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

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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.

To aid various projects in verifying the requirements, ESA's Space Debris Office has initiated the upgrade of the DRAMA "Debris Risk Assessment and Mitigation Analysis" software suite. The software 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.

The objective of SESAM is to assess a spacecraft's survivability by modelling the re-entry of a space system into the Earth's atmosphere. The destruction of a re-entering object is a complex, highly stochastic multi-disciplinary problem. The dynamics of the entry must be coupled with the aerothermodynamics, the thermo-mechanical loads evaluation, and the deformation and fragmentation processes. Together with the detailed modelling of these processes, the object properties in terms of geometry, mass distribution and materials, are also required.

Several tools to model the re-entry process have been developed by space agencies and industry. They can be classified in two main categories: object-oriented and spacecraft-oriented. The first is characterized by a finite-element approach to modelling the objects and processes involved; the second uses simpler models of spacecraft and components, together with trajectory and aerothermodynamics calculations to model the demise.

The upgraded SESAM follows the object oriented approach implementing state-of-the-art features and innovative functionalities. Among others, an interesting and unique feature (not found in literature) is implemented: users can build up spacecrafts as combinations of multiple primitives (spheres, cones, cylinders and boxes) with 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). This is achieved combining fast aerothermodynamic predictions with innovative shading factors computations (fraction of visible primitives) based on voxels techniques from computer graphics. SESAM is presented in this paper. Results produced are used by the SERAM module of DRAMA to assess the risk on-ground of objects surviving re-entry.

Keywords: space debris, re-entry, risk, survivability, spacecraft

Nomenclature

The following terminology is used within this paper:

PRIMITIVE is the object shape definition, e.g., sphere, cone, cylinder or box. OBJECT refers to each modelled spacecraft component alluding to a primitive.

FRAGMENT is a collection of objects. This last term can be used for both, the initial body and the partial re-entry fragmentations, being composed by either one single object or several objects.

Acronyms/Abbreviations

DAS: Debris Assessment Software
DRAMA: Debris Risk Assessment and Mitigation Analysis
ESA: European Space Agency
SARA: (Re-entry) Survival and Risk Analysis
SESAM: Spacecraft Entry Survival Analysis Module
SERAM: Spacecraft Entry Risk Analysis Module

1. Introduction

Over recent years, the risk to the world's population of death or injury caused by space debris has been increasingly recognised as a serious issue for the space-faring community. Debris can come from a number of sources, including failed launches, spent launcher stages, satellites at the end of their lives, operational debris, on-orbit break-up or collisions, etc. Many objects demise during entry to the Earth's atmosphere, but fragments can survive and reach the ground leading to risk to people. Guidelines and technical standards for limiting and mitigating the amount of debris both in orbit and 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 [3,4].

Because of increasing concerns about the rising population of space debris, requirements have been imposed on satellite operators that satellites must be removed from operational orbits within 25 years of the end of their missions. This can be achieved 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. These de-orbited spacecraft add to the amount of returning debris each year.

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 either by a controlled de-orbit, or by ensuring a passive and safe re-entry within a 25-year timeframe. For a controlled de-orbit, 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. However, the impact in mass and cost of a controlled re-entry, ensuring that the impact footprint is over an ocean area, with sufficient clearance of landmasses and traffic routes, can be prohibitive, and hence an uncontrolled entry is preferred where possible. 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 the risk could potentially be reduced below this level by design changes.

Non-nominal mission scenarios must also be considered, and so there are a parallel set of requirements imposed on all spacecraft regarding the casualty risk that could be caused in an unplanned re-entry, for example from a failed launch scenario, or where system failures mean that a spacecraft is unable to carry out its planned controlled entry.

The casualty risk requirement can be a significant constraint on a spacecraft design. In particular, because uncontrolled re-entry is not allowed if the total casualty risk is larger than the requirement of 10^{-4}, achieving this threshold allows significant savings in cost and mass. Therefore, the estimation of the human casualty risk is critical to determine the compatibility of the mission and system with this type of end-of-life disposal strategy.

A generally-accepted re-entry casualty risk metric has been defined by Klinkrad [4]. The calculation of the on-ground casualty risk covers three aspects, outlined in Figure 1.

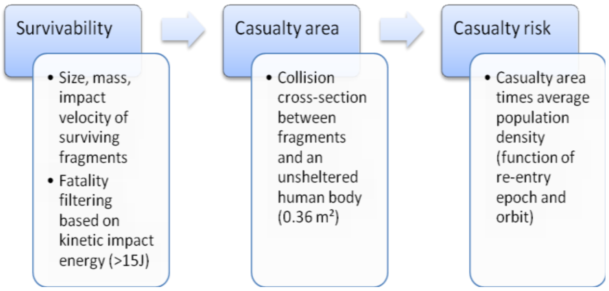


Figure 1: Re-entry casualty risk metric

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 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 by the mean population density corresponding to the re-entry event (i.e. orbit inclination and re-entry epoch): this is a "long-term assessment". These types of computations are implemented in several re-entry tools, e.g. the SERAM module of DRAMA [5], DAS [6] and DEBRIS [7].

