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DRAMA 3.0 - Upgrade of ESA's debris risk assessment and mitigation analysis tool suite

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ABSTRACT

In recent years some countries have established national regulation related to space debris mitigation, while many others are currently considering to follow similar steps. In general, this involves the adoption of already existing and widely accepted standards and international guidelines, such as ISO 24113 or the UN Space Debris Mitigation Guidelines. In order to support the verification of the compliance with existing recommendations, guidelines or even national laws, ESA has been developing the Debris Risk Assessment and Mitigation Analysis (DRAMA) software tool suite. Since 2014, when an ESA instruction came into force rendering space debris mitigation requirements applicable for any ESA satellite mission, DRAMA is being an essential part in mission design and subsequent compliance verification by the Agency. Today more than 1000 users world-wide from industry, academia and agencies are working with the software to address issues such as the remaining orbital lifetime of the spacecraft after disposal or the associated on-ground risk for an uncontrolled re-entry. The recent upgrade to DRAMA 3.0 entails the incorporation of the latest Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model, evolving from MASTER-2009 to MASTER-8; an extensive analysis of Conjunction Data Messages(CDM) which serve as the crucial input to estimate annual collision avoidance manoeuvre rates; a dedicated Python framework to run parametric analyses; and a significant extension of SARA, the tool used for the assessment of on-ground risk upon atmospheric re-entry. The latter includes improvements in the materials database, the aerothermodynamics and aerodynamics as well as an update of the world's population model. In this paper, the improvements in DRAMA 3.0 are introduced with a focus on showing instructive examples of how the new DRAMA software is being used in the context of verifying compliance with space debris mitigation requirements.

1. Introduction

With the endorsement of the UN Space Debris Mitigation Guidelines by the global community in 2007 [1], many countries and organisations continued to incorporate those recommendations into standards and national laws, significantly reinforcing space debris mitigation as an essential part in satellite mission design.

The DRAMA software saw its first release in 2004 with the objective to enable satellite programmes to assess their compliance with the recommendations contained in the European Code of Conduct for Space Debris Mitigation (CoC) [2,3]. The various aspects of the mitigation guidelines have been addressed by four different tools:

The *Assessment of Risk Event Statistics* (ARES) tool allows to assess the annual rates of close approaches between an operational spacecraft and tracked objects in Earth orbits along with statistics on the required number of collision avoidance manoeuvres and associated Δv and propellant mass.

The *MASTER-based Impact flux and Damage Assessment Software* (MIDAS) facilitates the evaluation of debris and meteoroid impact rates during a satellite's lifetime based on input coming from ESA's MASTER model and, by applying single and multiple wall damage equations, the probability of penetration for a given wall design.

The *Orbital SpaceCraft Active Removal* (OSCAR) tool allows for the computation of the orbital lifetime and the evaluation of different disposal options after the End-of-Life (EOL).

The *re-entry Survival And Risk Analysis* (SARA) tool assesses which and how many components of a spacecraft would survive a re-entry and computes the combined on-ground casualty risk given a world population model and the impact footprint of all surviving fragments.

With the evolution of the space debris mitigation standards in Europe, seeing the French Space Operations Act [4] come into force and the parallel development of the International Standardization Organisation (ISO) space debris mitigation standard [5], the DRAMA software was upgraded in 2014 to DRAMA-2 [6]. A new tool called CROC was added to the existing four, to compute the cross-sectional areas for complex spacecraft and different possible attitude laws after the end of mission. With ESA's adoption of ISO 24113:2011 into its *Space Debris Mitigation Policy* via the European Cooperation for Space Standardization (ECSS)

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Acronyms/Abbreviations

ACPL	Accepted Collision Probability Level
ARES	Assessment of Risk Event Statistics
CAM	Collision Avoidance Manoeuvre
CDM	Conjunction Data Message
CoC	European Code of Conduct for Space Debris Mitigation
CROC	CROss-section of Complex bodies
DRAMA	Debris Risk And Mitigation Analysis
ECSS	European Cooperation for Space Standardization
EOL	End-Of-Life
ESA	European Space Agency
GEO	Geosynchronous Earth Orbit
GUI	Graphical User Interface
GWP	Gridded Population of the World
ISO	International Standardization Organization
LEO	Low-Earth Orbit
MASTER	Meteoroid And Space debris Terrestrial Environment Reference
MIDAS	MASTER-based Impact flux and Damage Assessment
NASA	National Aeronautics and Space Administration
OSCAR	Orbital Spacecraft Active Removal
RAAN	Right Ascension of the Ascending Node
SAR	Synthetic Aperture Radar
SARA	re-entry Survival And Risk Analysis
SRP	Solar Radiation Pressure
SDMP	Space Debris Mitigation Plan
TLE	Two-Line Elements
UN	United Nations
UNWPP	UN World Population Prospects

[7] and coming into force in 2014, space debris mitigation requirements have become applicable to any Agency project. The DRAMA software has been identified as the main tool to support the verification of those requirements.

