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ORIGINAL PAPER

ADEO: the European commercial passive de-orbit subsystem family enabling space debris mitigation

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Abstract
The ADEO subsystem is a scalable drag augmentation device that uses the residual Earth atmosphere present in Low Earth Orbit (LEO) to passively de-orbit of satellites between 1 and 2000 kg. For the de-orbit maneuvre, a large surface is deployed which multiplies the drag effective surface of the satellite significantly. Thereby the drag force is increased as well causing accelerated decay in orbit altitude. Advantageous about a drag augmentation device is that it does not require any active steering and can be designed for passive attitude stabilization thereby making it applicable for non-operational, tumbling spacecrafts as well. The ADEO subsystem consists of four deployable booms that span four sail segments in a planar shaped configuration. While the sails are made of an aluminum-coated polyimide foil, its coating thickness was chosen such that it provides sufficient protection from the LEO space environment. The current activity commenced in August 2018 is going to provide a fully qualified Protoflight Model (PFM) for a follow-up "In Orbit Demonstration" (IOD) in 2021/2022 (ADEO is selected as payload on the European Commission IOD/IOV satellite programme). In May 2020, the team passed the Manufacturing Readiness Review (MRR). An extensive Breadboarding- and Engineering Model campaign including life tests had already been carried out in 2019. The first ADEO-L PFM consists of a 5 m x 5 m dragsail deployed under control of own onboard electronics. Optionally, ADEO-L systems can be equipped with a so-called "watchdog routine" inside the electronics which is able to recognize the point in time when the satellite has come to the end of its life circle. With the help of an on-board battery the sail will be deployed automatically after a certain time in orbit. Operating like this, ADEO-L can be truly called "100% passive", a "CleanGreen Space Mission". First commercial candidate missions to be targeted after the successful EC-IOD mission were already identified by Airbus DS (DE) and QinetiQ (BE).

Keywords Passive De-orbit · CleanGreen Space Mission · Dragsail · Cleanspace · Space Debris Mitigation · Reference Mission · Proto Flight Model

1 Introduction

The space debris environment especially in the low earth orbit (LEO) is an increasing risk for all spaceflight missions. Without effective mitigation measures the debris density will increase to a level where spaceflight as a whole becomes more and more endangered. Especially collision fragments larger than 1 cm will become a dominant part in the debris population. Therefore, to ensure safety for future space flight, end-of-life de-orbiting of satellites and upper stages becomes a necessity [1, 2].

For the de-orbiting of satellites in the low earth orbit, several concepts are applicable. At present, many spacecraft use an active thruster system for a controlled re-entry, which adds an undesired significant extra mass to the system because of the additional propellant and because of the need for a GNC system to ensure the force vector acts in the desired direction. The biggest disadvantage of an active thruster de-orbit system is that its end-of-life (EOL) propulsion system and the GNC need be still functional after about 10–15 years in orbit. In case of any malfunction, the de-orbiting will not take place.

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Therefore the future goal should definitely be the use of a passive and independent working system to ensure that a reliable de-orbit can still be performed also when the satellite unexpectedly goes out of function. In addition, a passive solution shall be concepted as such that it would add much less mass than extra propellant and associated extra satellite control systems.

And, still if one needs to use an active system a redundancy using a passive system should be considered to fully ensure the de-orbiting ambitions of future space missions.

The fully passive ADEO subsystem family presented here relies on the utilization of the natural drag decay in low earth orbit by increasing the drag area of the satellite at EOL.

Drag augmentation devices (sometimes referred to as "Dragsail") are using the residual earth atmosphere present in the low earth orbit [3]. For enabling the de-orbit manoeuvre, a large surface is deployed which increases the drag effective surface of the satellite. Thereby the drag force is increased as well causing accelerated decay in orbit altitude. Depending on the size of sail, the S/C mass and the initial altitude, the de-orbit time can be reduced by up to a factor of 10. Another advantageous about a drag augmentation device is that it does not require any active steering and can be designed for passive attitude stabilization. Thereby, it is also applicable for non-operational, tumbling spacecrafts. To accelerate the natural orbit decay the drag area can be increased without significantly increasing the mass of the satellite. It is therefore necessary to deploy a very lightweight dragsail at EOL of the satellite. This kind of structures is known as gossamer structures [4, 5]. Besides the ADEO dragsail subsystem some other concepts have been presented so far, such as in [13, 14]. In comparison to these systems, the ADEO dragsail family stands out against them and makes it unique for several reasons: First, the ADEO sail area is customizable to fit satellites and upper stages with a weight of up to 2000 tons and for initial orbital altitudes of up to 800–900 km for dragsail deployment. The sail area can easily be raised up to 100 m^2 and the interface to the S/C can also easily adapted without major design changes. Secondly, strong emphasis was placed on the material and subsystem selection, as well as the qualification investigations to have ADEO suitable for a wide range of S/C missions. Mission lifetimes of up to 15 years during which ADEO is on standby and in stowed configuration, and an additional lifetime of 25 years, beginning with the spacecraft's EoM (end-of-mission) where ADEO is deployed, can be realized. During the whole time system and materials withstand the harsh environmental conditions, such as the ATOX, UV and temperature environment.

