DEBRIS: AN OBJECT ORIENTED CODE FOR FOOTPRINT, SURVIVABILITY AND RISK ASSESSMENT

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ABSTRACT

The analysis and simulation of the destruction of an object entering in the atmosphere is a complex and multi-disciplinary problem, where several factors, covering both mission and system design parameters are involved. In this frame, uncertainties play a key role and therefore reliable and efficient numerical simulation tools are needed to support the trade-offs, the definition and the selection of de-orbiting strategies, trajectory profiles, design-for-demise choices, and also for safety requirement verification.

In this paper we describe DEBRIS, the Deimos Space in-house tool, part of the Planetary Entry Toolbox. DEBRIS is an object oriented code based on engineering models that has been used in both ESA and non-ESA projects, from Phases 0 up to Phases D. In addition to the tool description, recent examples of applications are also provided.

1 INTRODUCTION

The atmospheric flight and the breakup of space vehicles are characterized by a set of complex and coupled physical phenomena such as hypersonic aerodynamics, heating, ablation, fragmentation and fragments interaction. After the main vehicle breakup, most of its fragments demise during entry. However, some fragments, e.g. titanium tanks and stainless steel reaction wheels, usually reach ground, representing a potential risk to the population in the case of uncontrolled entry, where the ground impact can be anywhere under the orbit ground track.

From a re-entry standpoint, an uncontrolled entry differs from a controlled one for the limited knowledge of the vehicle state at the Entry Interface Point (EIP) as well as the shallower nature of the entry angle. Both effects lead to a larger uncertainty and dispersion in all the entry events: break-up, fragmentation, explosion, demise and ground impact. For a controlled entry the compliance with the casualty risk requirements is ensured by the selection of the timing and entry gate state for the de-orbit manoeuvre to conduct debris fall-out towards non-populated areas (open ocean). For an uncontrolled entry instead, the identification of the critical items is crucial. The footprint size and fragments survivability are determined by many factors as the entry conditions, the materials employed, the shape and the internal layout. These are both mission and system design parameters drivers of the safety assessments. Uncertainties also play a key role in this critical part of the mission and system design where reliable and efficient numerical simulation tools are needed to support the trade-offs, the definition and the selection of de-orbiting strategies, trajectory profiles, design-for-demise choices, and also for safety requirement verification.

In this paper we describe DEBRIS, the Deimos Space in-house tool, part of the Planetary Entry Toolbox [1]. The Planetary Entry Toolbox is an internal suite of SW Tools created to support the Design and Analysis of the entry into planetary bodies, mainly for Earth, Moon, Mars and Titan. This suite has supported all the atmospheric flight activities comprising Mission Analysis, Aerodynamics, Flight Mechanics and GNC requirements activities carried out in Deimos Space since 2003. Therefore, long heritage and validation has been achieved. The Planetary Entry Toolbox contains the tools required to support the safety assessment in a controlled or uncontrolled entries. In particular, the following modules are used:

- 3DoF/4DoF/6DoF/9DoF EDL high fidelity propagation (EndoSim module) in open & close loop covering orbital, entry, descent and landing.
- Debris and re-contact analysis (DEBRIS module)
- Atmospheric analysis module
- Aerodynamic analysis module: inspection and generation (HYDRA and CFD).
- Flying Qualities Analysis Tool [2]

DEBRIS is based on an **object oriented approach**[1]. This means that the break-up of an entry vehicle is modelled as a single event; after the vehicle breakup, each separate fragment is analysed independently. The main outputs are the estimation of the impact area of the debris produced by a vehicle breakup, its survivability, short- and long- term risk assessments and re-contact

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[1] Object oriented is used in the sense of focusing on individual objects rather than on the entire spacecraft as a whole, and not in its common software engineering sense.

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analyses. Besides, DEBRIS can deal with both nominal and off-nominal conditions: to deal with uncertainties and disturbances (e.g. initial conditions, vehicle properties, atmosphere), Monte Carlo and/or worst case simulations have been extensively used together with advanced statistical post-processing and analysis of the simulation results. In addition to the description of the tool capabilities, recent examples of applications of this state of the art tool are also provided in this paper.

