THE DEBRIS MITIGATION FACILITY: DEVELOPMENTS, CONCLUSIONS, USE CASES AND WAY FORWARD

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ABSTRACT

In 2020, the Debris Mitigation Facility (DMF) was initiated as a set of activities with the objectives to: integrate space debris mitigation (SDM) related databases, tools, combining the European Space Agency (ESA) Debris Risk Assessment and Mitigation Analysis (DRAMA) and Meteoroid and Space debris Terrestrial Environment Reference (MASTER) software, and processes into a common framework; move towards digital engineering; improve and innovate existing analytical capabilities; and enable an open-source community approach. Major challenges included a changing space environment, and the anticipation of ESA's Zero Debris policy. This resulted in various additions to the DRAMA tools. Moreover, a space debris forum has been initiated to host the DRAMA roadmap, several open-source Python scripts to support DRAMA analyses, and to facilitate multi-lateral discussions between users. The objective of this paper is twofold: summarising the developments of the DMF activities over the past few years and present the new features of DRAMA in the context of Zero Debris.

Keywords: Space debris; Mitigation; DRAMA; DMF; Zero Debris; MASTER.

1. INTRODUCTION

The Debris Mitigation Facility (DMF) was drafted as an initiative to develop a single unified set of software tools and procedures in view of the European Space Agency's (ESA) requirements and international regulation in the domain of space debris mitigation. Several industrial and ESA internal activities were initiated since 2020 and finally concluded in 2024.

Those activities entailed evolutionary developments for the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite and the Meteoroid and Space debris Terrestrial Environment Reference (MASTER) model. In parallel, ESA's Zero Debris (ZD) approach emerged and significantly matured during those years, introducing various new aspects and more stringent requirements in space debris mitigation since it entered into force in late 2023. Software, guidelines, procedures, trainings, and many more have been greatly shaped by the world-wide DRAMA and ZD communities. We believe that collaborations within these activities have strengthened relationships within those communities and created many new ones that might prove beneficial in the common addressing of space debris mitigation.

In this paper, we reflect on the period of DMF-related developments between 2020 and 2024. Section 2 introduces the new tools and procedures, summarizes the findings of the community workshop, presents the current DRAMA roadmap, and discusses the lessons learned. In Section 3 a satellite mission is presented as a use case to highlight the many new features. Finally, Section 4 concludes and discusses the way forward.

2. EVOLUTION OF DRAMA AND MASTER WITHIN DMF

2.1. Context

Potential space debris impacts put individual spacecraft and space missions in general at risk. Although for objects large enough to be tracked from ground, risk mitigation is mainly achieved via operational collision avoidance, smaller objects below detection sensitivity limits may still have sufficient impact energy to cause significant damage up to mission loss and structural breakup. The MASTER model facilitates risk assessments via space debris flux estimates on target orbits. MASTER has been maintained for more than 30 years and has also been instrumental in establishing mitigation guidelines primarily through the Inter-Agency Space Debris Coordination Committee (IADC) [1].

To assess compliance with those recommendations, a set of software tools was developed in the early 2000s and bundled into the DRAMA software suite, which saw its first release in 2005 [2]. DRAMA has been used during early design phases of many space missions to estimate the expected collision avoidance manoeuvre rate, or the remaining orbital lifetime of a disposed spacecraft; to conduct vulnerability assessments; and to study the atmospheric breakup and demise during reentry, as well as associated on-ground risk for potentially surviving fragments.

As part of the DMF developments, the DRAMA tools and MASTER have been integrated into a common framework. Related industrial (and internal) activities were initiated in a timely manner to anticipate the significant changes implied by the Zero Debris policy and to prepare DRAMA for the next evolutionary step in supporting analyses in that new context.

Past publications have documented our steps along these developments, including [3, 4, 5, 6, 7].

2.2. The Debris Mitigation Facility

The main objectives formulated for the DMF in 2020 were to

- create a **single framework** combining DRAMA and MASTER,
- move towards **digital engineering**,
- ensure maximum compatibility with **latest standards**, and
- enable new and strengthen existing **connections within the community**.

Seven larger industrial activities and one major internal development were conducted according to the schedule show in Fig. 1. Those developments are foreseen, at the time of this writing, to result in a two-staged software release in 2025, in the following referred to as DRAMA 4.0 and DRAMA 4.1, respectively.

The development of a new framework, including a new graphical interface for the upcoming DRAMA 4.0 software, was part of **DMF-01**, the first activity initiated in 2020. It was contracted to OKAPI:Orbits, the Institute of Space Systems at TU Braunschweig, Hyperschall Technologie Göttingen (HTG), and iTTi. The new software works along a mission-centric data model allowing the definition of multiple objects as part of that mission as well as their temporal and spatial connections and dependencies. Moreover, dedicated workflows facilitate automated assessments and a compliance verification with respect to mitigation requirements.