To meet a broad range of consumer needs HPS GmbH developed three different classes of dragsail-based de-orbiting subsystems:

1.1 ADEO-N

Nano subsystem for cubesats and small satellites:

S/C mass:	10–100 kg
S/C orbital altitudes:	Up to 800 km
Volume (stowed condition):	100 × 100 × 60 mm (0.6 U)
Dragsail area:	1.5–5 m^2
Total mass:	below 1 kg

First ADEO-N ("NABEO—Pride of Bavaria") launched with the Rocket Lab Kickstage on November 11th 2018.

1.2 ADEO-M

Medium class: overlapping L- and N-class.

1.3 ADEO-L

Large subsystem for large satellites S/C mass:	100–2000 kg
S/C orbital altitudes:	Up to 800 km
Volume (stowed condition):	430 × 430 × 180 mm
Dragsail area:	25–100 m^2
Total mass (without battery):	9.3–13.5 kg

1.4 ADEO-N: ready for use

The first ADEO-N was launched as "Pride of Bavaria" in November 2018 with the Rocket Lab Mission called "It´s Business Time". The next pictures (Fig. 1) depict the launch system itself and flight pictures before the ADEO-N deployment. This first flight mission has been co-funded by the Bavarian Ministry of Economics.

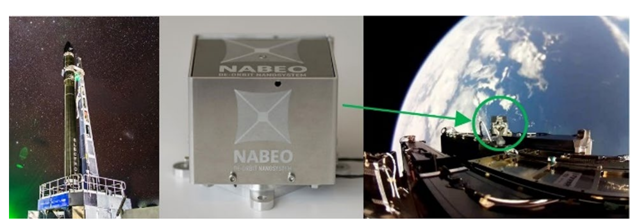

Fig. 1 middle & right picture: ADEO-N ("NABEO—Pride of Bavaria") with Rocket Labs mission "It´s Business Time" (left picture) (© HPS GmbH)

The ADEO-N subsystem was extensively tested and investigated in August 2019 during a parabolic flight with Novespace to enhance the subsystem (Fig. 2). It provided important data for the further optimisation of ADEO-N. This activity has been co-funded by the German Space Agency DLR.

2 ADEO- L: preparing for first misSION

2.1 ADEO- L general description

The following picture (*Fig. 3*) shows—as application example—the animated view of the deployed ADEO-L subsystem mounted on the 260 kg P200 platform of QinetiQ Space.

The next picture (*Fig. 4*) shows a view of the naked subsystem shortly after initiation of the deployment.

Fig. 3 Animated view of deployed ADEO-L, ©Platform P200 (QinetiQ Space), ©De-Orbit System (HPS GmbH)

2.2 Support structure (baseplate, top plate and I/F bracket)

The overall envelope volume of the subsystem is equal to 430 × 430 × 180 mm.

The ADEO-L subsystem design consists of two main plates representing the bottom and top part of the support structures for the deployment spools.

The base plate is an aluminium plate which serves as main I/F to the brackets connecting the subsystem to the satellite panel. All the different components of the subsystem are attached to the base plate. The interface hole pattern to the satellite consists of 8xM6 bolts (thread part is expected on the satellite side).

The top plate is an aluminium plate serves as the top interface for the main components of the subsystem.

2.3 HDRM

The Hold-Down-and-Release-Mechanism (HDRM) has the purpose to release all the launch locks of the ADEO once the deployment commences. The launch locks are locking the boom spool as well as the sail spools to ensure that no parts will move or rotate during launch or satellite operation.

The linear guide subassembly together with the HDRM subassembly are installed on the top plate and they are in charge of locking the spools during launch and storage time to ensure that the sail and the booms are not uncoiling prematurely.

For the HDRM, a top cover is installed with a compression spring and a screw connected to the release-nut of the mechanism. When the HDRM is triggered the top cover is pushed away from the top plate by the compression spring.

A release nut mechanism is considered for ADEO-L subsystem.