In 2019 another major upgrade was released with DRAMA-3. The latest version, which is available as a free download from https://sdup.esoc.esa.int, reflects on knowledge gained in different areas over the last few years and includes additional features requested by the user community.

The background population, which is used by both ARES and MIDAS was updated to MASTER-8. The new MASTER model comes with a recalibration of the two major breakups of Fengyun-1C (2007) and Cosmos-Iridium (2009). The new reference epoch is No. 1, 2016. Moreover, the Grün meteoroid model is now supported.

MIDAS makes use of MASTER-8's new target orbit propagation feature to integrate flux along an evolving orbit.

The analysis of more than a million CDMs made an update of ARES' catalogue uncertainty tables possible, which were mainly based on Two-Line Elements (TLE) before. Also, the radar equation saw an update to improve the filtering of objects at lower altitudes.

The SARA tool saw a major upgrade, introducing many new functionalities:

- Improved modelling of objects and components, including connected-to and nested-in relations;
- Release and explosion triggers as a function of different parameters, such as the altitude or the dynamic pressure;
- Aerodynamic and aerothermodynamic coefficient database for primitive shapes;
- Shadowing effects for connected objects;
- Simulation of the ablation of metals and CFRP materials;
- Update of the on-ground population model according to the latest Gridded Population of the World (GWP) and UN World Population Prospects (UNWPP) models.
- A dedicated Monte Carlo module to run parameter variations;
- Improved Graphical User Interface (GUI) providing visual feedback on the object tree and a three-dimensional view of the designed satellite;

In order to support the integration into other tools, a dedicated DRAMA Python package has been developed. Many users were already looking forward to this feature in order to run parametric analyses using the different DRAMA tools.

In this paper, an example of a DRAMA project is presented in Section 2, highlighting the major steps usually encountered during the satellite mission design for space debris mitigation related aspects. Widely accepted and standardised techniques and algorithms are referenced while discussing the individual tools. Finally, the current DRAMA roadmap and an outlook are provided in Section 3.

2. Working with DRAMA-3.0

For any ESA mission, the Space Debris Mitigation Plan (SDMP) has to be provided already at a very early stage in the project. The DRAMA software would be used to perform a first assessment and derive the required estimates that feed into the SDMP. The mission discussed in this paper is a fictitious Earth observation satellite called *Melpomene* (a tutorial, which contains the DRAMA project files, can be downloaded from https://sdup.esoc.esa.int). The basic set of parameters required to get started is shown in Table 1.

Many, if not all of the parameters in Table 1 are already known since the very beginning of the design phase, at least as a first order approximation or rule-of-thumb directly derived from the mission objectives.

2.1. Computing the cross-section with CROC

The first step in a DRAMA project is to obtain a coarse model of the satellite with the CROC tool, which makes the computation of the projected area (or cross-section) possible. The latter serves as a crucial input for the risk assessment and orbit propagation performed in subsequent steps.

Modelling the main body as a box with the dimensions from Table 1, adding two solar panels as flat boxes to the sides and the Synthetic Aperture Radar (SAR) as another flat box attached to the Earth-facing (nadir) surface of the satellite, one obtains a model as shown in Fig. 1

During the nominal mission, the satellite would have a fixed orientation and probably follow a certain attitude law according to the mission profile. That part is out of scope for the DRAMA analysis, which is rather addressing the on-orbit dwell time after the end of the mission. In that case, the satellite would not have any means of active attitude control and would therefore experience a rotational motion due to external forces and resulting torques. In the absence of any justification for a specific attitude mode, the general assumption is that the satellite

Table 1
Mission parameters definition for *Melpomene*.

