SATELLITE INFLATABLE DEORBITING EQUIPMENT FOR LEO SPACECRAFTS

Benjamin Rasse¹, Patrice Damilano², Christian Dupuy³

¹Airbus Defence and Space, rue du Général Niox 33165 St Médard en Jalles (France)
Email: benjamin.rasse@astrium.eads.net

²Airbus Defence and Space, 31 rue des Cosmonautes 31402 Toulouse (France)
Email: patrice.damilano@astrium.eads.net

³CNES, 18 avenue Edouard Belin 31401 Toulouse Cedex 9 France
Email: christian.dupuy@cnes.fr

ABSTRACT

Debris remediation and mitigation is one of the biggest challenges space engineering has to face today. Debris removal is taken into account as early as during the design phase of a space system by selecting the right materials, including the need for demise in the design and introducing de-orbiting strategies and corresponding subsystems. Today Airbus Defence and Space dedicates part of its activity to the development of a passive de-orbiting subsystem embedded in LEO satellites (altitude ~ 750 km). Based on the IDEAS in-flight prototype (currently in phase D with a qualification campaign completed mid 2014) developed in the framework of the CNES MICROSCOPE project, the subsystem consists in the deployment of aero-braking membranes by an inflatable boom made of aluminum laminate at the end of the spacecraft’s operational life. On this basis, the system optimization - with different geometries of the deorbiting subsystem - is carried out to ensure re-entry in less than 25 years with a minimum impact on architectural design of the vehicle. Airbus Defence and Space’s final objective is to address the market with “off-the-shelf” flight-ready deorbiting equipment meeting the requirements of the forthcoming Space Debris French legislation.

1. INTRODUCTION

Debris remediation and mitigation is one of the biggest challenges space engineering has to face today. Debris removal is taken into account as early as during the design phase of a space system by selecting the right materials, including the need for demise in the design and introducing de-orbiting strategies and corresponding subsystems. An increasing number of spacecraft are now on low earth orbit (LEO). As a consequence of spacecraft fragmentation, a growing population of orbital debris has been induced. Therefore spacecraft shall be de-orbited at the end of their operational lives to lower the amount of orbital debris. A new legislation, the French Space Act relating to space operations (decree in June 2009, applicable in 2021), requires that the systems must be designed, produced and implemented so that, once the space object has completed its operational phase, it is de-orbited, preferably with a controlled atmospheric re-entry, but in case of impossibility of meeting this requirement, it must be designed and implemented so that it is no longer present in orbit twenty-five years after the end of the operational phase with a uncontrolled atmospheric re-entry. A certification office led by CNES will be in charge of checking the decree application. Today Airbus Defence and Space dedicates part of its activity to the development of a passive de-orbiting subsystem embedded in LEO satellites (altitude ~ 750 km) and compliant with the French legislation. This paper will first present the inflatable passive deorbiting equipment IDEAS which has been developed in the framework of the MICROSCOPE mission (300-kg, circular orbit 700-km). The programme is in phase D and the flight model is to be delivered by the end of 2014. The subsystem will be operational and flight-proven by the end of 2017. It consists of two inflatable 4.70 m booms, each deploying two aero-braking membranes. An extensive qualification campaign of the material and subsystem has been carried out following ESA-CNES regulations and TRL7/8 is now considered achieved. Based on IDEAS, mass reduction and new architectures have then been investigated in order to improve re-entry performances. The modularity and scalability of the technology enables the system’s adaptation onto various panel geometries and satellite classes. In this framework,
2. IDEAS DEORBITING SYSTEM

The IDEAS aero-braking system is a GOSSAMER structure designed to be deployed as post mission disposal in order to increase the ballistic coefficient (ratio mass/surface) of the MICROSCOPE satellite (CNES) and to allow re-entry within 25 years. The IDEAS development has been carried out jointly with Air Liquide for the inflating subsystem, Airbus Defence and Space for the deployable assembly and with the CNES as system and project coordinator. The MICROSCOPE launch is scheduled for the first semester 2016 and the post mission disposal should take place at the end of 2017.