Concerning the survivability analysis, it has to be considered that the destruction of a re-entering object is a complex, highly stochastic multi-disciplinary problem. The dynamics of the entry must be coupled with the aerothermodynamics and the thermo-mechanical loads evaluation to fully model melting, deformation and fragmentation processes. Together with the detailed modelling of these processes, the object properties in terms of geometry, mass distribution and materials, are also required. In this frame, uncertainties play a significant role to cover both modelling approximation and unknown aspects (e.g object geometric, mechanical and aerothermodynamical properties, atmospheric properties, entry conditions, etc.).

Several tools to model the re-entry process have been developed by the space agencies and in industry. They can be classified in two main categories: object-oriented and spacecraft-oriented. A spacecraft-oriented approach is characterized by a detailed modelling of most of the objects and processes involved, albeit approximately. When parts of the spacecraft are separated, all of them are followed either to complete demise or to the ground. The output represents a very detailed assessment, but it requires significant effort to build the spacecraft model, and high computational efforts are needed to perform the calculations. An object-oriented approach, on the other hand, uses simpler models of a spacecraft and its components, together with trajectory and aerothermodynamics calculations to model the demise. The common idea of an object-oriented approach is to model break-up of a spacecraft as a single event: at a certain point of the entry trajectory the level of loads acting on the spacecraft results in structure collapsing. After the main breakup, trajectory propagation and thermal analysis are performed for each fragment independently.

Object-oriented tools produce faster results and 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 means. 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.

In the following chapters, DRAMA is introduced with a focus on the object-oriented SESAM module. Former SESAM functionalities are recalled and the upgrades introduced are described with a discussion of the results obtained on an initial set of test cases.

2. DRAMA

To aid various projects in verifying the risk requirements, in 2015 ESA's Space Debris Office has initiated the upgrade of the DRAMA "Debris Risk Assessment and Mitigation Analysis" software suite. The software 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.

The DRAMA suite comprises several different tools, of which the (Re-entry) Survival and Risk Analysis (SARA) 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".

Within this framework, DEIMOS Space is responsible for the upgrade of the SESAM (Spacecraft Entry Survival Analysis Module) module of DRAMA.

3. Former SESAM functionalities

The former SESAM is an object-oriented code based on the following functionalities and modelling features:

- ☐ The software has been developed in Fortran.
- ☐ 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.
- ☐ A single spacecraft break-up event is modelled. 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. A scketch is shown in Figure 2.

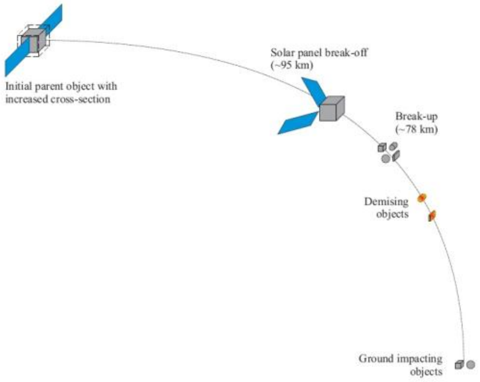


Figure 2: Former SESAM breakup model [5]

- ☐ Spacecraft components are a based on a pre-defined object list of simple shaped primitives (sphere, box, cylinder, flat plate).

- ❑ During the re-entry analysis of the fragments, each object is treated individually and does not influence the motion of the others (for example shadowing).
- ❑ Trajectories are propagated in 2 degree of freedom in terms of altitude and downrange. The variable solver Runge-Kutta 4-5 method is used to integrate the dynamics.
- ❑ Concerning the environmental model, the US Standard Atmosphere 1976 is used together with a two-harmonics gravity model. 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.
- ❑ 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.
- ❑ Aerothermodynamic models are available for common simple geometrical shapes that are sphere, cylinder, flat plane or box.
- ❑ Once an element is approximated as one of these shapes, its dimensions have to be roughly provided. No specification of the thickness is necessary being no distinction between solid and hollow elements; therefore, for the dynamic and thermal analysis computation the exact mass of the element has to be provided as an input.
- ❑ Only randomly tumbling objects are taken into account, being the most common motion for the debris; therefore no lifting capability is modelled.
- ❑ For each shape, a drag coefficient profile is assumed. During the hypersonic flight, it depends on Knudsen number to model Free Molecular Flow, Transition and Continuum regimes. 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.
- ❑ The heat transfer formulation is similar to that implemented in ORSAT, in which heat flux in continuum and free molecular flow are distinguished. A 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.
- ❑ The aerodynamic drag values in hypersonic flow and aerothermodynamic heating coefficients have been adopted from NASA's ORSAT 5.0 (Object Reentry Survival Analysis Tool) with only minor changes.
- ❑ 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.
- ❑ Only ablation of metallic materials (melting) is implemented.