Parameter	Value(s)
Main body dimensions	1.0 m × 1.0 m × 1.0 m
Solar panels	3.0 m × 0.8 m × 0.03 m
SAR dimensions	5.0 m × 0.5 m × 0.03 m
Dry mass	500.0 kg
Orbit epoch	2016-11-01
Orbit altitude	700.0 km
Eccentricity	0.00013
Inclination	98.2°
RAAN	10.0°
Arg. of perigee	90.0°
Assumed radius for collision avoidance	4.0 m
Wall thickness of main body	3.0 mm (Aluminium)
Wall design	Whipple shield (3 cm spacing)
Drag coefficient	2.2
SRP coefficient	1.3

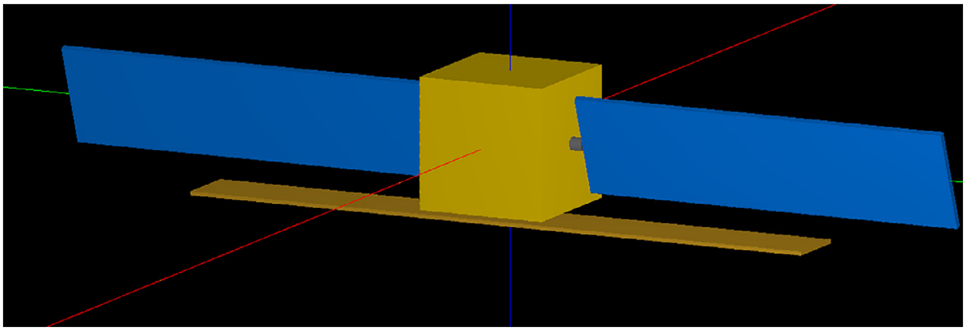

Fig. 1. CROC model of the *Melpomene* satellite.

would be randomly tumbling. This may or may not be true in the real world, but it is important to have this default option available in the compliance verification process. However, if there is sufficient evidence that the satellite could enter into a certain attitude mode, for instance a gravity gradient stabilisation, a more prudent approach might be required.

For *Melpomene* it is assumed that a randomly tumbling mode will be attained and CROC computes the average cross-section based on an integration of the projected area from different view angles. A result of about 4.5m^2 is obtained.

2.2. Flux and damage statistics with MIDAS

The impact and damage assessment is often mandatory, for instance if NASA's debris mitigation standard applies [8]. In that document, the requirements are defined as:

1. [...] during the orbital lifetime [...], the probability of accidental collision with space objects larger than 10 cm in diameter does not exceed 0.001 [...].
2. [...] during the mission [...], the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal maneuver requirements does not exceed 0.01.

The ISO 24113 standard is addressing impact risk assessments as well [5]:

- During the design of a spacecraft an assessment shall be made of the risk that a space debris or meteoroid impact will cause the spacecraft to break-up before its end of life.
- During the design of a spacecraft for which a disposal manoeuvre has been planned, an assessment shall be made of the risk that a space debris or meteoroid impact will prevent the successful disposal

A flux analysis with MIDAS can be easily configured. Using the orbit parameters from Table 1, the cross-section of 4.54m^2 obtained with CROC, and running in the *Impact Flux Analysis* mode, one can extract the results to check for both NASA requirements (as those mention numerical thresholds explicitly) from the data file containing the number of impacts as a function of the object diameter. For convenience, the *reverse cumulative* data files are also generated by MIDAS and those provide the numbers for objects larger than a given size.

For the *Melpomene* case, one obtains a probability of $0.86 \cdot 10^{-3}$ (per year) for impactor objects larger than 1cm. If the satellite would be operated for more than 11.6 years, the 0.01 threshold would already be exceeded, assuming that the definition of "compliance with applicable postmission disposal manoeuvre requirements" is neglected here. For objects larger than 10cm the result is $0.60 \cdot 10^{-4}$ per year, which would mean that the threshold could be reached after about 16.6 years. There is a caveat for the larger objects, as collision avoidance could be an effective means to further reduce the contributions of the large (and known, i.e. catalogued) objects.

More detailed analyses can be performed to study the effectiveness of shielding concepts, if compliance with a certain penetration probability threshold is required. For *Melpomene*, the six surfaces of the main body were analysed in the *Damage Analysis* mode, assuming an Earth-oriented mode. As an example, the *front* surface would be oriented with an azimuth and elevation angle of 0.0° each, the *rear* surface with an azimuth of 180.0° and elevation of 0.0°, etc. The front surface is equipped with a Whipple shield, as defined in Table 1. The obtained result is shown in Fig. 2.

In the reverse cumulative distribution, the annual probability of no penetration for objects larger than 0.1mm is about 99.85%, including both space debris and micrometeoroid impacts. It can also be seen that the shielding is effective for impactors having a size of up to about 2mm (where the reverse cumulative probability starts to increase in Fig. 2). All larger objects would penetrate the surface. But as the flux for increasing objects size is decreasing, the probability of no penetration is very high for larger objects.

2.3. Manoeuvre statistics with ARES

With increasing traffic in near-Earth space, close encounters with other active satellites and space debris occur more frequently and may put the entire mission at risk. Even worse, a potential catastrophic collision may result in thousands of fragments that would enhance the operational burden on other satellites in terms of required avoidance manoeuvres. A collision avoidance capability is therefore obligatory in responsible satellite operations. The new revision of ISO 24113:2019 [5] adresses this point and asks for an active management of collision risk.