It is worth mentioning that another type of tool to model the re-entry and demise of a spacecraft exists, based on a **spacecraft-oriented approach**. This approach is characterized by a detailed modelling of all the objects and processes involved, including aero-thermal interactions, thermo-mechanical loads, melting and deformations. 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. Hence it is clear this approach is suitable for verification of a limited set of well-defined cases, but not to run fast assessments considering a wide range of possible cases. HTG's Spacecraft Atmospheric Re-Entry and Aerothermal Break-up (SCARAB) tool, [3], is currently the only operational spacecraft-oriented modelling software.

Object- and spacecraft-oriented approaches therefore have complementary strengths, trading off fast evaluation of a wide range of possible designs against more detailed analysis of a specific design. It is important to emphasise the importance of the spatial information, layout, shielding, protection between components and break-up process as a key step from an object-oriented to a spacecraft-oriented tool. During the development of an individual mission, an object-oriented approach may be preferred in early phases when different designs are being considered, before a final design is analysed in detail with a spacecraft-oriented approach. This has been done for example in the frame of ExoMars Phase B-C/D and D4D projects, where the DEBRIS tool was used for a fast trade-off of break-up scenarios in order to select the most demanding ones to be assessed in detail with SCARAB.

Finally, in the new version of ESA Spacecraft Entry Survival Analysis Module (SESAM) module of the Debris Risk Assessment and Mitigation Analysis (DRAMA) suite, innovative functionalities have been introduced, trying to solve the gap between the spacecraft and the object oriented tools [4]. SESAM was developed under Deimos Space responsibility.

2 DEBRIS TOOL DESCRIPTION

2.1 Modelling

The core of DEBRIS is the simulation of the entry trajectory: simulations are based on the EndoSim Simulator, in which all of the vehicle and environmental models, as well as simulation options, are user-defined. To deal with uncertainties, parametric search or Monte Carlo approaches can be employed.

Considering debris assessments 3-DOF simulations (position and velocity) are usually suitable to represent the **re-entry dynamics** of the vehicle down to the breakup point and those of the fragments down to the demise altitude, or ground. The fragments are likely to be tumbling bodies and therefore they are modelled as ballistic low-lift objects. However, in case a very detailed assessment is required, trajectories can be also based on 6-DOF dynamics to increase the level of accuracy of the results. This requires the availability of the full aerodynamic characterization (force and moments) together with a Centre of Gravity (CoG) and Inertia models of the vehicle and of the fragments.

The **aerothermodynamics** of a vehicle is another key point in the trajectory computations and debris assessments. It determines the drag profile, which drives the thermo-mechanical loads acting on the entry vehicle and therefore its breakup. Concerning the fragments, the final kinetic energy and possible demise altitude are strictly related to their deceleration profiles. Therefore, basic profiles of the drag coefficients depending on the regime (Mach and Knudsen numbers) can be assumed or a full aerodynamic characterization depending also on the vehicle configuration, the attitude, the angular rates, and possible active surface deflections. A database for simple object shapes such as sphere, cylinder, box and flat plate is also available.

Thermal flux estimations are usually based on empirical or semi-empirical laws, as those of Tauber for the convective heat flux [5]. However, in case of high-speed entry, both convective and radiative heat fluxes are modelled and possible coupling effects can be also considered. Based on its range of validity, a suitable model for each problem has to be identified by the analyst. Average factors dependent on the object shape are also applied in case of randomly tumbling bodies. Finally, thermal models as the lumped mass are employed to provide estimations of the fragment temperature and to determine if it will completely ablate in the atmosphere or not.

The **breakup** represents the total collapse of the object and it is usually based on thermo-mechanical loads. In particular, the thermal criterion is the most commonly applied in re-entry. However, depending on the problem, a suitable condition or conditions combination can be set considering any other trajectory parameter.

For example, a threshold on dynamic pressure could be considered to determine the solar arrays break-off since this event is most likely to happen when the bending torque generated by each solar array reaches the breaking limit of the arm connecting them to the main S/C bus.

After the breakup, the distribution of mass and dimension of the fragments can be based on a detailed debris catalogue or on statistical distributions, depending on the available information. Fragment trajectories are run down to ground and in case of complex objects, the shielding effect is also modelled through multiple levels of fragmentation (parent-child approach). The fragments are then filtered based on thermo-mechanical loads and kinetic energy criteria to identify those that reach ground.

