High Performance Space Structure Systems GmbH

ADEO-N – Deployable Passive De-Orbit Sail Subsystem Enabling Space Debris Mitigation for CubeSats, SmallSats and Constellations

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ABSTRACT:

The ADEO-N subsystem is the smallest of a scalable drag augmentation device family ADEO that uses the residual Earth atmosphere present in Low Earth Orbit (LEO) to passively de-orbit small satellites. For the de-orbit manoeuvre a large surface is deployed which multiplies the drag effective area of the satellite significantly. Thereby the drag force is increased, causing accelerated decay in orbit altitude. An advantage of a drag augmentation device compared to other de-orbit methods is, that it does not require any active steering and can be designed for passive attitude stabilization thereby making it applicable for non-operational and non-stabilized spacecrafts as well. The ADEO-N subsystem consists of four deployable booms that span a sail in a planar shaped configuration. While the sail is made of an aluminium coated polyimide foil. Its coating thickness was chosen such that it provides sufficient protection from the LEO space environment. ADEO-N was qualified in the first half of 2021 and was launched in a 3.6 m^2 drag sail configuration on 30th of June 2021 on D-Orbit's "Dauntless David" ION Satellite Carrier for its "In Orbit Demonstration" (IOD). The in-orbit deployment of the ADEO-N drag sail is planned for end of 2021, beginning of 2022, and will accelerate the orbit degradation of the ION Satellite Carrier in the following months.

1. INTRODUCTION

The space debris environment especially in the low earth orbit (LEO) is an increasing risk for all spaceflight missions. Furthermore, mega constellations, currently under construction or planned, will increase the overall density of objects in LEO. Without effective mitigation measures the debris density will increase to a level where spaceflight as a whole becomes more and more endangered and might even be denied for certain altitudes when no effective solution will be introduced in the next years. Especially collision fragments larger than 1 cm will become a dominant part in the debris population. Therefore, to ensure safety for future space flight, efficient end-of-life de-orbiting of satellites and upper stages becomes inevitable (ESA [1] and ESA [2]). It is however likely that in future the de-orbit must be ensured in significantly less time than 25 years in order to preserve an orbit environment that allows space flight. Current considerations assume that a target of less than 5 years will be necessary.

For the de-orbiting of objects in LEO, such as satellites or rocket bodies, several concepts are applicable. The most evident and economical one is passive de-orbiting, which means to let the orbit of the object decay naturally after the End-of-Mission (EOM) until re-entry, which limits the orbit height for the mission to comply with reasonable de-orbiting times. One alternative is an active de-orbiting measure. At present, many spacecrafts use an active thruster system for a controlled re-entry, which adds an undesired significant extra mass and sometimes complexity to the system, because of the additional propellant and the need for a Guidance, Navigation and Control (GNC) system to ensure the force vector acts in the desired direction during the deorbit manoeuvre. The additional mass and complexity do not serve the initial mission of the spacecraft. The biggest disadvantage of an active thruster de-orbit system is that its End-of-life (EOL) propulsion system and the GNC need to be still functional after EOM up to about 10-15 years in orbit. In case of any malfunction the de-orbiting will not take place in the prescribed time.

A promising future design goal for mitigation could likely be the use of a passive and independent working system to ensure that a reliable de-orbit can still be performed even when the satellite unexpectedly malfunctions. In addition, a passive solution can be concepted as such that it is lighter in mass than extra propellant and less complex than associated extra satellite control systems.
Also, if an active system is required by a certain mission, a redundancy by using a passive system could be considered in order to fully ensure the de-orbiting ambitions of future space missions or accelerate the re-entry into the atmosphere.

Drag augmentation devices (also referred to as “Drag Sail”) are using the residual earth atmosphere present in LEOs (Vincent et al. [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 advantage of a drag augmentation device is that it does not require any active steering and can be designed for passive attitude stabilization. In order to accelerate the natural orbit decay, the drag area can be increased without significantly increasing the mass of the satellite. For doing so it is necessary to deploy a very light-weight drag sail at EOL of the satellite. This kind of structures are known as gossamer structures (Seefeldt et al. [4], Seefeldt [5]).

