EQUIVALENT RE-ENTRY BREAKUP ALTITUDE AND FRAGMENT LIST

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ABSTRACT

The concept of equivalent re-entry breakup altitude and fragment list tries to build a bridge between the two re-entry analysis approaches (i.e. object-oriented and spacecraft-oriented) by using the strengths of both and overcoming their drawbacks. The results of a full spacecraft-oriented analysis are post-processed to provide a statistical analysis of the breakup process, i.e. average or most-probable equivalent fragmentation altitudes. The surviving fragments of a full spacecraft-oriented analysis, which are arbitrarily shaped and can consist of several subsystem components, are transformed into equivalent simple-shaped fragments. Equivalence between both re-entry analysis approaches is achieved if this concept provides nearly identical on-ground risk results. This paper describes the development of the concept of equivalent re-entry breakup altitude and fragment list, and its application to a test scenario for uncontrolled re-entries.

NOMENCLATURE

AOCS	Attitude & Orbit Control Subsystem
AOP	Argument of Perigee
AZM	Flight Azimuth (rel. to East direction, North positive)
EPS	Electrical Power Subsystem
FP	Footprint
FPA	Flight Path Angle (rel. to local horizon)
HNS	Harness
OBDH	Onboard Data Handling
PL	Payload
RAAN	Right Ascension of Ascending Node
SAW	Solar Array Wings
STS	Structure Subsystem
TAN	True Anomaly
TCS	Thermal Control Subsystem
TTC	Telemetry, Tracking & Command

1. INTRODUCTION

Almost all space agencies have developed numerical analysis tools to determine the on-ground risk caused by surviving fragments from spacecraft re-entering into the Earth's atmosphere [1, 2]. There are in general two classes of tools used for this purpose: the so-called object-oriented and spacecraft-oriented tools.

Object-oriented tools can be operated quite easily and do not need much computing capacity. However, these tools have to rely on a user-defined fragment list describing all potentially surviving fragments as simple-shaped geometric objects (e.g. spheres, boxes, cylinders, flat plates). The breakup process itself is not analyzed or predicted by these tools, but is subject to the assumptions and experience of the tool operator.

Spacecraft-oriented tools try to predict the fragmentation process, providing more information about breakup altitudes, number of fragments, and fragment shapes. This requires a more detailed description of the re-entering spacecraft and more sophisticated analysis algorithms. The time and costs for spacecraft-oriented analyses can be about one order of magnitude higher than for object-oriented re-entry analyses. The much higher computing time for such an analysis prevents the application of this approach in real Monte-Carlo type safety assessments.

The concept of equivalent re-entry breakup altitude and fragment list tries to build a bridge between these two re-entry analysis approaches by using the strengths of both and overcoming their drawbacks. The two ESA re-entry analysis tools SCARAB (spacecraft-oriented) and SESAM (object-oriented) are used to analyze an artificial test scenario for uncontrolled re-entries to assess this concept.

1.1. SCARAB

SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up) is a spacecraft-oriented software tool allowing the analysis of mechanical and thermal destruction of spacecraft and other objects during re-entry (controlled or uncontrolled). It is an integrated software package (six degrees-of-freedom flight dynamics, aerodynamics, aerothermodynamics, thermal- and structural analysis) used to perform re-entry risk assessments (quantification, characterization and monitoring of surviving fragments during re-entry). The software application has been validated with in-flight

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measurements, re-entry observations and wind tunnel experiments, and it has been compared to other re-entry prediction tools of the international community.

SCARAB has been developed under ESA/ESOC contracts since 1995 under the lead of HTG (Hypersonic Technology Göttingen) and with support from other European and international partners. It is considered as operational software. The software development has evolved over time, based on lessons learned from preceding software versions, upgrades and specific re-entry analyses performed for various satellites (e.g. ROSAT, BeppoSAX, TerraSAR-X, GOCE, Sentinel-2/3, SWARM), and for the ATV and the ESA launcher programs. Typical launch vehicle (or similar) re-entry applications have been: Ariane-5 stages (EPC, EPS/VEB, ESC-A), Vega stages (Zefiro-9, AVUM), and ATV.