The DRAMA 4.0 release aims to provide this new framework, still relying on the same tool functionality in the backend as DRAMA 3.1. That newly introduced branching concept is visualised in Fig. 2: the DRAMA 3.1 branch continues to receive maintenance and support, as it is still being used in many projects. New developments and features (especially in the context of Zero Debris) are implemented on the DRAMA 4.x branch, with the first set of changes to be released with DRAMA 4.1.

The **DMF-02** activity resulted in a long-awaited update of the MASTER population, which is now labelled as "2408", referring to its reference epoch in August 2024. A significantly higher degree of automation has been introduced in the population generation with the goal to facilitate more regular updates (approximately once per year) in the future.

Several major updates were implemented for the individual DRAMA tools within **DMF-03**. The activity was contracted to Deimos Space, OKAPI:Orbits, and HTG. The primary objective was to address attitude-related aspects. For instance, as of DRAMA 4.1 the tool ARES (Assessment of Risk Event Statistics) will have the capability to assess differential drag strategies and account for varying orientation as a function of the viewing angle when assessing collision probabilities.

In that context, it is also interesting to mention that there have been several related activities outside the scope of DMF, but providing very relevant upgrades to the existing tools. In particular, the ElectroCAM activity, which ran via ESA's Technology Development Element (TDE), shall be highlighted here: contracted to GMV, Politecnico di Milano, and Universidad Carlos III de Madrid, the ARES software was extended to account for low-thrust propulsion in collision avoidance. This feature will also become available with DRAMA 4.1.

The **DMF-04** activity, contracted to etamax, assessed various existing databases from in-situ detectors and prepared them for inclusion in the MASTER population validation process. An interesting lesson learnt was also that many previously identified data sources had to be excluded, as entire data sets and relevant additional information was missing.

New functionalities some users may be familiar with from ESA's PROOF (Program for Radar and Optical Observation Forecasting) tool [8] were added to DRAMA within **DMF-05**, contracted to OKAPI:Orbits and HTG. The objective was to take the complex 3D model of the satellites and assess its trackability with respect to a ground-(or space-)based network of sensors.

An extension of the existing aero-thermal database module in the DRAMA tool SARA (reentry Survival And Risk Analysis) was done in **DMF-06**, contracted to R.Tech. As a result, DRAMA 4.1 will be released with an extension to the object model primitives: the hollow hemisphere [9], databases to cover lattice-based and concave shapes, as well as the functionality to add user-defined shapes.

The additional features and improvements developed during the DMF-03, -05 and -06 activities were integrated into the framework as part of the **DMF-07** activity, contracted to OKAPI:Orbits and iTTi.

Finally, the **DMF-08** activity was a short study conducted in 2024 by Belstead Research, which adds a glass material model to the existing metal and CFRP models in the SARA tool, also anticipated for DRAMA 4.1.

In general, DRAMA 4.1 is meant to address many analysis aspects demanded by the Zero Debris approach. As those keep evolving, sometimes faster than DRAMA software upgrades and patches, and with the idea to support the community in more complex analysis tasks, ESA's Space Debris Office is also hosting dedicated

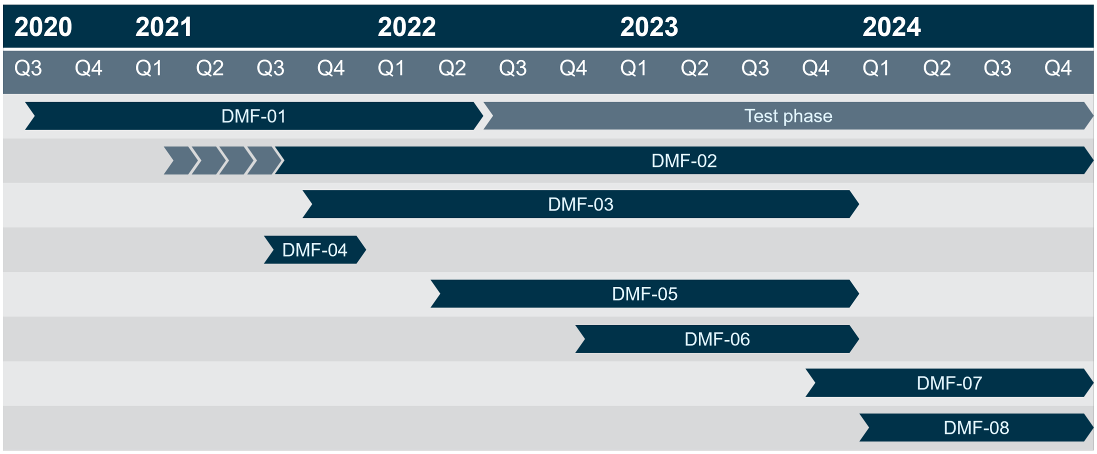

Fig. 1: Actual schedule of all the DMF activities.