2.1. IDEAS Architecture

The IDEAS system is made of three subsystems: the inflating subsystem and two booms/sails subsystems (see Fig. 1).

Each boom/sails subsystem weights 6.7 kg and the common inflating subsystem 3.1 kg for a total mass of 16.5 kg.

The inflating subsystem’s main component is a titanium tank containing 133 g of N₂ at 190 bars in order to inflate the two booms (193 litres) up to 300 mbars pressure. Three pyro-valves complete the subsystem to first deploy at 50 mbars and then rigidify the booms at 300 mbars. A constant leakage in the subsystem allows a full flushing-out of the booms after 24 hours.

The boom-sails subsystem is made of a 4.7 m boom (diameter: 0.16 m), two 1.85-m² sails each and a Hold-Down Release Mechanism (HDRM). The boom material is polyimide-aluminium laminate (130 µm thick) with a thin SiOₓ coating to protect the polyimide against ATOX corrosion. Its mass is 248 g/m². By inflating the boom with a 300 mbars pressure, the strain in the boom material is beyond its yielding point. After release of the pressure, the deployed assembly keeps a residual stiffness exactly like a soda can.

The sails are also made of a polyimide-aluminium laminate but only 50 µm thick. Each face is coated with SiOₓ and its mass is around 100 g/m². Once deployed, the membranes interact with the thin upper atmosphere and create a drag force which accelerates the re-entry. The thermo-optical properties of the polyimide shall limit the membrane temperature under solar exposure.

In the stowed configuration, the boom is maintained by the HDRM (see Fig. 2), which consists of a low-shock pyro-bolt called Pyrosoft. Before the inflating phase, the Pyrosoft is fired and the strap is opened, enabling boom deployment. The deployment dynamic is controlled and guided through a subsystem called TADECS (Tetragonal Accordion Deployment Control System), inserted in the folded boom, which releases the folds one-by-one (see Fig. 2). TADECS is a patent-filed by Airbus Defence and Space.

![Fig. 1. Inflating subsystem (left) and stowed boom-sail subsystem (right)](image)
As shown in Fig.3, the IDEAS system is set-up on +X MICROSCOPE’s panel. The booms are deployed with a 21° angle w.r.t vertical. This configuration ensures an average aerodynamic surface of 5 m² in tumbling dynamics for the MICROSCOPE satellite. The introduced angle minimizes the variation around this mean value.

2.2. Materials testing

Sustaining LEO space environment during 25 years is the main driver behind the new materials introduced by IDEAS. Therefore, an extensive Airbus-CNES joint characterization and qualification campaign has been performed on the sail membrane and the boom materials. The tests included:

- Outgassing tests done w.r.t E-ECSS-Q-70-02-A.

The table below summarizes the results:

<table>
<thead>
<tr>
<th>Material</th>
<th>Test Results</th>
<th>Test</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boom laminate</td>
<td>TML = 1.3%, RML = 0.20%, CVCM = 0.02 %</td>
<td>ECSS-Q-ST-70-02C</td>
<td>OK</td>
</tr>
<tr>
<td>Sail membrane</td>
<td>TML = 0.22%, ML = 0.9%, CVCM = 0.00%</td>
<td>ECSS-Q-ST-70-02C</td>
<td>OK</td>
</tr>
</tbody>
</table>