The ARES software estimates the annual manoeuvre rate for a given target satellite and orbit. In a recent upgrade, knowledge gained from the collection of more than one million CDMs over the course of four years resulted in a significantly improved characterisation of the catalogue uncertainties [9]. As most operators today base their decision on whether or not to perform a collision avoidance manoeuvre (CAM) on CDMs, it appears very convenient to replicate this function in the software. In addition, the background population was updated from MASTER-2009 to MASTER-8. Fig. 3 shows analysis results for *Melpomene*.

The method requires the definition of a sphere to compute the collision probability. An encompassing sphere with a radius of 4m was used here. Assuming the manoeuvre *go/no-go* decision is made with one day lead time, the annual manoeuvre rate is obtained as a function of the accepted collision probability level (ACPL). The ACPL is typically a value that is defined in the operations procedures. It may also be selected based on how much risk is mitigated. From Fig. 3 an annual manoeuvre rate of about 0.75 is required for an ACPL of 10^{-4}. The risk reduction for the same ACPL is about 95%. Mitigating the entire risk involves a significantly increased manoeuvre rate: an ACPL of 10^{-6} requires about five manoeuvres per year.

2.4. Orbital lifetime with OSCAR

Any satellite operated in either the Low-Earth Orbit (LEO) or Geosynchronous Earth Orbit (GEO) *Protected Region* needs to be disposed of

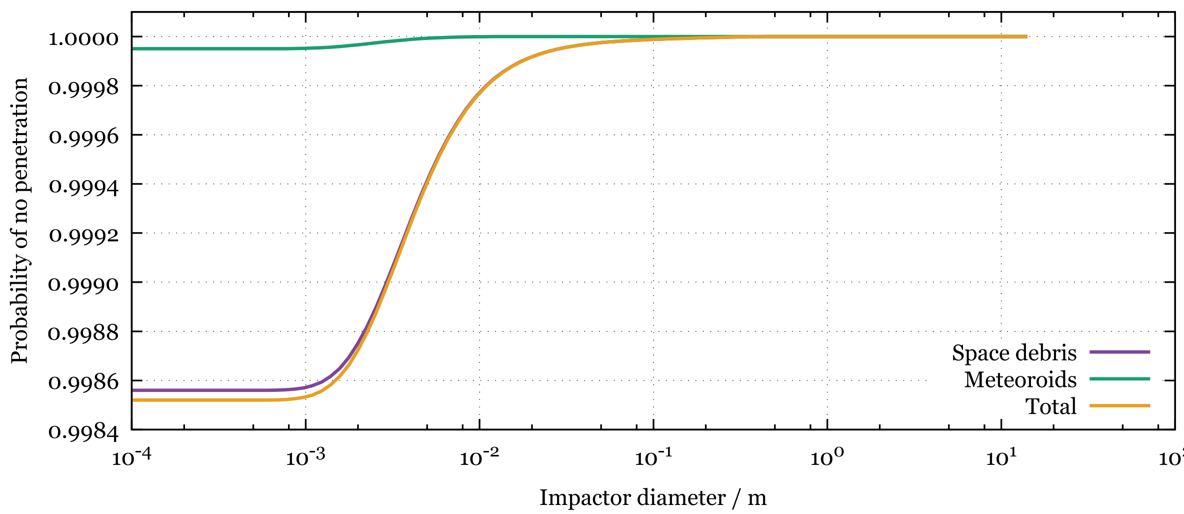

Fig. 2. Reverse cumulative probability of no penetration for the leading surface.