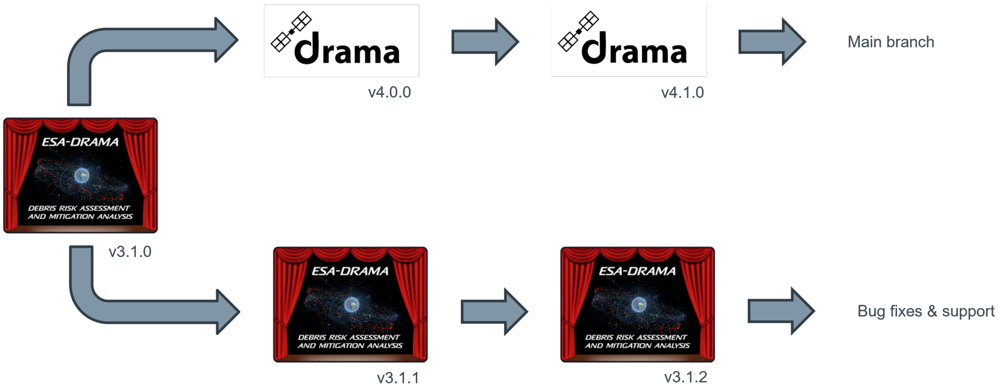

Fig. 2: Current approach in DRAMA software maintenance and support.

Python scripts on the debris user forum (see also Section 2.3.2. Examples are the Monte Carlo uncertainty assessment for controlled and uncontrolled re-entries, and the cumulative collision probability computation.

2.3. Engaging with the community

Exchanges with the broader DRAMA community in the 2020 - 2024 time period happened primarily through three focused workshops held in 2021 [4], in 2022 [10], in 2025 (a paper summarising those results in detail is being drafted at the time of this writing), the Zero Debris Operations Workshop in 2023 [11], via the space debris forum, and also in countless encounters of more bilateral nature. They facilitated a collectively deeper understanding of the diverse perspectives, techniques, and approaches with which members of the community face the complex set of problems in space debris mitigation. Weaving the perspectives, knowledge, skills and resources of many stakeholders facilitates a creative process and provides critical input potentially translating into meaningful action, supporting a culture of shared responsibility and ownership, nourish advocacy for a space environment aligning with our sociocultural and -economic space visions, and further reinforcing the consent on the models, processes, and guidelines applied and followed by the community. This notion has been confirmed by the International Risk Governance Center (IRGC) stating that the ”involvement of diverse stakeholders in the review and development process would help ensure that every relevant aspect of the risk is taken into account and general agreement on the relevance of the metric exists” and adding that efforts ”similar to the ones conducted by ESA to engage with stakeholders to improve space debris modelling would be helpful” [12]. Similarly, the Innovation Value Chain (IVC), developed by Darren McKnight, illustrates that process in Fig. 3. When people come together and com-

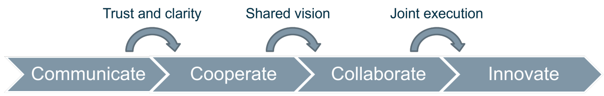

Fig. 3: Innovation Value Chain (IVC) according to Darren McKnight (2004).

municate, clarity and understanding are achieved, trust emerges. This enables cooperation, which may result in a shared identity and a shared vision to address the problem at hand. Deeper collaborations get established, potentially institutionalise and lead to a joint execution, ultimately providing the community with the innovation they need to achieve their goals.

In the following, we summarise and present from our perspective the community work in the frame of DMF, including how the current DRAMA roadmap (Section 2.4) has been shaped.

2.3.1. DRAMA community workshops

The first workshop was held over three days in March 2021. In the middle of the COVID-19 pandemic, about 80 to 100 participants met virtually to discuss: how we as a community obtain measurements on the space debris environment and how model validation is performed; how the MASTER model is used in daily practice; and finally, how we anticipate future developments and model the evolution of the space debris environment. Major outcomes include the community's support to establish an openly accessible MASTER roadmap (see Section 2.4); the appreciation of involving community members in the early stages of software development and testing; as well as the collection and publication of lessons learnt from flown in-situ detectors. Those were published later on the space debris user forum [13]. A more detailed collection of workshop impressions and results is provided in [4].

The workshops in June 2022 and January 2025 were both held in a hybrid format, with 60 (in 2022) and 70 (in 2025) participants coming to the European Space Operations Centre (ESOC) in Darmstadt, Germany, and many more (about 70 in 2022, about 180 in 2025) connecting online from all over the world. We recognise the value of the hybrid setup: despite existing on-site capacity limits, individual travelling and time constraints, the option to just connect online free of charge represents an inclusive approach. Fig. 4 shows the workshop participants and provides a feeling for the human touch in our efforts in space debris mitigation.

The DRAMA workshop in June 2022 followed a similar idea of the 2021 workshop to facilitate multi-stakeholder exchanges, this time with thematic in-person round tables, as well as virtual ones for the online participants. The round table topics included: reentry modelling, disposal analysis, damage assessment, collision avoidance, risk perception, communication, impact of large constellations, data collection and sharing, global space industry trends, responsible behaviour, and a general DMF Q&A session. Important contributions during that workshop included (recurring) discussions on adequate modelling granularity and level of abstraction in reentry modelling, as well as a broader support to introduce more qualified components (e.g. through plasma wind tunnel tests (PWT)), such as the reaction wheel currently available in DRAMA 3. Participants also stressed the need to standardise Ballistic Limit Equations (BLE) and associated use-cases.

