DESIGN FOR DEMISE TECHNIQUES FOR MEDIUM/LARGE LEO SATELLITES REENTRY

Lilith Grassi [(1)], Simone Bianchi [(1)], Roberto Destefanis [(1)], Ronny Kanzler [(2)], Pierre Bassaler[(3)], Stéphane Heinrich[(4)],

[(1)] TAS-I, Thales Alenia Space, Strada di Collegno, 253, 10146 Torino, Italy,), Email: lilith.grassi@ thalesaleniaspace.com
[(2)] HTG, Hyperschall Technologie Göttingen GmbH, Albert-Einstein-Str. 11 D-37191 Katlenburg-Lindau GERMANY, Email: r.kanzler@htg-hst.de
[(3)] TAS-F, 5 Allée des Gabians, 06150 Cannes, France, Email: Pierre.Bassaler@ thalesaleniaspace.com
[(4)] ALTRAN, 4 Allée des Cormorans, 06150 Cannes, France, Email: stephane.heinrich@altran.com

ABSTRACT

Design for Demise is the design of spacecraft systems and hardware aimed at reducing the casualty risk on ground during re-entry events. Design for Demise is a key topic to support the compliance of future missions with the Space Debris Mitigation guidelines. The purpose of this paper is to present system level investigations performed in the context of the ESA funded study "Multi-disciplinary assessment of Design for Demise techniques" (from now on, the D4D study) which aimed at identifying the most promising design for demise techniques and technologies, so as to derive guidelines and recommendations for future projects.

1 INTRODUCTION

The D4D study started in September 2014. The consortium is led by TAS-I, with HTG, TAS-F and ALTRAN as sub-contractors. After the final presentation held in February 2016, the contract was extended with the goal to perform additional investigations , which are currently still on going.

The main activities performed during the study were the following:

- Identifying satellite critical items with respect to the on-ground casualty risk.
- Identifying design concepts to improve demisability of spacecraft at components, subsystem and system level.
- Applying the D4D techniques to a case study and estimating the risk reduction.
- Deriving general guidelines and potential future improvements.

2 CRITICAL ITEM IDENTIFICATON

The starting point of the study was the identification of the LEO satellites critical items w.r.t. re-entry risk, which encompassed the following steps:

- A review of the re-entry analyses, performed in the past by HTG, using its SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up) tool [1] on the spacecraft of the Sentinel fleet, with a mass ranging from 800 kg to 2 tons, covering typical mission objectives (specifically Earth Observation in LEO) and equipped with the typical payload for that purpose.
- A set low fidelity sensitivity analyses to evaluate the various parameters affecting the demise
- Detailed re-entry risk analyses of a refined SCARAB model of Sentinel-1, the satellite selected as study case for the application of the D4D techniques.

2.1 Re-entry risk analyses of the study case Sentinel-1 (baseline model)

The ESA Earth Observation satellite Sentinel-1 is a two ton LEO spacecraft mounting a large Synthetic Aperture Radar (SAR) Antenna. Sentinel-1 was selected as study case since it is both representative of LEO satellites and very challenging for what concerns the reduction of the re-entry risk because of its mass and the presence of a large payload. The configuration of Sentinel-1 was deeply analysed and a detailed model of the S/C was developed (see Figure 1). SCARAB, developed by HTG, was used for the simulations. A total of 53 SCARAB simulations were performed and deeply analysed in order to identify the main critical components.

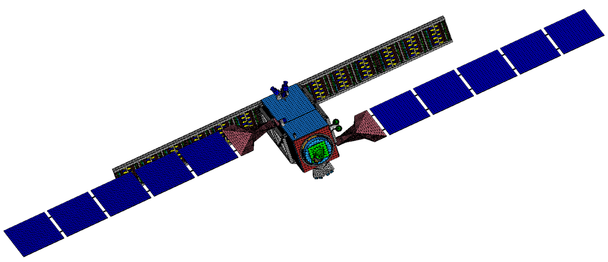

Figure 1: Sentinel-1 SCARAB model

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

The results of the simulations show that the average Casualty Area (CA) of the baseline Sentinel-1 model is about 15.2 ± 2.6 m^2, which leads to a re-entry risk equal to 2.01E-04 (assuming an uncontrolled re-entry at the year 2050), almost twice the value of 1:10000 which is the upper limit for the casualty risk threshold per re-entry typically used by existing guidelines. In fact for Sentinel-1, taking into account the polar orbit and the assumed re-entry year, the maximum allowed CA to comply with the 1:10000 re-entry risk requirements is 7.6 m^2. In the paper we will refer directly to the CA of Sentinel-1 as a measure of the casualty risk.

The identified critical items are: the tank, reaction wheels (RWs), magneto torquers (MTQs), balance mass, Synthetic Aperture Radar antenna (SAR) and Laser Communication Terminal (LCT). Figure 3 shows the contribution of the various items to the overall CA with the SAR antenna as the major contributor to the risk.

Each critical item was analysed in order to define the following aspects: survivability reasons (material, mass, altitude of exposure, component configuration, etc.), re-entry and fragmentation process, uncertainties associated with the resulting CA, reliability of re-entry analysis results and relevance of model granularity.

