DOI: 10.13009/EUCASS2017-569

Upgrade of ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) Tool: Spacecraft Entry Survival Analysis Module

Irene Pontijas Fuentes(1), Davide Bonetti(1), Federico Letterio(1), Gonzalo Vicario de Miguel(1), Gonzalo Blanco Arnao(1), Pedro Palomo(1), Cristina Parigini(1), Stijn Lemmens(2), Tobias Lips(3), Ronny Kanzler(3)

(1) DEIMOS Space S.L.U., Spain, irene.pontijas@deimos-space.com
(2) European Space Agency (ESA), Germany, stijn.lemmens@esa.int
(3) Hypersonic Technology Göttingen, Germany, t.lips@htg-hst.de

Abstract

In 2015, ESA's "ESA Space Debris Mitigation Compliance Verification Guidelines" handbook was released, dealing with the practical aspects of how missions can demonstrate their compliance to, among others, the applicable maximum on-ground risk figures. Therefore, to provide algorithms and methods allowing spacecraft system designers and operators to prove the compliance of their spacecraft with the applicable regulations, ESA's Space Debris Office decided to carry out the upgrade of the "Debris Risk Assessment and Mitigation Analysis" (DRAMA) software suite implementing up-to-date methods as well as innovative and unique functionalities. The tools provided by DRAMA enable an assessment of mitigation strategies for the operational and disposal phases of a mission, including the risk posed due to mission's space debris and the effectiveness of an end-of-life strategy. Within this framework, DEIMOS Space is responsible for the SESAM (Spacecraft Entry Survival Analysis Module) module of DRAMA, being subcontractor of HTG under an ESA contract.

1. INTRODUCTION

Over recent years, the rising population of space debris has been increasingly recognized as a serious issue for the space-faring community. Mitigation is required, either by moving satellites to a safe long-term orbit at the end of their active life, or by disposing of them by re-entering the Earth's atmosphere. For energetic reasons, the former option is preferred for spacecraft in MEO or GEO, and the latter from LEO. However, the side effect of re-entry is the risk to human population and properties from surviving objects. Therefore, guidelines and technical standards for limiting and mitigating the amount of debris in orbit and defining the acceptable levels of risk to the population on the ground, have been published by all the major space agencies, including NASA [1][2] and ESA [3].

To minimise the risk to population, a requirement is imposed on spacecraft whose planned disposal method is re-entering the Earth's atmosphere that the risk of casualties must be below 10^{-4}. Compliance with this requirement can be achieved by a controlled de-orbit, where the safety concern is not the survivability of elements but the size of the footprint in order to fit it into a safe area, usually the open ocean, with sufficient clearance of landmasses and traffic routes. However, the impact in mass and cost of a controlled re-entry can be prohibitive, and hence the alternative is to ensure passive and safe re-entry within a 25-year timeframe. As uncontrolled re-entry is fully passive, it does not rely on the satellite still functioning correctly at end of life, and so maximises the useful life by avoiding the need to de-orbit a still-functioning satellite. Larger spacecraft cannot generally reduce the risk adequately for uncontrolled entries, and must therefore be designed to have a controlled entry landing in the ocean. Smaller satellites can be assumed to demise fully on entry without any changes being needed. In between, there are satellites which may have a casualty risk above 10^{-4}, but low enough that risk could potentially be reduced below this level by design changes.

Since the 10^{-4} casualty risk requirement can be a significant constraint on a spacecraft design, its proper estimation is critical to determine the compatibility of the mission and system with this type of end-of-life disposal strategy. To assess it, a generally-accepted re-entry casualty risk metric has been defined by Klinkrad [4]. Based on it, the calculation of the on-ground casualty risk covers three aspects, outlined in Figure 1. First, the surviving fragments have to be determined and characterized concerning their size, mass and impact velocity. Fragments with impact energy less than 15 J are not expected to cause injury and so are usually ignored. Second, the casualty area, which

DOI: 10.13009/EUCASS2017-569

represents the collision cross-section between a fragment and an unsheltered human body, has to be calculated. Finally, the casualty area must be transformed into casualty risk/probability. For controlled entry this is done using the population density within the footprint area predicted for the time of re-entry, and is referred to as “short-term assessment”. In the case of uncontrolled entry, where the time and location of entry are not known or controlled, this is achieved by multiplying the total casualty area with the mean population density corresponding to the re-entry event (i.e. orbit inclination and re-entry epoch), referred to as “long-term assessment”.

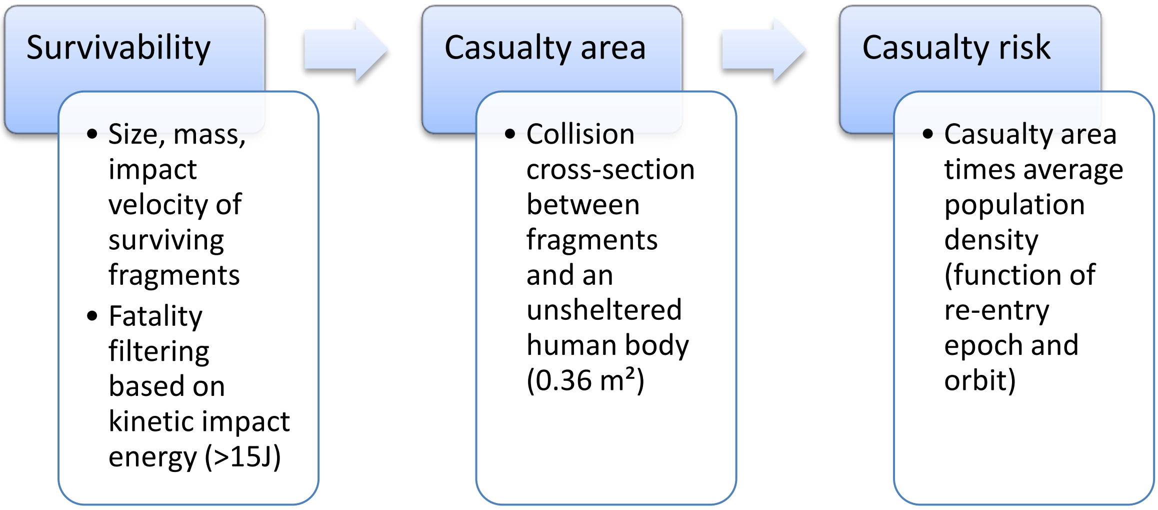


Figure 1: Re-entry casualty risk metric

In order to provide algorithms and methods allowing spacecraft system designers and operators to prove the compliance of their spacecraft with the applicable regulations, several tools have been developed by space agencies and industry. They can be mainly classified in two categories: spacecraft-oriented and object-oriented. The first approach is characterized by a detailed modelling of objects and processes involved, therefore, the output represents a very detailed assessment, but requiring significant effort to build the spacecraft model and to perform the calculations. The second approach uses simpler models of a spacecraft and its components, together with trajectory and aerothermodynamics calculations to model the demise, but allowing us to run fast and extensive parametric and statistical analyses. Therefore, object-oriented tools are usually adopted in the first project phases when multiple trade-offs at mission and system level have to be considered. They provide valuable inputs for the definition of the mission and system architecture with initial identification of elements that are likely to survive the re-entry and that could be a risk for ground population and property. With this information, the system engineers can steer the spacecraft design towards safer solutions implementing mitigation measures early in the project development and save costs. In more advanced project phases, as the system definition gets into more details, spacecraft oriented tools are usually adopted to verify that the mission and system design solution is compatible with the casualty risk requirements. DRAMA [5], DAS [6] and DEBRIS [7] are examples of object-oriented tools and SCARAB [8] is an example of spacecraft-oriented tool.