A particularly high level of engagement emerged on the impact of large constellations. Beyond the dedicated round table, the debates extended also into the ensuing wrap-up session and fed into other round tables on the next day, especially about responsible behaviour. As an interesting example, the comment was made that we need regulations to address what exactly is being put into orbit, which value it provides, and the understanding that LEO is a shared space for everyone and thus exchanges on values of space missions are justified. It was further emphasised that within the community, relationships between entities and their people should foster mutual confidence and trust, which could then lead to more willingness in exchanging relevant information of more sensitive nature.

The DRAMA Clinics represented a new idea, based on a similar concept successfully deployed in several workshops by the International Laser Ranging Service (ILRS) community, to facilitate a direct exchange between tool users and developers. Participants were able to join one of the five parallel hybrid sessions to engage in discussions on very detailed software aspects for the tools ARES, MIDAS (MASTER-based Impact and Damage Assessment Software), OSCAR (Orbital Spacecraft Active Removal), SARA and MASTER. This allows for a better shared understanding of how the tools have been designed, what the potentials and limitations are, but also to collectively discover ways of improving and adapting the tools to current and anticipated use cases. Many experienced users shared their views on how they apply the tools and discussed what could be useful developments in the future, while there were also many newcomers among the participants who saw this as a good opportunity to just learn more about those tools. Detailed results on the 2022 workshop can be found in [10].

The latest edition of the DRAMA workshop was held in January 2025 in Darmstadt in a similar fashion to its predecessors. Despite a stronger focus on in-person round tables, and thus potentially less exchange for online participants, the high number of people attending the sessions from all over the world proved reassuring that community work is growing in our common domain. Besides the familiar round table topics of reentry modelling; damage assessments; disposal analyses; collision avoidance; and data collection & sharing, four new round tables were introduced: trackability & brightness assessments; space debris x futures; Zero Debris, atmosphere & ocean impact assessments; and modelling support for interplanetary missions.

We saw continued discussions on different modelling approaches, in particular related to finding the right amount of detail, or balance, in reentry, but also disposal analyses. Modelling gaps were identified and discussed, in particular related to ceramics and carbon-fibre reinforced polymers (CFRP) for various components. Gaps that could be addressed through more PWT experiments. Many new and challenging topics in the ZD context were discussed, including: the higher complexity in the verification of compliance of the 5-year remaining lifetime rule, given that it is stronger affected by solar and geomagnetic activity; the definition of breakup and the concept of partial fragmentations, or the modelling of a transition region; responsible behaviour in space operations

Fig. 4: A diverse community that gathered for the DRAMA workshops in June 2022 (left) and January 2025 (right).

even if your own satellite is non-manoeuvrable; mission extensions and related health monitoring and decision criteria related to post-mission disposal.

Returning to the discussion of space debris futures, that started with the 2021 workshop, participants in the Space Debris x Futures round table were tasked to envision a 200-year simulation in their minds. While the imagination and expression of the immediate future appeared easy following an extrapolation of the prevailing time line, difficulties to anticipate more mid-term futures became apparent, with very relevant questions raised: facing our implicit (unconscious) biases, how to get out of path dependency, the business-as-usual, the status-quo, the prolonged past?

Regarding the relatively new guidelines (see also Section 2.3.2), valid criticism received was that wording is often complex and that knowledge is widely distributed and might not be easily accessible, as it lives with individuals of our community and might not even be written down anywhere. The need to do significantly more research in the domain of atmospheric and ocean impact of space debris disposal was also stressed.

The DRAMA Clinics were repeated, this time introducing also a dedicated clinic for the introduction of the new DRAMA 4.x software to the user community, with support by one of the main developers, Frederik Läuferts from OKAPI:Orbits. The overall resonance was even higher than with the first edition. Many participants asked for recording the sessions; not having them in parallel, so that one could attend several clinics; and also to repeat them, potentially more often. The more detailed workshop outcomes are currently being compiled and will be published soon.

2.3.2. Space debris user portal and forum

For the past decade, the space debris user portal (SDUP)[1] has been the primary means to make MASTER, DRAMA, and other tools, as well as associated documentation and additional materials accessible. In detail, the following content can be found online:

Via the DRAMA downloads page[2]:

- The **latest installer** for DRAMA-3.1.1 and the three supported operating systems Windows, Linux, and macOS;
- The **previous installers** long-term support is currently provided for, back to DRAMA 2.0.7.;
- The **Final Report of DRAMA-2** is showing its age, but nevertheless provides the main documentation of DRAMA's individual tools, as long as no more specific technical note is available (for instance in the case of the OSCAR tool);
- The **Final Report of DRAMA-3** details the upgrades to the SARA tool that led to a major version increase from DRAMA-2 to DRAMA-3 in March 2019;
- The latest **Software User Manual** (SUM) for DRAMA-3.1.1. For future versions, as of DRAMA-4, it is envisaged to transition from a PDF to a web-based version of the SUM;
- The **ARES Technical Note** was created as a separate document from the original DRAMA-2 documentation during the transition to DRAMA-3, where the ARES tool saw significant upgrades, based on an extensive analysis of ESA's CDM database [14] feeding ARES' uncertainty information for the manoeuvre rate estimation;
- The **MIDAS Technical Note** was created as a separate document from the original DRAMA-2 documentation in 2022, motivated by the earlier ARES split and to continue the trend to have more specific and tool-focused documentation. It is more or less consistent with the DRAMA-2 Final Report documentation, but should be the document consulted for more recent updates;
- The **Guideline on Collision Avoidance (ARES)** collects lessons learnt in working with the ARES tool and how to employ it primarily in a requirements compliance verification work-flow. It is currently under review to reflect the changes introduced by Zero Debris, involving also required tool changes to assess the impact of active vs. active satellite collision avoidance. Traditionally, a key assumption in ARES has been that any close approach would be with space debris (or passive secondary objects) only;

[1] `https://sdup.esoc.esa.int/`
[2] `https://sdup.esoc.esa.int/drama/downloads`

- The **Guideline on Small Debris Risk Assessment (MIDAS)** is the analogue to the ARES guidelines (see above) in the context of small debris risk and vulnerability assessments;
- The **Guideline on DRAMA Materials (SARA)** provides lessons learnt and recommendations and guidance for the practical implementation and usage of materials used in the verification of requirements related to reentry;
- The **Guideline on DRAMA Spacecraft Modelling** aims to capture current best knowledge of the destructive reentry process and associated uncertainties. It provides guidance in the modelling of spacecraft in that process specifically within DRAMA;
- The **DRAMA Python Package** has gained broad popularity since its first introduction with DRAMA-3 in 2019. It facilitates tool automation and has been significantly extended in the scope of DMF, serving as the backend layer to interface between the individual DRAMA tools and the new frontend;
- Two **tutorials** are provided to get started with DRAMA. The basic one (Calliope) works along a step-by-step instruction and a simple small satellite mission to illustrate what the different DRAMA tools can provide. The second tutorial (Melpomene) explores more advanced features.
- All related **Release Notes** describing the changes for each published DRAMA version (since 2.0.1).

Via the MASTER downloads page[3]:

- The **latest installer** for MASTER-8.0.3 and the three supported operating systems Windows, Linux, and macOS;
- The previous version **MASTER-2009**;
- The **MASTER-8 Condensed Population Files (version 2408)** represent the latest MASTER reference population as of August 1, 2024. They are currently available for the entire history (since 1957) until the reference epoch, whereas the future population files are being prepared for release at the time of writing;
- The **MASTER-8 Population Files for Individual Debris Sources (version 2408)** are recommended to be used for more detailed analyses where the need arises to assess spectra of the individual debris sources, for instance during the design of in-situ impact detectors. There are minor deviations between the individual sources and the condensed population files. The former can be understood to provide a better resolution and a more accurate representation in specific size regimes.
- **MASTER-8 Population Files (version 1911)** represent the former reference population on November 1, 2016. They should not be used for new projects, unless a comparison to the updated reference population is warranted.
- The **MASTER-8 Final Report** provides the technical documentation of the MASTER model and the validation process for the reference population in November 2016. For the latest reference epoch (and future updates) the validation report will be issued separately (see note below on the debris forum);
- The **Software User Manual** documents the usage of the GUI associated with the MASTER stand-alone software. In the frame of DMF, MASTER has been integrated into the new DRAMA GUI. While the current MASTER GUI will receive bug fixes and related support, new features in MASTER (such as the population overlay introduced in DMF-01 and -07) will be only available through the DRAMA-4 GUI. However, users working with MASTER via the command line or the Python package, can still continue to use them with the necessary modifications for interface changes.
- All related **Release Notes** describing the changes for each published MASTER version (since 8.0.1).

For the major software tools DRAMA and MASTER, a set of known issues[4] and frequently asked questions are also collected and published on SDUP.

Additionally, four openly accessible documents, where no user account is required, are hosted on SDUP[5]:

- Design for Demise Verification Guidelines, v. 1;
- ESA Re-entry Safety Requirements (ESSB-ST-U-004 issue 1);
- ESA Space Debris Mitigation Compliance Verification Guidelines (ESSB-HB-U-002 issue 2); and
- ESA Space Debris Mitigation Requirements (ESSB-ST-U-007 issue 1) [6].

DRAMA-associated databases have co-evolved during the DMF period: the Database Information System Characterizing Objects in Space (DISCOS)[7], for instance, has improved its API and introduced a database of inhabitable spacecraft and constellations. The European Space maTerIal deMisability dATabasE (ESTIMATE)[8] saw many updates, with the latest findings presented during the 2025 DRAMA workshop [15]. In the previous two workshop editions, several participants have pointed out existing barriers: the DISCOSweb rate limit and the fact that ESTIMATE is only accessible given an affiliation with ESA Member States and on a need-to-know basis.