- Ageing tests including humidity and thermal cycling tests. No damage was noted on the membrane and the boom laminate. The ageing tests did not degrade the material’s mechanical performances.
- Radiation tests with 41 Mrad-82 Mrad doses w.r.t ECSS-Q-ST-70-06C. No damages were observed on the material or the bonding joints.
- Micrometeoroid impact to assess rip risk. The micro-meteoroid campaign demonstrated that impacts in the aluminium are ductile (see Fig. 4) and that there is no risk of rip propagation. Based on the MASTER-2005 tool, the space debris cumulative flux (particles > 1 µm) seen by the membranes is estimated at 1.36.10^7/m²/year leading to a surface loss smaller than 0.1% over a 25 year period.
- ATOX resistance tests. The protection provided by the SiOx coating appears to be efficient. No significant mass loss was noted after ATOX exposition.
- Folding tests. Superficial cracks and fragments of the SiOx coating were observed after the folding and compacting process (see Fig 4). The laminate polyimide-aluminium foil was also partially disrupted at bends. These defaults are not deemed critical to the membrane’s integrity.
- Thermal expansion coefficient evaluation.
- Thermo-optical properties.
### Table 2: Thermo-optical properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Absorptance $\alpha$</th>
<th>Emissivity $\varepsilon$</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail membrane</td>
<td>0.362</td>
<td>0.685</td>
<td>ECSS-Q-ST-70-09C</td>
</tr>
</tbody>
</table>

All these tests have demonstrated the ability of the IDEAS materials to sustain space environment during 25 years without creating debris or fragments.

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**2.3. Subsystem testing**

The IDEAS qualification was performed on a flight representative EQM model in compliance with the ECSS-E-10-03A rules. The test campaign consisted of:
- Sinus and random vibration (see Fig. 5)
- Shock test
- Thermal vacuum cycling
- Leak test
- Functional deployment and rigidization test
- Mechanical performances of the deployed boom

The environment testing demonstrated the robustness of the IDEAS mechanical design and results were in line with test predictions.

The HDRM opening test (see Fig. 6) validated the strap motorization, the strap locking mechanism after opening and the Multi Layers Insulation (MLI) design. Subsequently the deployment was nominally performed in 323 seconds without any blocking point or deviation of the boom axis. Rigidization was correctly achieved with a 300 mbar pressure: external aspect of the boom was smooth with no folding. (see Fig. 6)

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The last step of the test campaign consisted in evaluating the boom’s mechanical properties. The maximal compression load before buckling was 22.5 N. The bending test was performed by applying a transverse effort to the boom’s top extremity. The maximal bending moment before buckling was 8 N.m. This mechanical stiffness and resistance are deemed sufficient to withstand in-orbit loads after the deployment due to aerodynamic pressure and spacecraft spin.

![Fig. 7. Plastic deformation upon maximal bending stress](image1)

### 3. NEW ARCHITECTURES PROPOSALS

Thanks to the achievements done during the IDEAS project, several optimizations of the system have been identified. Based on the IDEAS building blocks, a study was performed in order to reach a better ballistic ratio ($S_{\text{deployed}} / M_{\text{system}}$) for SIDE and to integrate panel accommodation constraints.

One of the main aspects of the SIDE mechanical design is the modularity (see Fig. 8) and scalability of its main components so as to be easily accommodated on all types of spacecraft:

- The length of the boom can be extended up to 10 m in order to increase the deployed sail area if needed
- The number of sails attached to the boom can be increased (see Fig. 8)
- The attachment angle of each sail to the boom can be adapted to the spacecraft panel’s specificities
- The width of the sail can be extended up to 1.20 m. Its length is not limited.

![Fig. 8. SIDE modularity examples](image2)

Typically implemented on the +X panel, the stowed equipment height is around 300 mm. An accommodation on Y or Z panel can be easily envisaged.

With the feedback from the IDEAS design, possibilities of mass savings have been investigated:

- Simplification of the inflating subsystem by merging the inflating and the rigidization fluidic lines. The boom deployment and rigidization will be done in a single phase.
- HDRM re-design by introducing a second pyro-bolt and suppressing the strap and its locking mechanism.
- Review of heavy mechanical parts which can be optimized
From these mass optimizations two architectures have been defined which cover the mini-satellite category (100 kg -500 kg):

- A mono-boom architecture, called SIDE-1, with an 8-metre boom which provides an extra aerodynamic surface of 5.35 m² for a mass around 8 kg. This configuration is compatible with satellites up to 250 kg.
- A bi-booms architecture, called SIDE-2, with two 6.5-metre booms which provide an extra aerodynamic surface of 7 m² for a mass around 12 kg.