In Germany the development of space sail systems has a history of more than 20 years. During that time mainly, the R&D sector of the German Aerospace Center (DLR) carried out technical developments. But also HPS is researching and developing sail technologies since this time. These past developments had a strong focus on solar sailing. In the 1990s, first solar sail breadboards were tested using a 20 m × 20 m sail in a joint DLR, NASA/JPL and ESA project, followed by several development and study projects like ODISSEE (Leipold et al. [6]) and GEOSAIL (Agnolon [7]). The ground demonstration is presented in Leipold et al. [8] and the study activities are summarized in Leipold et al. [9]. The German Aerospace Center has then continued such developments in the Gossamer-1 [4] and GoSolAr (Sproewitz et al. [10]) projects, which also focused on solar array applications. In addition, developments in the CubeSat field appeared. In 2010 a deployment mechanism for a CubeSat drag sail was developed on bread board level (Seefeldt [11], Seefeldt et al. [12]). The development was then continued by the student group Space Sailors, that finally demonstrated the drag sail deployment successfully on the Rocket Experiments for University Students (REXUS) 14 sounding rocket. The drag sail mechanism and the test of the sounding rocket is presented in Wolff et al. [13] and the deployment strategy is shown in Figure 1 and the deployment is shown in Figure 2. Within the ESA funded ADEO activities the known and developed technology was industrialized resulting in the ADEO product portfolio of the HPS GmbH (see Stelzl [14]) and in the here presented ADEO-N sail. Besides the ADEO drag sail subsystems some other concepts have been recently presented in the field, such as in Taylor et al. [15] and Palla et al. [16].

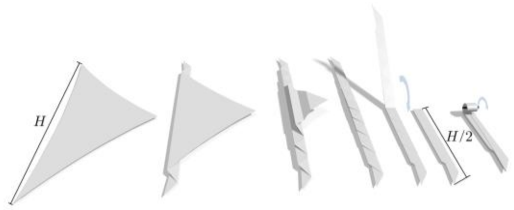

Figure 1: Stowing by zig-zag folding parallel to the hypotenuse of the sail segment.

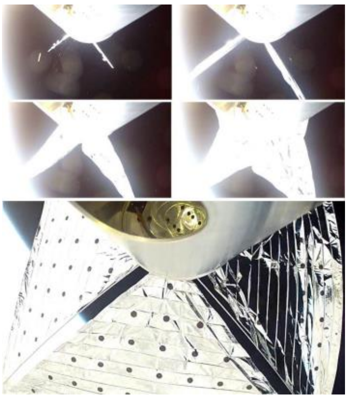

Figure 2: Deployment of the Space Sailors drag sail on a REXUS sounding rocket in 2013.

The fully passive ADEO-N subsystem presented here, which is the smallest version in the ADEO family, relies on the utilization of the natural drag decay in low earth orbit by increasing the drag area of the satellite at EOL.

In comparison to other systems the ADEO drag sail family stands out against them and makes it unique for several reasons: First, the ADEO sail area is customizable in order to fit satellites and upper stages with a weight of up to several hundred kilograms and for initial orbital altitudes of up to 800 km for drag sail deployment. The sail area can be raised up to 100 m² and the interface to the S/C can also easily be adapted without major design changes. ADEO-N, as smallest version of the ADEO family, is designed for sail sizes between 1.5m²-5.0m². 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 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.

2. ADEO-N: PREVIOUS MISSIONS

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 (*Figure 3*) 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.

