DRACO SCIENTIFIC RETURN CONCEPT: DETERMINING THE TRUTH OF SATELLITE DEMISE

B. Jilete(1), S. Lemmens(2), J. Van den Eynde [(3)], A. Rosenbaum [(4)], J. Beck [(5)], S. Loehle [(6)], I. Sakraker [(7)], A. Turchi [(8)], J. Ferreira [(9)], J. Silha [(10)], B. Helber [(11)], L. Tarabini-Castellani [(12)], P. Minacapilli [(13)], S. Sanchis [(14)]

[(1)] GMV for ESA, ESAC Villafranca (Spain), Email: Beatriz.Jilete@ext.esa.int
[(2)] ESA, ESTEC Noordwijk (Netherlands), Email: Stijn.Lemmens@esa.int
[(3)] ESA, ESTEC Noordwijk (Netherlands), Email: Jeroen.Van.den.Eynde@esa.int
[(4)] ESA, ESTEC Noordwijk (Netherlands), Email: Alex.Rosenbaum@esa.int
[(5)] Belstead Research, Ashford (UK), Email: james.beck@belstead.com
[(6)] HEFDiG (IRS), Pfaffenwaldring 29 Stuttgart (Germany), Email: loehle@irs.uni-stuttgart.de
[(7)] Institute of Structures and Design, DLR, Pfaffenwaldring 38-40 Stuttgart (Germany), Email: isil.sakraker@dlr.de
[(8)] ASI, Via del Politecnico snc Rome (Italy), Email: alessandro.turchi@asi.it
[(9)] University of Southern California, Los Angeles, CA 90007 (USA), Email: jose.ferreira@usc.edu
[(10)] Astros Solutions, Comenius University Bratislava (Slovakia), Email: jiri.silha@astros.eu
[(11)] VKI, Chaussée de Waterloo, 72 (Belgium), Email: bernd.helber@vki.ac.be
[(12)] Indra-Deimos, Rda. de Pte. 19 Tres Cantos (Spain), Email: ltarabini@indra.es
[(13)] Indra-Deimos, Rda. de Pte. 19 Tres Cantos (Spain), Email: pminacapilli@indra.es
[(14)] ESA, ESTEC Noordwijk (Netherlands), Email: Sara.SanchisCliment@ext.esa.int

ABSTRACT

ESA's DRACO (Destructive Re-entry Assessment Container Object) mission will be the world's first demonstration of recording the break-up process of a satellite in-situ while demising during a destructive re-entry.

DRACO is a fully representative small satellite platform that will undergo controlled re-entry from Low Earth Orbit. The platform hosts a dedicated instrument (Demise Data Collection Unit - DDCU) that will collect a variety of measurements from specific objects of interest, including the spacecraft structure itself. It also hosts a capsule designed to survive the destructive re-entry which will transmit the data collected by the DDCU back to ground via a relay satellite system.

Lessons learned from previous attempts (i.e. VAST/VASP, REBR, iBall, Hayabusa, ATV-1, etc.) show that repeatable experiments are required to reduce the still too large uncertainties associated with the understanding of destructive re-entry physics; that small scale physics extrapolated from ground-testing still needs to be validated for relevant scales; and that the understanding of the physics associated with controlled and uncontrolled re-entries are at the same level of maturity. Hence, DRACO's mission objectives are threefold: to demonstrate the break-up process of a spacecraft during re-entry enabling better scale of ground-tests to flight, to establish an understanding of destructive aerothermal break-ups not accessible from ground or by model, and to test early fragmentation design for demise (D4D) technologies.

In order to demonstrate the understanding of the process and physics on large-scale systems, the objects of interest considered in the DRACO mission are: the spacecraft structure made of aluminium sandwich panels to understand the fragmentation process; Composite Overwrapped Pressure Vessels (COPV) tanks to determine the system design impact at equipment level with Design-for-Demise (D4D) techniques; and material samples to characterise their response during the re-entry process and validate ground test results.

This paper describes the fundamental and unique dataset that the DRACO mission is being designed to acquire. The measurements are divided into three categories:

- Contextual data of the trajectory (attitude, position and rotational rates) and local flow conditions (altitude and dynamic pressure) will be gathered by means of IMU and GNSS systems. This will provide information on when different demise processes are taking place and support the trajectory rebuilding.
- Qualitative data on the general phenomenology will be obtained by means of infrared and visual cameras to improve the understanding of which processes are taking place, and which are dominant. Images are expected to show the structure fragmentation, the early stages of COPV demise and the behaviour of joints.
- Quantitative data on local temperatures, deformations and separation events will be recorded by means of thermocouples and strain gauges, to understand what happens at local levels in terms of spacecraft structure break-up and critical on-board components demise.