By integrating the results of the detailed re-entry risk analysis performed on the Sentinel-1 with the literature survey and the parametric Low-Fidelity analysis, the considerations on the identified critical items were extended to each component category (i.e.: to same type of component implemented on different categories of LEO satellites). The main features of the identified critical items are reported hereafter.

Tank: as expected the titanium tank survives in all the simulations. Tank is a platform equipment always critical, with a medium contribution to the S/C overall casualty area (about 25% of the platform CA , i.e. without considering the P/L). The reason of survivability is the material, whereas the mass of the component and the altitude of exposure are not relevant: even small tanks are predicted to arrive on ground with little or no demise. There is no fragmentation during re-entry: the minimum CA relates directly to the initial cross section of the tank, whereas higher CAs can be due to structural elements that remain attached to the tank.

Reaction wheels: the four Sentinel-1 RWs are predicted to survive in all the simulations. The main reason of survivability is the material. However, the component configuration and hence the granularity of the model can affect the simulations results. RWs are composed by several subcomponents (e.g., case, wheel, motor) made of different materials with different criticality and the internal parts are exposed late to the heat flux. In the study case baseline simulations, RWs were modelled in three separated parts: case, flywheel and shaft (as a single part of aluminium or stainless steel). However, the analyses showed that the RWs configuration (and thus the model granularity) is not the reason of their survivability. The RWs survive even if exposed at the very beginning of the re-entry. With the current, simplified RW model, no fragmentation occurs during re-entry and the CA is related to the initial cross section of the connected flywheel and shaft.

MTQs: In almost all simulations three MTQs survive but in two simulations one of the MTQs demise. The separation altitudes of the MTQs cover a relatively wide range, from about 68 km down to about 45 km. For the two cases where one MTQ demises, the separation altitude is at 65.6 km and 67.4 km, respectively, for the specific MTQ considered. This is a clear indication that the reason of survivability is the late exposure to the heat flux.

Ballast mass: Sentinel-1 ballast masses are made of stainless steel. On board, several masses are installed: the small ones (less than about 5 kg) usually demise, while the big ones mounted internally (with a mass of about 50 kg) arrive on ground. The reason of survivability is clearly the combination of material and mass.

SAR: the SAR antenna is the major contributor to Sentinel-1 CA, whit an average CA of about 6.5 ± 2.4 m^2. The high uncertainty is due to the fragmentation process that happens during the re-entry: different simulations can generates very different number of fragments.

Regarding the reason of survivability an analysis of the simulations showed that all the surviving fragments originate from the SAR Central panel: this is due to its reduced exposure to the heat flux, while the lateral wings of the antenna are exposed from the very beginning of the re-entry. Moreover, from the analysis of the 53 baseline simulations, emerged that the final CA is affected by the separation altitude of the SAR central panels: higher separation altitude leads to lower CA. This aspect, that was deeply investigate in the course of the study as explained in the next paragraphs, was the starting point to identify a strategy to reduce the risk caused by the SAR.

LCT: The LCT survives in one single piece in all the simulations. However, it has to be pointed out that, due to the unavailability of details of the LCT design, the SCARAB model used is very coarse. In fact the CA could even be potentially higher due to the possible fragmentation of the LCT during re-entry. In general, the demisability of optical payload deserves a dedicated approach, due to the peculiarity of each payload. A study funded by ESA and led by TAS-I to investigate potential D4D techniques for optical payload is currently on-going.

Finally, some **fragments** of the spacecraft H/C structural panels can survive the re-entry. The fragments are originated from section of panels that remained attached to surviving items (as, for instance, the tank) down to low altitudes. Therefore. in general H/C panels are not considered critical items because their survivability is due to the shielding provided by other critical elements of the platform.

In general, harness and batteries can be considered as not critical. A detailed model of Batteries developed by HTG in the context of the Sentinel-2 project showed that Li-Ion batteries should completely demise during re-entry. Their survivability reported in past studies was due to due low granularity of the battery models. In Sentinel-1 analyses, performed in the context of the D4D study, batteries are implemented with a simplified model (in order to not increase computational time) and neglected from the list of re-entering items. Also ,for what concern the Harness, the survivability reported in past simulations was due to the low granularity of the models. Increasing the granularity of the model, the Harness demise, and therefore can be considered as a non- critical item.

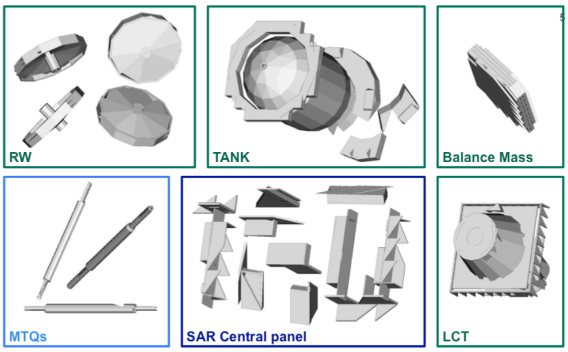

Figure 2: Sentinel-1 identified critical Items

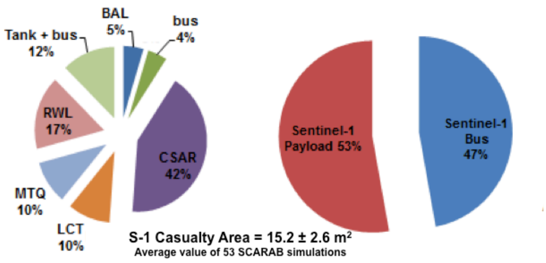

Figure 3: Results summary of SCARAB analysis of Sentinel-1 baseline model

A detailed post-processing of the results of the 53 re-entry risk simulations was performed. *Figure 4* shows the casualty area vs. the number of fragments evaluated by comparing the results of 53 SCARAB simulations. Figure 5 shows an enlargement of the same plot, focused on some items, to highlight their distributions. It can be seen, for example, that for SAR fragments there is a clear correlation between CA and number of fragments.