4. RE-ENTRY PERFORMANCES

Passive re-entry performances were assessed by Airbus Defence and Space for satellites on circular SSO orbits (typical inclination of 98.8°) between 700 and 800 km. The study was also limited to mini-satellites (100-500 kg) which likely do not exceed the specified limit of human casualties of 0.01% per uncontrolled re-entry. In this case, an uncontrolled de-orbit is permissible.

The performance evaluation was performed with the STELA software which is the reference tool used by CNES for re-entry duration. (See [2]). The used atmosphere model was the NRLMSISE-00. The main assumption used in the simulation was a constant mean solar activity (Flux F10.7 = 140). This assumption allowed to study cases of re-entry which were de-correlated from the solar activity and independent from the starting date. The spacecraft model was identical to the MICROSCOPE spacecraft (see Fig.1) with a minimal surface of 0.6 m², a maximal surface of 2.2 m² and a mean surface in tumbling configuration of 1.65 m². Relative attitude of the spacecraft re-entry was computed independently and re-injected in the STELA tool by hybridizing the drag coefficient file.

The Fig.9 shows the typical re-entry of a 250-kg spacecraft with SIDE-1. De-orbiting is done in 26 years instead of 126 years without SIDE system. Due to its overall geometry, the satellite will topple as soon as the aerodynamics drag will supersede the others forces involved in the spacecraft’s attitude stability. This flipping point shall be low enough (around 500-525 km) in order to finish the re-entry with a minimal aerodynamic surface in less than 25 years.

Both architectures were benchmarked with IDEAS and de-orbiting strategy using a high-thrust impulsive Hohmann-type manoeuvre that sent the spacecraft onto an elliptic orbit with a 25-year remaining lifetime. According to [1], this solution leads to a minimal ΔV requirement.
for satellites where an uncontrolled re-entry is admissible. [1] has also demonstrated that monopropellant thrusters seem to be the best trade-off taking into account availability, maturity level and performances. Fig.10 shows the domains for SIDE-1 (resp. SIDE-2) respecting the 25 years re-entry criterion. Two abacuses representing the de-orbiting performances of 7 kg (resp. 12 kg) have been added so as to compare the performances of SIDE to an equivalent mass of hydrazine.

Up to 750 km altitude, there is no real mass penalty to embark a SIDE-1 or SIDE-2 on a satellite with a monopropellant propulsion subsystem. Beyond this altitude, SIDE loses its efficiency in comparison to thrusters.

5. INFLATABLE DE-ORBITING SYSTEM

In order to be compliant with the coming legislations imposing a re-entry in less than 25 years, most of the spacecraft will likely propose to use the chemical propulsion subsystem for the post mission disposal (see [1]). The SIDE equipment offers anyway specific advantages which worth to be taken into consideration in the spacecraft design and mission.

5.1. Fail-Safe Deorbiting Subsystem

One major asset of the proposed de-orbiting subsystem in comparison with propulsion subsystems is the ability to perform post mission disposal on loss of the satellite. The SIDE can be linked to Hardware Watchdog (WD) which triggers the boom release and its inflation in case of a major failure (battery failure, OBC failure). No energy (except the pyro signals) is required to perform sail-boom deployment.

The subsystem is also efficient in case of attitude control loss (propulsion subsystem major failure, AOC equipment failure) and is more reliable than a braking thrust which requires full operability and is hazardous at EOL. The boom can also act as de-tumbling device by modifying the spacecraft inertia and can enable attitude stabilization (Earth communication, Sun direction) even if this will cause the re-entry to start earlier than expected. Finally SIDE provides a functional redundancy to the de-orbiting function done typically by the propulsion subsystem and improves re-entry reliability.
5.2. Hydrazine tank threshold effect and Mission life extension

As mentioned in §4, there is no mass penalty to embark a specific inflatable de-orbiting equipment aside a monopropellant propulsion subsystem. On one hand, by suppressing this hydrazine mass (around 30% of the volume), it could be possible to change the propellant tank to a smaller one (hence the so called “tank threshold effect”). The consequences are the following:

- Cost reduction
- Mass gain beyond the hydrazine mass
- Internal accommodation volume gain, opening new scale factor gains.