Additionally, spectral markers are included in the

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

spacecraft with different concepts that are illustrated in the paper. With the help of an airborne observation campaign, additional data will be acquired to improve the understanding of the fragment cloud evolution and ablation signatures of specific materials, which will eventually support the break-up event and sequence characterisation.

1 INTRODUCTION

Due to the increased launch traffic into Low Earth Orbit (LEO), the number of spacecraft and launcher upper stages re-entering the Earth´s atmosphere and undergoing a destructive re-entry process are increasing [1].

Space Debris Mitigation Requirements (ISO 24113:2023 adopted by the European Space Agency (ESA) via ESSB-ST-U-007 Issue 1 [2]) impose design and operational constraints to limit the risk to persons and infrastructure on-ground, associated with the fragments generated by destructive re-entry. ESA´s Space Debris Mitigation Requirements standard [2], has been prepared in the frame of the implementation of ESA´s Agenda 2025, where ESA set the ambitious target to have a "net zero pollution" strategy by 2030.

Currently, calculating the on-ground casualty risk for a re-entering spacecraft relies heavily on re-entry simulations [3]. This assessment is based on extrapolations and has only limited representativeness. The physics that govern the processes that occur during a destructive re-entry are poorly understood. Some past flight experiments, such as VAST/VASP (1971-1973) [4], [5], REBR (2012) [6], i-Ball (2012), and ATV-5/BUC (2014) [7], have shed some light on the behaviour of representative large-scale spacecraft during re-entry. But the majority of the current knowledge on spacecraft demise processes is derived from ground-based tests in (plasma) wind tunnels that act as anchor points for simulations [8]. As such, current predictive models only allow risk assessments with large uncertainties. These large uncertainties imply the need for further in-orbit experiments to close the knowledge gaps on representative length scales break-up processes and on type of re-entry.

To address these uncertainties, the Destructive Re-entry Assessment Container Object (DRACO) mission has been initiated by ESA. DRACO consists of a fully representative small satellite platform that will undergo controlled destructive re-entry from LEO. It is instrumented by a device called DDCU (Demise Data Collection Unit - DDCU) that will collect a variety of measurements in-situ. The data will be stored within a re-entry capsule that survives the re-entry and transmits the data for analysis on-ground via a satellite communications relay link.

2 DRACO MISSION OVERVIEW

As indicated in the introduction, differently from the aforementioned flight experiments, DRACO mission is characterised by the fact that the host platform itself and its internal components will be instrumented with a variety of sensors including infrared cameras. This will allow understanding of how the environmental conditions are evolving and to observe how and when equipment fail, fragment and demise. Besides, specific Design-for-Demise (D4D) hardware is being flown to compare and demonstrate the improvement gained using such components compared to traditional alternatives. Furthermore, spectral marker materials (understood as a specific material combination that produce a recordable signal at given environmental conditions) are included at relevant locations, to improve the understanding of the fragmentation process.

2.1 Mission Objectives

The DRACO mission will be the world's first demonstration of recording the break-up process of a satellite in-situ while demising during a destructive re-entry.

The main objective of the mission is to gather in-situ data to support the characterisation of the full-scale physical processes that lead to the break-up of a satellite and its components in the dynamic regimes not accessible in ground-based facilities. This top-level mission objective can be further decomposed. The DRACO mission's three main mission objectives are:

1. to demonstrate the break-up process of a spacecraft during re-entry enabling better scale of ground-tests to flight.
2. to establish an understanding of destructive aerothermal break-ups not accessible from ground or by model.
3. to test early fragmentation design-for-demise (D4D) technologies.

In order to fulfil these objectives, following scientific requirements will drive the mission design:

1. to design a satellite instrumented to record the physical behaviour during its own destruction upon atmospheric break-up, representative of an uncontrolled re-entry from LEO.
2. to base the hardware on a representative small satellite platform.
3. to target thermomechanical driven failure modes between 70 and 100km altitude.
4. to obtain spectral information from both in-situ and airborne observations.

2.2 Mission Profile

DRACO will be launched in 2027 into LEO. An overview of its mission profile is shown in Figure 1.