SCARAB version 3.1L [3] has been used for this paper.

1.2. SESAM

HTG has also developed SESAM (Spacecraft Entry Survival Analysis Module), a module of the ESA DRAMA (Debris Risk Assessment and Mitigation Analysis) software [4]. SESAM is an object-oriented re-entry analysis code based on a user-defined fragment list of simple shaped objects (sphere, box, cylinder, flat plate) which are released at an also user-defined breakup altitude. The aerodynamic drag and aerothermodynamic heating coefficients are the same as in NASA's ORSAT 5.0 (Object Reentry Survival Analysis Tool, [5]).

SESAM version 1.1a has been used for this paper.

1.3. Test Case

The primary test case for this paper is a standard SCARAB test scenario for uncontrolled re-entries (UNC). The properties of an artificial satellite have been derived in the frame of an ESA study called *Risk Assessment for Destructive Re-entry* [6, 7] as an average representation with respect to size, mass budget, and subsystem components of scientific one-ton class Earth observation satellites in low Earth orbit. The size of the box-shaped main body is 1.8 m x 1.8 m x 3.2 m. The two solar arrays have a size of 1.3 m x 3 m each. The mass budget for this satellite and its subsystems is shown in Tab. 1. Fig. 1 shows the SCARAB model (with and without structure). Tab. 2 contains the basic SESAM fragment list for UNC.

Table 1. UNC Mass Budget

Subsystem	**Mass [kg]**
AOCS	76.681
EPS	120.797
HNS	73.445
OBDH	41.311
PL	437.047
SAW	84.037
STS	319.633
TCS	29.717
TTC	15.422
Total	**1198.090**

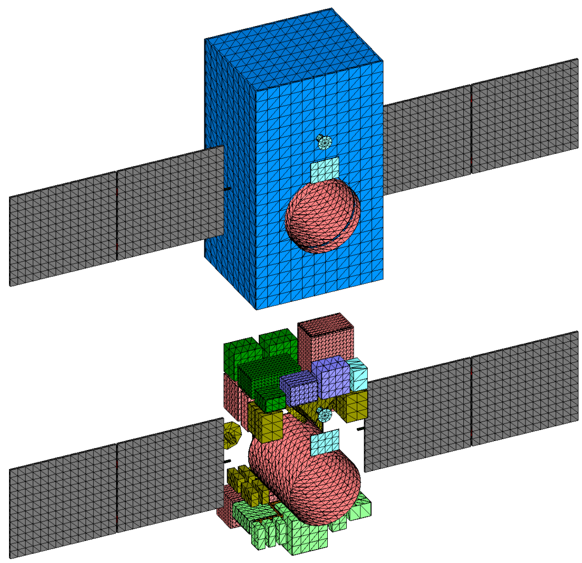

Figure 1. SCARAB Model of UNC

2. BASIC RE-ENTRY ANALYSIS RESULTS

As a first step, basic re-entry analysis results have been produced with SCARAB and SESAM for the UNC test case. The initial conditions are given in Tab. 3. The different initial Kepler elements used by SCARAB and SESAM ensure equal geodetic initial conditions upon reaching the re-entry interface at 120 km altitude (see Fig. 2). Minor differences in the geodetic parameters result from different state vector conversion routine implementations of the tools. Both tools have been used with their default settings:

- SCARAB:
  Zonal harmonic terms up to J4, MSISE-90 atmosphere model ($F_{10.7} = 100$, $A_p = 6$), thermal fragmentation at melting temperature, minimum fragment mass 300 g
- SESAM:
  Zonal harmonic terms up to J2, US-76 atmosphere model, solar panel break-off at 95 km altitude, break-up at 78 km altitude, fragment release temperature 300 K