Furthermore, to deal with possible residual fuel remaining into the vehicle an explosive event can also be modelled based on NASA's EVOLVE model [6]. In this case, statistical distributions of the fragment mass, size and velocity are computed as function of the initial object mass.

2.2 Analysis capability

Thanks to the flexibility of the internal atmospheric simulator, flight qualified in multiple projects (IXV [7] and ExoMars 2016 [8]), a wide set of analyses have been run for different re-entry scenarios and for different applications. They are summarized below:

- Analysis and support the design of the **End-of-Life disposal** of satellites and service modules. Recent examples are Proba-3, reported in section 3.1, and Deimos-2 [9].
- Study **Design-for-Demise** (D4D) solutions, shown in section 3.2.
- **Safety assessment** of Earth and planetary entry probes, an example is provided in section 3.3, and vehicles in case of failure [7].
- **Footprint estimation** of launcher stages fallout, including the impact of explosion in case of residual fuel, and asteroid debris impact [10]. An example is included in section 3.4

3 EXAMPLES OF APPLICATION

3.1 End of Life disposal of satellites

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). Instead, a controlled re-entry must be performed such that the impact footprint can be ensured over an ocean area, with sufficient clearance of landmasses and traffic routes. 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 recent example of assessment in this area is based on Proba-3 scenario. Proba-3 is the third in ESA’s series of missions for validating developments in space systems, and is aimed at demonstrating the technologies required for formation flying of multiple spacecraft. Baseline launch is foreseen in 2019 aboard an Indian PSLV launcher. The mission comprises two spacecrafts, between 200 kg and 300 kg, which are supposed to re-entry at the end of their mission, based on an uncontrolled entry from an eccentric orbit.

Each spacecraft is modelled considering almost 50 components, 4 shapes, 8 different materials, and with up to 2 levels of shielding (parent-child approach). The analysis is based on a statistical approach, where uncertainties are applied on environment, initial state, main spacecraft and components mass and size, material thermal properties, aerodynamic forces and aerothermodynamic model parameters. In total, more than 35000 simulations have been run and analyzed.

Concerning the main S/C breakup, the results for both S/C shows that the main drivers are the thermal and material properties of the external panels and the atmospheric density; mass and size have instead a lower impact. The influence of each MC uncertainty in the break-up altitude, in one of the two cases analysed, is shown in Fig. 1.

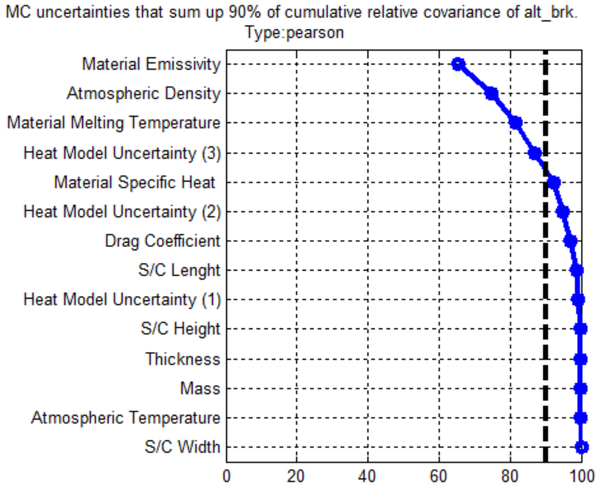

Figure 1. MC uncertainty influence on breakup altitude

The survivability analysis of both S/C components allowed the identification of 12 risky objects that reach ground. The kinetic energy at impact as function of the ballistic coefficient of the 8 surviving elements coming from one of the two S/C is shown in Fig. 2. Since the potential on-ground risk for human casualty is assumed for any object with an impacting energy in excess of 15 J, this threshold can be applied to filter the surviving objects when computing the risk. The detailed results of one of these elements are shown in Fig. 3 in terms of demise altitude, casualty area, final energy and final mass.