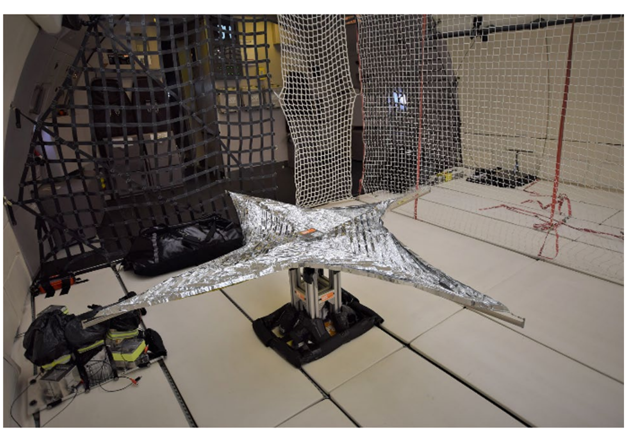

Fig. 2 ADEO-N during parabolic flight in August 2019 (© HPS GmbH)

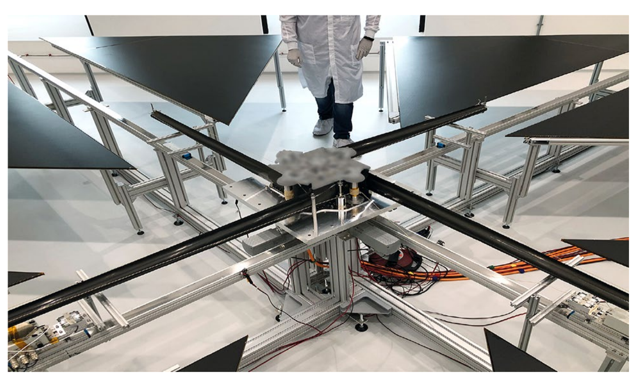

Fig. 4 ADEO-L Engineering Model during deployment testing in 2019 (© HPS GmbH)

2.4 Linear guide assembly

The linear guide assembly has a spring loaded pin that is used to adjust the total length of the assembly allowing preloading of the launch locks.

Once the top cover of the HDRM assembly is released, the eight linear guides (four for the sail spools and four for the boom spool) locking the sail and the boom spool are moving towards the centre of the subsystem releasing their respective locks.

The tolerances related to the dimensions affecting the functional performance of the linear guides have been carefully assessed including thermal expansion effects to ensure that there is always a minimum of clearance.

2.5 Boom deployer

Once the HDRM is released and all the spools are free to turn, a motor will be activated to pull out the boom through the boom guide over a boom belt. One boom belt is used for all four booms (verified by an Engineering Model).

2.6 Deployed sail configuration

The deployment of the sails is driven by the deployment by the booms. The deployed configuration is visualised in next figure (Fig. 5). The deployed booms of the nominal ADEO-L have a length of approximately 3.7 m, forming a squared area divided in four triangle sectors where the four drag sail segments are extended. The side length of the square is 5 m. The sails are equipped with crack stoppers, mitigating the risk for a large hole due to a small space debris impact.

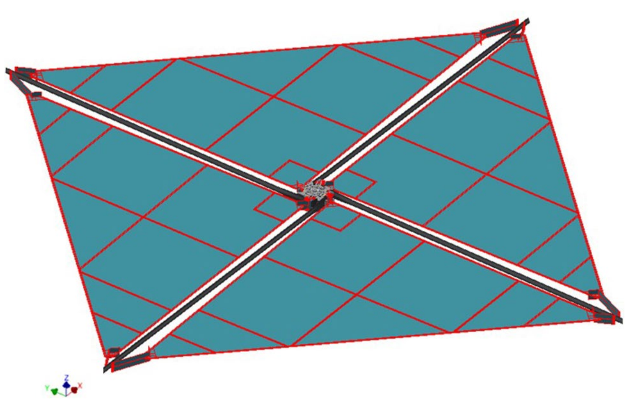

Fig. 5 ADEO-L Deployed configuration with crackstoppers

3 Subsystem analysis

3.1 Mechanical analysis

A full set of analysis have been performed including modal analysis, quasi-static analysis, random vibration analysis and shock analysis to demonstrate the structural integrity of the subsystem. All strength margins of safety are positive, the first natural frequency of the subsystem is > 140 Hz.

3.2 Thermal analysis

A thermal analysis has been performed for the ADEO-L deorbiting subsystem. The study focuses on the prediction of the maximum and minimum temperatures obtained during the sub-system lifetime, considering different passive thermal protections. Aging effects were taken into account for the thermo-optical properties of the model in the analysis. Two different configurations were evaluated: the stowed and the deployed.