The upgrade of ESA's “Debris Risk Assessment and Mitigation Analysis” (DRAMA) software suite, which is considered as an objected-oriented tool, is intended to fill the gap between those two type of tools taking the best aspects of each world. In particular, the upgraded SESAM (Spacecraft Entry Survival Analysis Module) module of DRAMA, whose objective is to assess a spacecraft’s survivability by modelling the re-entry of a space system into the Earth’s atmosphere, is presented in this paper. Among others, an interesting and unique feature (not found in literature) is implemented: users can build up spacecrafts as combination of multiple primitives (spheres, cones, cylinders and boxes) using two types of relationships between them: “included in” (one primitive is fully shielded by another one) or “connected to” (two primitives are both partially exposed to the flowfield). Therefore, the spacecraft fragmentation is a process (not a single event anymore) which is the result of the evolution of the relationships established between the primitives, taking into account aero-thermodynamic characteristics. Aero-thermodynamic coefficients are automatically computed for the full spacecraft and for each spacecraft fragment under analysis based on innovative methods from computer graphics. Moreover, the explosion model has been reviewed, the ablation modelling has been extended to deal with CFRP-like materials and now SESAM is flexible enough to allow the users to define, for instance, different break-up triggers or re-entry attitude motions as well as to plug-in their own environmental or aerothermodynamics models (using those that best fit their needs) in order to cover a wider range of re-entry scenarios than before.

DOI: 10.13009/EUCASS2017-569

2. DRAMA TOOL

The ESA's DRAMA suite enables an assessment of mitigation strategies for the operational and disposal phases of a mission, including the risk posed due to mission's space debris and the effectiveness of an end-of-life strategy. It comprises several different tools, of which the (Re-entry) Survival and Risk Analysis (SARA), which support the analysis of controlled and uncontrolled re-entries from LEO up to HEO regions as well as objects returning from interplanetary space, is relevant here. SARA itself consists of two modules, the Spacecraft Entry Survival Analysis Module (SESAM), which "simulates the controlled or uncontrolled re-entries of spacecrafts into the atmosphere and calculates the survivability of spacecraft fragments" and the Spacecraft Entry Risk Analysis Module (SERAM) which "is able to calculate the casualty risk assessment, based on the data provided by SESAM".

DRAMA 2.1.0 is the current available version for the public of the ESA's space-debris software tool, but, recently it has been updated to extent its functionalities in order to fulfil all the requirements imposed by the new applicable "ESA Space Debris Mitigation Compliance Verification Guidelines" handbook (released in 2015). At the time of writing of this paper, the DRAMA upgrade is in its final phase of validation and verification testing.

3. SESAM MODULE

In this section the upgrades carried out under DEIMOS Space responsibility in the SESAM module of DRAMA tool are described and compared with the former features implemented in DRAMA 2.1.0. Basically, the upgraded SESAM module keeps the object oriented approach but extending the currently available functionalities and including state-of-the-art features and innovative functionalities. Figure 2 shows a high-level system context of the upgraded SESAM module, which clearly defines the three main areas of aerothermodynamics, dynamics and environmental models in which the upgrades has been implemented.

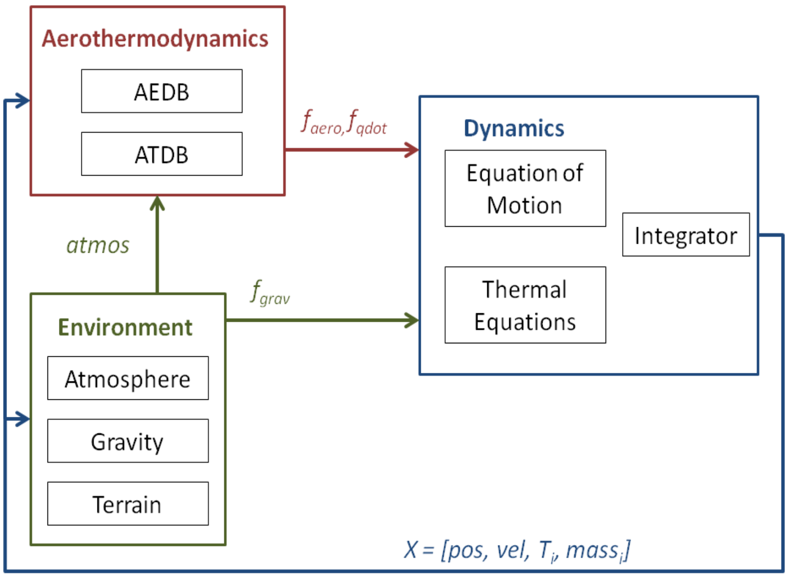


Figure 2: SESAM High-level System Context

3.1 Software architecture

DRAMA 2.1.0 was developed in **Fortran**, however, the upgraded SESAM module has been entirely re-engineered, using an **object-oriented programming paradigm** and the **C++ programming language**, see Figure 3. This choice brings several benefits, in terms of tool maintainability and extendibility, along with a clear coupling between the object-oriented programming paradigm and physical spacecraft model. It allows a more generic handling of the relationships among objects composing a spacecraft (or a fragment of a spacecraft), their shapes properties, their relative positions and attitude, their material properties and so on. The new SESAM architecture is now more structured and flexible, simplifying future tool improvements.

DOI: 10.13009/EUCASS2017-569

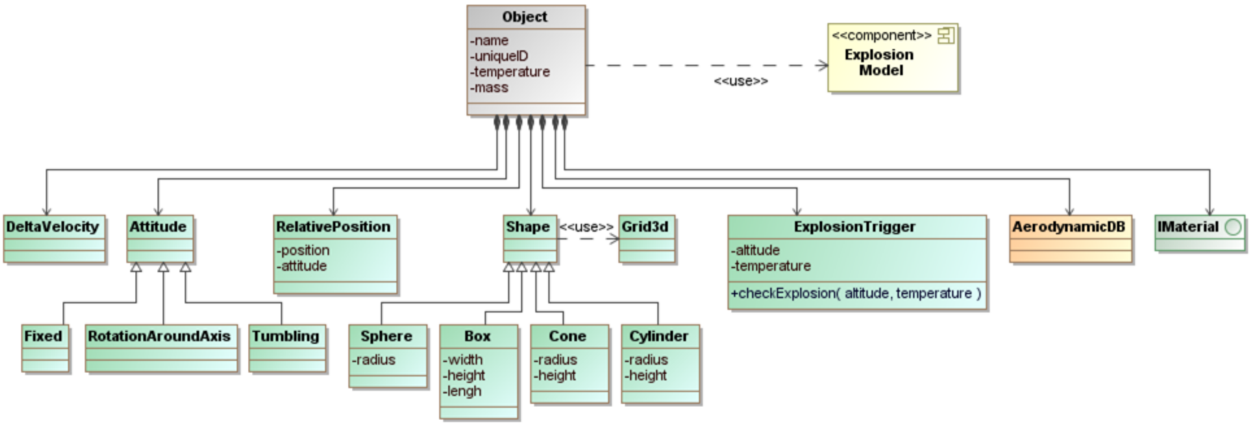


Figure 3: Upgraded SESAM Object Class Diagram

3.2 Object-oriented approach

DRAMA 2.1.0 follows an object oriented approach, therefore, the **spacecraft is modelled on one single level of parent and child concept**: initially the spacecraft is modelled as a single simple object (e.g. a box of rough dimensions and total mass) which virtually contains all the other spacecraft components without presenting any type of relationship between them. These spacecraft components are based on a pre-defined object list of simple shaped primitives: **sphere, box, cylinder and flat plate**.

A **single spacecraft break-up event** is modelled assuming that at a certain point of the entry trajectory the level of loads acting on the spacecraft results in the total structure collapsing. All the fragments are released at a pre-defined **fixed break-up altitude** (78 km). Solar panel break-off is possible and is set at 95 km. After the main breakup, trajectory propagation and thermal analysis are performed for each fragment independently, meaning that **each object is treated individually** and does not influence the motion of the others (for example shadowing).