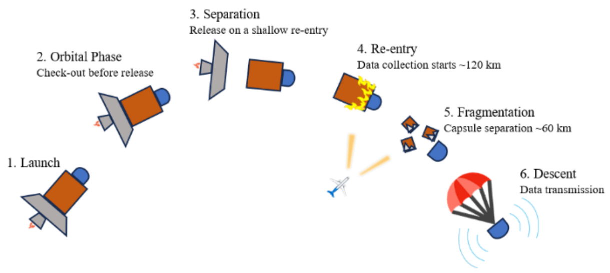

Figure 1. DRACO mission profile

Two operational phases can be identified:

- In-orbit phase: from the end of Launcher Upper Stage (LUS) operations up to the Entry Interface Point (EIP) at 120 km.
- Re-entry phase: from EIP at 120 km, going through the fragmentation of the platform, capsule release at 60 km, stabilisation of the capsule and parachute release, and data transmission.

The initial phase is expected to last only a few orbits, after which the LUS will perform a separation manoeuvre targeting a Flight Path Angle (FPA) of less than -1° at EIP, as the goal is to be representative of an uncontrolled re-entry from LEO. However, the re-entry as described will be controlled mainly for two reasons: to ensure meeting the applicable re-entry casualty risk requirements ([2],[3]) and enable an airborne observation campaign.

Before the re-entry phase starts, i.e. prior to the EIP, the DDCU will start the recording. 200 intrusive sensors distributed around the platform and located on various Objects of Interest (OoI), together with 4 imaging cameras will be enabled aiming to return at least 20 Mbytes of data. More details on the type of sensors are given in section 3. The measurements are stored in the DDCU which will forward the data following a prioritisation algorithm, to a small re-entry capsule. Both DDCU and capsule are protected with dedicated Thermal Protection System (TPS): the DDCU to survive the fragmentation phase (until around 70 km), and the capsule to survive the entire re-entry phase. The capsule will be separated from the demising host platform at around 60 km altitude. Upon deployment of a parachute, necessary to increase the capsule´s descent duration before splashdown, data transmission through a satellite relay network will follow.

To enhance the dataset acquired by DRACO, an airborne observation campaign will be established. Additional data will be acquired to improve the understanding of the fragmentation cloud evolution and ablation signatures of specific materials, which will eventually support the break-up event and sequence characterisation. The airborne observation requires a night-time entry, ideally under new moon conditions.

2.3 System Concept

The host spacecraft of the DRACO mission will be a fully representative small satellite. The total wet mass of the spacecraft, including sensors, OoIs, DDCU and re-entry capsule will be 150-200 kg.

In order to fulfil with the mission objectives stated in section 2.1, several components have been identified as OoIs for the mission. Consequently, they will be instrumented in detail. The DRACO mission´s OoIs are:

- The structural aluminium sandwich panels and other structural elements.
- Composite Overwrapped Pressure Vessels (COPV) tanks. One of them will be manufactured under the D4D paradigm.
- Material samples.

These OoIs will be instrumented with intrusive sensors (like thermocouples and strain gauges) and will have dedicated imaging cameras pointing to them. They will also include marker materials with strong spectral emission signature to get verifiable insights of the fragmentation process.

The COPV tanks will be located in the bottom part of the spacecraft, in order to be representative. Due to size constraints, they will be mounted vertically to guarantee image recording capability (see Figure 2).

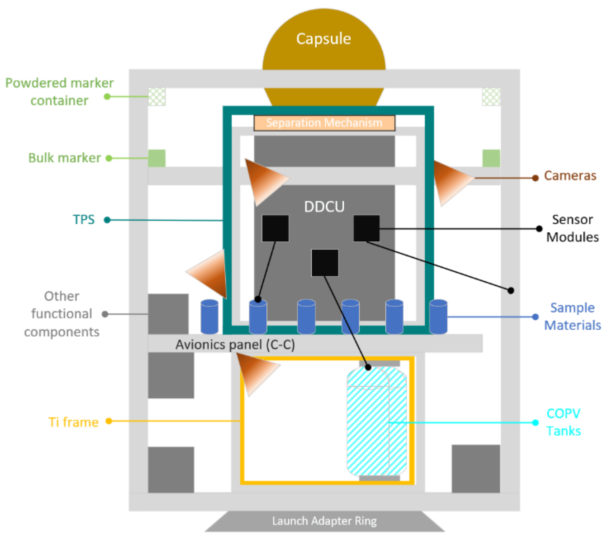

Figure 2. DRACO configuration layout

To maximise the demise data that can be collected during the fragmentation phase, the avionics panel that the DDCU and sample materials are connected to, will be made of a hard-to-demise material like carbon-carbon. This will guarantee that the objects subject to study remain attached for enough time to capture the demise process. The avionics panel will have a cut-out in one of its corners to allow image recording along through the platform to bottom panel corner.