The analysis of the stowed configuration showed that the colder temperatures in the main structural and functional components are obtained when ADEO-L is completely shadowed by the S/C and protected by aluminium plates with white paint coating, reaching the coldest temperature at altitudes of 800 km. The hottest temperatures were obtained when the de-orbiting system is covered by clean aluminium plates, as expected.

The temperature distribution in the main structural and functional components when protecting ADEO-L with MLI (Multi-Layer-Insulation) showed the lowest difference between the maximum and minimum temperatures reached within the considered load case.

4 ADEO-L verification

4.1 Overall verification approach

The life testing of the hardware has been carried out in 2019 on Engineering Model (EM) level (called "breadboard" within the project), with which already many qualification tests have been performed (Fig. 6).

The ADEO-L development was guided by the following strategy:

(1) Critical assemblies (critical for life) were defined in preliminary design
(2) Critical assemblies brought to detailed design state already for PDR (Preliminary Design Review)

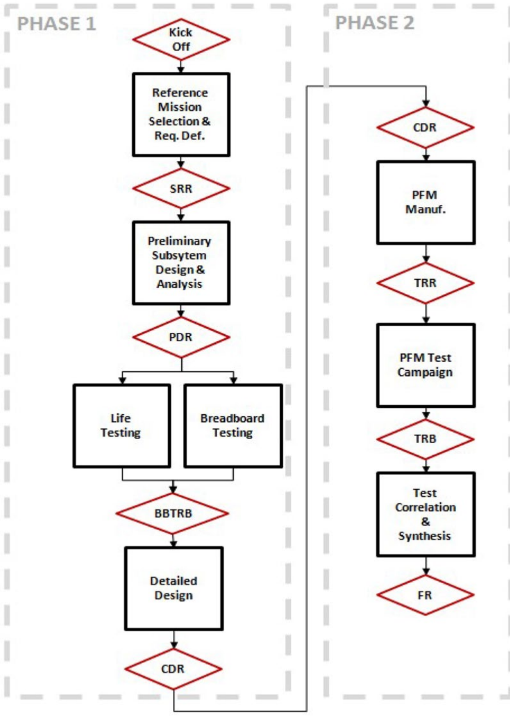

Fig. 6 Project ADEO-L development flow chart

(3) Manufacturing and confidence life test on these critical assemblies parallel to EM test. The extensive Life Test Campaign mainly included (2019): Full deployment tests under ambient environment, vibration tests, thermal cycling tests, partly deployment tests under thermal vacuum in cold and hot conditions and functional tests.
(4) Detailed design (implementation of design changes according to improvement potential identified during the EM life test)
(5) CDR (Critical Design Review) and Kick off of Phase 2 with manufacturing of PFM (May 2020)
(6) PFM test campaign
(7) Test correlation, PFM refurbishment and packing/storage

4.2 Confidence life test models

The following components have been considered as most critical items in the ADEO-L design:

- Boom Deployer
- HDRM
- Sail

According to ECSS-E-ST-33-01C, the life test factors are for ground testing 4 and for in-orbit 10. On the

Test	Condition	No of PFM Test	Applied Factors [AD5]	No of Life Test
Booms Rolling/unrolling	on ground, ambient	1 x (only booms)	4x	4x
Full Deployment	on ground, ambient	2 x	4 x	8x
Vibration	On ground, ambient	1 x	Qual. + Accept.	1x
TVAC Cycling	On ground, TVAC	1 x	Qual.	1x
Venting*	On ground, TVAC	1 x	N/A	N/A
Part. Deployment	on ground, TVAC	1 x	4 x	14 x
Orbit Deployment	In orbit, TVAC	1 x	10 x	
Functionality Tests	On ground, ambient	5 x	4 x	20 x

Fig. 7 Confidence Life Test Requirements

mechanisms, only the following tests have been deemed necessary to be considered in specific separate life tests (Fig. 7):

A venting test is not considered necessary for confidence life tests as during previous development activities ("ADEO-1" & "Deployable Membrane" both performed between 2014 and 2017), venting (rapid decompression) did not show any impact on performance of demonstrators.

In September and October 2019, the confidence life test model campaign was carried out at DLR Bremen including ambient deployments, TVAC cycling, vibration and TVAC deployments. Additional extensive material analysis and test programs were accomplished to ensure the quality as well as to conclude on possible effects of manufacturing, such as folding effects on ATOX resistance of the sail. The following images (Fig. 8 and Fig. 9) shall give some impressions from the tests.