By evaluating the distribution of the various items, a categorization of components that survive the re-entry was derived, according to the reason of their survivability and behaviour during re-entry:

- **Category 1**: items break into smaller fragments (as, for instance, the Synthetic Aperture Radar). The CA is a function of the number of fragments.
- **Category 2**: items arrive in one single, partially ablated piece or demise completely, depending on their initial mass and exposure to heat flux (as, for instance, in the case of magnetorquers). The CA is directly related to the initial cross section of the item.
- **Category 3**: items arrive in one single, partially ablated piece partially, but with the current design they are not expected to demise under any condition (as, for instance, in the case of tank and reaction wheels). The CA directly related to the initial cross section of the item.

Identifying critical items and defining the reason of survivability is the first step to identify and fine-tune D4D techniques, as described in the next section.

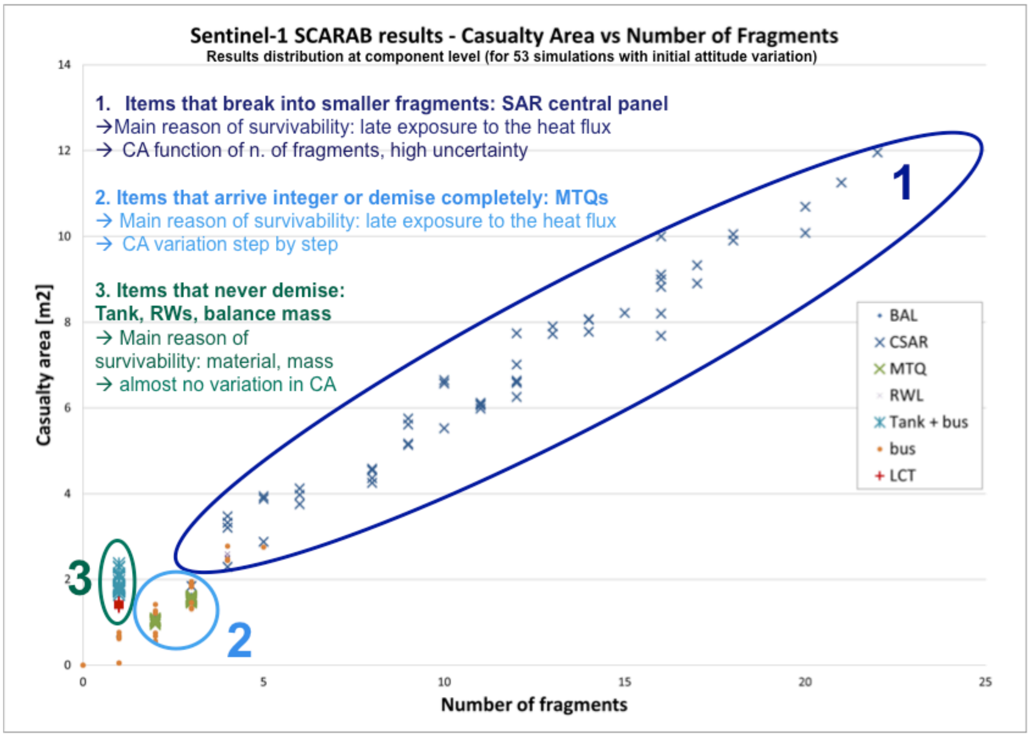

Figure 4: Casualty area vs number of fragments

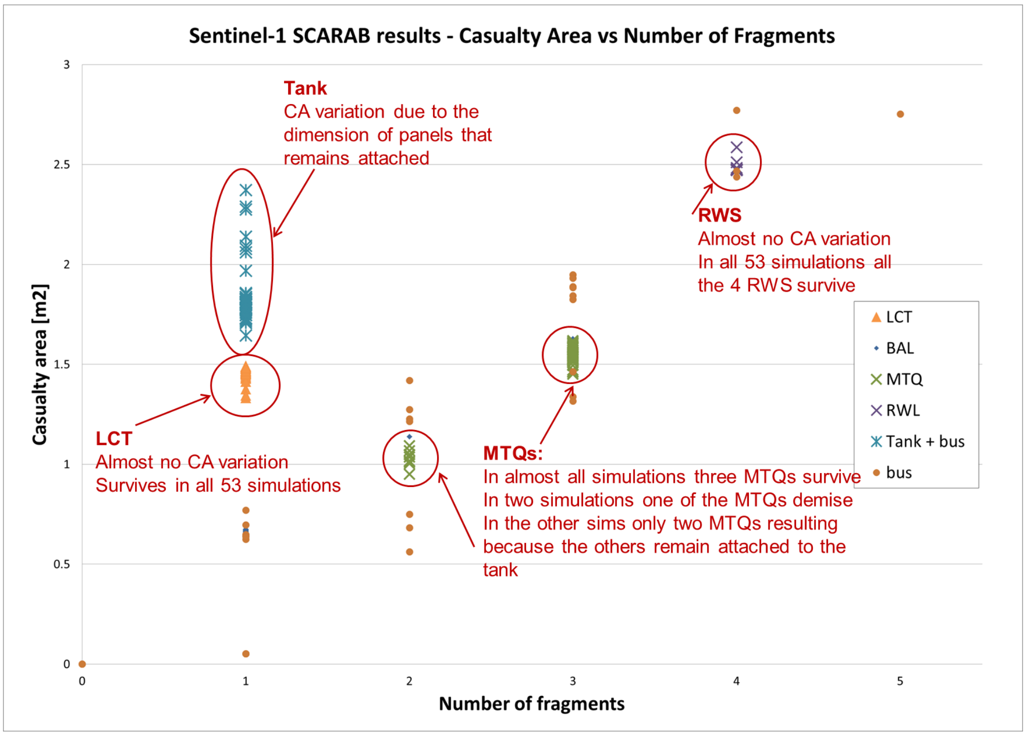

Figure 5: Casualty area vs number of fragments (detail)

3 D4D TECHNIQUES

In parallel to the identification of critical items, a broad and detailed review of the D4D techniques aimed at reducing the re-entry risk has been performed, both taking into account approaches reported in literature and investigating new solutions. The technologies needed to implement the identified D4D techniques were identified as well, and the impact at system level was preliminarily assessed.

The D4D techniques can be classified according to both their level of application (e.g., system or component level) and the strategies adopted to improve the demise (e.g., increase of the heat rate, reduction of the number of fragments, etc.).

Table 3-1: D4D approaches

Approach	Implementation strategy
Reduction of the heat load required to demise the fragment	Component level Material substitutions * Mass reduction Manufacturing / Layering / Segmentation * Break-up at component level
Increase of the heat rate in order to demise the fragment	Component level • Ballistic coefficient / Components shapes System level • Increase the Break-up Altitude * • Open structure • S/C configuration (avoid shielding) * Mission level • Attitude at re-entry time • Flight path angle
Reduce the number of fragments	Component level • Containment System level • Containment / survival block
Reduce Ekin below 15 J	Component level • Layering *
Reduce overflown population density	Mission level • Orbit inclination Re-entry date

Table 3-1 summarizes possible approaches and strategies to reduce the on-ground re-entry casualty risk identified during the study. Several approaches to D4D have been identified, and the possible implementation strategies at component, system and mission level are reported for each of them. The solution marked with an asterisk are the ones that were implemented in the modified study cases, as described in paragraph 4.1. A detailed description of the identified techniques is reported in [3].