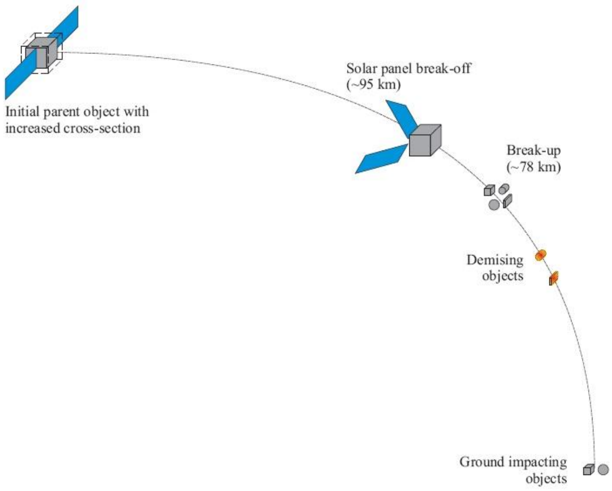


Figure 4: DRAMA 2.1.0 break-up model [5]

The upgraded SESAM takes the object oriented approach one step forward, and now the **spacecraft** (or the spacecraft fragment) **is modelled as a combination of multiple primitives** with two types of relationships between them: "**included in**" (one primitive is fully shielded by another one as in the parent/child concept) or "**connected to**" (two primitives are both partially exposed to the flow field and share a thermal conductive area). There are no limitations in the number of parent/child relationships that can be defined. The new available list of simple shaped primitives are: **cones, boxes, cylinders, spheres**.

Spacecraft fragmentation (division into multiple fragments) **is a process** (not a single event anymore) which is the result of the evolution of the relationships established between the primitives. The "included in" or the "connected to" relationships are broken based on the integrated time histories of the aerothermodynamics of the fragment model along the propagated trajectory. When a relationship is broken, a list of fragments is generated. The **thermal criterion is the default trigger** for the spacecraft fragmentation, however, users can define specific breakup triggers

DOI: 10.13009/EUCASS2017-569

for particular objects (at inclusion or connected-to level); whichever trigger limit is reached first (default or user-defined) triggers the break-up. The available **user-defined triggers** are: altitude, heat flux, dynamic pressure, load factor and temperature.

During the re-entry analysis of the fragments composed by multiple connected primitives, the **influence of shadowing is taken into account**. The fraction of visible primitive is computed at each time step and is used as relative weight in the sum of the fragment aerothermodynamics properties. This is achieved combining fast aerothermodynamic predictions with innovative shading factors computations (fraction of visible primitives) based on voxels techniques from computer graphics (see further details in section 3.4.3).

3.3 Environment

In DRAMA 2.1.0, the **US Standard Atmosphere 1976** is used together with a two-harmonics gravity model. No winds are considered. An atmosphere variability of ±20% in density can also be applied in case of surviving objects to know the dispersion of the impact location needed for the risk analysis.

In the upgraded SESAM, a default global atmospheric model covering the whole-year atmospheric variability, including solar and magnetic activity, is provided based on the **US Standard Atmosphere 1976, NRLMSISE00 model and the Horizontal Wind Model 2014**. Moreover, **user defined profiles** can also be provided as function of the altitude. Atmosphere variability in density can be applied via a scaling factor for Monte Carlo campaigns. A two harmonics gravity model is also included as well as terrain model based on WGS84 Oblate Earth.

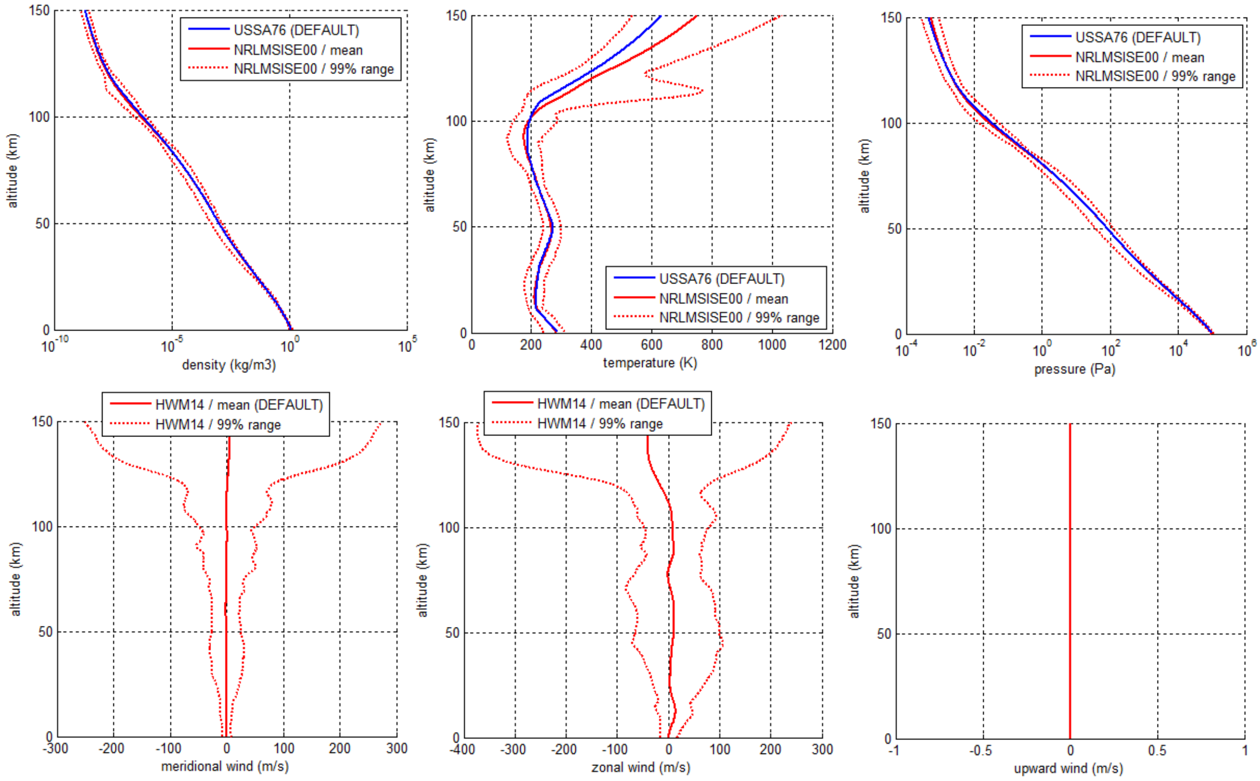


Figure 5: Upgraded SESAM atmospheric model

3.4 Aero-/Aerothermodynamics

In DRAMA 2.1.0, aero-/aerothermodynamic models are available for common simple geometrical shapes (sphere, cylinder, flat plane and box) based on **analytical formulations**. However, in the upgraded SESAM, solving the aerothermodynamics of a generic fragment shape (any combination of multiple primitives) flying at any attitude and in any flight regime (from free molecular flow to subsonic) is not an easy task. Therefore, in order to keep the computation reasonably fast, the approach followed is a linear combination of pre-computed free-stream primitives aerothermodynamic databases. These **pre-computed databases** are available for common simple geometrical shapes

DOI: 10.13009/EUCASS2017-569

(sphere, cylinder, box and cone); they have been computed using DEIMOS in-house tools (**HYDRA** and **HADES** modules from **PETbox** [9]) including dependencies on the flow regime. The weights of this linear combination correspond to the fractions of visible surface of each primitive (if a primitive is fully shaded, its “visibility factor” is zero and it doesn’t contribute to the fragment’s aerothermodynamics). To compute these visibility factors a new module called Voxelator has been introduced in the upgraded SESAM. Alternatively, if needed, **user defined databases** as function of Mach and Knudsen number are allowed.

3.4.1 AEDB

In DRAMA 2.1.0, for each shape, a **drag coefficient** profile is assumed, but **no lifting capability** is modelled. During the hypersonic flight, this drag profile depends on Knudsen number to model Free Molecular Flow, Transition and Continuum regimes (values adopted from ORSAT 5.0). At Mach equal to 1, the drag coefficient is reduced by 50% to model the subsonic aerodynamics, which is important to determine the ground impact energy. In fact, fragments are assumed to impact ground at their terminal velocity.