Fig. 8 Boom Spool Deployer Ambient Deployment (© HPS GmbH)

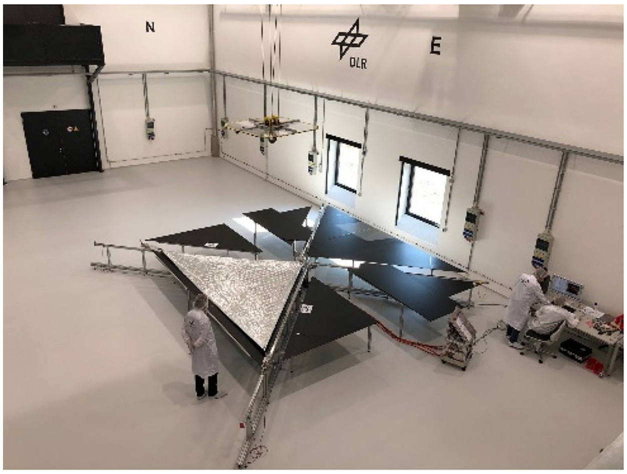

Fig. 9 Sail Ambient Deployment (© HPS GmbH)

No	Test /Activity	Description
1	**FULL DEPLOYMENT IN AMBIENT**	One time full deployment
2	Packing and Inspection	Packing of PFM and readying for following test including rotation test of spools
3	**TVAC CYCLING**	4 Cycles, based on requirements [RD1]
4	Functionality Test	*
5	**VIBRATION TEST**	Sine & Random, based on requirements [RD1]
6	Functionality Test	*
7	**VENTING**	Profile, based on requirements [RD1]
8	Functionality Test	*
9	**TVAC (partial) DEPLOYMENT**	One time partial deployment, based on requirements [RD1]. One thermal cycle to be carried out before start of deployment.
10	Packing and Inspection	Packing of PFM and readying for following test including rotation test of spools
11	**FULL DEPLOYMENT IN AMBIENT**	One time full deployment
12	Packing and Inspection	Packing of PFM and readying for PFM flight including rotation test of spools

Fig. 10 ADEO-L PFM Test Campaign

4.3 Test plan for first ADEO-L PFM

The following table (Fig. 10) shows the ADEO-L PFM test campaign.

5 ADEO-L: in orbit demonstration & ready for orders

In April 2018, the European Commission issued a call for Expression of Interest IOD/IOV Experiments. A total of 57 applications were received and evaluated by independent EC and ESA reviewers, which led to the final pre-selection done during the Central Phase Analysis. As a result, 39 applications have been “retained globally” to undergo feasibility studies. Thirty of the retained applications were identified as being suitable for the first IOV/IOD-mission, expected in 2021/2022 (“i.e., experiment FM to be available in 2020”), including the ADEO-L PFM.

Iterations with the mission prime (still to be selected by ESA) are expected to start in Q3/2020. After the ADEO-L PFM test campaign, the PFM will be refurbished, potential adaptations to the satellite needs will be implemented in 2021.

Despite the fact that ADEO-L can state a TRL 8 only by December 2020, the ADEO-L is ready to order for further LEO missions. Typically Phase B2-studies are targeted for the harmonisation of interfaces to the satellite or even for adaptation for sail size needs.

Two cases are planned:

“Recurring ADEO-L” (based on same design as of ADEO-L PFM), delivery time 12 months, to be reduced to 6 months in the next years,

“Scaled ADEO-L”, which leads to an ADEO-M or an ADEO-XL model (delivery time 24 months).

6 Conclusions

The paper at hand shows that a de-orbiting subsystem like the ADEO dragsail-family, developed by HPS and partners since 2014, can be a very reliable and cost efficient way to ensure a quick de-orbit time. A de-orbiting device like ADEO as integral part of the spacecraft from the beginning can be a solution for any system below 800 km orbit that otherwise would have to call for an extra cleaning mission by some space debris pickup service at the end of operational lifetime.

Past developments under contract to ESA, like the ADEO-1 demonstrator activity or the Deployable Membrane material study as well as the de-risk activity ADDA (showing that de-orbiting via dragsail is possible using a dynamic analysis approach), increased greatly the TRL of the subsystem as well as the confidence in it.

The currently ongoing ADEO-L PFM activity is incorporating all the knowledge gained in the previous activities leading to TRL 8 by end 2020.

It is foreseen that the ADEO-L subsystem will reach TRL 9 through an In-Orbit Demonstration mission in 2021/2022.

For first commercial flights, the technology is ready to be implemented, recurring products or tailored ADEO-subsystem are ready for orders.

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