For each critical component, and according to its critical category, is possible to identify the main category of D4D approaches that can lead to the demise: the D4D approach to be followed derives directly from the typology of critical items categorization, as summarized in Table 3-2.

Table 3-2: Critical item category vs D4D approach

D4D approach / Category	1	2	3
Reduction of the required heat load to demise the fragment (by redesigning the item)			x
Increase of the heat rate in order to demise the fragment	x	x	
Reduction of the number of fragments: Containment at component / system level			x
Reduction of Ekin below 15 J			x

For the first two categories of critical items, an early exposure to the heat flux can lead to demise.

For the third category of items, survivability is mainly related to the characteristics of the materials, and only a redesign of the critical items (e.g., changing critical material, layering, configuration) can lead to its demisability. The alternative approach is to adopt a Survival / containment block (short term solution) to reduce the number of the fragments that reach the ground.

This last approach was the subject of several discussions. This solution has not been tested during this study and the common agreement is that, for platform elements, the most preferable approach is to develop demisable components (such as tank and RWs). However, for other elements (for example, components of optical payload) in which no suitable solutions to reach the design can be found, this approach can still be interesting and should be evaluated more in detail to assess its feasibility and appeal

4 MODIFIED STUDY CASE

As explained in the previous section, the D4D approach to improve the S/C demisability was derived directly from the categorization of the critical items.

A set of the most promising D4D techniques, combining component and system level approaches, was applied to the Sentinel-1 case study and four modified models were defined and modelled in SCARAB. The main D4D techniques investigated included the potential use of a monolithic Al-Li tank (instead of the baseline titanium tank), modified reaction wheels with fly wheel made from aluminium alloy, MTQ relocated to a location earlier exposed to the aerothermal fluxes, systems allowing the early aperture of the external panels of the S/C main body and mechanisms allowing an early detachment of the SAR antenna during the re-entry.

In order to support the selection of the D4D techniques to be applied to the case study, several sensitivity analysis performed with TADAP (Trajectory and Aerothermodynamic Debris Analysis Program), the 3DoF re-entry tool developed by TAS. The main results are reported in the next section together with the details of the various techniques implemented.