In the upgraded SESAM, for each fragment shape, **drag, lift and side force coefficients** are computed for each flight condition as a combination of the primitives composing the fragment. The weights of this linear combination correspond to the fractions of visible surface of each primitive computed by the Voxelator module. Fragments impact velocity is obtained from the trajectory propagation.

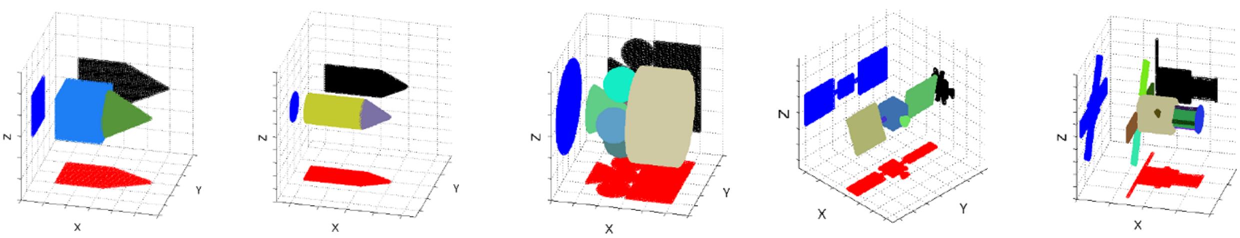
3.4.2 ATDB

In DRAMA 2.1.0, the aerothermal model formulation is similar to the one implemented in ORSAT, in which an uniform, averaged and shape dependent heat flux on the surface is assumed to model the incoming surface heat for a tumbling fragment: this is done by considering an approximate equivalent curvature radius depending on the shape. Averaged heating coefficients are adopted from ORSAT 5.0 distinguishing between continuum and free molecular flow.

In the upgraded SESAM, the estimation of the incoming aero-thermal heat fluxes of each fragment under analysis is carried out following two steps. As a first step, for each exposed primitive the integrated heat flux over the external surface is computed based on stagnation heating correlations for continuum and Free Molecular Flow and the application of averaging factors depending on the shape, dimensions and attitude motion. As a second step, shading factors are applied to take into account the influence of shadowing effects between primitives.

3.4.3 Voxelator

Voxelator is the new module implemented in the upgraded SESAM to compute the visibility factors needed to estimate the aerothermodynamics of a generic fragment shape. As a first step, the fragment is modelled as a combination of small 3D cubes. This allows the creation of a 3D matrix of scalar values where zeros are set in the empty space and scalar values (1 to N) are assigned to the space filled by a given set of N primitive. In computer graphics, these are known as voxels (3D extension of the 2D pixels). As a second step, for each fragment attitude, visibility factors for each primitive are computed as the ratio of the visible number of voxels in the scene associated to a given primitive to the total number of visible voxels if the primitive was placed in the domain by itself. This new module allows computing the visibility factors by manipulating a 3D matrix only (without the need for a more complicated ray-tracer module that needs appropriate surface meshes for each fragment). The price to pay is that non linear effects are not captured (e.g. aerodynamic interactions of fragments made of multiple primitives).



(a) Cube and Cone (b) Cylinder and Cone (c) Generic Upper Stage (d) Generic Spacecraft (e) Deimos 2

Figure 6: Examples of voxelized objects, from [10]

DOI: 10.13009/EUCASS2017-569

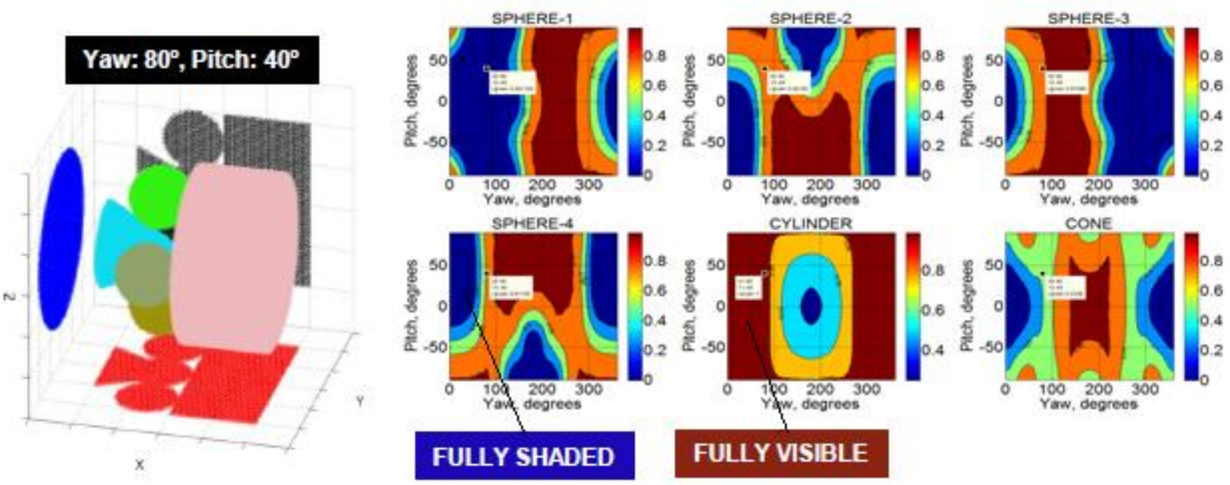


Figure 7: Examples of visibility factors (Generic Upper Stage Model), from [10]

3.5 Dynamics

In DRAMA 2.1.0, **thermal analysis is fully decoupled from the dynamics**. When the temperature reaches the melting temperature, melted mass is estimated but it does not affect the mass and size of the object considered in trajectory propagation. However, in the upgraded SESAM, **thermal analysis and dynamics are coupled**, therefore, mass losses are considered during the trajectory propagation of the fragments.

3.5.1 Equations of motion

In DRAMA 2.1.0, trajectories are propagated in **2 degree of freedom** in terms of altitude and downrange. Only **randomly tumbling** objects are taken into account. The variable time step solver **Runge- Kutta 4-5** method is used to integrate the dynamics.

In the upgraded SESAM, trajectories are propagated in **3 degree of freedom** of a point mass under a given attitude mode. Different attitude modes can be specified for the fragments: **randomly tumbling, tumbling around a given axis and fixed attitude**. Moreover, once a fragment composed by several objects is broken, there are two possibilities for the new fragments generated: to inherit the attitude from the parent fragment or to assume randomly tumbling motion. The fixed time step solver Runge-Kutta 7-8 method is used to integrate the dynamics.

3.5.2 Thermal equations

In DRAMA 2.1.0, only ablation of **metallic materials** (melting) is implemented based on a **lumped mass model**. A material database is included, considering typical space materials (AA7075, A316, TiAl6V4, Copper and Inconel) but also allowing the inclusion of user defined materials up to 15 new ones. **Thermal properties** are modelled as **temperature independent**.

In the upgraded SESAM, the heat balance for a re-entry object is evaluated considering the incoming aero-thermal heating and heat rejection through radiation in order to compute the evolution of its mass, external area, and temperature. **Conduction** between "connected-to" objects is also included in the thermal dynamics. Two ablation models depending on the material type are developed: one for **metallic materials** (based on a nodal approach) and another one for **CFRP-like materials** (based on a layered approach). In this last case of CFRP-like materials: pyrolysis (the epoxy matrix is decomposed under the action of the incoming aerodynamic heat flux) and oxidation (when the epoxy component near the outer border of the wall has gone, the remaining "charred" carbon fibres start to burn, with the carbon being transformed from the solid state to gaseous carbon oxide) effects have been also modelled based on [12]. A material database is included, considering typical space materials. The tool also allows the inclusion of user defined materials (no limited to 15 new ones). **Thermal properties** can be modelled as **temperature dependent** (e.g. emissivity, specific heat capacity and heat conductivity).