The space debris user forum[9] has been introduced as part of DMF-01 to aid in the transition towards more multi-lateral exchanges for common problems encountered by many community members. Several discussions have already started there, while from ESA side it is also

[3] `https://sdup.esoc.esa.int/master/downloads`

[4] e.g. for DRAMA: `https://sdup.esoc.esa.int/drama/known-issues`

[5] `https://sdup.esoc.esa.int/documents/`

[6] also referred to as the *Zero Debris Standard*

[7] `https://discosweb.esoc.esa.int/`

[8] `https://estimate.sdo.esoc.esa.int/`

[9] `https://debris-forum.sdo.esoc.esa.int/`

used to make additional content available: the difference to what is hosted on SDUP is that the forum offers a place where content may also evolve along the discussions by members. Those members might also be outside ESA or the core DRAMA developing teams and offer their contributions, too, in the spirit towards a more community-centered evolution. Key resources on the forum include:

- The **MASTER - Population Report - 2024/08 Reference** [16] describes the latest MASTER population update with relevant changes along many charts and numbers;
- **Example scripts for performing Monte Carlo analyses using SARA** [17] provide open access Python code to illustrate a setup calculating the SRA and DRA (Safety and Declared Reentry Areas) for a mission, as well as the on-ground casualty risk, as part of a controlled reentry's safety analysis;
- Another example for a **Monte Carlo analysis for a 3U CubeSat mission** provides modified code of the above for a small satellite parametric analysis [18];
- A proof-of-concept for the computation of the **Cumulative Collision Probability** is provided as Python scripts using the DRAMA tools in a work flow similar to the ones used in DRAMA-4 [19];
- The **Lessons Learnt from Past Missions** collects relevant lessons learnt from previous flights of in-situ instruments as a result of DMF-04 and DRAMA workshop inputs [13];
- DRAMA and MASTER **Roadmaps** are also available (see below in Section 2.4).

2.4. Roadmap

During the DRAMA workshops, as well as part of many gatherings of the core developers of DRAMA, community members collected many inputs to shape current and future activities for DRAMA and MASTER. They have been collected and shared for further discussion in the new debris user forum as a roadmap for both DRAMA [20] and MASTER [21]. This provides more transparency for current implementation work, as well as means to discuss and anticipate future changes and the addition of new features to MASTER and DRAMA.

The roadmaps also outline the version branching (as discussed earlier in Section 2) and associate the features and additions with each anticipated software version, which later, upon finalization and publication, transition into the release notes.

3. EXEMPLARY MISSION

To highlight some of the added functionalities that have come out of the DMF developments, this section will showcase some new features by using ESA's Swarm constellation as a case study.

3.1. Mission definition

The orbits as well as other parameters of the Swarm spacecraft relevant for the analysis are listed in Tab. 1. The orbits for Swarm-A (SWA) and Swarm-C (SWC) are almost identical. As a consequence, the analysis will be done for SWA and Swarm-B (SWB) only. Orbital parameters were extracted from Two-Line Elements (TLE) data, mass and drag area are taken from operational data. One notable improvement of the updated DRAMA 4 user interface becomes apparent when analysing this mission: We can now define multiple (operational) orbits as different mission phases that share the same spacecraft configuration. This allows us to easily run the same analysis for multiple orbits/spacecraft configurations. The tumbling

	SWA	SWB	SWC
Semi-major axis / km	6824	6869	6824
Eccentricity / 10^{-4}	1.32	1.34	1.32
Inclination / deg	86.982	88.061	86.994
RAAN / deg	237.95	131.90	234.67
Arg. of perigee / deg	89.18	91.796	89.74
Mass / kg	380	414	380
A_D (oper.) / m^2	1.1	1.1	1.1
A_D (tumb.) / m^2	5.3	5.3	5.3

Tab. 1: Osculating classical orbital elements of the three Swarm spacecraft, extracted from TLE data from February 24, 2025, using CSTATE.

area is based on an analysis performed using the CROC tool. While previously, only CROC was available to compute the cross-sections of spacecraft in their various configurations, and under various view angles, DRAMA 4.1 introduces the Coefficient Estimator (CE), to complement and eventually replace the CROC tool. CE allows the computation of various coefficients and areas, under different aspect angles and considering up to two rotating components. As a consequence, allowing the deprecation of CROC removes the dependency on Java 8, alleviating some of the trauma of the DRAMA setup. The

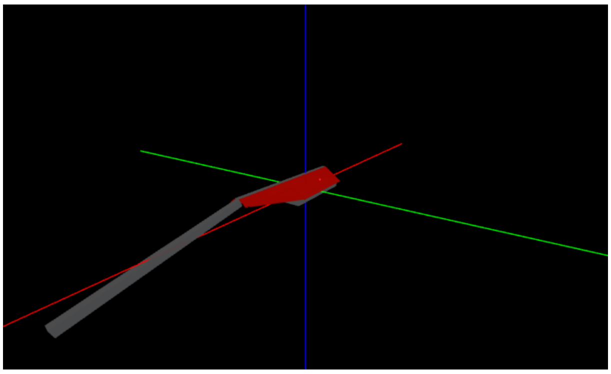

Fig. 5: Spacecraft model used to generate cross-section data, as seen in the DRAMA 4 GUI

spacecraft model shown in Fig.5 was generated based on internal design documents. Operationally, a hard body radius (HBR) of 4.55 m is assumed for collision avoidance purposes. This corresponds to the radius of the encompassing sphere, having it's centre in the spacecraft centre of mass. To characterise the space debris environment, the latest MASTER reference population is used (as per Zero Debris Standard), available on SDUP[10], which at the time of writing corresponds to August 2024.

