the current assumptions.

GODOT is an extendible and flexible flight dynamics library that can also be used for orbital lifetime estimation. As DRAMA, it utilises the NRLMSISE-00 model but with the MSFC 50% percentile solar activity seen in 2 (b). The propagation uses the RungeKutta787 method with an accuracy of 10^{-11}. The results for both the 50% and 95% percentile MSFC can be seen plotted together with DRAMA in Fig. 4. Contrary to the DRAMA results, with MSFC50 the satellite does not decay in the required 5-years at 540 km altitude at any of the years in study. Instead, the requirement is only met at altitudes below $\approx$ 510 km, clearly highlighting the dependency of the results on the solar activity.

5.4. Outcomes

The implementation of the 5-year rule by the FCC and ESA has significantly limited the operational altitudes of the MARlin satellite in LEO to below $\approx$ 550 km, as per the DRAMA results. Other smallsats of similar characteristics (namely ballistic coefficient) will also be subject to this constraint. This is shown to be highly dependant on the solar activity taken as assumption for the analysis, which remains to be confirmed from the relevant regulatory entities. Other methods are not feasible for this class of satellite or for the NewSpace approach of the project, requiring either a significant delta in schedule or cost.

While the implementation of the regulation is a significant step in addressing the critical issue of space debris mitigation, it may also make the LEO region more crowded at lower altitudes, leading to an increase in collision avoidance manoeuvres and therefore operational complexity.

This is reflected in the MARlin satellite, as this rule became a critical design driver and may even lead to an early stop of the station-keeping manoeuvres, causing a switch to a decay mission from 2035 onwards. This switch to a decay mission ensures the MARlin is compliant with the rule for both its nominal and extended lifetimes. However, should the MSFC50 become required for ensuring compliance with EoL disposal regulations instead of the DRAMA solar activity cycle, the satellite will be forced to operate at an even lower orbit, or begin decaying much sooner.

6. CASUALTY RISK

Casualty risk on re-entry is "determined by the fragments which are generated from the spacecraft under the effect of aerothermal and mechanical loads during re-entry and survive along the re-entry trajectory until ground impact" [10].

6.1. Requirements

ESA [11] and the FCC [9] define the threshold for the casualty risk of a re-entry event at 10^{-4}. If this is not accomplished through an uncontrolled re-entry, a controlled re-entry should be programmed to respect this threshold. As the latter option is not achievable for this mission - and unlikely for any similar missions - as detailed in Section 5, a successful demise of most of the satellite is necessary.

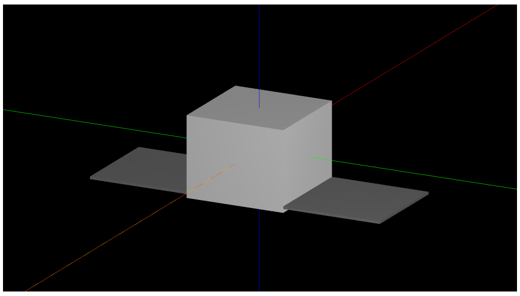
6.2. Modelling

Casualty risk analysis can be performed with the SARA module of ESA's DRAMA software, according to the modelling guidelines in [10]. The modelled configuration for the initial preliminary iterations includes the solar panels, a simplified satellite structure, the reaction wheels, propellant tanks, and the optical payload, accommodated within the satellite structure and composed of its various optical components - see Fig. 5. The selection of the critical elements for the analysis comes from the indications in [10] and the current literature on this subject, from which it is possible to conclude that various components or materials in the MARlin satellite may be hard to demise, namely:

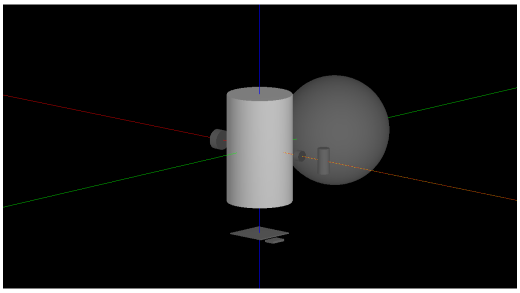
- from the optical payload and its mechanical interface – CFRP, titanium alloys, and ceramic-glass elements,
- from the reaction wheels – titanium flywheel and ball bearing units,
- and from the propulsion system – composite overwrapped pressure vessels and ceramic elements

6.3. Results

The preliminary analysis shows that, with a conservative approach to components under significant uncertainty, the contribution from the payload-related components alone is higher than 50% of the casualty risk threshold of 10^{-4}, illustrating how challenging it is to comply to these standards when equipping small satellites with state-of-the-art optical instruments. When the resulting casualty risk threshold appears to be on the verge of non-compliance, two sets of measures can become a priority - adopting design for demise methodologies or identifying and correcting excessively conservative modelling decisions.