4.1 D4D techniques at component and system level

For the titanium **tank,** the reason of survivability is the very high heat of demise of the titanium, two D4D techniques were compared: a Monolithic Al-Li tank and a COPV tank.

However TADAP parametric analyses showed that, in case of redesign of the tank with these materials, and considering the typical tank separation altitudes (as for the baseline scenario), the re-designed tank could not demise completely, with the possibility of breaking in several fragments in fact increasing the final CA w.r.t. the titanium tank. In this case the D4D solutions would lead a major risk instead of reducing it. Therefore two different approaches were analyzed: re-designed tank with and without early aperture of the bus

For the **RW** the main reason of survivability is the materials, in particular the stainless steel of the wheel and of the internal mother and bearing.

The re-design solution investigated within D4D study consisted in replacing the stainless steel wheel with an aluminium wheel. ALTRAN dimensioned an aluminium wheel in order to reach the performances of the original stainless steel wheel (see Figure 6).

As said before the component configuration is not the reason of survivability for current RWs that would survive in any case even if exposed earlier but could be relevant for re-designed RWs. In order to support the selection of the best approach to demise the RWs a set of parametric low fidelity simulations were performed with TADAP: a simplified model composed by three elements (aluminium case, aluminium wheel and intern motor bearing, simplified as a cylinder made of steel). For the simulations a Sentinel-1 re-entry like trajectory was assumed varying the altitude of exposure. Figure 7 reports the summary of the results: the figure shows the RWs at the separation altitudes of the baseline model the internal part of the RWs are likely to survive.

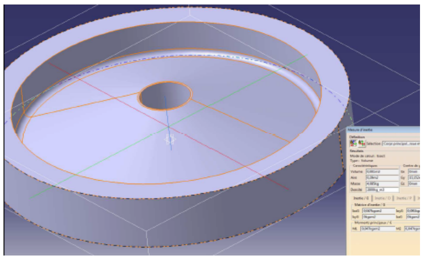

Figure 6: Preliminary dimensioning of an aluminium fly wheel

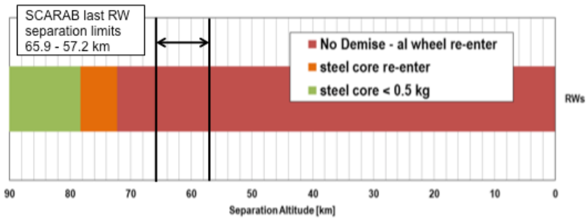

Figure 7: results of TADAP parametric simulations on re-deigned RWs

The potential need of combing rim re-design with system level approach had to be assessed, therefore two different scenario analyzed: redesigned RWs with and without early aperture of the bus, and with an without I/F weakening.

Moreover, the granularity of the SCARAB model was improved and a very detailed model constituted by 26 different internal elements was implemented.

Summarizing the RW are a very critical platform component, several aspects deserved to be investigated in order to evaluate the demisability of modified aluminium RWs, i.e.: redesign of the wheel, I/F weakening, combination with S/C early break up and finally improved granularity of the model.

For the **MTQ** the reason of survivability is late exposure to the heat flux as explained in section 2.1. An early separation from the mound panel should lead to the complete demise of the component, therefore only system level solution have been investigates: the MTQ were relocated on the internal side of the external panel and the granularity of the SCARAB model of the mounting I/F was improved taking into account the glue of the inserts.

Ballast mass: or the Balance mass the reason of survivability is the combination of material and mass. The solution investigated implements a layering of the mass combined with a passive release system (see

Figure 8)

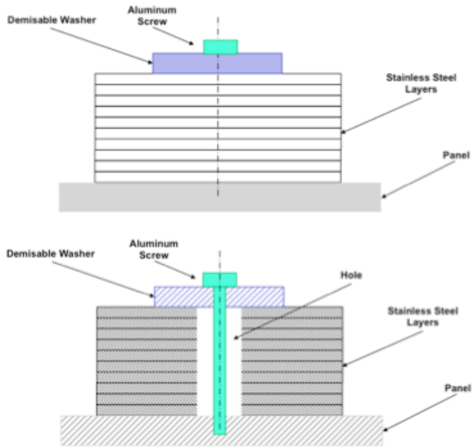

Figure 8: Ballast mass re-design based on layering

As explained in paragraph 2.1 all the **SAR** fragments reaching the ground originates from the central panel, due to its reduced exposure to the heat flux. Therefore, in order to reach the demise of the SAR, a system to ensure an SAR earlier separation was implemented in the SCARAB model.

The techniques for early separation were based on the "demisable joint" (see Figure 9) (TAS-I patent N.TO2014A000998) based on a demisable washer, allowing the early aperture of the external panels of the S/C main body and an early detachment of the SAR antenna during the re-entry.

For the external bus panel early separation bus demisable joint based on the same concept used for the SAR bracket were implemented in SCARAB.