Table 2. Basic SESAM Fragment List for UNC

Name	Shape	No. of fragments	Width/Diam. [m]	Length [m]	Height [m]	Mass [kg]	Material
Parent*	Box	1	3.2	1.8	1.8	1114.053	-
SAW	Plate	2	3.0	1.3	-	42.019	-
Attitude & Orbit Control Subsystem:†							
AOCS-B1	Box	2	0.4	0.4	0.3	4.432	AA7075
AOCS-B2	Box	4	0.3	0.2	0.1	1.206	AA7075
MTQ	Cylinder	3	0.1	0.7	-	0.563	AA7075
GPS-Ant	Cylinder	2	0.3	0.15	-	1.737	AA7075
RWL	Cylinder	4	0.34	0.06	-	8.686	A316
STR	Box	2	0.3	0.15	0.15	0.529	AA7075
Electrical Power Subsystem:							
EPS-B1	Box	2	0.4	0.4	0.3	4.432	AA7075
EPS-B2	Box	1	0.3	0.3	0.2	12.865	AA7075
Battery	Box	1	0.7	0.4	0.3	99.067	AA7075
Harness:							
HNS1	Cylinder	1	0.05	0.8	-	4.838	Copper
HNS2	Cylinder	2	0.05	0.38	-	2.298	Copper
HNS3	Cylinder	1	0.05	0.4	-	2.419	Copper
HNS4	Cylinder	1	0.05	0.75	-	4.536	Copper
HNS5	Cylinder	1	0.05	0.975	-	5.896	Copper
HNS6	Cylinder	1	0.05	1.55	-	9.373	Copper
HNS7	Cylinder	1	0.05	0.24	-	1.451	Copper
HNS8	Cylinder	1	0.05	0.85	-	5.140	Copper
HNS9	Cylinder	1	0.05	0.9	-	5.443	Copper
HNS10	Cylinder	1	0.05	0.7	-	4.233	Copper
HNS11	Cylinder	1	0.05	1.2	-	7.257	Copper
HNS12	Cylinder	1	0.05	0.26	-	1.572	Copper
HNS13	Cylinder	1	0.05	0.25	-	1.512	Copper
HNS14	Cylinder	1	0.05	0.29	-	1.754	Copper
HNS15	Cylinder	2	0.05	0.86	-	5.201	Copper
HNS16	Cylinder	1	0.05	0.5	-	3.024	Copper
Onboard Data Handling:							
OBDH-B1	Box	1	0.2	0.2	0.2	6.073	AA7075
OBDH-B2	Box	1	0.5	0.5	0.5	4.196	AA7075
OBDH-B3	Box	1	0.5	0.4	0.2	21.581	AA7075
OBDH-B4	Box	5	0.3	0.2	0.1	1.206	AA7075
OBDH-B5	Box	1	0.5	0.3	0.2	3.433	AA7075
Payload:							
Telescope	Cylinder	1	1.0	1.2	-	42.843	AA7075
PL-B1	Box	2	0.4	0.4	0.4	57.101	AA7075
PL-B2	Box	2	0.6	0.3	0.2	35.584	AA7075
PL-B3	Box	1	0.3	0.2	0.1	5.512	AA7075
PL-B4	Box	2	0.3	0.1	0.1	2.79	AA7075
PL-B5	Box	4	0.5	0.4	0.2	22.085	AA7075
PL-B6	Box	1	0.7	0.6	0.4	109.402	AA7075
Thermal Control Subsystem:							
TCS-B1	Box	1	0.4	0.3	0.3	25.285	AA7075
TCS-B2	Box	1	0.4	0.4	0.3	4.432	AA7075
Telemetry, Tracking & Command:							
Antenna	Cylinder	3	0.3	0.15	-	2.101	AA7075
TTC-B1	Box	1	0.4	0.3	0.1	7.953	AA7075
TTC-B2	Box	1	0.3	0.3	0.2	1.167	AA7075

*incl. STS
†excl. RWL housing and brackets

Table 3. Initial Conditions

	SCARAB	SESAM
Date [dd.mm.yyyy]	01.01.2010	
Time, GMT [hh:mm:ss]	12:00:00	13:08:30
Semi Major Axis [km]	6510	6466.25
Eccentricity	0.001	0.00258
Inclination [deg]	98.6	98.61
RAAN [deg]	0	0.07
AOP [deg]	0	60.66
TAN [deg]	0	223.05
Altitude [km]	120.014	120.039
Latitude [deg]	-73.91	-73.85
Longitude [deg]	93.43	93.40
Velocity [km/s]	7.908	
FPA [deg]	-0.1	
AZM [deg]	123.27	123.37