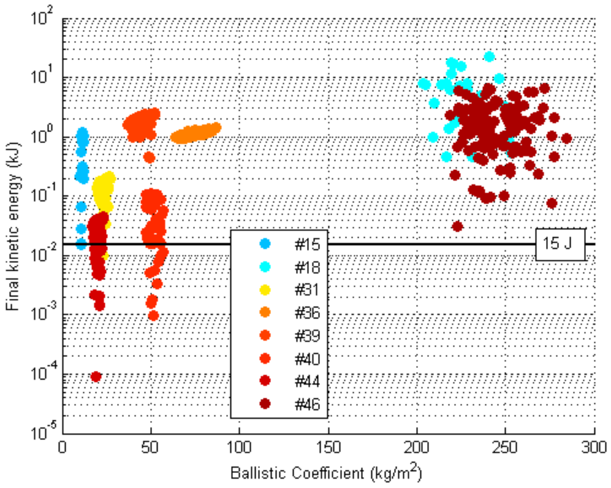

Figure 2. Surviving component final energy and BC

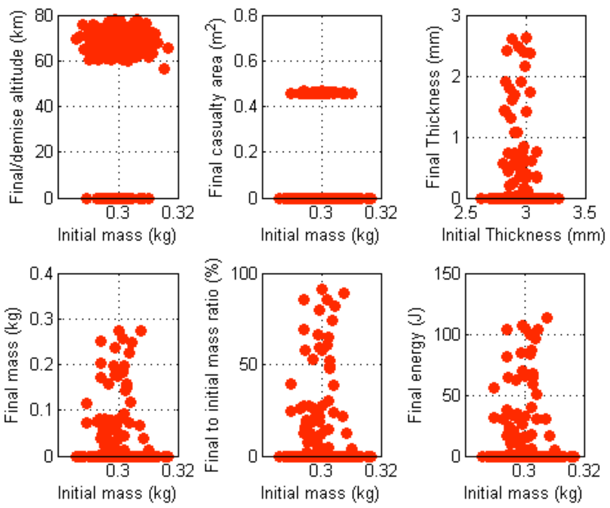

Figure 3. Component #40 detailed results

Regarding the risk assessment, due to the large uncertainty in the re-entry date at present, a long-term estimation approach has been deemed more appropriate and representative for the current analyses. However in the future, close to the actual re-entry date, a near-term assessment will be necessary. For this long-term assessment an uniform impact probability distribution in geographic longitude is assumed; the latitude band of interest is instead a function of the orbital inclination for circular re-entry orbits, however, in the current case of a re-entry from a highly eccentric orbit, eccentricity and argument of perigee have also to be considered (see the impact probability distribution in Fig. 4). The analysis results in the satisfaction of the 10^{-4} threshold with ample margins for both S/C individually and also for the global mission.

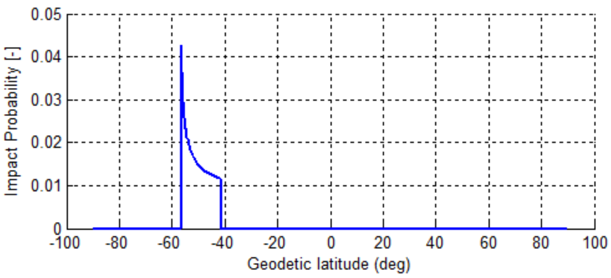

Figure 4. Impact probability in case of eccentric orbit

3.2 Design for demise assessments

Design-for-Demise (D4D) is the solution at system design level proposed to ensure compliance with the risk requirement using uncontrolled entry. In this area, Deimos UK has been working as a prime in the *Multi-Disciplinary Assessment of Design for Demise Techniques* study [11]. The main object is to identify, analyse and evaluate through detailed numerical simulations a set of techniques that yield a design able to reduce the re-entry casualty risk of any element of a satellite. DEBRIS tool has been intensively used in different steps of the project based on a statistical approach to take into account environmental, mission and object modelling uncertainties (e.g. initial conditions, aerodynamics, material properties). The idea is to run fast and extensive analysis to guide the verification performed with high fidelity simulation tool (SCARAB, run by HTG).

In the beginning of the project, support has been done to identify the critical elements and the most promising D4D techniques. Some common components, including titanium alloy propellant tanks and Silicon-Carbide optical benches, always survive, while some, such as solar arrays and aluminium structural elements, can be relied on to demise.