DOI: 10.13009/EUCASS2017-569

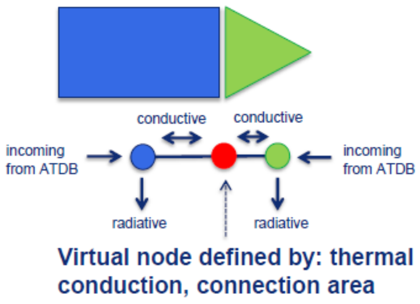


Figure 8: "Connected-to" relationship approach

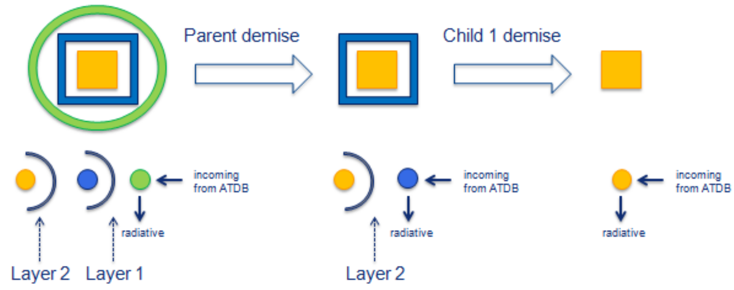


Figure 9: "Included" relationship approach

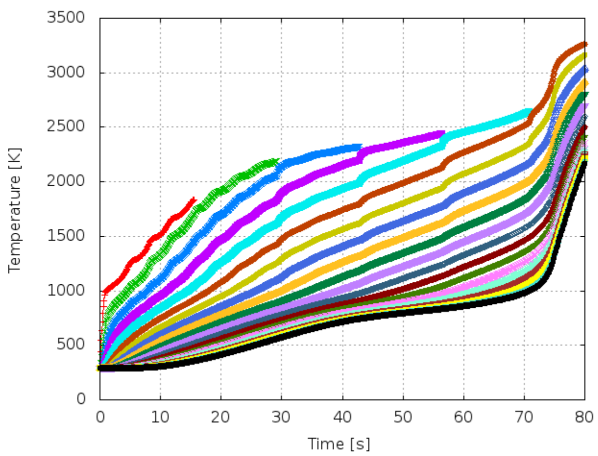


Figure 10: Example of layer temperatures evolution in CFRP-like materials

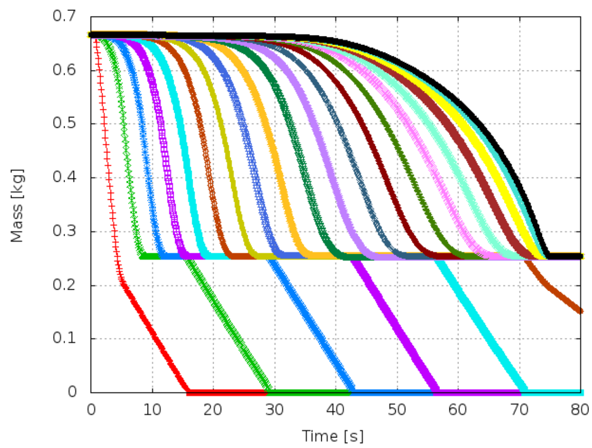


Figure 11: Example of layer masses evolution in CFRP-like materials

3.5.3 Explosion module

An explosion model based on **NASA's EVOLVE 4.0** [11] has been implemented in the upgraded SESAM to generate a list of new fragments following an explosion event (see explosion example in Figure 12 and Figure 13). This fragment generator has been implemented considering the following requirements:

- Mass conservation: No mass is allowed to be lost. The total mass of all explosion fragments must be identical to the mass of the spacecraft before the explosion.
- Thermal energy conservation: The thermal energy of all fragments must be identical to the thermal energy of the spacecraft before the explosion. It is assumed that no thermal energy from the explosion is added to the fragments. The fragments are only accelerated by the explosion (transfer of kinetic energy only).
- As the EVOLVE 4 model does not provide any direct information about the shape of explosion fragments, the fragment generator needs a shape identification algorithm that can provide the necessary geometric data.
- Each fragment can consist of only one homogeneous material. But the spacecraft before the explosion consists of a very heterogeneous mixture of several materials. Therefore, the fragment generator has to generate the fragments for each material separately. This can be interpreted as separate explosions for each material that the original spacecraft consists of. In order to fulfil the mass conservation requirement, the fragment generator needs the total mass for each material in form of a material specific mass budget.
- The spacecraft state vector at explosion time must be combined with the fragment ejection velocity vector (uniform direction distribution assumed) to provide the initial state vector for each explosion fragment.
- Thermal energy conservation is ensured by an also material specific initial temperature budget as input data for the fragment generator. SESAM has to provide the mean temperature of all spacecraft parts consisting of the same material. These temperatures will be used as initial temperatures of the explosion fragments. Therefore, all fragments consisting of the same material will have the same initial temperature.

Regarding the explosion triggers, there are two possibilities available, either based on altitude or based on temperature.

DOI: 10.13009/EUCASS2017-569

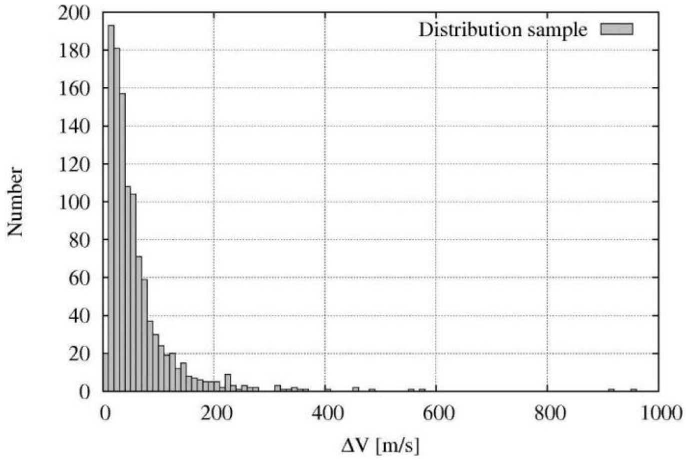


Figure 12: Example of ejection velocities for an upper stage explosion

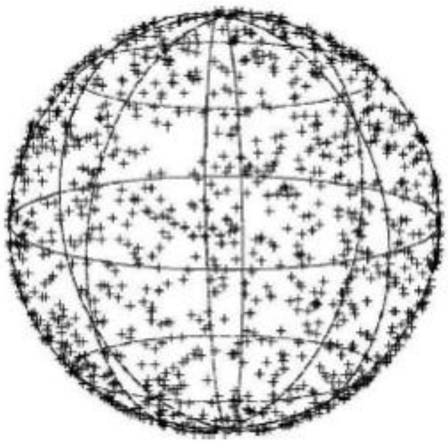


Figure 13: Example of ejection directions for an upper stage explosion

3.5 SESAM output

The main outputs provided by the upgraded SESAM module are:

- Trajectory files for the re-entry initial body and its fragments in order to provide the time evolution of their main thermal and trajectory parameters from the initial re-entry point down to their final conditions (demise, ballooning, skip-out or ground impact point).
- Final thermal state for the child fragments of the re-entry initial body (revealing which elements survive) and the ground dispersion, this information is used as an input to the SERAM module that run the risk casualty assessment. Now, the cross-section at impact considering mass losses during the re-entry trajectory and floating capability over water/oceans are evaluated for the surviving fragments.
- Figures showing the altitude vs. time and altitude vs. downrange flown by all objects from the re-entry point down to their demise, ballooning, skip-out or impact point.

Figure 14 and Figure 15 show an example of the graphical output produced for an explosion event triggered at 100 km of altitude above ground. Up to 60 new fragments are generated, of which 18 are demised during the re-entry flight (blue plus-markers), 10 reach ground posing risk to human and 32 experience a significant mass reduction but (red square-markers) being not considered risky since their kinetic energy is below the 15 J threshold.