3.2. Results

Based on the established mission definitions, some of the results that can be obtained using the new DRAMA 4.1 features will be highlighted in the following sections. These results do not aim to provide a complete debris mitigation assessment in accordance with ESSB-ST-U-007, but simply to demonstrate select functionalities that users can expect.

3.2.1. Collision risk during operations

Beyond the assumed tumbling A_D (tumb.) and operational cross-sections A_D (oper.) outlined in Section 3.1, improvements within ARES 4 allow the collision probability to be biased according to the collision geometry. This leverages the cross-section computation of CE, to scale the collision area according to the impact azimuth/elevation. This gives a more representative number than using the averaged cross-section, albeit far less conservative than using the radius of an encompassing sphere.

Using DRAMA 4, we can analyse compliance with various collision risk requirements from the ESA Standardisation Steering Board (ESSB), the Orbital Debris Mitigation Standard Practices (ODMSP), or the French Space Operations Act (FSOA), using either ARES, or the built-in workflows. For the Swarm mission, we get the following results, as shown in Fig. 6, when analysing the target accepted collision probability level (ACPL), i.e. the operational manoeuvre threshold. The target of a

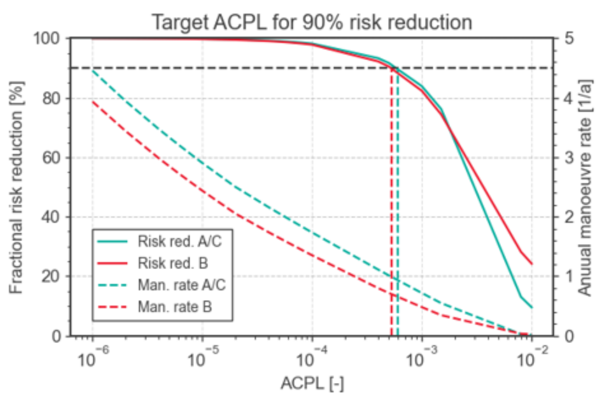

Fig. 6: Accepted collision probability and resulting manoeuvre rate for SWA and SWB.

90% risk reduction is achieved at an ACPL close to 10^{-3}, which means that the maximum value of 10^{-4}, as defined in the ESSB standard, should be used.

[10] `https://sdup.esoc.esa.int/master/downloads`

3.2.2. LEO orbital clearance

Assessing compliance with the orbital clearance requirements outlined in section 5.4.2 of the ESSB standard required the addition of two new features:

1. Computation of the cumulative collision probability after the disposal phase and until the reentry;
2. Check for orbit interference with constellations and protected regions.

For the first point, a workflow has been introduced that uses MASTER, in combination with OSCAR, to calculate the cumulative collision probability of a given disposal orbit and compare it to the threshold value of 10^{-3}.

To check for orbit interference, a new functionality has been introduced to OSCAR, allowing the user to input custom protected regions, for which the propagator will check if and when they are being crossed. In addition, the DRAMA 4 GUI can now load an up-to-date file with constellation orbits, generated from DISCOSweb data, which is then used by OSCAR. An example output of this workflow is shown in Fig. 7, showing the summary results of the various components of the requirement that is being checked.

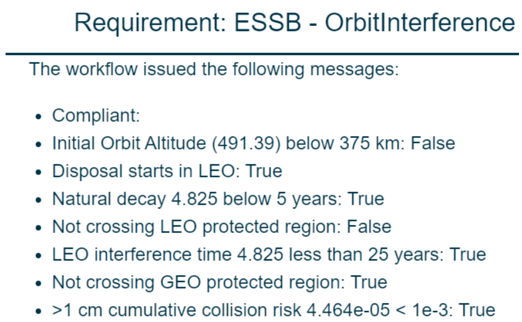

Fig. 7: Summary output of orbital clearance workflow in DRAMA 4.1.

Significant improvements have been made to the OSCAR tool for analysing orbital lifetime. Most notably, this includes the addition of two new disposal options:

1. Circular delayed de-orbit
2. Resonance disposal

While before, only elliptic disposal orbits could be analysed, OSCAR 4 now also includes the analysis of circular disposal orbits. The resonance disposal feature performs a grid search, to potentially exploit resonances between the orbital period and perturbations. In addition, OSCAR now includes a 6 degree-of-freedom attitude propagation module, which allows the consideration of long-term attitude motion, giving more accurate lifetime estimations for tumbling objects. Of course, the included workflows have also been adjusted to reflect the new target lifetime of five years, as outlined by ESSB-ST-U-007.