Among other elements, Reaction Wheels (RW) have been analysed. They have been modelled as a Stainless Steel flywheel and motor contained in an Aluminium housing using a parent-child approach. 16 different types of RW, based on real models used for space applications have been analysed. In all of the cases, it has been demonstrated that the housing is not critical in terms of ground casualty risk, while both medium-high weight flywheels (>1kg) and motors (>3.5 kg) can reach ground without or with only partial melt. A very simple model for the motor is used here (solid stainless steel box); further analysis suggests that motor is going to break in smaller pieces and demise. Therefore the critical part of the RW is the flywheel. The results in terms of demise altitude, casualty area and final mass and energy for the flywheels are shown in Fig. 5 in which different scenarios have been analysed, including equatorial and polar orbits, different spacecraft masses, and controlled entry for comparison.

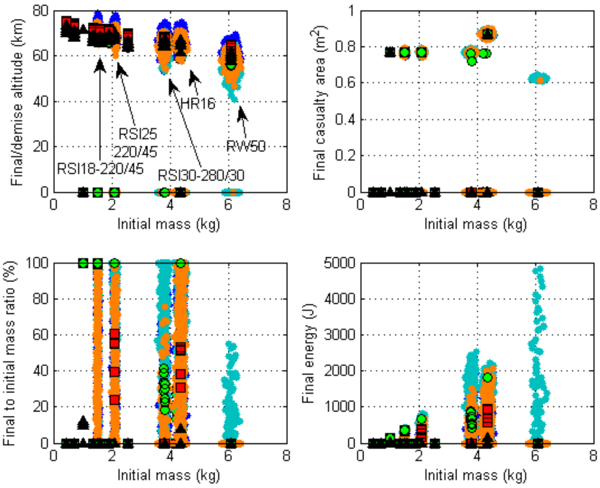

Figure 5. Flywheel simulation results: red, green and black dots are the nominal shots respectively for the uncontrolled Polar Orbit and Equatorial LEO and the controlled scenarios; blue, light blue and orange dots are the MC shots for the same scenarios

In the second part of the project, a preliminary assessment of CarbonSat study case based on a 900 kg satellite has been carried out using DEBRIS and later running a high fidelity verification analysis based on SCARAB (analysis run by HTG). Both the baseline and the modified solution implementing the D4D solutions have been analysed. One of the most promising D4D technique analysed was a change of the material of the tank, from the hard-to-demise titanium alloy to an aluminium-lithium alloy. The DEBRIS simulation results in the complete demise of the modified tank at altitudes between 70.4 km and 82.2 km. Profiles of altitude, downrange and temperature for the baseline and the modified tank design are shown in Fig. 6 and Fig. 7.

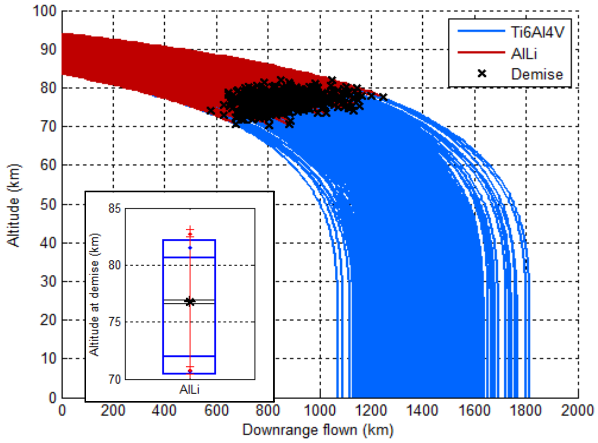

Figure 6. Altitude versus downrange

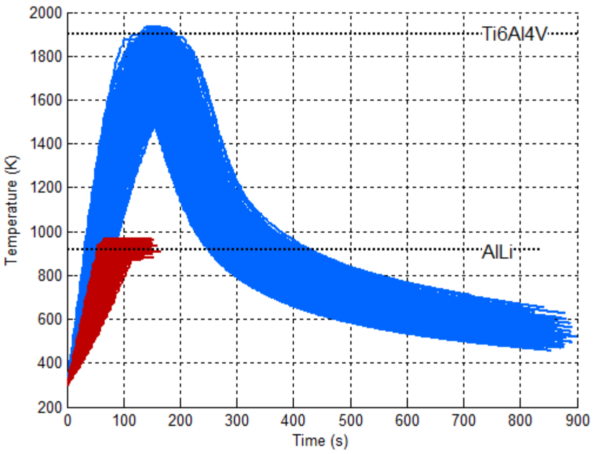

Figure 7. Temperature evolution

3.3 Safety of Earth and planetary entry probes and vehicles in case of failure

This type of analysis is related to the fast estimations of the **ground footprint** based on Monte Carlo simulation or Worst Case approach. Different information can be provided, as mission success figures (e.g. 99% probability footprint) or verification of safety requirements (e.g. 10^{-7} probability footprint). Additionally, DEBRIS is capable of running **assessments on the relative distance** between the fragments of one vehicle with respect to another one. Both distances during flight and at ground are usually checked to identify potentially dangerous components.