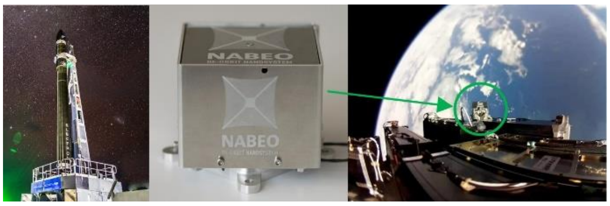

Figure 3: middle & right picture: ADEO-N ("NABEO – Pride of Bavaria") with Rocket Labs mission "It´s Business Time" (left picture) (© HPS GmbH)

The ADEO-N subsystem was extensively tested and investigated in August 2019 during a parabolic flight with Novespace in order to enhance the subsystem (*Figure 4*). It provided important data for the next generation of ADEO-N. This activity has been co-funded by the German Space Agency DLR.

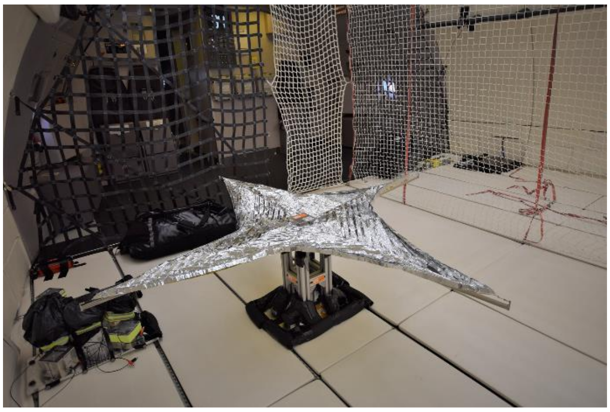

Figure 4: ADEO-N during parabolic flight in August 2019 (© HPS GmbH)

3. ADEO-N GENERAL DISCRIPTION

ADEO-N2 is designed to fit the 1U CubeSat envelope, meaning the overall size is 100 x 100 x 100 mm, consisting of mechanical interface at the bottom, CubeSat shells on the sides and a top plate. Figure 6 shows ADEO-N2 on the shaker table during the vibration test in stowed configuration.

Stowing and Deployment Strategy

While for the Space Sailors design and also for the other ADEO designs a combination of folding and coiling was used a more complex folding strategy was perused for ADEO-N, to allow stowage of a sail with up to 5 m². In contrast to the space sailors design the sail is not split into segments. An overview about different stowing and deployment strategies of our developments is given in Seefeldt [17].

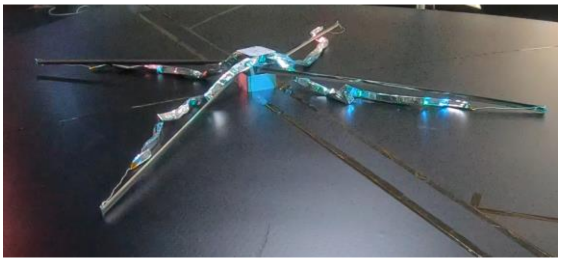

Figure 5: ADEO-N2 PFM with partially folded sail.

Support Structure (Baseplate, Top-Plate, Shells)

The aluminium baseplate of ADEO-N2 serves as mechanical I/F to the S/C. It is designed to be interchangeable to allow tailored solutions for the S/C need. One main aspect of the IOD/IOV mission is, that ADEO will remain mechanical connected to the S/C and will not be released into orbit by the S/C. The electrical I/F for the deployment activation of the sail is a single cable, which can be adapted in length and with a connector. Therefore, the design allows for a flexible adaption for different satellites.
For ADEO-N2 the interface is located at the bottom of the Cube. The aluminium shells are connected to the baseplate. Together with the baseplate these parts are non-moveable throughout the deployment of the sail, which allows to place ADEO-N within a S/C's structural perimeter or next to other cubes or structures.
The aluminium top plate covers the sail and its deployment mechanism moves upwards during the deployment.

HDRM & Deployment Mechanism

The Hold-Down-and-Release-Mechanism (HDRM) serves as launch lock, securing all movable parts of ADEO-N2 during on-ground handling, integration, launch and the mission of the satellite.
During the deployment the HDRM unlocks these parts and thereby allows the Deployment Mechanism (DM) to move the booms, the sail and the top plate upwards, out of the 1U envelope.