(a) platform



(b) telescope assembly, reaction wheels, tank and dummy mass

Figure 5: Representation of the preliminary SARA model for casualty risk analysis

Design for demise consists of replacing problematic components or materials with others easier to demise or employing any other strategies that aid this demise. A straightforward example of this for the MARlin satellites would be to replace the optical payload mechanical interfaces with aluminium alloys. Such measures may come at a significant cost - either financial or in performance -, and for this particular action, deviating from these materials would jeopardize the optical performance. Another possible action would be to replace the reaction wheels with fully demisable alternatives, which in this case is out of scope given the low maturity of the current technical solutions and the programmatic constraints of the mission. Additional design strategies, although not necessarily classified as design for demise, can lead to a lower casualty risk by focusing on a reduced casualty area. The casualty area is a circle in which the tangent circles of the debris area and the vertical projection of a human are inscribed, thus, its total value for a re-entering satellite is significantly affected by the number of components. For instance, assuming that the propulsion system is composed of two pressure vessels, adopting a non-demisable connection between them or replacing both with a single tank with the same total value will reduce the casualty risk. With the latter approach applied to the preliminary model, the casualty risk added by the pressure vessels is lowered by 40%, which signals the impact of such measures.

While the examples listed above can exert a significant effect on programmatic aspects of the mission as they drive the satellite design, reducing the number of modelling uncertainties and its level of conservativeness is theoretically easier to achieve as it only affects the modelling task. In reality, since the current data on this subject is scarce, this activity becomes subject to simplified and conservative models that can lead to either overly optimistic or pessimistic results.

An example of one point of uncertainty in this preliminary analysis is the behaviour of the CFRP baffle. In DRAMA's current material database, CFRP is highly resistant to demise - however, this is based on composite systems used for overwrapped tanks, which are not necessarily representative of every CFRP constituent combination, manufacturing process, or thickness. This has already been confirmed by experimental analysis on additional composite systems, with the widely used L20 and LY556 resin systems showing improved demisability in comparison with cyanate ester matrices [12, 13]. These new CFRP models with higher demisability are expected to arrive along with DRAMA 4.1, still in 2025. The higher demisability epoxy matrices fit the case of the CFRP baffle and many other CFRP components in small satellites, thus leading to a significant decrease in the predicted casualty risk when available, and confirming how conservative the current estimations may be.

Other impactful contributors to the re-entry risk of the MARlin satellites are the glass and ceramic-glass lenses and mirrors of the optical payload, which represent around 30% of the total casualty risk of the optical instrument in the preliminary model. In this regard, the extended materials library for DRAMA's 4.1 release [13] can be highlighted as an important advancement towards correlation with experimental data.

Despite the described advancements, material models are still sparse and their low maturity level affects the accuracy of the results, the difficulty associated with needed assumptions to simplify the models and the expertise required of the regulatory entities to scrutinise them. The urgency to develop this subject further can be justified by how these challenges affect the goal of the casualty risk threshold by leading to models that are often recognised to be adjustable for compliance by exploiting optimistic simplifications and the difficulties from emerging licensing bodies to recognise it.

7. CONCLUSION

This paper highlighted the many uncertainties related to space debris mitigation and how they affect the design of the MARlin mission. The presence of several different regulatory entities and somewhat lack of communication between them has posed difficulties in finding the applicable regulations to the project. To mitigate this, the more conservative ESA guidelines were used in the estimation of CAM, study of end-of-life disposal and casualty risk mitigation.

A significant safety margin was applied to the number of CAM/year to account for the growing amount of space debris and of mega-constellations in the LEO region. A future set of operational procedures for conjunction events, serving as recommendation, is needed to facilitate satellite operations.

An in-depth parametric study was also conducted to analyse MARlin's compliance with the recently updated 5-year decay rule, showing that an altitude below 540 km is advisable, as well as a decay starting in 2035 the latest. While this tackles the space debris accumulation in LEO, it will also lead to a significant increase on the number of satellites in the lower altitude orbits, complicating operations.

Finally, a preliminary analysis on the casualty risk modelling of the satellite showed that the payload is a significant contributor to the 10^{-4} limit of the casualty risk. An increased development effort and availability of demisable components would facilitate the implementation of a design for demise approach in small satellite missions. Additionally, further research on material demisability would improve modelling accuracy and allow for a more transparent proof of compliance of the casualty risk threshold, as is expected to happen with DRAMA's material database update. Both of these measures are crucial for smallsats, which are often unable to perform controlled re-entry due to the lack of chemical propulsion and low EoL reliability.

While increased attention is given to space debris regulations, particularly in Europe and in the US, global constraining guidelines are yet to be implemented as legal framework. While this facilitates access to space for companies in some regions, it is counterproductive in tackling the evolving concerns with space debris.

ACKNOWLEDGMENTS

The presented work has been performed under the NSP Agenda consortium Work Package 3 (WP3), dedicated on the VHR component of the Atlantic Constellation. The authors would like to express their gratitude to their respective colleagues in the integrated N3O-CEiiA team, but also in particular to OHB-System, OHB-Sweden, GEOSAT, and to all partner entities within the WP3 consortium for their valuable contributions to the continuing success of this very challenging programme.

This article has been produced with financial assistance of the European Commission (EC). The views expressed herein shall not be taken to reflect the official opinion of the EC.

Following the pandemic caused by COVID-19, the EC has put forth a Recovery and Resilience Facility (RRF) aiming “to mitigate the economic and social impact of the coronavirus pandemic and make European economies and societies more sustainable, resilient and better prepared for the challenges and opportunities of the green and digital transitions.”

The work presented in this paper was supported by a large number of people. The authors wish to acknowledge to the N3O and CEiiA Space Unit colleagues, for their exceptional support.

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