The example proposed in this paper is related to the Carrier and Descent Module safety assessment part of the mission analysis activities performed by Deimos Space within the ExoMars 2020 project Phase C, in support to the prime Thales Alenia Space Italy. ExoMars 2020 is an ESA mission in collaboration with Roscomos; one of the main objectives is to land a rover on Mars through a ballistic entry of a 2000 kg Descent Module (DM). The DM is released by a Carrier Module (CM) 30 minutes before the Entry Interface Point; after the separation event the CM will continue towards the planet, and break up while entering into the Martian atmosphere.

To analyse the risk of re-contact between the DM and the CM fragments, a detailed debris analysis has been carried out based on more than 24000 shots Monte Carlo simulation. Uncertainties are applied on solar array break-off and CM main breakup altitudes and also on the mass and aerodynamics of the CM and its fragments. The CM model includes almost 60 different components that represent the 90% of the CM total mass. They have been classified by shape and material, as shown in Fig. 8. The ballistic coefficient (BC) of the CM components varies from 1.5 kg/m^2 up to 1688 kg/m^2 against the BC of the DM which varies from 80 to 130 kg/m^2 depending on the flight regime. It is noted that survivability of the CM components has not been analysed as no detailed inputs to run the thermal model were available at the time of running these analyses.

The distance of the CM before its breakup and the DM is shown in Fig. 9. The separation distance between the two vehicles results 1.46 km at the Entry Interface Point (EIP) with almost no variability and it increases until the solar panel break-off. However, after this event the trend is inverted due to the significant increase of the CM ballistic coefficient produced by the separation of the solar panels (from values lower to higher than that of DM). The minimum distance is reduced down to 1.13 km at the CM breakup.

Concerning the CM fragments, the minimum distance during flight and on ground are shown in Fig. 10. Based on that, the following classification of the fragments is done:

- BC higher than 50 kg/m^2: these components get close to the DM during the flight. Among them, it is worth mentioning the 16 stainless steel thrusters which flies quite close to the DM at altitudes around 43 km.
- BC between 15-250 kg/m^2: the ground impact point is close to the DM landing site. In this range of BC there are numerous elements that are likely to survive the entry (e.g. titanium tank, tungsten balance masses). Fig. 11 shows the ground footprint of all the CM components.
- BC lower than 15 kg/m^2: these components fly away from the DM during their whole re-entry trajectory.