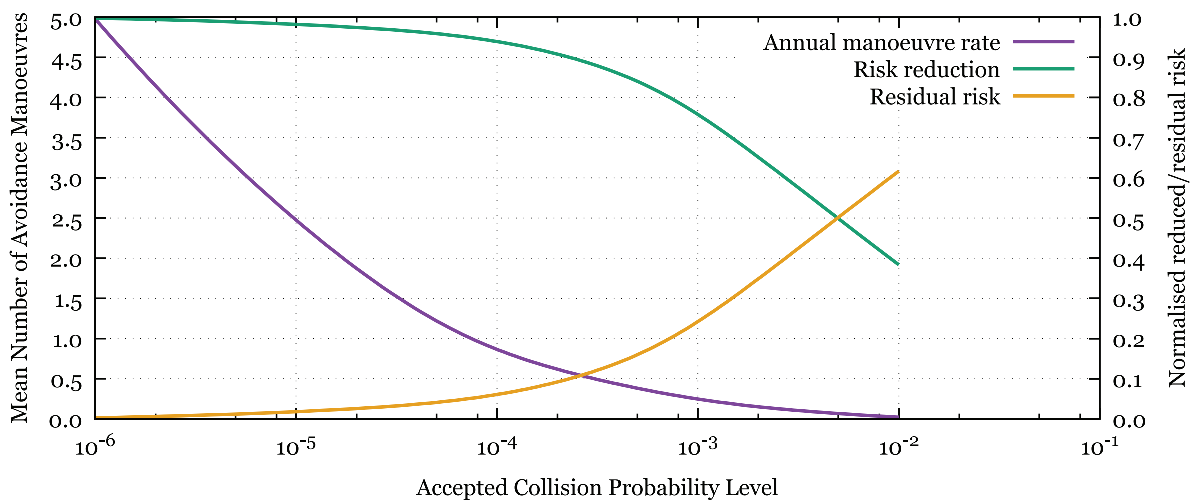

Fig. 3. Annual manoeuvre rate, risk reduction and residual risk as a function of ACPL.

after the end of the mission in order to minimise its impact on those regions. The OSCAR software supports in finding disposal orbits which are attained by means of different technologies, such as chemical or electric propulsion, electrodynamic tether or drag augmentation devices.

Several options exist for the *Melpomene* mission according to ISO 24113 [5]. Staying on the operational orbit at an altitude of 700km is not an option, as the estimated remaining lifetime is about 90 years. A *latest prediction* scenario forecast according to the Modified McNish & Lincoln method was applied for the solar & geomagnetic activity. The satellite was assumed to be randomly tumbling after the end-of-mission and the obtained cross-section from CROC could be used.

The preferred disposal option in ISO 24113 is the retrieval of the satellite and returning it to ground, but it is also the most expensive one and rarely adopted. In most cases, the decision has to be made between an immediate controlled re-entry and a transfer to an orbit with a significantly lower remaining lifetime in order to comply with the *25-year-rule*. In the latter case, the satellite would experience an uncontrolled re-entry after that period.

A controlled re-entry for *Melpomene* (via OSCAR's *direct de-orbit* mode) requires a ΔV of about180ms^{-1} and about 48kg of (monopropellant) hydrazine. Alternatively, OSCAR can be launched in its *delayed de-orbit* mode to find a disposal orbit for a given target remaining lifetime. Fig. 4 shows the result, i.e. by how much the perigee altitude needs to be reduced to have a remaining lifetime of 10 years in this example.

In a single burn scenario, a ΔV of 72m s^{-1} needs to be provided to lower the perigee altitude to about 432km.

The above example was computed in the *latest prediction* scenario for solar & geomagnetic activity. For ESA missions, the recommendation is to also compute the remaining lifetime in the *ECSS* and *Monte Carlo* scenarios and then select the most conservative one, i.e. the one giving the highest lifetime. This is especially important for scenarios where the solutions are near the 25-year margin or, where a minimum on-orbit lifetime needs to be guaranteed. In the latter case, mission designers usually select the scenario providing the lowest lifetime and search for an altitude where the minimum lifetime requirement is fulfilled.

A very important aspect is that any lifetime estimate is inversely proportional to the cross-section. A malfunction in the deployment of solar panels or any other cross-section augmenting structure may render the mission unsuccessful and leave a satellite stranded in its orbit. If the orbital lifetime under successful deployment would be compliant with the 25-year-rule but otherwise not, the deployment mechanism becomes an essential component of the disposal method. ISO 24113 demands a probability of successful disposal of at least 90% which then needs to be verified by the mission designers. Alternatively, if there is no further constraint on orbital altitude, a worst-case scenario can be assumed, where deployment fails but the lifetime would still be below 25 years. The latter option is often selected by small satellite missions.