The output of SESAM, which is composed by the S/C and fragment trajectory, the thermal state for the child objects (revealing which elements demise) and the ground dispersion, is used as input to the SERAM module that run the risk casualty assessment.

4. Upgraded SESAM Architecture

SESAM module has been entirely re-engineered, using an object-oriented programming paradigm and using the C++ programming language. 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.

Figure 3 shows a high-level system context of the SESAM module, which clearly defines the three main areas of aerothermodynamics, dynamics and environmental models.

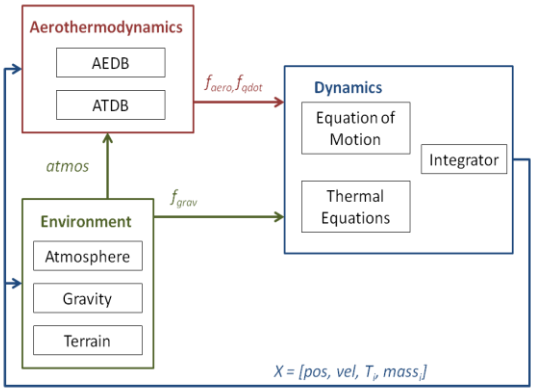


Figure 3: SESAM High-level System Context

However the real step forward with respect of the previous SESAM module has been the modelling of the spacecraft throughout the generalization of the concept of shapes, which allows an easy implementation of the relationships among the objects composing a fragment and the extension of the current model with more complex ones or further shapes. The followed approach also allows the extension of the attitude or the material components, as depicted in Figure 4.

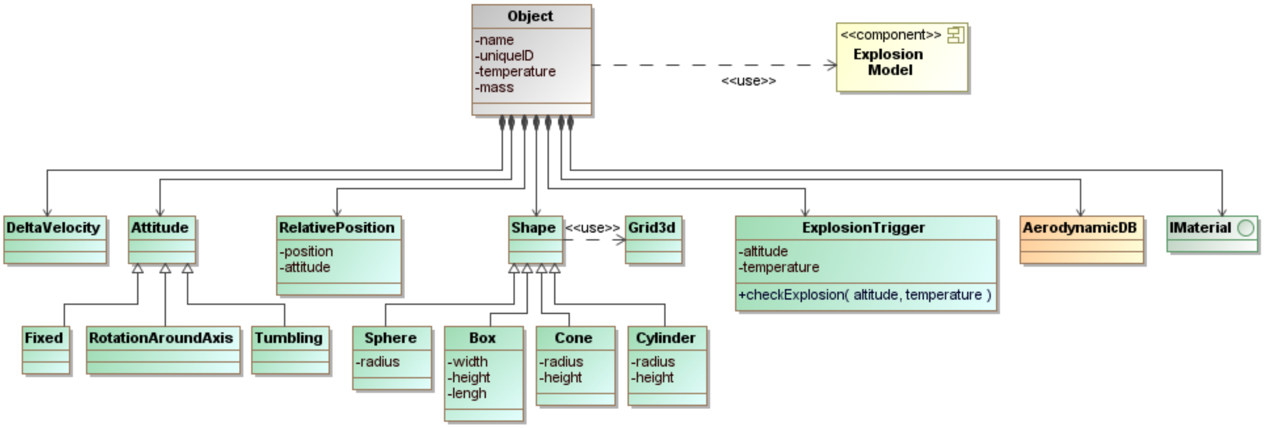


Figure 4: SESAM Object Class Diagram

5. Upgrades of SESAM functionalities

The upgraded SESAM keeps the object oriented approach including state-of-the-art features and innovative functionalities. With respect to the former SESAM, the main updates implemented are:

- The spacecraft (or the spacecraft fragment) is modelled as a combination of multiple primitives (spheres, cones, cylinders and boxes) with two types of relationships between them: "included in" (one primitive is fully shielded by another one as in the parent and child concept) or "connected to" (two primitives are both partially exposed to the flow field and share a thermal conductive area).
- Spacecraft fragmentation (division into multiple fragments) is a process (not a single event) 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, user can define specific breakup triggers for particular objects (at inclusion or connected-to level); whichever trigger limit is reached first (default or user-defined) triggers the break-up.
- Spacecraft components are a based on a pre-defined object list of simple shaped primitives including cones.
- 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.
- Trajectories are propagated in 3 degree of freedom of a point mass under a given attitude mode. The fixed solver Runge-Kutta 7-8 method is used to integrate the dynamics.
- Thermal analysis and dynamics are coupled, therefore, mass losses are considered during the trajectory propagation of the fragments.
- Concerning the environmental model, default values are provided based on the US Standard Atmosphere 1976 and the Horizontal Wind Model 2014. However, the user can provide any other profile as function of the altitude.
- A material database is included. The tool also allows the inclusion of user defined materials; thermal properties can be modelled as temperature dependent (e.g. emissivity, specific heat capacity and heat conductivity).
- Aerothermodynamic models are available for common simple geometrical shapes that are sphere, cylinder, box or cone. Default values, pre-computed using HYDRA and HADES modules from PETbox [11], are provided with dependencies on the flow regime. If needed these values can be modified by the user.
- A thermal network is built where each primitive is represented by a thermal node. The time evolution of temperature in the primitives is the results of the incoming and outgoing heat fluxes in each node along the fragment trajectory. Conduction is considered in case of "connected to" relationships.
- Different attitude modes can be specified for the fragments: randomly tumbling, tumbling around a given axis and fixed attitude; therefore lifting capability is included.

☐ 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. Fragments impact velocity is obtained from the trajectory propagation.

☐ The ablation modelling has been extended to 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 fibers start to burn, with the carbon being transformed from the solid state to gaseous carbon oxide) effects have been modelled based on [8]. This functionality has been developed by HTG.

☐ Updated interfaces to the explosion model (based on NASA's EVOLVE 4.0 [9]) have been implemented to generate a list of new fragments following an explosion event. This functionality has been developed by HTG.

☐ Cross-section at impact and floating capability over water/oceans are evaluated for surviving fragments.

6. SESAM fragments modelling

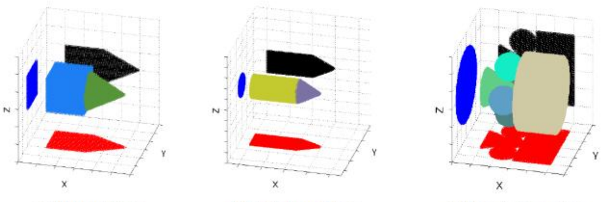
The connected-to relationship introduced in the upgraded version of SESAM implies the possibility of having fragments whose external shape is not a simple primitive geometry. This feature adds a lot of flexibility in the spacecraft modelling but also introduces new complexity and challenges not found in any previous object-oriented tool.

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. In order to keep the computation reasonably fast, the approach followed in the upgraded SESAM is a linear combination of pre-computed free-stream primitives aerothermodynamic databases (alternatively, the user can set its own databases). 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).

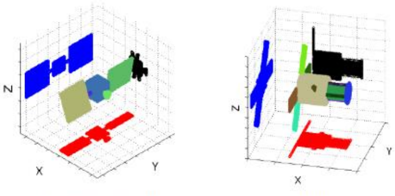
To compute these visibility factors a new module in the SESAM has been introduced. As a first step, the fragment is modelled as a combination of small 3D cubes. This allows the creation of a 3D matrix of scalar values where zeros are set in the empty space and scalar values (1 to N) are assigned to the 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 "voxelator" module of SESAM 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 5: Examples of voxelized objects, from [10]

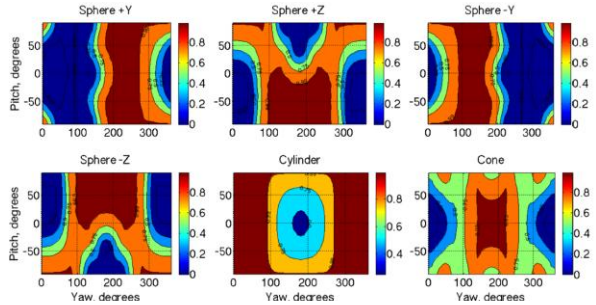


Figure 6: Examples of visibility factors (Generic Upper Stage Model), from [10]

7. Results and discussion of test cases

The SESAM upgraded module has been tested by DEIMOS Space to demonstrate the new features implemented (new shapes, relationships, new attitude motions and so on) and to assess how they affect to the fragmentation process. In this section, the main results of 4 selected test cases run using the upgraded SESAM module of DRAMA are presented showing the new functionalities. In all 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 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 aluminum and titanium materials.
- The initial fragment has been tested using the whole set of available re-entry attitudes (randomly tumbling, tumbling around a given axis and fixed attitude). Once the initial fragment 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. (See Table 2).
- The following co-rotating initial conditions have been set at the Entry Interface Point: velocity = 7.5 km/s, flight path angle = -2.5°, latitude = 10°, longitude = -5°.