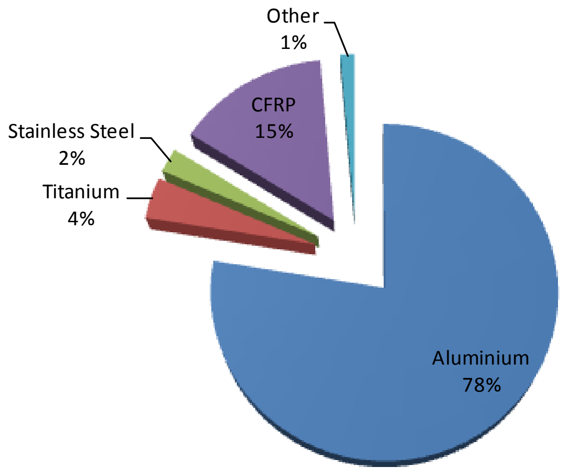

Figure 8. CM Composition in terms of materials

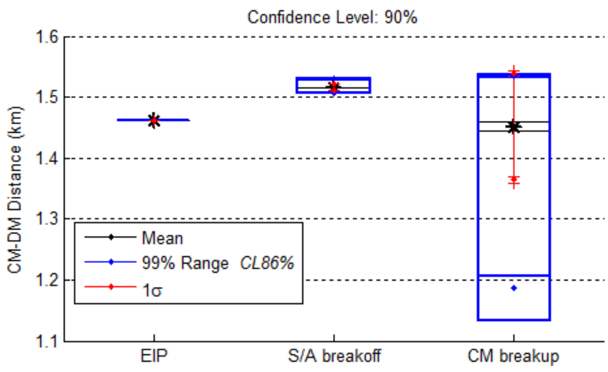

Figure 9. CM-DM Distance down to CM breakup

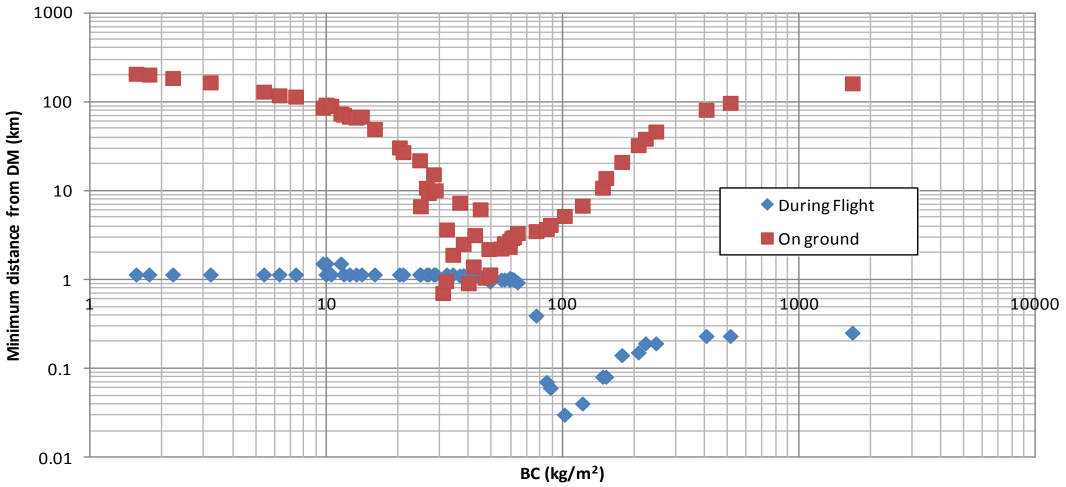

Figure 10. Minimum distance during flight and on ground

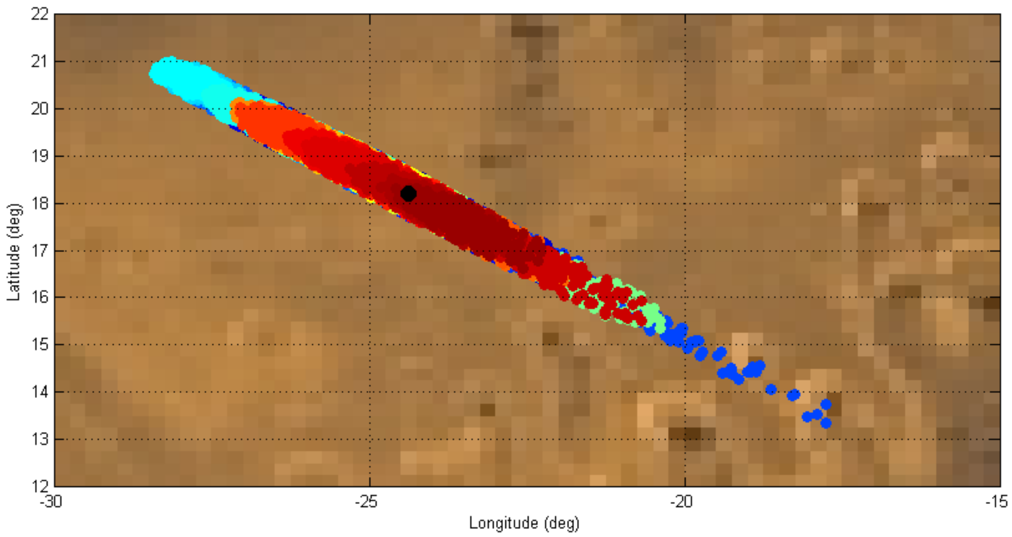

Figure 11. Ground footprint of CM components (coloured dots) and DM reference landing site (black dot)

3.4 Footprint of launcher stages fallout

Launcher flight safety is based on a set of key principles, primarily (a) choice of a nominal trajectory which avoids overflying areas where an explosion of the rocket could allow debris to cause harm to populations in the vicinity, combined with (b) the ability of the launch control system to neutralise the launcher in the case of dangerously non-nominal flight. Therefore, the assessment of the possible debris footprint generated in case of launcher stages fallout is required.