3.2.3. Trackability and brightness assessment

Two new requirements introduced in the Zero Debris standard (or ESSB-ST-U-007) relate to the trackability of a spacecraft, and its apparent brightness for an on-ground observer. To allow an assessment of these requirements, completely new tools have been introduced to DRAMA 4, which are based on the PROOF software [8].

The detectability and trackability workflows allow the simulation of optical-, radar-, and laser-based observations, for both on-ground and space-based sensors. Users are able to define a custom sensor network, based on the service provider for space situational awareness (SSA) products. However, DRAMA 4 comes preconfigured with a network calibrated to mimic the United States Space Surveillance Network (US SSN). With this, a user can easily get an estimate of the uncertainties within the CDMs generated via the US SSN. This workflow takes into consideration the geometry and material properties of the spacecraft, along with its orbit. It will provide detailed feedback on the simulated observation passes, and compute a 3×3 covariance matrix, along with uncertainties in radial, transversal, and normal (RTN) directions. An exemplary output for the SWA/B inputs can be seen in Tab. 2.

SWA			
	Radial (R)	Transv. (T)	Normal (N)
R	9.123e-11	1.052e-10	-8.021e-11
T	1.052e-10	1.847e-10	-7.745e-11
N	-8.021e-11	-7.745e-11	5.75e-10
St. Dev.	0.093 m	5.85 m	0.024 m

SWB			
	Radial	Transversal	Normal
R	4.293e-10	3.921e-10	-6.133e-10
T	3.921e-10	2.800e-09	-1.861e-09
N	-6.133e-10	-1.864e-09	1.848e-09
St. Dev.	0.1780 m	13.028 m	0.00742 m

Tab. 2: Estimated covariance and uncertainties in RTN for Swarm A and B using trackability analysis workflow

For Swarm, we can compare these results to the actual covariances from CDMs generated over the past year, as shown in Tab. 3:

	σ_R/m	σ_T/m	σ_N/m
SWA	16.6	920	8.5
SWB	14.3	460	8.9
SWC	16.9	880	8.7

Tab. 3: Median recorded standard deviation in RTN position in CDMs within 12h of TCA for Swarm during 2024.

We can see that DRAMA underestimates the uncertainties significantly. However, this analysis provides a good first order estimate for the uncertainties that are to be expected for a mission in the design phase. Furthermore, these results only represent the accuracy achieved via tracking through the US SSN, whereas an operator can generate improved orbit accuracy through dedicated tracking, using data from GNSS systems.

Furthermore, they can be used as inputs for ARES, to refine the collision avoidance and manoeuvre strategy, and inform users on what improvements can be expected for different/additional SSA providers.

Based on these new tools, an additional workflow has been added, allowing for the assessment of the brightness of a spacecraft, to check for compliance with the International Astronomical Union (IAU) recommendations. As inputs, the spacecraft properties and orbits are used. The reflectivity properties of the different materials of the spacecraft can be specified. In addition, the user can specify different observer positions, for which the apparent brightness during each crossing will be computed. Currently, the output consists of a list of observations during a crossing, and the brightness of the object. As currently no widely accepted method exists for computing a representative value for the brightness, it is left to the user to post-process the results provided by this workflow. In Fig. 8, the results of the analysis for the SWB orbit have been plotted as a function of elevation and azimuth for all the passes computed.

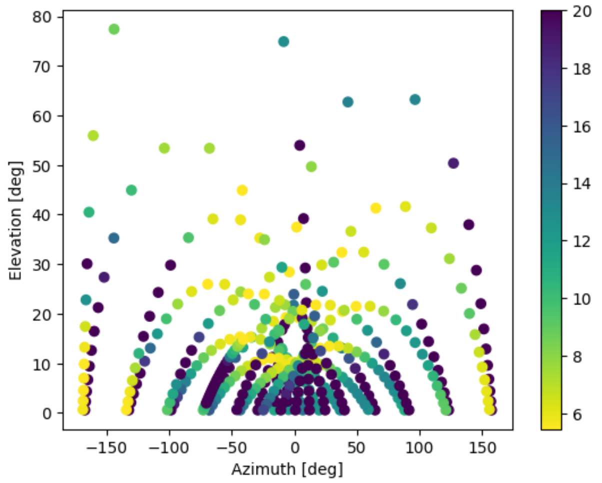

Fig. 8: Results of brightness analysis for SWB for all computed passes, as a function of azimuth and elevation.

4. CONCLUSION AND WAY FORWARD

Five years after their beginning, the DMF activities are set to culminate in the release of DRAMA 4.1 later this year. Many valuable lessons were learned during this time, in particular the workshops provided great opportunity to gather feedback and engage with the community. The space debris forum has been established as a further means for the community to engage in discussions in a public way. The clinics hosted during the last two workshops provided another great way to gather feedback and support the DRAMA users, and the aim is to host these semi-annually in the future. All of these insights have proven invaluable in shaping DRAMA to be a software that can be used successfully by a worldwide community and to keep up with the rapidly evolving field of space debris mitigation.

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