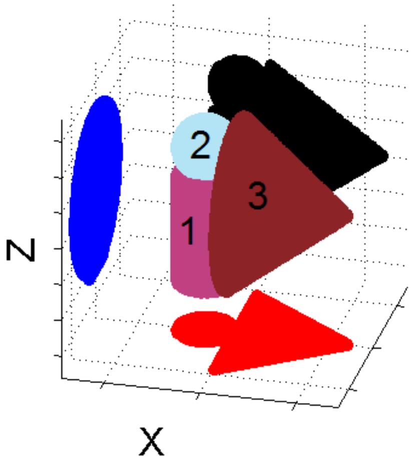


Figure 7: Voxelized fragment for test cases

Table 1: Fragment catalogue

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

Table 2: Fragment attitude modes tested

Test Case	Initial Attitude	Attitude after break
A	Tumbling	Tumbling
B	Fixed	Inherited
C	Fixed	Tumbling
D	Around X-Axis	Tumbling

Test Case A:

The heat balance for a re-entry fragment is governed by the incoming aero-thermal heating, and by the heat rejection through radiation. In the upgraded SESAM, a third term, the conduction through connected-to relationships, is also considered.

Due to the randomly tumbling motion of the fragment assumed for the re-entry in this test case, Objects 1, 2 and 3 are all exposed to the external heat flux for most part of the trajectory leading to an increase of their temperatures. However, Objects 4, 5 and 6 are fully shielded by Object 1 due to the defined parent and child relationships, therefore they don't receive any heat and their temperatures remain constant while the corresponding parent object is alive.

During the first part of the trajectory there is conduction from Object 1 to Objects 2 and 3 because of its higher temperature with respect to them. However, its contribution to the heat balance of these objects is minor, three orders of magnitude smaller than the aerothermal convective heat flux.

Object 1 is the first object to get close to the aluminium 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 (look for 'Object 1 breakup' tag in figures). Object 1 starts flying alone but Objects 2 and 3 remain together. Since Object 1 is not shielded anymore and the fractions of visible surface of the Objects 2 and 3 are also higher than before the breakup, there is an increase in the incoming heat fluxes for all of them.

Once Object 1 reaches its melting temperature the melting phase starts and its mass is consumed by ablation. It's demised around 230 s (look for 'Object 1 demise tag in figures) releasing Objects 4 and 5 (also Object 6 but this sphere is contained inside object 5), the included-in relationship is dissolved.

Object 3 is the next object to get close to its material melting temperature (aluminium), around 233 s: at this point the connected-to relationship between this object and Object 2 is broken (look for 'Object 3 breakup' tag in figures). Both objects fly alone until reaching ground and shading factors do not apply anymore since they are fully exposed to the external heat flux. Only Object 3 is slightly ablated because the melting temperature is reached for a short time. Object 2 is made of titanium, a hard-to-demise object: its high melting point is not reached during this test case simulation. For this reason it hits ground with its full initial mass.

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

Test Case B:

A fixed motion for the re-entry fragment is assumed for this test case considering an angle of attack of 15º and a sideslip of -15º. Due to this attitude, Object 3 is mainly facing the external heat flux for most part of the trajectory leading to a high increase of its temperature, while Objects 1 and 2 are almost fully shielded behind Object 3 receiving a really low portion of the heat flux and therefore their temperatures are almost constant. Moreover, Objects 4, 5 and 6 are fully shielded by Object 1 due to the parent and child relationships.

During the first part of the trajectory, in this case, there is conduction from Object 3 to Objects 1 and 2 because of its higher temperature with respect to them.

Object 3 is the first object to get close to 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 (look for 'Object 3 breakup' tag in figures). Object 3 starts flying alone but Objects 1 and 2 remain together and for both fragments it's assumed that they inherit the fixed attitude motion in this test case. Moreover, Object 3 is not shielded anymore and the fractions of visible surface of Objects 1 and 2 are now higher than before the breakup because they are not shielded by Object 3: the incoming heat fluxes for all of them increase.

Once Object 3 reaches its melting temperature, its mass is consumed by ablation. This object is only partially demised during flight and reaches ground with approximately 85% of its initial mass.

Object 1 is the next object to get close to its material melting temperature (aluminium), around 244 s: at this point the connected-to relationship between this object and Object 2 is broken (look for 'Object 1 breakup' tag in figures). Both objects fly “alone” until impacting ground, therefore they are fully exposed to the external heat flux. Only Object 1 reaches its melting point and it's partially ablated, up to approximately 70% of its initial mass is consumed. Object 2 is not melted since it's made of titanium and its high melting temperature is not reached. For this reason it hits ground with its full initial mass. Since Object 1 is not demised, the included-in relationship is not dissolved, and this object lands containing inside Objects 4, 5 and 6 (no contribution to the casualty risk).