An example of assessment in this area has been recently carried out during the evaluation of different options for a UK vertical launch facility location for small satellites in the north of Scotland [12]. To quantify the safety of each trajectory the FAA regulations for operating a launch site [13] are used to determine the flight corridor and calculate the corresponding expected casualty rate. The flight corridor is determined directly from the trajectory which then feeds in to the expected casualty rate calculation which also requires population data. Fig. 12 shows an example trajectory, flight corridor and the populations that were included in the casualty rate calculations. Populations were modelled as circles where the size of the circle approximates the area that the population covers, i.e. a large circle indicates a dispersed population rather than necessarily a large one. It is noted that for more easterly launches it may be necessary to consider additional populations in Scandinavia.

Based on the above approach, the expected casualty rate for trajectories to different orbits can be calculated for all candidate launch sites. Fig. 13 shows the contribution of different regions to the overall expected casualty rate, for direct launch trajectories to a 500 km SSO, from different launch sites along the North coast of Scotland (located as indicated on the map in the figure).

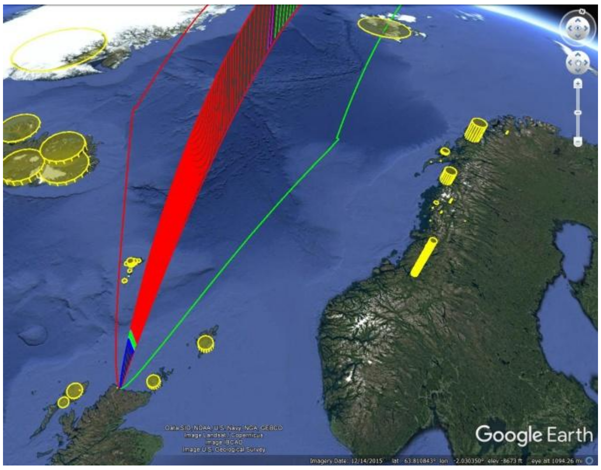

Figure 12. Example of nominal trajectory and flight corridor for a UK launch facility

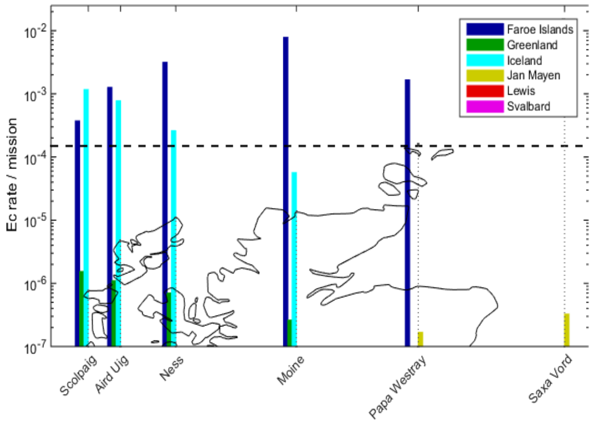

Figure 13. Contribution of different regions to the overall expected casualty rates for various launch sites across the north of Scotland

4 CONCLUSIONS

In this paper the DEBRIS tool is presented. It has been developed and used to perform safety assessment based on debris footprint, fragment survivability, risk and re-contact analyses.

This tool has been used in a wide set of applications since 2003, and it is continuously evolving in line with program demands and computational capabilities. It supported Mission Analysis activities from project Phase 0 to Phase D, such as:

- Estimation of the footprint area of launcher stages, S/C, re-entry vehicles and asteroid fragments.
- Analysis of the impact area in case of vehicle failure during re-entry.
- Assessment of the disposal of service modules and planetary entry carriers.
- Assessment of re-entry EoL disposal strategies.
- Assess and support Design-for-Demise solutions.

In particular, in this paper examples of application have been presented related to the Proba-3 end of life disposal, the Design-for-Demise (D4D) study, ExoMars 2020 Carrier Module safety analyses and finally the selection of a UK launch site for small satellites.

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