As described earlier, the DDCU will record and store the incoming data from the sensors and cameras. In order to optimise the routing of the harness and avoid too many holes in the TPS protecting the DDCU, the sensors will be routed by several sensor modules connected to the DDCU, and also thermally protected. A prioritisation algorithm will sort the recorded data to maximise the likelihood of obtaining the most valuable data through the limited data downlink. The DDCU will send the data to the re-entry capsule which has onboard storage capacity. The release of the capsule will be triggered using a built-in timer at an altitude of approximately 60km. After capsule stabilisation it will deploy a parachute and send the data to ground via a satellite relay network.

3 DRACO MISSION SCIENTIFIC PAYLOAD CONCEPT: SENSORS AND MEASUREMENT TYPES

In the previous section the OoIs to be instrumented were listed, comprising the structural aluminium sandwich panels and other structural elements, COPV tanks and material samples.

The DRACO mission will use 200 intrusive sensors: temperature thermocouples, strain gauges and heat flux gauges. Besides, it will implement on 4 SurfCam cameras (two will be VIS/NIS, the other two VIS/SWIR). These sensors and cameras will provide quantitative local demise-related measurements and their context.

Additionally, contextual information of the spacecraft trajectory (trajectory, position and rotational rates) and local flow conditions (altitude and dynamic pressure) will be obtained by means of IMU and GNSS systems in the platform and re-entry capsule.

The primary scientific interest in observing and measuring the fragmentation of the external structure and other structural elements like the secondary structure and their connections are: understanding whether fragmentation is driven by thermal or mechanical failure mechanisms, understanding the effect of tumbling in the fragmentation process and understanding whether there is a failure cascade of events or if failures are concentrated locally. In order to obtain insights on what happens during the fragmentation process a combination of quantitative data and context is needed:

- Temperature data from a range of locations on the structural panels, connections between the structural panels and secondary structure and connections of the other OoIs to the platform.
- Deformation data from a range of locations on the structural panels.
- Visual and infrared images of the critical fragmentation areas, e.g. the corners of the spacecraft.
- Heat flux measurements of the environment. The spacecraft is expected to be tumbling during the re-entry phase. Hence, there is a high uncertainty on the heat flux which is being experienced by the different spacecraft parts. This type of measurement will be key to support calibration operations in ground-testing facilities.

In order to obtain the aforementioned dataset, the following sensor configuration will be designed:

- Thermocouples will be located in the sandwich panels (one in the back face of the outer facesheet, one in the front face of the inner facesheet) at least three locations in each of the panels (near each edge corner, at each upper edge centre, at the panel centre).
- Strain gauges will be located close to the locations selected for the thermocouples (back face of the inner facesheet). To obtain a consistent deformation data, a rosette of 4 strain gauges will be located at each point.
- Heat flux gauges will be placed in at least three locations: two close to panel corners on adjacent panels, and one close to an edge on a panel which also has a corner heat flux gauge. These heat flux gauges will be similar to a calorimeter (simple cupper slug calorimeters are foreseen) and instrumented with two thermocouples.
- 2 of the four cameras will be dedicated to in situ observations. One will be placed pointing at one of the structure corners, giving a clear view of the failure mechanisms of the panel and frame structure. The other one will be pointing to the avionics panel cut-out getting observations along through the platform to bottom panel corner. This will allow observation of the demise of a high demisable structure when connected to a lower demisable structure (i.e. avionics panel).

The scientific interest of the COPV tanks is two-fold: to test early fragmentation D4D technologies and to understand whether mechanical loads can affect the molten clump of residue of the mounting structure observed in many recovered wrapped tanks on-ground. Also to understand whether thermally induced plastic deformation of the liner could occur.

Two identical COPV tanks, in shape and size, will be mounted. They are cylindrical tanks with spherical caps. The difference between them is that one has been manufactured in such a way to enhance its demise properties. In order to guarantee enough time to get insights about the demise process, they are mounted on a reinforced titanium frame by means of hard-to-demise connections (see Figure 2).

In order to obtain insights on the overall picture, the following type of measurements are needed:

- Temperature data at different depths of the overwrap layer.
- Deformation measurements specifically near the mounting structure and inside the liner.
- Visual and infrared images.