Test Case C:

This test case is a variation of previous test case B, the same initial fixed attitude for the re-entry fragment but randomly tumbling motion is now assumed for partial fragmentations. Therefore, the same trajectory is flown down to Object 3 breakup at 211 s, when the connected-to relationships between this object and Objects 1 and 2 are broken (look for 'Object 3 breakup' tag in figures). Two fragments are generated, one composed by Object 3 and another one composed by Objects 1 and 2 (still connected), but now both fragments fly in tumbling motion. It's possible to notice that the three tumbling objects are exposed to lower heat fluxes than in test case B in which the initial fixed attitude was inherited after the break-up.

Object 1 gets close to its melting temperature, around 243 s, leading to the breakup of the connected-to relationship between this object and Object 2 (look for 'Object 1 breakup' tag in figures). From now on both objects fly alone until impacting ground.

Only Object 1 and 3 suffer ablation during the re-entry impacting partially demised, with approximately 50% and 80% of their initial masses, respectively. However, Object 2 is still not ablated. Moreover, due to the fact that Object 1 is not demised, the included-in relationship is not dissolved, and Objects 4, 5 and 6 keep contained inside this object (no contribution to the casualty risk).

Test Case D:

A tumbling motion around the X-axis for the re-entry fragment is assumed for this last test case, considering an angle of attack of 25º and an angle of sideslip of 25º (similar attitude in terms of angle of attack and sideslip than in test cases B and C), but now the initial fragment is spinning around X-axis. For partial fragmentations a randomly tumbling motion is also assumed as well as in test case C.

As noticed in previous test cases B and C, due to this attitude, Object 3 is mainly facing the external heat flux for most part of the trajectory leading to a high increase of its temperature, and being the first object to get close to its melting point, around 217 s. At this point the connected-to relationships between this object and Objects 1 and 2 are broken (look for 'Object 3 breakup' tag in figures) stopping the heat transfer by conduction between them.

Down to the Object 3 breakup event, Objects 1 and 2 are almost fully shielded behind Object 3 being exposed to a really low portion of the incoming heat flux. Besides, Objects 4, 5 and 6 are fully shielded by Object 1. After the Object 3 breakup event, Object 3 flies alone in tumbling motion until it reaches ground but ablated (approximately 90% of the initial mass survives). Objects 1 and 2 remain together exposed to higher heat fluxes than before the breakup since they are not shielded by Object 3 anymore.

Object 1 is the next object to get close to the aluminium melting temperature, around 251 s, therefore the connected-to relationship between this object and Object 2 is broken (look for 'Object 1 breakup' tag in figures). Both objects fly alone until impacting ground, Object 1 with ablation (up to 75% of the initial mass survives) and Object 2 without ablation. Since Object 1 is not demised, the included-in relationship is not dissolved, and this object hits ground containing inside Objects 4, 5 and 6 (no contribution to the casualty risk).