The re-entry trajectories of the surviving fragments are shown in Fig. 3. The most obvious difference between both results is that the SCARAB impacts occur at larger downrange values with less spreading compared to the SESAM impacts. The shifting of the footprint toe point by 412.2 km is caused by the different aerodynamic methods of the tools. The deviation of the toe fragment trajectories begins already at higher altitudes (see Fig. 2). The different footprint lengths (SCARAB footprint length: 63.5 km; SESAM footprint length: 281.4 km) are caused by the different fragmentation altitudes. All SESAM fragments are released at 78 km altitude, the default break-up altitude of SESAM. All surviving SCARAB fragments are generated at altitudes around 50–60 km. However, neither footprint location nor footprint length have an influence on the on-ground risk from an uncontrolled re-entry. Therefore, the on-ground casualty risk related results have to be compared.

2.1. Casualty Risk Assessment

Fig. 4 shows the surviving UNC fragments as predicted by SCARAB. These six fragments are: three of the four reaction wheels, one harness fragment, the remains of the battery (attached to some harness cords and remains of one of the four PL-B5 boxes), and a combined PL-B5 and PL-B6 fragment. The total surviving mass is 107.650 kg.

In SESAM, eight fragments survive: four reaction wheels, the battery, two PL-B2 boxes, and the PL-B6 box. The total surviving mass is 39.142 kg.

In order to determine the probabiliy of a human casualty, the casualty area A_c is used:

$$A_c = \sum_j \left(0.6 + \sqrt{A_j}\right)^2 \qquad (1)$$

A_j represents mean cross-sections of the surviving fragments. The constant 0.6 is equal to the square-root of the cross-section of an average human body (0.36 m^2). This

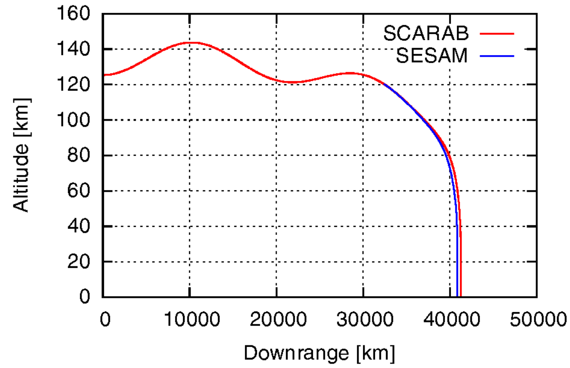

Figure 2. UNC Re-entry Trajectory - Basic Results (footprint toe fragment only)

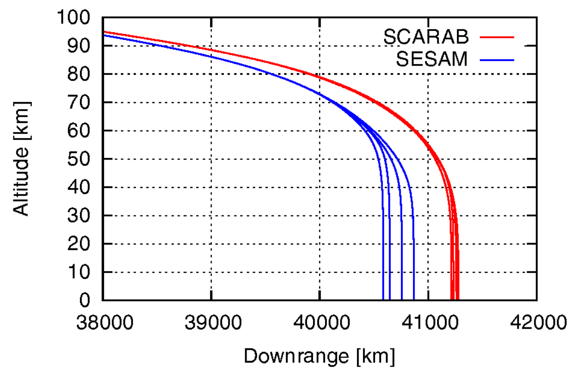

Figure 3. UNC Re-entry Trajectory - Basic Results (surviving fragments only)

definition has been taken from the NASA Safety Standard 8719.14 [8]. Tabs. 4 and 5 show the casualty area calculations for the SCARAB and SESAM results.

Casualty areas can be transformed into casualty risk figures P_c by applying the following equation:

$$P_c = A_c \cdot \bar{\rho}_{pop}(i,t) \qquad (2)$$

$\bar{\rho}_{pop}$ is the mean population density for the over flown latitude band (given by the orbit inclination i) and the re-entry epoch t. Population density data for calculating the mean population density as function of inclination have been taken from the *Gridded Population of the World, Version 3 (GPWv3)* [9].