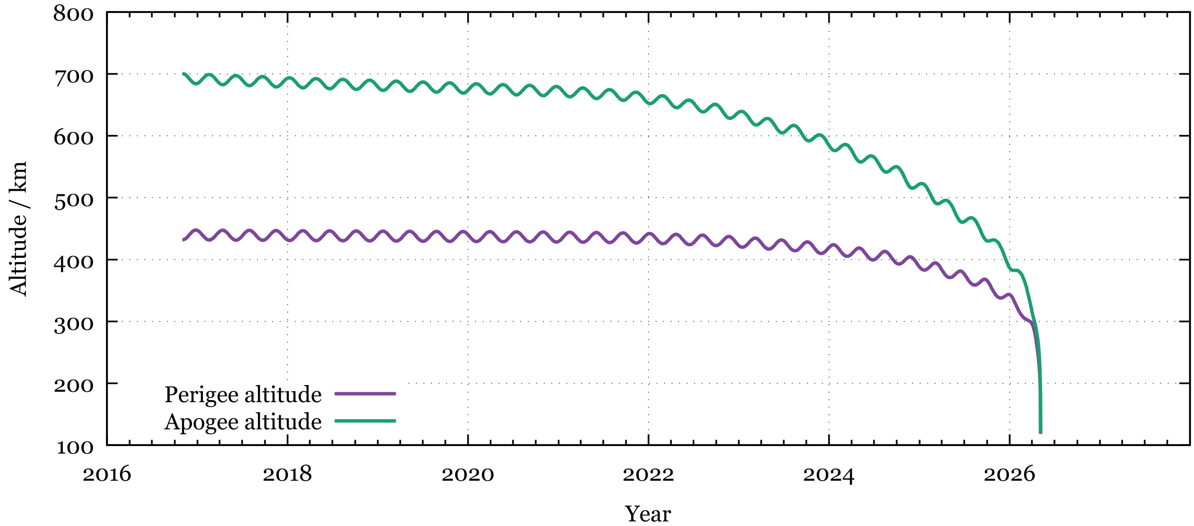

Fig. 4. Evolution of perigee and apogee altitude for the obtained disposal orbit.

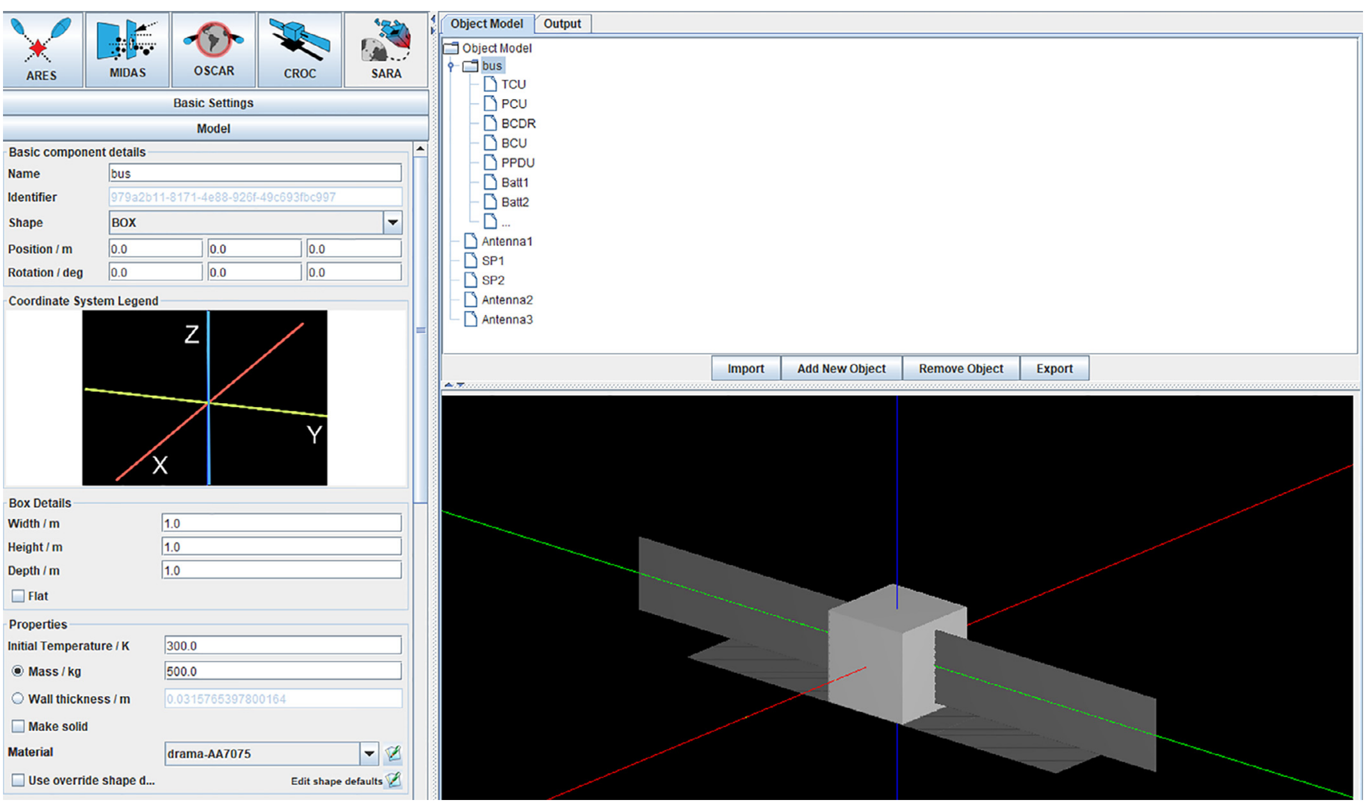

Fig. 5. New object tree model in SARA showing the *Melpomene* satellite.