In order to obtain the aforementioned dataset, the following sensor configuration will be designed:

- Thermocouples will be embedded in the overwrap fibres at different depths and at the inside of the liner. One thermocouple will be placed between the liner and the overwrap and another one embedded in the overwrap. This, at two locations: one on the cylindrical part and another in the hemispherical part.
- Two rosettes of 4 strain gauges each, will be located on the internal side of the liner, one close to the connection to the bosses and the other in the cylindrical part.
- 1 of the four cameras will be dedicated to in-situ observations. The camera needs to be connected to the DDCU through the bottom part of the avionics panel and be thermally protected. Due to size constraints on the lower part of the spacecraft and tanks dimensions, the tanks will be in vertical position and the camera will point at them from the opposite corner. This is required as the minimum focal length of the cameras is 100 mm.

The material response characterisation in in-flight conditions drives the interest of the third of the OoIs. This experiment will consist of 20 material samples. Each of these samples will investigate the demise behaviour of a material and/or a connection type. The material selection was performed based on the Probabilistic Assessment of Spacecraft Demise (PADRE) activity [9] where a list of potential critical objects and materials was summarised. The materials will cover titanium (baseline and with different coatings, and with different connection types like helicoil joints and adhesive joints), steel (baseline and with coating), aluminium (baseline and with coating), harness materials, glasses (zerodur, fused silica, borosilicate), silicon carbide, Glass Fiber Reinforced Plastics (GFRP) and Carbon Fiber Reinforced Plastics (CFRP). The samples will be designed as hollow cylinders with spherical caps.

In order to guarantee enough time to get insights about the demise process, they are mounted on the low demisable avionics panel (see Figure 2).

In order to obtain insights on the overall picture of the demise process, the following type of measurements are needed:

- Temperature data at different locations.
- Visual/infrared images.

This will be achieved by the following sensor configuration:

- Thermocouples will be located in each sample on the inside of the hollow hemispherical section at two locations. One on the side facing the DDCU and another one facing the flow.
- 1 of the four cameras will be pointing at a sub-set of these 20 samples.

Furthermore, there is critical interest in the joining mechanisms. Hence, thermocouples and strain gauges will also be placed on the frame structure, inserts and joining structures. The number of locations is dependent upon the specificities of each of the OoIs.

Additionally, spectral markers will be included in the spacecraft. The type of material to be considered needs to emit strong and specific signatures that can be observed remotely by an airborne instrumentation. The specific signatures are selected to be different to the ones commonly observed during spacecraft re-entries. A preliminary selection will target lanthanum (La I signature), sanidine (K I and Na I signatures) and chromite (Cr I and Na I signatures). The concept foresees having two types:

- Powder inside a demisable cube shape container. This will enable short but intense flashes. Powdered grains of 1mm-1cm lanthanum will be used. Placing the containers attached to the outer panels will give confirmation of main outer panels separation. Two of this type of containers will be placed onboard.
- Bulk cubes. A total of up to 6 will be mounted at different corners. Placing the cubes of different materials in a clever way will support the re-entry dynamics reconstruction and events timing synchronisation, knowing that the order of radiation from higher to lower altitudes are: lanthanum, sanidine and lastly chromite.

This concept is rather novel and has limited heritage [10]. This will require wind-tunnel tests to support the design. Additionally, these tests will give some indication of the feasibility to embed markers in the material samples to identify the breach of the material and/or in the COPV tanks to identify the reaching of the liner, the breach of the liner and potentially the recession rate of the overwrap material.

4 CHARACTERISATION OF BREAK-UP EVENTS CHAIN DURING DESTRUCTIVE RE-ENTRY

Combining the concept of operations described in section 2.2 and the OoIs, sensors and measurement types detailed in section 3, the dataset that DRACO mission will obtain can be addressed.

The re-entry capsule will have its own sensors. Namely, IMU recording at high rates, GNSS, pressure sensors and temperature sensors.

The platform will carry additional payloads that will provide valuable contextual data. Gyrometers providing data at high rates, magnetometers, sun sensors, GNSS and startrackers.

The spacecraft will be activated once separated from the launcher upper stage, at around 500 km altitude. At this instant the re-entry capsule will start recording IMU data at 10 Hz until the end of the mission. Simultaneously, the platform´s equipment will start its recording activities. Gyrometers at 10 Hz until the end of the fragmentation phase, magnetometers at 5 Hz until the end of fragmentation phase, sun sensors at 1 Hz until the EIP, GNSS data at 1 Hz rate until the end of the fragmentation phase and startrackers at 1 Hz rate until the EIP.