By taking into account the SIDE equipment at the very beginning of the design, a more compact satellite can be defined with unexpected mass gain.

On the other hand, SIDE is also a good solution to extend the spacecraft’s lifetime without changing its design (added hydrazine, tank size). The spared hydrazine is then dedicated to the operational life of the satellite instead of the re-entry. Typically 30% of the embedded hydrazine is used for reentry operation. This roughly corresponds to a 30% increase of lifetime.

5.3. Mixed re-entry strategies

At iso-architecture (hydrazine mass, satellite mass), the SIDE equipment opens the flight domain of the satellite to higher altitudes. A mixed reentry strategy consists of a first lowering of the perigee to an altitude where the SIDE system is efficient and then to deploy SIDE. The reentry will proceed nominally with the passive re-entry. Mixed re-entry strategies are consistent with a global optimization including hydrazine tank threshold effect.

As an example, a 250-kg satellite at 715 km needs 7 kg hydrazine to perform an uncontrolled reentry within 25 years by lowering its perigee to 496 km. By combining a braking manoeuvre to lower the perigee and then the deployment of a mono-boom SIDE-1, the satellite can start at 870 km:

- First decrease the perigee to 660 km with 7 kg of hydrazine
- Then deploy the aero-braking sail to finish the uncontrolled re-entry within less than 25 years

If the satellite performs reentry using thrusters only, it needs 14 kg of hydrazine to decrease the perigee down to 450 km.

5.4. Re-entry Operations Costs

A major advantage of SIDE in comparison with thrusters braking manoeuvre is the simplicity of the operations to be carried out.

The deployment sequence of SIDE can be triggered on a single TC “Fire & Forget” without parameter and its completion lasts less than 10 minutes, meaning that the whole process will be completed during a single ground station visibility window. Only a reduced OPS team is necessary to perform the re-entry.

On the contrary, transferring a spacecraft to an elliptical orbit with thrusters requires a lot of preparation, a complete OPS team and several ground stations visibilities. After the braking boost, the final orbit shall still be assessed with ground infrastructures. Finally the de-orbiting cost of the spacecraft with thrusters could exceed the cost of a SIDE system itself.

6. CONCLUSION

The technology of passive aero-braking re-entry developed by Airbus Defence & Space in the frame of IDEAS project funded by CNES has reached today a high level of maturity (TRL7/8) and shall be “mission proven” in 2017. By developing new architectures based on these building blocks, Airbus Defence & Space proposes lightweight, low cost deorbiting equipment for mini-satellites (100kg-500 kg), filling the requirements of space legislation which comes into effect in 2021.

Satellite inflatable deorbiting equipment seems to be a competitive alternative to thrusters for all mini-satellites up to 750 km altitude. The addition of a de-orbit function on a spacecraft has in most cases a significant effect on satellite design; SIDE appears to be a low cost, reliable and lightweight solution. Embarking SIDE aside a monopropellant propulsion subsystem can also be envisaged as it provides potential spacecraft design optimization such as tank size reduction and operation cost savings.

This study was intended to highlight also the functional advantages of SIDE and to provide a global overview of its performances (mass, re-entry duration) to the satellite architect in the early phase of spacecraft design. However the selection of SIDE will have to be made in case by case taking into account the spacecraft mass, its altitude and the space availability on external panels.

Acknowledgements


References


7. REFERENCES

References


Acknowledgements

The work presented in this paper was performed by Airbus Defence and Space and CNES in the frame of the IDEAS programme.
Progress in space safety lies in the acceptance of safety design and engineering as an integral part of the design and implementation process for new space systems. Safety must be seen as the principle design driver of utmost importance from the outset of the design process, which is only achieved through a culture change that moves all stakeholders toward front-end loaded safety concepts. Superb quality information for engineers, programme managers, suppliers and aerospace technologists.

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