An uncontrolled re-entry is not always possible. Especially if the assessed casualty probability for such a re-entry is above 10^{-4}, a controlled re-entry is mandatory. This is the main task of the SARA tool.

2.5. Re-entry risk with SARA

The SARA tool saw a major upgrade and offers many new functionalities. A very obvious one when launching the DRAMA GUI is the 3D view of the satellite and a hierarchy (tree) view of the modelled components, as shown in Fig. 5. What used to be a quite tedious task in the previous DRAMA versions, is now facilitated by means of drag & drop and duplication functionalities, but also the import and export of entire component libraries. Those can also be easily exchanged with colleagues.

Keeping the *object-oriented* approach, where upon breakup of the main body of the satellite all inner components are released and analysed independently, significant improvements were made in the establishment of an aerodynamics and aerothermodynamics database for primitive shapes; the new ablation models for metal and carbon fibre reinforced polymer (CFRP) materials; shadowing effects or the triggering of breakups and explosions. Moreover, the new Monte Carlo module runs parametric analyses, for example variations in the dimensions of a given object or its orbit.

Table 2
Objects reaching ground and their casualty probability for an uncontrolled re-entry of *Melpomene* in 2041.

Object	Casualty prob. $\times 10^{-5}$
SAR Antenna	5.61
Payload box	2.18
Telemetry & Control Unit	1.57
Battery ($\times$2)	1.52 ($\times$2)
Tank ($\times$4)	1.03 ($\times$4)
Reaction wheel ($\times$3)	0.93 ($\times$3)

The *Melpomene* satellite is shown in Fig. 5 with its solar panels and the SAR antenna. Some generic components were defined to be inside the main body of the satellite (see full example on https://sdup.esoc.esa.int), as displayed in the tree view. It is also possible in the new version of SARA to define connected-to relations, which results in so-called *compound* objects and is required for top-level objects. In the *Melpomene* example, the SAR antenna and the two solar panels are connected to the main body.

As SARA only simulates the last part of the orbit, the semi-major axis and eccentricity need to be configured such that the initial altitude is below 150km. This was often perceived problematic in previous DRAMA versions, especially for eccentric orbits. The new SARA version is capable of performing a hand-over to OSCAR in case the object would survive a dip into the atmosphere and continue on its ascending path for another orbit. It may even happen that several hand-overs between SARA and OSCAR would be required (done automatically by the software) until the satellite is finally captured by the Earth's atmosphere.

A circular orbit with an altitude of about 90km was selected for *Melpomene*. The re-entry analysis reveals 12 surviving objects listed in Table 2.

With the risk module, which saw an important upgrade to reflect the latest world population model (GWPv4) and the current predictions by the UN World Population Prospects (UNWPP), an overall casualty probability of $1.93 \cdot 10^{-4}$ is obtained. The contributions due to the individual surviving objects are also provided as shown in Table 2. The SAR antenna is quickly identified as the main driver of the computed casualty probability, followed by the tanks (as there are four in total). The downrange distribution of the surviving objects is shown in Fig. 6 with a footprint of about 1000km length.

It can also be seen that the solar panels detach at an altitude of 90km and the satellite experiences a breakup at 78km when all other objects are being released and analysed further by the aerodynamics and aerothermodynamics modules.

```python
from drama import oscar

project  = 'oproj.dpz'

inc  = [i for i in range(10,25,5)]
raan = [r for r in range(100,140,10)]

output = oscar.run(inc=inc, raan=raan,
                   project=project)
```

Fig. 7. pyDrama code example to run parametric analysis in OSCAR.

An uncontrolled re-entry would not be an option for *Melpomene*, as the threshold of 10^{-4} is violated. However, it is possible to study design options which could enable the demise of certain components. As an example shown here, the SAR antenna can be segmented into three different components. To do so, three different SAR antennas are defined in the object model top level, each having a third of the antenna's original length and mass. The two outer antenna part are connected to the central one, which itself is connected to the main body of the satellite as in the initial setup. Running this case shows that the SAR antenna does not survive the re-entry, thereby reducing the casualty probability by $5.61 \cdot 10^{-5}$.