For the inclination of UNC (96.8 deg) and the re-entry epoch (2010) a mean population density of 10.167 persons/km^2 has been taken from Fig. 5. This yields casualty risks of $4.6 \cdot 10^{-5}$ (SCARAB) and $6.6 \cdot 10^{-5}$ (SESAM). The risk predicted by SESAM is about 43% higher than the risk predicted by SCARAB. The casualty risk is primarily driven by the number of surviving fragments, contributing about 0.8 m^2 casualty area for each surviving fragment.

Figure 4. Surviving UNC Fragments - Basic Results (SCARAB)

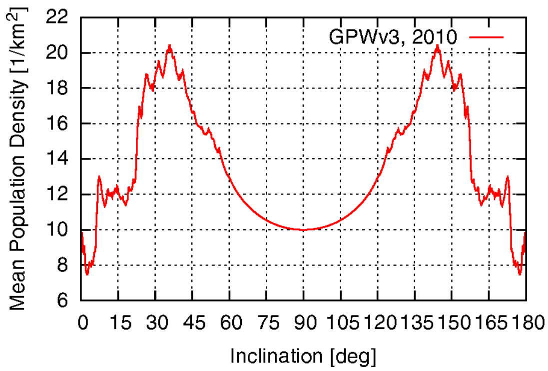

Figure 5. Mean Population Density (GPWv3, 2010)

3. FRAGMENTATION STATISTICS

Fig. 6 shows a fragmentation event frequency histogram of the SCARAB analysis results obtained for UNC (bin size 1 km). Two fragmentation regimes can be identified. Above 90 km altitude, all fragmentation events can be primarily attributed to solar panel break-off and partial thermal destruction of the outer structure of UNC (see also Fig. 7 showing UNC at 90 km altitude). Below 90 km altitude, breakup of the main satellite body and release of internal components begins.

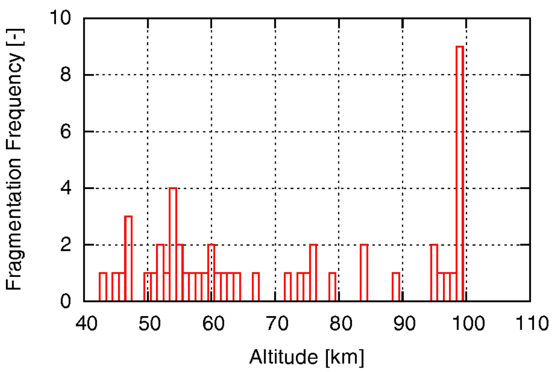

Figure 6. Fragmentation Event Histogram

Table 4. Casualty Area SCARAB

Fragment	Surviving Mass [kg]	Mean Cross-section [m^2]	Casualty area [m^2]
RWL	8.687	0.043	0.652
RWL	8.718	0.043	0.653
RWL	9.303	0.045	0.660
HNS	2.618	0.020	0.550
Battery*	72.542	0.282	1.280
PL-B5/6	5.783	0.063	0.726
Total	**107.650**		**4.520**

*plus PL-B5 and HNS

Table 5. Casualty Area SESAM

Fragment	Surviving Mass [kg]	Mean Cross-section [m^2]	Casualty area [m^2]
RWL (4x)	1.610	0.041	0.642
Battery	13.940	0.153	0.983
PL-B2 (2x)	0.347	0.093	0.818
PL-B6	18.068	0.273	1.259
Total	**39.142**		**6.446**

Figure 7. UNC at 90 km Altitude

Using a bimodal Gaussian distribution density function (see Eqs. 3 and 4), mean values μ_1 and μ_2 and standard deviations σ_1 and σ_2 for the upper and lower fragmentation regime could be determined. $N_{>90}$ is the number of fragmentation events above 90 km altitude. $N_{<90}$ is the number of fragmentation events below 90 km altitude. N is the total number of fragmentation events. The results of this statistical assessment are shown in Tab. 6 and Fig. 8.