At least 10 minutes before the EIP the instrument will be activated. This covers the fragmentation phase until capsule separation at around 60 km altitude. During this phase, on top of the re-entry capsule´s IMU data, pressure and temperature data, the platform´s gyrometer, magnetometer and GNSS data the instrument measurements are added. This includes temperature data at relatively high rate of 4 Hz, deformation data at 1 Hz, heat flux inferred measurements at 4 Hz and images from the cameras.

Once the fragmentation phase is over, and the re-entry capsule is released, only data from this phase will be ingested in the stream to be sent to the satellite relay after black-out.

One important aspect to highlight is related to the number of images required to fulfil science needs and their quality. The importance of the images is to capture the general phenomenology happening during the fragmentation process, giving context to the other in-situ measurements about which processes are taking place, and which are dominant. Therefore, it is preferable to obtain many low-quality images rather than just a few high-resolution images. Targeting a minimum size feature of 1 cm by 1 cm to be resolved is considered enough to reconstruct the chain of events that will occur.

Another aspect to consider is related to which data is considered more relevant for the re-entry community, as this will support the design of the DDCU prioritisation algorithm. Images from the structure together with demise-related data (temperature and environmental measurements) and trajectory attitude is considered as high priority data to be obtained. Temperature data and images coming from material samples and COPV tanks also lais in this category. As strain gauges are less reliable at high temperature, deformation data from structure and COPV tanks is considered as medium priority.

5 SUMMARY

This paper aims at giving an understanding of how the DRACO mission will help to close some knowledge gaps on the re-entry physics and give added-value data on the understanding of atmosphere and satellite dynamics.

The DRACO mission is being designed in a bespoke way to achieve mission objectives but keeping the representativeness of a standard satellite mission going through un-controlled re-entry. The ultimate goal is to obtain the described dataset to close the loop between risk analysis tools, ground-testing facilities and in-flight behaviour.

ACKNOWLEDGEMENTS

The authors acknowledge the work performed by the industrial partners in the development of the DRACO mission (Indra-Deimos, Fluid Gravity Engineering, Von Karman Institute for Fluid Dynamics, Belstead Research, DIAL Dynamic Imaging Analytics, PEAK Technology, Astros Solutions, and their respective subcontractors).

The authors acknowledge the contribution of DRACO Science Advisory Group addressing the needs that the re-entry community has which drive the unique DRACO scientific payload design that is described in this paper.

REFERENCES

[1] ESA Space Debris Office (2024), ESA´s Annual Space Environment Report.

[2] ESA Space Debris Mitigation Working Group (2023), ESA Space Debris Mitigation Requirements, ESSB-ST-U-007 Issue 1.

[3] ESA Re-entry Safety WG (2017), ESA Re-entry Safety Requirements, ESSB-ST-U-004 Issue 1.

[4] Stern R.G., “Aerothermal Heating for Satellite Reentry Conditions, Aerospace Report No. TR-2004(8506)-2,” Sep. 2004.

[5] R. G. Stern, “Reentry Breakup and Survivability Characteristics of the Vehicle Atmospheric Survivability Project (VASP) Vehicles, Aerospace Report No. TR-2008(8506)-3,” 2008.

[6] A. S. Feistel, M. A. Weaver, and W. H. Ailor, “Comparison of reentry breakup measurements for three atmospheric reentries.”

[7] S. Giagkozoglou, C. Dittert, H. Weihs, R. Greger, J. Thömel, and N. Murray, “Design and Test of a Small Entry Capsule for the Break Up Camera BUC on ATV 5,” in 5th International ARA Days, Arcachon (France), 2015.

[8] J. Van den Eynde et al., Overview of the DRACO Development Status, HiSST 2024.

[9] J. Beck, I. Holbrough, J. Merrifield, M. Spel, J.M

Party, D. Briot, S. Bianchi, E. Minisci, "Probabilistic Assessment of Spacecraft Demise (PADRE) FR".

[10] Loehle, S.; Eberhart, M.; Hufgard, F.; Leiser, D.; Hoerner, I.; Duernhofer, C. et al. (2025): Lanthanum as a Spectrographic Marker for Break-up Analysis from Airborne Observation Missions. In: 3rd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions Engineering (FAR 2025). Arcachon, France.