2.6. Parametric analyses with Python

A new feature in DRAMA-3 is the Python package which comes together with the DRAMA installer (the documentation can be found at https://sdup.esoc.esa.int/drama/python_package_docs). Many users embed the DRAMA tools in their own programs and it seemed only logical to provide a Python wrapper around the different Fortran, C++ and Java programs. Moreover, parallel processing and different statistical and plotting features have been implemented to allow for quick analyses, as the one shown in Fig. 7 for a parametric variation of the inclination and the right ascension of the ascending node in OSCAR.

It is possible to import existing DRAMA projects via the well-known export files (*.dpz), as done in this example, where the *project* parameter of the *run* function is used. The latter automatically selects the available number of cores for the simulation and returns a convenient results dictionary. A full support of all possible input is not yet possible, but users can use the code already available and modify it according to their needs.

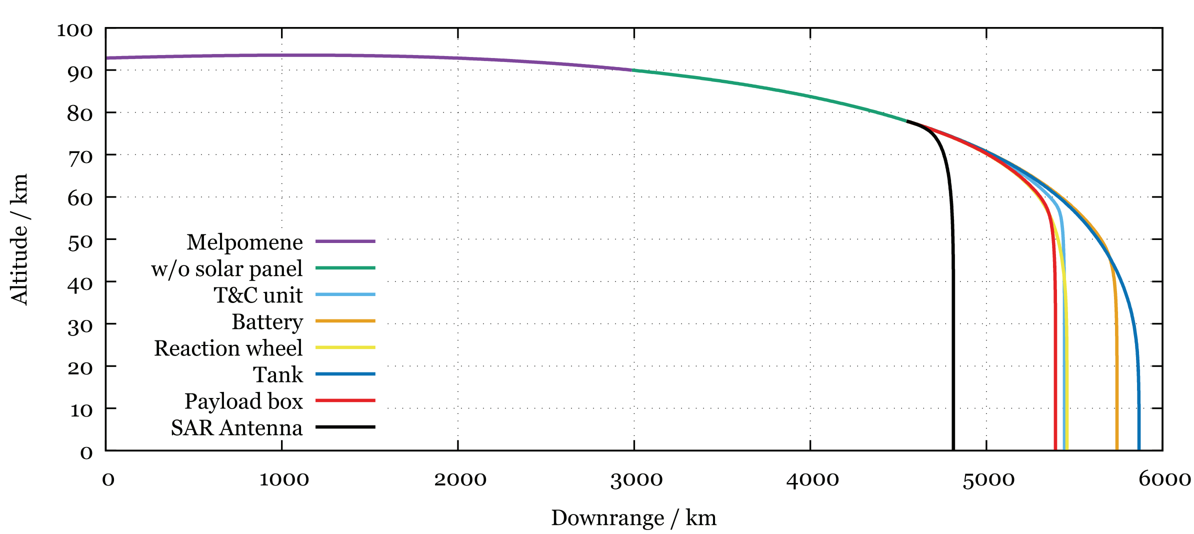

Fig. 6. Altitude vs. down-range for surviving objects.

3. Conclusion and outlook

The DRAMA-3 release in 2019 was reflecting on the knowledge and experience gained over the past few years. The ARES tool was upgraded after an extensive analysis of more than one million CDMs. An aerodynamic and aerothermodynamic coefficient database has been established for SARA, taking also shadowing effects into account. Moreover, CFRP-like material can now be studies as well as effects due to metal oxidation or ablation.

The DRAMA software today is being continuously developed, based on various feedback received from users via email (space.debris.support@esa.int), during dedicated trainings and personal communication, including bug reports but also feature requests. The latest release is DRAMA 3.0.3 from April 2020.

Besides a list of identified smaller features that will surely find their way into one of the upcoming patch releases, the DRAMA roadmap also foresees some more large-scale activities to further improve the software.

During the on-going operation of ESA's Aeolus satellite, many CDMs have been collected in very low altitude orbits recently, which showed a rather low sampling so far in ARES' uncertainty tables

A methodology is going to be introduced to simulate entire components in SARA, consisting of different materials, calibrated through past wind tunnel experiments. The feasibility of such an approach has been demonstrated successfully with a modelled reaction wheel, which is going to be the first component added in such manner in one of the next versions.

The DRAMA tool suite will see another evolutionary step in the following years in a series of activities combined under the so-called *Debris Mitigation Facility* (DMF). The existing tools will be further integrated to support a mission-centric and model-based engineering approach to facilitate a full debris mitigation analysis, assessing compliance with current standards and providing the users with the required input for their space debris mitigation report. Moreover, the DMF will have an additional focus on stronger user collaboration including an open-source release.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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