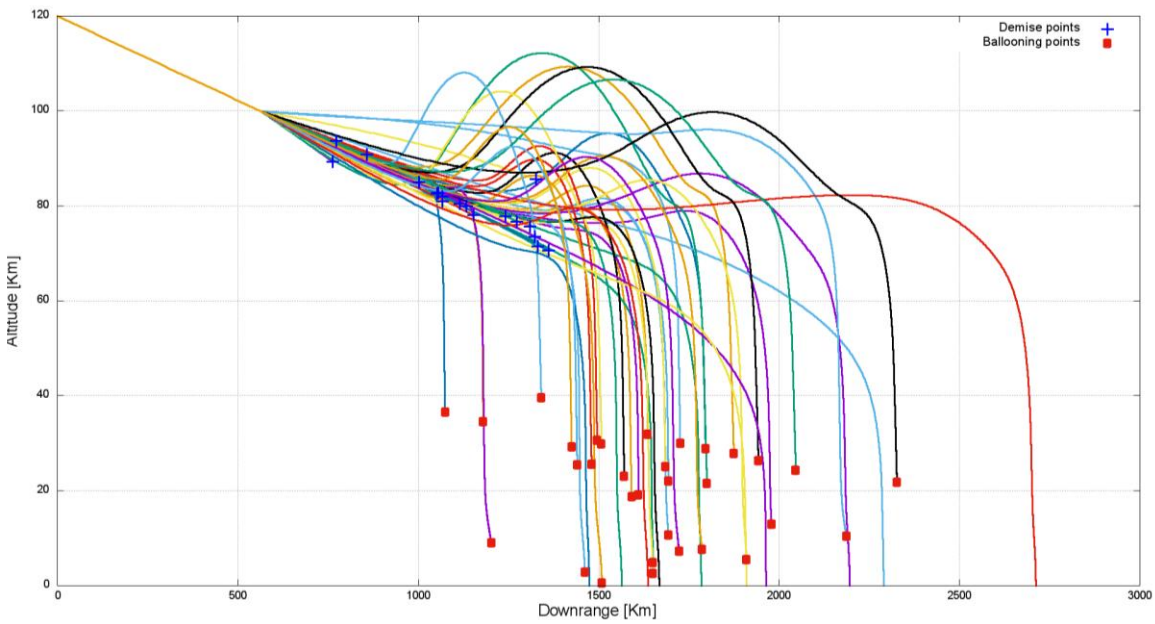


Figure 14. Example of altitude vs. downrange

DOI: 10.13009/EUCASS2017-569

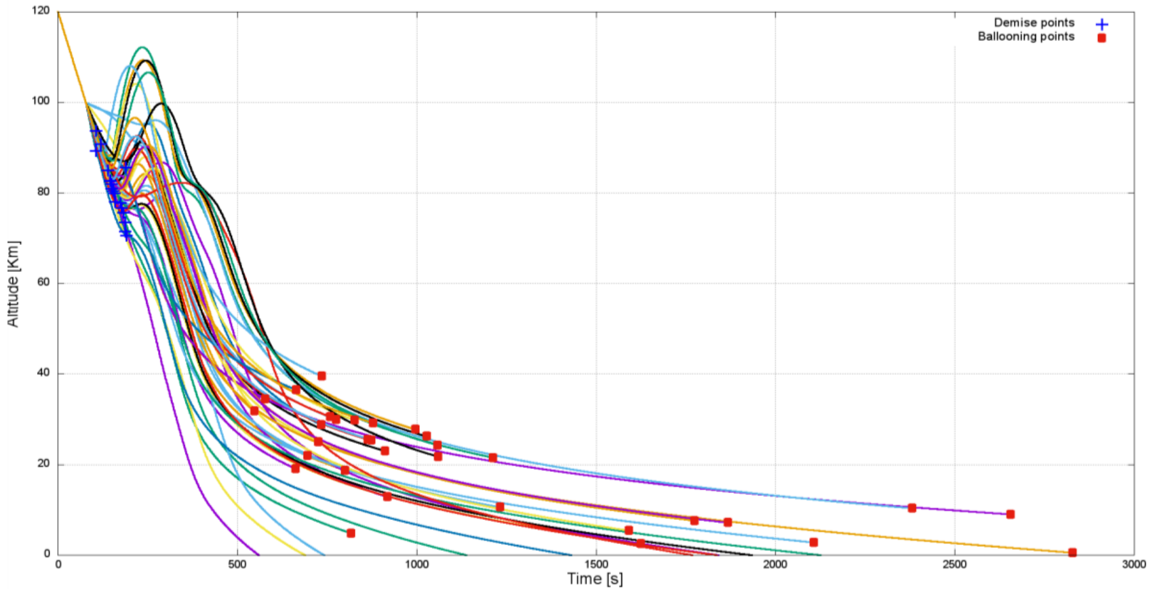


Figure 15. Example of altitude vs. time

4. TEST CASES

The upgraded SESAM module of DRAMA has been tested by DEIMOS Space to demonstrate the new features implemented (new shapes and relationships, new attitude motions, conduction heat and so on) and to assess how they affect to the fragmentation process. In this section, the main results of two representative test cases run are presented showing the new functionalities (additional test cases can be found in [13]). In the test cases shown hereafter, the same re-entry body has been considered but in each test this body is flying under different attitude modes.

- The initial fragment has been defined as a combination of all the available primitives types and relationships between objects. The fragment is basically composed by a (**purple**) cylinder connected to a (**brown**) cone and a (**light blue**) sphere; moreover, the (**purple**) cylinder is containing inside a box and a sphere. This last sphere also contains another sphere inside. (See Figure 16 and Table 1). Therefore, the capability of a two-level of parent-children relationship is tested.
- The initial fragment is assumed to be composed by objects made of standard aluminium and titanium materials.
- The initial fragment has been tested using two different re-entry attitudes: randomly tumbling (**Test Case A**) and fixed attitude (**Test Case C**). Once the initial fragment is broken, randomly tumbling motion is assumed for the new fragments generated in both test cases.
- The following co-rotating initial conditions have been set at the Entry Interface Point (EIP): velocity = 7.5 km/s, flight path angle = -2.5º, latitude = 10º, longitude = -5º.

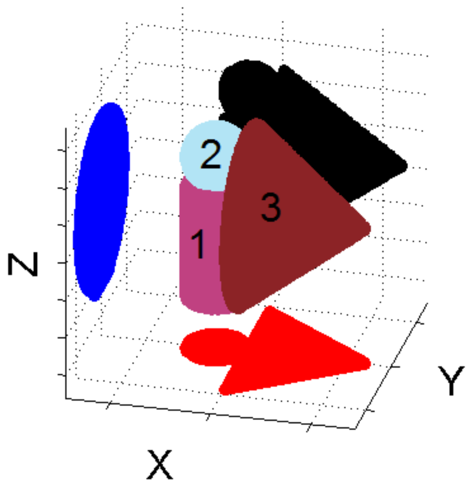


Figure 16: Voxelized fragment for test cases

Table 1: Fragment catalogue

Object 1	Cylinder	Aluminium	Connected-to Obj. 2, 3 Parent of Obj. 4, 5
Object 2	Sphere	Titanium	Connected-to Obj. 1, 3
Object 3	Cone	Aluminium	Connected-to Obj. 1, 2
Object 4	Box	Aluminium	Child of Obj. 1
Object 5	Sphere	Aluminium	Child of Obj. 1 Parent of Obj. 6
Object 6	Sphere	Aluminium	Child of Obj. 5

Table 2: Fragment attitude modes tested

Test Case	Initial Attitude	Attitude after break
A	Tumbling	Tumbling
C	Fixed	Tumbling

DOI: 10.13009/EUCASS2017-569

4.1 Test Case A

Test Case A is based on an entry object characterised by a randomly tumbling attitude motion. The trajectory profiles in terms of altitude, heat flux contributions, temperature and mass are shown in Figure **17**, Figure **19** and Figure **21**.

Due to the randomly tumbling motion, Objects 1, 2 and 3 are all exposed to the external heat flux for most part of their trajectory leading to an increase in their temperature. Instead, Objects 4, 5 and 6 are fully shielded by Object 1 due to the "included in" relationships, therefore they don't receive any external heat and their temperature remains constant while their parent Object 1 is alive. During this first part of the re-entry trajectory there is conduction between the connected objects. In particular, the direction of the conduction heat is from Object 1 to Objects 2 and 3 because of its higher temperature. However, the contribution of conduction to the global heat balance is minor, being three orders of magnitude smaller than the aerothermal convective heat flux.