$$G(h) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{h-\mu}{\sigma}\right)^2} \quad (3)$$

$$D(h) = \frac{N_{>90}}{N} G(h, \sigma_1, \mu_1) + \frac{N_{<90}}{N} G(h, \sigma_2, \mu_2) \quad (4)$$

Table 6. Distribution Density Parameters

	Above 90 km	Below 90 km
μ	97.866	60.373
σ	1.728	12.112
N	14	37

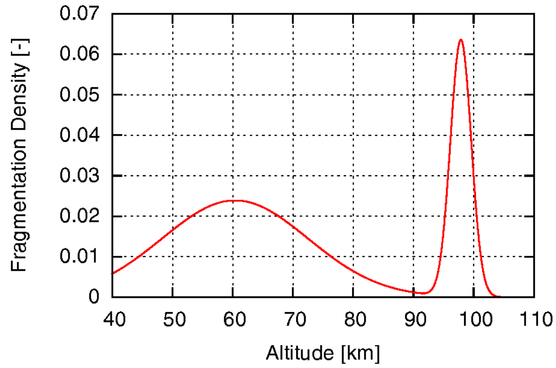

Figure 8. Fragmentation Density Distribution

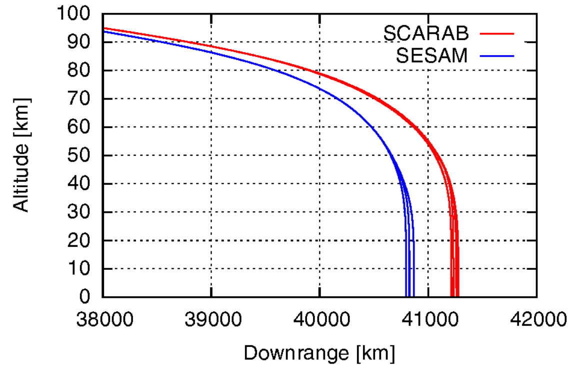

Figure 9. UNC Re-entry Trajectory - Equivalent Results (surviving fragments only)

4. EQUIVALENCY APPROACH

In order to achieve SESAM results which are equivalent to the basic SCARAB results, the following adaptations have been applied to the basic SESAM analysis:

- The solar panel break-off altitude has been increased from 95 km to 98 km, the mean fragmentation altitude determined for fragmentations occurring above 90 km altitude. The breakup altitude has been decreased from 78 km to 60 km, the mean fragmentation altitude determined for fragmentations occurring below 90 km altitude.
- The fragment release temperature has been increased from 300 K to 685 K, the mean temperature of the SCARAB main fragment at 60 km altitude.
- All subsystem components demising completely in SCARAB have been removed from the fragment list. The two boxes PL-B5 and PL-B6, surviving in SCARAB as a combined fragment, have been combined in the fragment list, i.e. masses and heights have been summed up. See Tab. 7 for the complete equivalent fragment list.

5. EQUIVALENT RE-ENTRY ANALYSIS RESULTS

The re-entry trajectories of the surviving fragments are shown in Fig. 9. The SCARAB impacts still occur at larger downrange values compared to the SESAM impacts. The shifting of the footprint toe point by 409.8 km is caused by the different aerodynamic methods of the tools. This is almost the same value as for the basic results (412.2 km). The footprint lengths (SCARAB footprint length: 63.5 km; SESAM footprint length: 71.8 km) are now very similar due to the equivalent breakup altitudes.

The equivalent SESAM analysis predicts six fragments to survive: four reaction wheels, the battery, and the combined PL-B5/6 box. The total surviving mass is 151.373 kg.

There is still a difference between both tools concerning which fragments survive. SCARAB: three reaction wheels and one separate harness cord. SESAM: four reaction wheels and no harness cord. But this difference does not affect the overall casualty risk which is dominated by the total number of surviving fragments.

The new casualty risk for the equivalent SESAM analysis is $5.2 \cdot 10^{-5}$ (derived from the casualty area results shown in Tab. 8). The risk predicted by SESAM is about 13% higher than the risk predicted by SCARAB, but the difference has been significantly reduced.

A comparison of the major results is shown in Tab. 9.