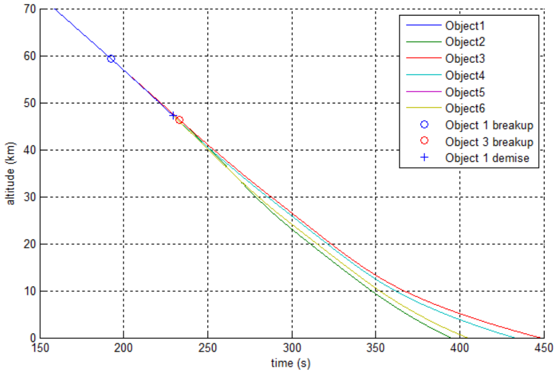


Figure 8: Altitude versus time (zoom), Case A

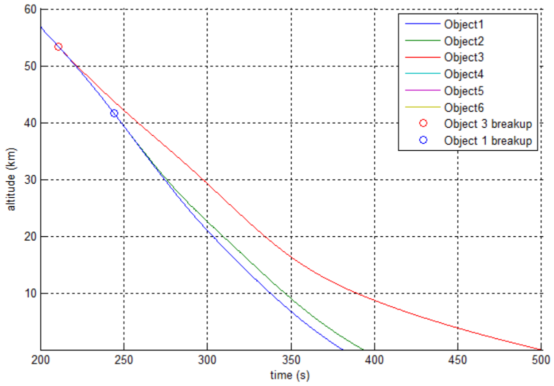


Figure 11: Altitude versus time (Zoom), Case B

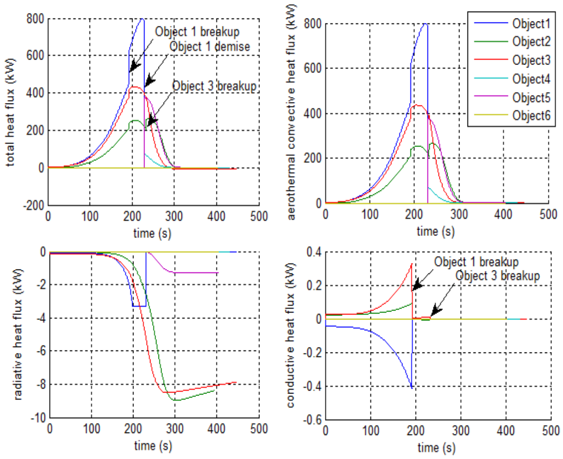


Figure 9: Heat fluxes evolution, Case A

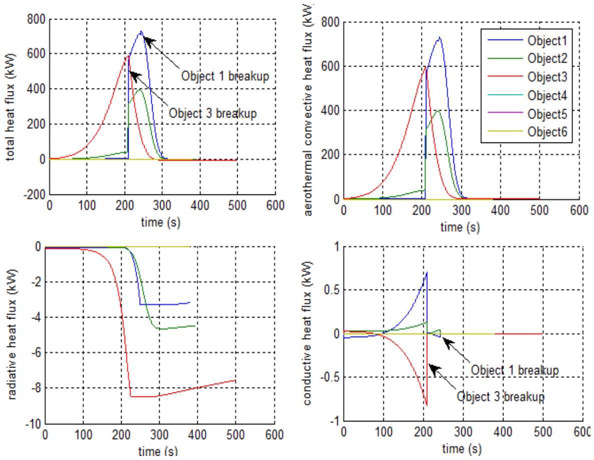


Figure 12: Heat fluxes evolution, Case B

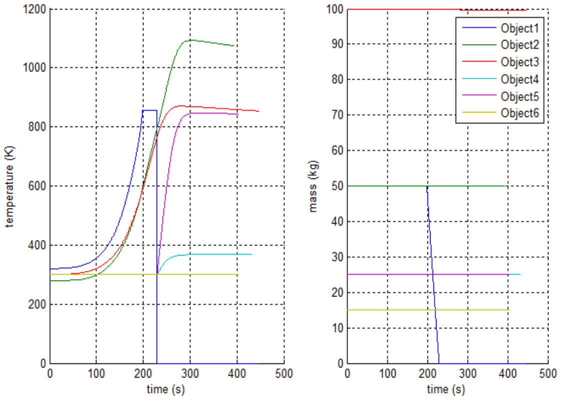


Figure 10: Temperature and mass evolution, Case A

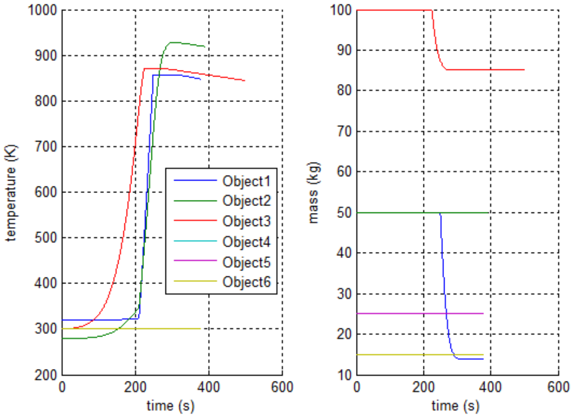


Figure 13: Temperature and mass evolution, Case B

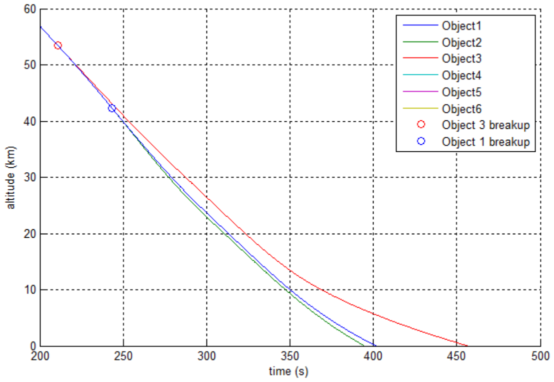


Figure 14: Altitude versus time (Zoom), Case C

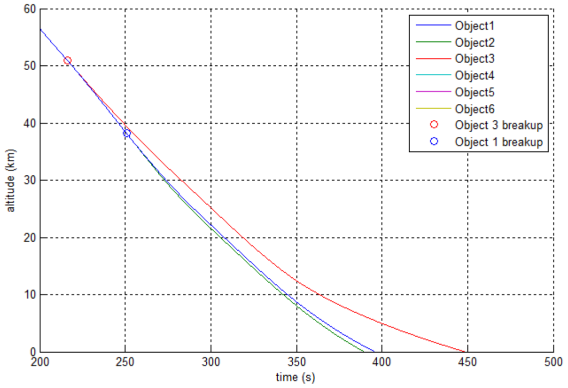


Figure 17: Altitude versus time (Zoom), Case D

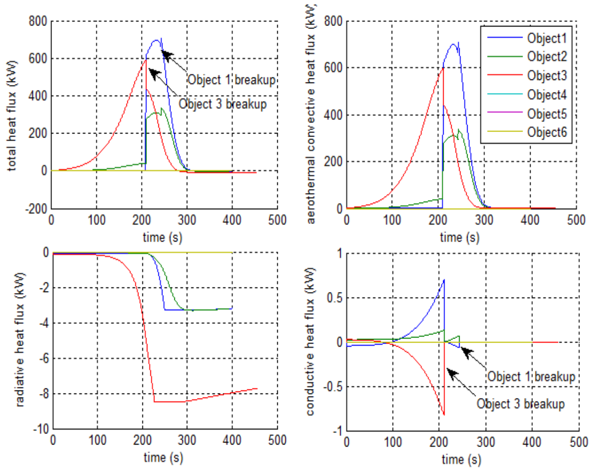


Figure 15: Heat fluxes evolution, Case C

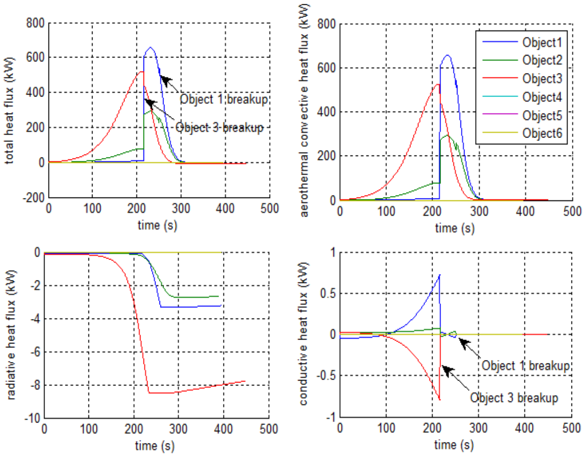


Figure 18: Heat fluxes evolution, Case D

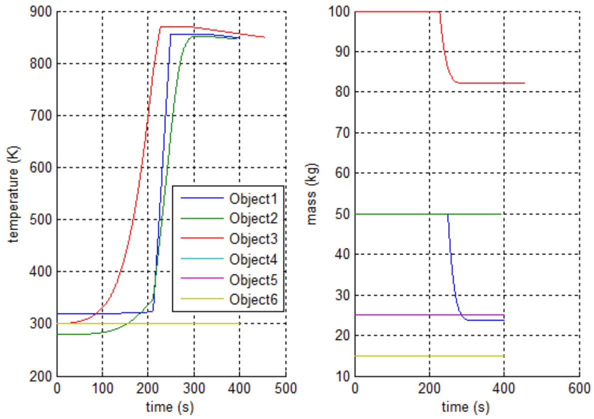


Figure 16: Temperature and mass evolution, Case C

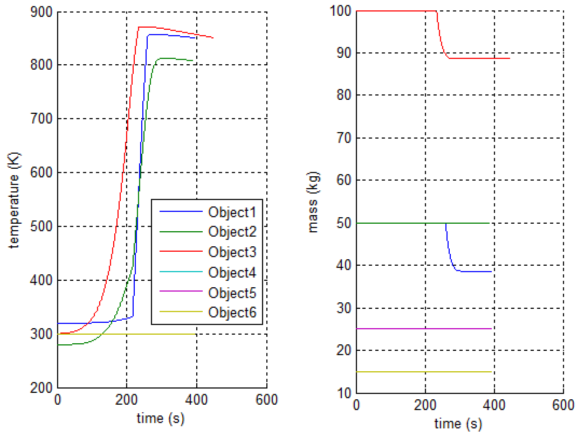


Figure 19: Temperature and mass evolution, Case D

8. Conclusions

The new SESAM module implemented in the upgraded version of DRAMA tool has been presented along the current paper. The multiple new capabilities introduced in the software code have been explained and the impact in the re-entry process has been shown in the provided results of the four selected test cases.

Spacecraft breakup/fragmentation is modelled in a more realistic way not being forced to be a single event (fixed at a pre-defined altitude) anymore; now it is a process resulting from the evolution of the relationships defined between the primitives as shown in the test cases reported in section 7 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 and aerothermodynamics models now are more sophisticated being also possible to replace them by the users (using those that best fit their needs).

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. Moreover, there are two attitude possibilities for the new fragments generated, to inherit the attitude from the parent fragment or to assume randomly tumbling motion, giving the capability to the user to test different scenarios due to the high uncertainty characterizing the breakup process. In fact the impact of the type of motion in the re-entry body demisability was assessed in the test cases carried out, being possible to notice differences in the breakup process and also different ablated masses but in line with the observed primitives exposure to the external heat fluxes.

Considering the obtained results it is possible to point out that even if the upgraded SESAM module follows the object oriented approach, the innovative functionalities implemented inside it 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 by end of 2016).

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