Object 1, which is made of aluminium, is the first object to reach the melting temperature, around 192 s after starting the re-entry. At this point the "connected to" relationships between this object and Objects 2 and 3 are broken (see 'Object 1 breakup' tag in Figure **17** and Figure **19**). Object 1 starts flying alone and it is now fully exposed to the incoming aerothermal heat fluxes. On the other hand, Objects 2 and 3 remain together with a fraction of visible surface higher than before as there is no shielding effects due to Object 1; this lead to a higher incoming heat flux.

Once Object 1 reaches its melting temperature, the melting phase starts and its mass is consumed by ablation. It demises around 230 s (see 'Object 1 demise tag in Figure **17** and Figure **19**). The "included in" relationship is dissolved leading to the release of Objects 4, 5 and 6 (Object 6 is contained inside Object 5).

Object 3 is the next object to reach its material melting temperature (aluminium), around 233 s, at this point the "connected to" relationship between this object and Object 2 is broken (see for 'Object 3 breakup' tag in Figure **17** and Figure **19**). Both objects start flying alone until they reach ground; in this phase they are fully exposed to the external heat flux. Object 3 is slightly ablated because after the dissolution of the relationship with Object 2 the melting temperature is kept for a short time. Instead, along the Object 2 trajectory, the melting temperature is not reached during this test case simulation. This last object is in fact made of titanium, a hard-to demise material, and it reaches ground with its full initial mass (no ablation).

Objects 4 and 5 temperature does not reach the melting point; therefore these objects survive the re-entry impacting ground without ablation. It's noticed that Object 6 also reaches ground but, being contained inside Object 5, then it doesn't contribute to the casualty risk.

4.2 Test Case C

Test Case C is based on an object entering in the atmosphere with a given attitude: the angle of attack and sideslip are respectively 15º and -15º. The trajectory profiles in terms of altitude, heat flux contributions, temperature and mass are shown in Figure 18, Figure 20 and Figure 22.

Due to the orientation of the vehicle, Object 3 is mainly facing the external heat flux for most part of the trajectory leading to a quick increase of its temperature. Objects 1 and 2 instead are almost fully shielded behind Object 3 receiving a really low portion of the heat flux and therefore their temperatures remain almost constant. During this part of the re-entry trajectory there is heat transfer by conduction from Object 3 to Objects 1 and 2 because of its higher temperature. Objects 4, 5 and 6 are fully shielded by Object 1 due to their defined "included in" relationships, thus they don't receive any external heat.

Object 3 is the first object to reach the aluminium melting temperature, around 211 s after starting the re-entry. At this point the "connected to" relationships between this object and Objects 1 and 2 are broken (see 'Object 3 breakup' tag in Figure 18 and Figure 20). Two fragments are generated: one is Object 3 and another one is composed by Objects 1 and 2 (still connected). The two fragments are assumed to be flying in tumbling motion. Moreover, the fractions of visible surface of Objects 1 and 2 are now higher than before because they are not shielded anymore by Object 3; therefore, the incoming heat fluxes increase.

Object 1 reaches its melting point around 243 s, leading to the breakup of the "connected to" relationship between this object and Object 2 (see 'Object 1 breakup' tag in Figure 18 and Figure 20). From now on both objects fly alone until impacting ground.

DOI: 10.13009/EUCASS2017-569

In this test case all the objects reach ground. Object 1 and 3 suffer ablation during the re-entry; their final masses are approximately 50% and 80% of their initial masses. However, Object 2 impact ground without ablation. Objects 4, 5 and 6 remain inside Object 1 so they are not contributing to the casualty risk.