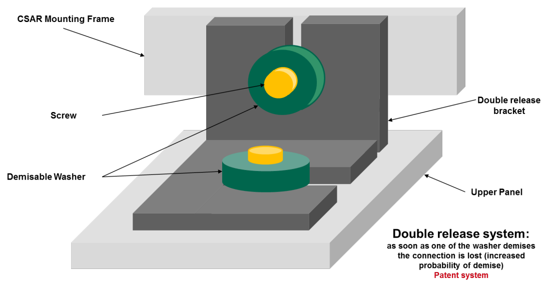

Figure 9: demisable joint (TAS-I patent)

A total of 25 SCARAB additional simulations were performed, implementing these modifications to the original design. The high fidelity re-entry simulations were supported by several sensitivity analysis performed with TADAP. The results were thoroughly analysed. A detailed description of the techniques applied to the study case is reported in [3].

In Table 4-1 reports the summary of the D4D modifications implemented in the four cases. The rationale behind the combination of various techniques was firstly to try to decouple as much as possible the implemented solutions, and then to evaluate the impact of early bus break-up comparing the results with and without External bus panel early separation.

Table 4-1: D4D modification summary

Case	1	2	3	4
Monolithic Al-Li tank	x		x	
COPV tank		x		x
RW Al rim + Model improved granularity	x	x	x	x
RW IF/ weakening				x
MTQ relocation + I/F Model improved granularity	x	x	x	x
SAR separation system type 1	x			
SAR separation system type 2		x	x	x
Ballast mass type 1	x		x	x
Ballast mass type 2		x		
External bus panel early separation			x	x

5 RESULTS ANALYSIS

For the baseline scenario analysis, a wide range of initial attitudes were analysed. From the results of this initial state parameter study, six reference cases were defined, based on the probable aerodynamically and gravitation gradient stabilized attitude of the Sentinel-1 spacecraft. The four D4D technique evaluation cases were simulated for each of these six initial attitude states to foster differing breakup behaviour and provide an uncertainty to the simulation results. For the analysis of the simulations, the results specific to each individual simulation shall not be considered isolated.

5.1 Re-entry risk analyses of the study case Sentinel-1 (D4D modified models)

1.1.1 Case 1 simulation results

The simulation results for case 1 are listed below. Compared to the baseline scenario, the total casualty area is about 26% lower, while the number of ground fragments and total ground fragment mass are reduced by about 55%. Also, the uncertainty is significantly higher as for the baseline scenario.

The main driver of the ground risk for case 1 are the CSAR panel and the Al-Li tank, which fragments into several pieces.

Table 5-1: case 1 simulation results

Attitude case	# of fragments	Tot. mass [kg]	Casualty area [m²]
1	9	96.080	6.649
2	9	88.147	6.879
3	25	146.837	15.967
4	14	82.955	8.873
5	13	96.591	9.087
6	20	71.949	12.399
Average	**15**	**97.1**	**9.98 ± 3.59 (36%)**
Baseline	26.6	187.4	15.23 ± 2.57 (17%)

1.1.1 Case 2 simulation results

The simulation results for case 2 are listed below. Compared to the baseline scenario, the total casualty area is about 31% lower, while the number of ground fragments is reduced by 62% and the total ground fragment mass is reduced by about 50%. The uncertainty is slightly higher than for the baseline scenario.

Table 5-2: case 2 simulation results

Attitude case	# of fragments	Tot. mass [kg]	Casualty area [m²]
1	8	118.978	7.513
2	17	95.242	11.313
3	16	106.925	10.848
4	9	124.052	8.016
5	17	83.237	11.120
6	9	102.433	6.798
Average	**12.7**	**105.1**	**9.27 ± 2.04 (22%)**
Baseline	26.6	187.4	15.23 ± 2.57 (17%)

1.1.2 Case 3 simulation results

The simulation results for case 3 are listed below. Compared to the baseline scenario, the total casualty area is about 40% lower, while the number of ground fragments is reduced by 58% and the total ground fragment mass is reduced by about 72%, because the tank and bus demise completely. The uncertainty is slightly higher than for the baseline scenario.

Table 5-3: case 3 simulation results

Attitude case	# of fragments	Tot. mass [kg]	Casualty area [m²]
1	12	57.619	7.236
2	13	53.821	7.554
3	16	61.324	8.434
4	9	52.627	5.361
5	16	65.020	9.541
6	19	63.231	10.701
Average	**14.2**	**58.9**	**8.14 ± 1.87 (23%)**
Baseline	26.6	187.4	15.23 ± 2.57 (17%)

1.1.3 Case 4 simulation results

The simulation results for case 4 are listed below. Compared to the baseline scenario, the total casualty area is about 41% lower, while the number of ground fragments is reduced by 65% and the total ground fragment mass is reduced by about 68. Compared to the baseline scenario, the uncertainty is significantly higher.

Table 5-4: case 4 simulation results

Attitude case	# of fragments	Tot. mass [kg]	Casualty area [m²]
1	8	59. 830	5.745
2	13	68.358	8.575
3	12	70.315	8.244
4	7	65.324	5.329
5	24	88.861	14.717
6	7	56.470	5.239
Average	**11.8**	**68.2**	**7.97 ± 3.62 (45%)**
Baseline	26.6	187.4	15.23 ± 2.57 (17%)

1.2 Critical component analysis

A synthesis of results of the four case studies estimating the efficacy of the various D4D techniques implemented in reducing the risk is reported in this section.