Table 8. Casualty Area SESAM - Equivalent Results

Fragment	Surviving Mass [kg]	Mean Cross-section [m^2]	Casualty area [m^2]
RWL (4x)	8.686	0.044	0.655
Battery	51.832	0.177	1.041
PL-B5/6	64.797	0.374	1.469
Total	**151.373**		**5.130**

Table 9. Result Comparison

	Basic SCARAB	Basic SESAM	Equiv. SESAM
FP length [km]	63.5	281.4	71.8
Surv. frags. [-]	6	8	6
Surv. mass [kg]	107.650	39.142	151.373
Cas. risk [-]	$4.6 \cdot 10^{-5}$	$6.6 \cdot 10^{-5}$	$5.2 \cdot 10^{-5}$

Table 7. Equivalent SESAM Fragment List for UNC

Name	Shape	No. of fragments	Width/Diam. [m]	Length [m]	Height [m]	Mass [kg]	Material
Parent*	Box	1	3.2	1.8	1.8	1114.053	-
SAW	Plate	2	3.0	1.3	-	42.019	-
Attitude & Orbit Control Subsystem:†							
RWL	Cylinder	4	0.34	0.06	-	8.686	A316
Electrical Power Subsystem:							
Battery	Box	1	0.7	0.4	0.3	99.067	AA7075
HNS:							
HNS1	Cylinder	1	0.05	0.8	-	4.838	Copper
HNS2	Cylinder	2	0.05	0.38	-	2.298	Copper
HNS3	Cylinder	1	0.05	0.4	-	2.419	Copper
HNS4	Cylinder	1	0.05	0.75	-	4.536	Copper
HNS5	Cylinder	1	0.05	0.975	-	5.896	Copper
HNS6	Cylinder	1	0.05	1.55	-	9.373	Copper
HNS7	Cylinder	1	0.05	0.24	-	1.451	Copper
HNS8	Cylinder	1	0.05	0.85	-	5.140	Copper
HNS9	Cylinder	1	0.05	0.9	-	5.443	Copper
HNS10	Cylinder	1	0.05	0.7	-	4.233	Copper
HNS11	Cylinder	1	0.05	1.2	-	7.257	Copper
HNS12	Cylinder	1	0.05	0.26	-	1.572	Copper
HNS13	Cylinder	1	0.05	0.25	-	1.512	Copper
HNS14	Cylinder	1	0.05	0.29	-	1.754	Copper
HNS15	Cylinder	2	0.05	0.86	-	5.201	Copper
HNS16	Cylinder	1	0.05	0.5	-	3.024	Copper
PL:							
PL-B5/6	Box	1	0.7	0.6	0.6	131.487	AA7075

*incl. STS
†excl. RWL housing and brackets

6. SUMMARY AND OUTLOOK

This paper has described the development of the concept of equivalent re-entry breakup altitude and fragment list, in order to build a bridge between the object-oriented and the spacecraft-oriented re-entry analysis approaches by using the strengths of both and overcoming their drawbacks. The two ESA re-entry analysis tools SCARAB (spacecraft-oriented) and SESAM (object-oriented) have been used to analyze a test scenario for uncontrolled re-entries, an artificial scientific one-ton class Earth observation satellite in low Earth orbit. Basic re-entry analysis results, based on the default settings of the tools and a basic fragment list, have been produced and compared. A statistical analysis of the SCARAB fragmentation process provided mean fragmentation altitudes below and above 90 km altitude.

Three equivalency principles have been applied to SESAM: equivalent fragmentation event altitudes (i.e. solar panel break-off and spacecraft breakup), equivalent fragment release temperature, and equivalent fragment list. The latter has been achieved by removing all subsystem components from the basic fragment list which are demising completely in SCARAB, and by combining those fragments from the basic fragment list which are surviving in SCARAB as connected fragments.

By applying this equivalency concept to SESAM, the result differences between SCARAB and SESAM could be reduced significantly. Especially the difference between resulting casualty risk figures could be reduced from 43% to 13%.

The development and assessment of this equivalency concept will be continued. Next steps will be application of the concept to other test scenarios, automation of the concept, and extension to other physical processes such as heating.

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