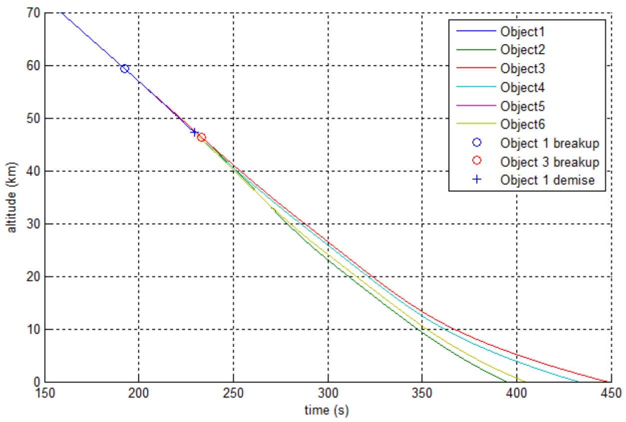


Figure 17: Altitude versus time (zoom), Case A

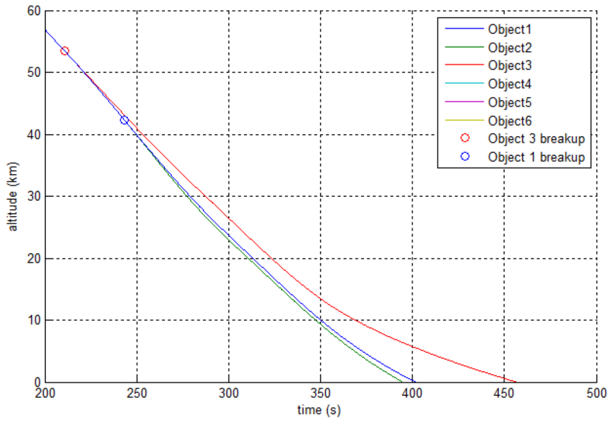


Figure 18: Altitude versus time (Zoom), Case C

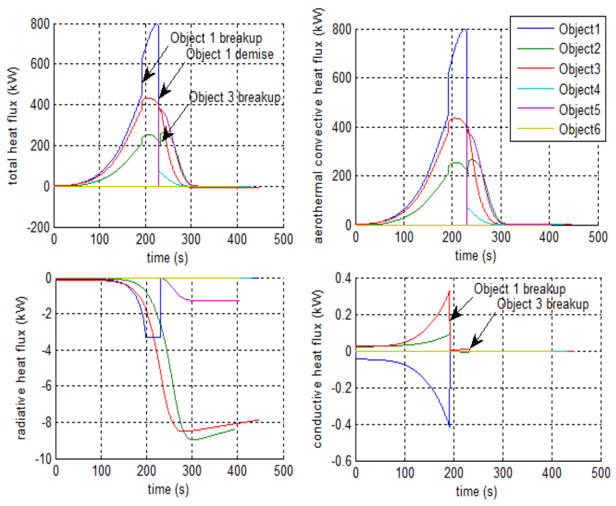


Figure 19: Heat fluxes evolution, Case A

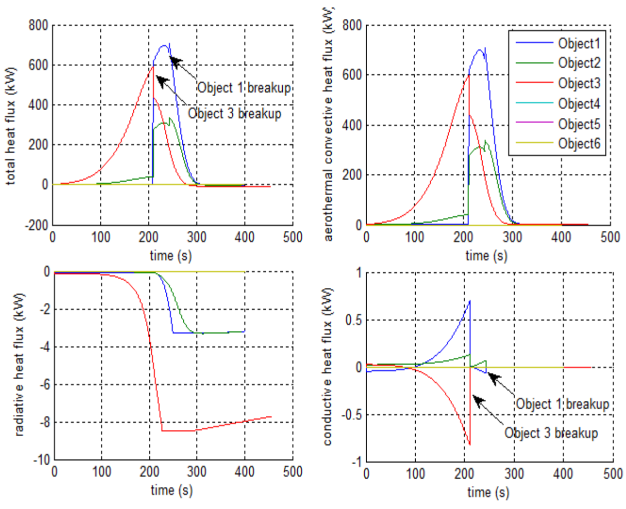


Figure 20: Heat fluxes evolution, Case C

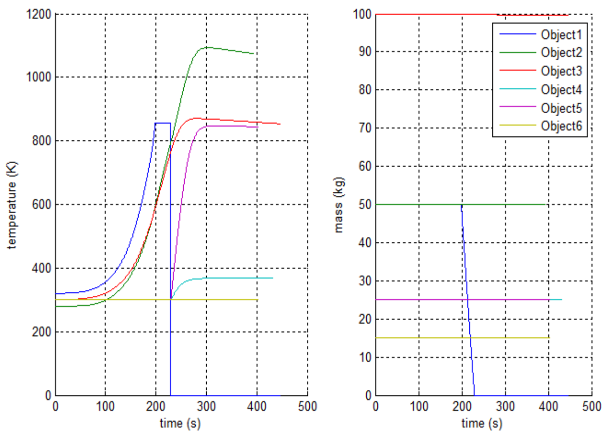


Figure 21: Temperature and mass evolution, Case A

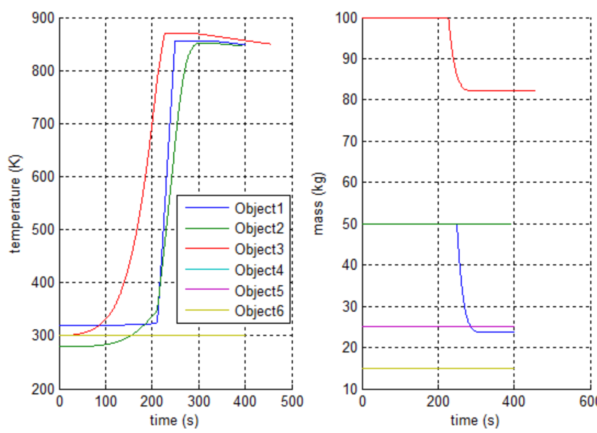


Figure 22: Temperature and mass evolution, Case C

DOI: 10.13009/EUCASS2017-569

4. CONCLUSIONS

To support spacecraft system designers and operators to prove the compliance of their spacecraft with the applicable regulations, ESA's Space Debris Office decided to carry out the upgrade of the "Debris Risk Assessment and Mitigation Analysis" (DRAMA) software suite implementing up-to-date methods as well as innovative and unique functionalities. Within this activity, SESAM module has been upgraded by DEIMOS Space, being subcontractor of HTG under an ESA contract. This new SESAM module has been presented along the current paper explaining the multiple new capabilities introduced in code as well as their impact in the re-entry process running some test cases.

SESAM has been rebuilt from scratch and its object oriented approach has been taken one step forward leading to a more realistic modelling of the spacecraft breakup/fragmentation process. This process is not being forced to be a single event (fixed at a pre-defined altitude) anymore; now it is the results of the evolution of the new "connected to" and "included in" relationships defined between the primitives as shown in the test cases reported in section 4 in which up to 3 different events happened during the re-entry trajectory. A default thermal criterion triggers the spacecraft fragmentation, however, user-defined breakup triggers for particular objects can be defined based, for example, on mechanical loads.

Atmospheric model now is more sophisticated based on a combination of US Standard Atmosphere 1976, NRLMSISE00 model and the Horizontal Wind Model 2014 models. The upgraded aerothermodynamic model uses pre-calculated aerodynamic and aero-thermodynamic coefficient databases for basic primitives including dependencies on the flow regime and, through the implemented 'Voxelator' module, shadowing effects between multiple connected objects are considered. Moreover, in both cases, atmosphere and aerothermodynamics, the users have the possibility to replace these default models using those that best fit their needs. The ablation algorithms can now analyse the behaviour of metals and CFRP-like materials, and NASA's EVOLVE 4.0 model has been implemented to cover the effect of explosion events.

Different attitude modes are now available for the fragments (randomly tumbling, tumbling around a given axis and fixed attitude) covering a wider range of re-entry scenarios than before. Concerning the fragments generated after the dissolution of a relationship, there are two attitude motions possible: inherited from the parent fragment or randomly tumbling motion. This feature gives to the user the capability to test different scenarios to model an uncertain event such as the breakup process. The two test cases presented in this work show the impact of two different initial attitude motions into the entry and survivability predictions of the same entry complex object. If in one case (Test Case A) one object demise and three fragments reach ground, in the other (Test Case C) three fragment reach ground but noon demise. These differences have a direct impact on the casualty area estimation and risk assessment, part of SERAM module computations.

Even considering that the upgraded SESAM module follows the object oriented approach, the innovative functionalities implemented give the upgraded DRAMA tool more flexibility and the possibility to deal with more complex spacecraft definitions and re-entry problems than the former version. Moreover, it's possible to state that the upgraded version presented within this paper is half way between object- and spacecraft- oriented tools, possibly being the first example of a new type of multi-objects oriented tool.

It is concluded that the upgraded DRAMA tool is a more powerful tool designed to better aid the mission designers to successfully assess and verify the current survivability and risk requirements. Work on the upgraded DRAMA tool is currently ongoing and a final version of it is expected to be released by ESA once the project will be completed (expected during 2017).

Acknowledgments

The authors would like to thank past DEIMOS Space interns, Piyush M. Mehta and Sergio Ramirez Navidad, for their outstanding contributions to PETbox and to the voxelator prototype.

References

[1] NASA Safety Standards, Guidelines & Assessment Procedures for Limiting Orbital Debris, August 1995.
[2] NASA Technical Standard, Process for Limiting Orbital Debris, NASA-STD 8719.14.
[3] ESA Space Debris Mitigation Compliance Verification Guidelines, February 2015.

DOI: 10.13009/EUCASS2017-569

[4] Klinkrad H., “Space Debris: Models and Risk Analysis”, Springer-Verlag, 2006.
[5] C. Martin, J. Cheese, N. Sanchez Ortiz, K. Bunte, H. Klinkrad, T. Lips, B. Fritsche, G. Koppenwallner, “Debris Risk Assessment and Mitigation Analysis (DRAMA) Tool”, Final Report of ESA/ESOC contract No. 16966/02/D/HK, QinetiQ/KI/Space/CR050073.
[6] Debris Assessment Software User’s Guide Version 2.0, 2012. https://sdup.esoc.esa.int.
[7] C. Parigini, I. Pontijas Fuentes. D. Bonetti, G. Blanco Arnao and D. Riley, “DEBRIS: An object-oriented code for footprint survivability and risk analysis”, 7th European Conference on Space Debris, 2017.
[8] Koppenwallner G., Fritsche B., Lips T., & Klinkrad H. (2005). SCARAB - a Multi-Disciplinary Code for Destruction Analysis of Space-Craft during Re-Entry. Proceedings of the 5th European Symposium on Aerothermodynamics for Space Vehicles, Cologne, Germany
[9] D. Bonetti, C. Parigini, G. De Zaiacomo, I. Pontijas Fuentes, G. Blanco Arnao, D. Riley and M. Sánchez Nogales, “PETBOX: FLIGHT QUALIFIED TOOLS FOR ATMOSPHERIC FLIGHT“, 6th International Conference on Astrodynamics Tools and Techniques (ICATT), Darmstadt, 2016.
[10] P. M. Mehta, G. Blanco Arnao, D. Bonetti, E. Minisci and M. Vasile, “Computer Graphics for Space Debris“, 6th International Conference on Astrodynamics Tools and Techniques (ICATT), Darmstadtium, 2016.
[11] Johnson, N. L. et al., “NASA’s New Break up Model for Evolve 4”, Adv. Space Research, Vol.29, no.9, pp 1377-1384, 2001; Pergamon Press.
[12] Kuch, M., Entwicklung eines Modells für die ablative Zerstörung von Kohlefaser-Epoxy Komposites beim Wiedereintritt, Master thesis, TU Braunschweig, 2011.
[13] D. Bonetti, I. Pontijas Fuentes, C. Parigini, G. Blanco Arnao, P. Palomo Pérez, F. Letterio, G. Vicario de Miguel, R. Travaglini, R. Sganga, S. Lemmens, T. Lips, R. Kanzler, “Upgrade of the Spacecraft Entry Survival Analysis Module (SESAM) of the ESA’s Debris Risk Assessment and Mitigation Analysis (DRAMA) Tool“, 67th International Astronautical Congress (IAC), Mexico, 2016.