The redesign of the internal **ballast mass** leads to complete demise in all simulated cases and for both ballast mass types investigated. For one of the case 1 simulations, two fragments of the unmodified external balance masses survived to the ground. This is due to uncertainty. To prevent any surviving balance mass fragments, the layering approach used for the internal balance mass could be implemented in general.

The driver of the **CSAR** casualty area is the central panel, which is mounted to the bus, due to the shielding provided by the bus and the panel itself. The average CSAR casualty area ranges from 3.13 m² for case 4 to 5.04 m² for case 3. Except for case 3, all cases show at least two simulations with 2 or less CSAR ground fragments and thus a good demise of the CSAR panel. At the same time, the number of simulations with high ground fragment count (more than 10) is similar. The large variation within the particular model modification cases shows the high uncertainty of the CSAR panel fragmentation process, even with similar separation altitudes.

For each single simulation case, **reaction wheel** fragments survive to the ground. Except for one simulation of case 3, all the simulations generate four reaction wheel ground fragments, namely the inner core made of iron and stainless steel. For cases 1 and 2, where the reaction wheel assembly is significantly shielded, even the bottom part of the aluminium case can survive. The driver of the final RW casualty area is the separation altitude of the RW assembly.

The late separation of the **magnetic torquer** mounted to the internal side of a lateral panel results in a single surviving fragment for two simulations of case 1 and one simulation of case 2. The lateral panel dismantlement for the cases 3 and 4 lead to complete demise of all three magnetic torquers.

The **monolithic Al-Li** tank was included in case 1 and case 3. Due to the relatively long shielding by the bus structure, complete demise of the tank could not be achieved. Furthermore, the tank broke up into several pieces for most of the simulations, increasing the casualty area compared to the baseline scenario. For the six simulation runs of case 3, the Aluminium-Lithium tank and the attached bus did demise completely due to the early exposure resulting from the lateral panel detachment.

The **COPV tank** was included in the case 2 and case 4 simulations. The tank survived for all simulation runs. The tables below list the final ground fragment properties for each simulation. For case 2, the mass loss of the CFRP by ablation is between 0.2 and 0.5 % of the total CFRP mass, while the total mass loss of the tank is 1.6 – 12.7 %. The inner Al-Li liner started melting away partly by the heat transported through the CFRP. Also, the fragments can have parts of the bus still attached when they hit the ground.

For case 4, the mass loss is higher due to the significantly shorter thermal shielding by the bus structure. Here, the tank itself survives to the ground, with only minor parts of the bus being attached. However the mass loss of the CFRP due to ablation is still very low, between 0.4 and 0.8 % of the total CFRP mass. The mass loss of the inner Al-Li liner is higher than for case 2, so that the total mass loss of the tank reaches from 14.5 to 22.7 %.

These results on the survivability of CFRP over-wrapped tanks are in agreement with the findings in [4].

1.3 Results summary

In Figure 10 are reported a summary of the results of the four modified cases vs the baseline and in *Figure 11* are reported the results at component level.

The main results are summarized hereafter:

Monolithic Al-Li tank:

- Breaks up into several pieces and the CA increases
- Earlier exposure through lateral panel dismantlement leads to complete demise of tank and associated bus fragments

COPV tank does not demise:

- COPV tank demisability is still an open point, especially w.r.t. the behaviour of an aluminium or Al-Li liner. Results are not conclusive. Also, current models do not consider deformation by mechanical stress during re-entry.

Reaction wheel:

- Redesigned RWs still survive in almost all the simulations, but CA is reduced
- Only one simulation showed 2 demising reaction wheels
- Separation altitude greater than about 78 km needed for demise
- Results are not conclusive: impact of relocation to be assessed (Relocation + panel separation could lead to complete demise)

Balance mass redesign:

- Layering approach was successful
- Design applicable to all balance masses with critical material

CSAR panel early separation:

- Mechanisms work in principle, but have to be improved to insure central panel separation above 86 km
- Effective separation altitude and fragmentation process is prone to general uncertainty and can lead to very high CA uncertainty

MTQ:

- Relocation and I/F increased granularity was

successful
- No need of lateral panel dismantlement

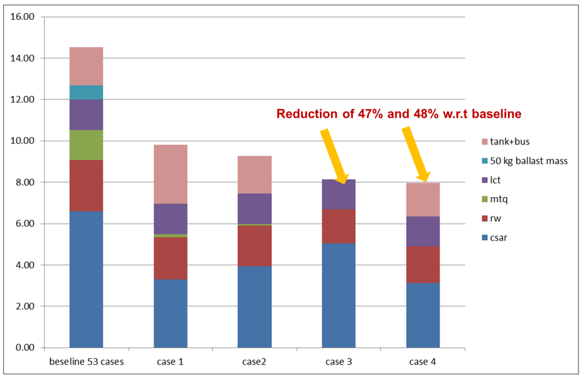

Figure 10: Baseline vs modified cases overall results

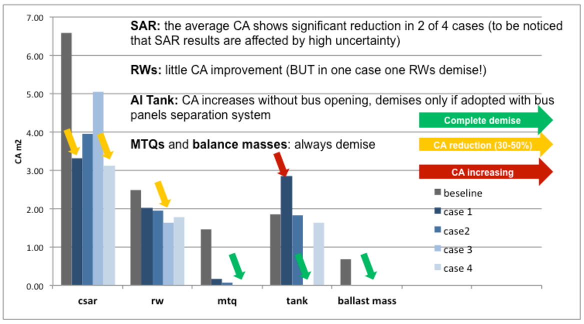

Figure 11: Baseline vs modified cases (component level)

Finally a best case scenario can be composed by combining the following techniques:

- Balance mass redesign (all cases)
- Reaction wheel redesign (from case 4)
- MTQs relocation and I/F weakening (from case 4)
- Aluminum-Li tank (from case 3)
- Lateral panel dismantlement (from case 4)
- CSAR separation mechanism (from case 4)
- Compliance of the average casualty area

In this scenario, the final casualty area is 6.34 ± 3.59m^2, with an improvement with respect to the baseline of about 58%.

It has to be noticed that from Task 3 to the end of the study, the focus was posed on the case study Sentinel-1, a 2 ton satellite with a big CSAR antenna, a quite challenging case from the point of view of the design. Therefore, some of the conclusions are related to the peculiarity of this case and should be adapted to cover different cases such as significantly smaller satellites. In particular, the needs of combining D4D techniques at component and system level could be related to the "difficulty" of the considered case study, for smaller satellite a component level approach could suffice to reach compliance.

In Table 5, the achievable reduction obtained with the D4D techniques adopted in Task 4 is summarized. Moreover, the potentially achievable reduction that could be reached by improving the technics according to the lessons learned during this study is also reported.

Table 5: Re-entry simulation results summary - Conclusion summary

	Techniques	**Strategy**	**Needs of D4D tech combination**	**Achieved CA reduction**	**Potentially achievable CA reduction**	**Applicability**
Component level	Al li tank	Material Swap	Yes – with early aperture of bus	100 %		Medium term solution
	Al RWs	Material Swap	Yes – with early aperture of bus and relocation	35%	Potentially 100% Relocation can lead to complete demise	Medium term solution
	Ballast mass layering	layering	No	100 %		Short term
System level	Relocation of critical components (applied to MTQs)	Increase heat flux		100 %	-	Short term
	Passive system for Early separation of appendix	Increase heat flux	No	50%	Potentially100% Increasing separation altitude at about 85-90 km	Medium term solution
	BUS early separation system	Increase heat flux	Yes	See component level impact	increase separation altitude	Medium term

6 CONCLUSION

Summarizing, in order to validate the D4D techniques, a total of 25 SCARAB simulations have been performed for the 4 model modification cases. The results show that the layering approach for the balance mass redesign was successful, leading to a complete demise of the balance mass. The CSAR panel early separation mechanisms worked in principle, but have to be improved to ensure the separation of the central panel above 86 km. The LCT showed no increase of demise, but here no particular technique was applied. The relocation of the magnetic torquers resulted in the complete demise, except for few outliers, which vanished with the lateral panel dismantlement. The reaction wheel redesign still showed surviving fragments, but, compared to the baseline scenario, the casualty area was reduced. Only one single simulation showed two demising reaction wheels. For complete demise of the RWs, a separation altitude above 78 km would be needed. This could be achieved for example by relocating the RWs on a less internal and less shielded position. The two approaches for demisable tanks implemented showed very different results. During re-entry, the monolithic Al-Li tank breaks up into several pieces, which may result in an increased casualty area contribution, if these pieces do not demise. On the other hand, an earlier exposure through lateral panel dismantlement leads to complete demise of tank and bus. For the COPV tank, the result is different. In the simulations, the COPV tank does not demise. However, the simulations on CFRP must be taken with caution, since a general assessment on the demisability of CFRP is difficult to achieve using the tools and implementations currently available. Especially the wide range of different CFRP compositions and thus material properties makes it difficult to reflect the exact properties and behaviour of the variety of real CFRP components. To address this, further material tests and modelling improvements need to be performed before a final conclusion can be drawn.

In general, the analyses showed that the design for demise is an iterative process and that, in order to improve demisability of large satellites, it is necessary to combine different techniques at both component and system level. In particular, techniques as Aluminum-demisable tank, demisable RWs, early aperture/detachments systems were identified as key technologies which deserve further investigations to allow the next generation of LEO medium / large satellites to significantly improve their compliance with the Space Debris Mitigation requirements.

7 AKNOWLEDGEMENTS

This work was funded by the European Space Agency under the contract No. 4000XXXXXX/14/NL/GLC.

8 REFERENCES

1. Lips, T., Fritsche, B., Homeister, M., et al., Re-entry Risk Assessment for Launchers – Development of the new SCARAB 3.1L, Proceedings of the Second IAASS Conference, SP-645, ESA Communication Production Office, ESTEC, Noordwijk, The Netherlands, 2007
2. ESA's invitation to tender n° ESA AO/1-7773/13/NL/GLC "Multi-Disciplinary Assessment of Design for DEMISE Techniques"
3. Final Report Multi-Disciplinary Assessment of Design for DEMISE Techniques, TAS-I
4. Lips, T., Fritsche, B., Kanzler, R., et al., About the Demisability of Propellant Tanks during Atmospheric Re-Entry from LEO, Proceedings of the 8th IAASS Conference "Safety First, Safety for All", Melbourne, Florida, USA, May 18-20, 2016