Boom Deployer

Similar to the Space Sailors design (see Wolff et al. [18]) ADEO-N makes use of steel tapes that are stable in end position. These tapes can easily be coiled. An enhancement is however that the deployment is additionally driven by a mainspring.

Once the sail and the booms are above the edge of the shells, the 1.5 m booms deploy perpendicular to the upwards direction and unfold the, in case of ADEO-N2, 3.6 m² sail.

Deployed Configuration

Once the EOL of the S/C is reached, the de-orbiting stage begins and the sail of ADEO is deployed. This is done as described in the previous paragraphs. The HDRM is unlocked, releasing the DM which pushes the boom deployer and the sail upwards, out of the cube. Once the DM is in its extended position, the booms are deployed, unfolding the sail. Figure 8 shows ADEO-N2 PFM in deployed configuration during the test campaign at DLR Bremen.

3.2 ADEO-N2 TEST CAMPAIGN

The test campaign was carried out together with DLR's Institute of Space Systems in Bremen. In different precursor projects DLR established test strategies for very unique and specialised space hardware (see Seefeldt et al. [19]). Especially for membrane spacecraft structures such as ADEO-N a "test as you fly" philosophy was beneficial, meaning the sequence of tests is such that it corresponds to the IOD/IOV mission profile as close as possible.
The test loads and levels were derived from reference missions and the IOD/IOV mission, qualifying ADEO-N2 not only for one specific launcher but all common launch vehicles.
Two models of ADEO-N2 were under test to allow qualification for the IOD/IOV flight, a Proto Flight Model and a Spare Model. Table 1 shows the sequence of the test program for the Proto Flight Model. With the Spare Model, a shock test was performed with corresponding ambient deployment tests before and after.
Figure 6 shows ADEO-N2 PFM in stowed configuration during the vibration test, mounted on an adapter plate, Figure 7 is a picture taken in thermal vacuum in DLR's Space Simulation Chamber right after the deployment test in hot thermal vacuum, and Figure 8 shows the Proto Flight Model after a deployment test in ambient, with fully deployed booms and stretched sail, ready for inspection.

Table 1: ADEO-N2 Test Program for Proto Flight Model

No	Test /Activity
1	Inspection
2	Grounding Test
3	DEPLOYMENT IN AMBIENT
4	Inspection and Resetting
5	VIBRATION TEST
6	Inspection and Grounding Test
7	DEPLOYMENT IN AMBIENT
8	Inspection and Resetting
9	Grounding Test
10	TVAC CYCLING
11	TVAC DEPLOYMENT (HOT)
12	Inspection and resetting
13	Grounding Test
14	TVAC DEPLOYMENT (COLD)
15	Inspection and resetting
16	Grounding Test
17	DEPLOYMENT IN AMBIENT
18	Inspection, resetting & packing

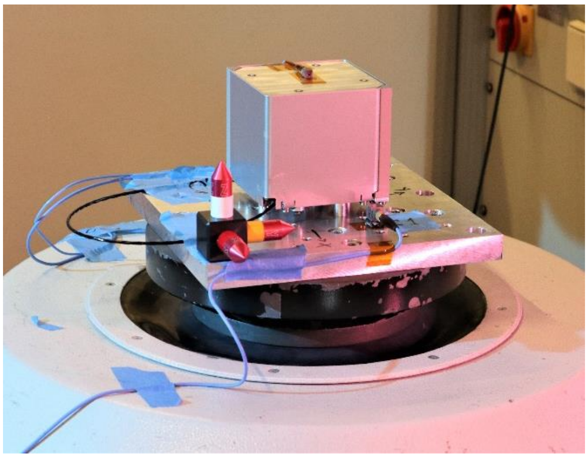

Figure 6: ADEO-N2 Proto Flight Model during vibration test at DLR.

Figure 7: Thermal-vacuum deployment (hot case 70°C). The picture shows ADEO-N just after a successful deployment under thermal-vacuum conditions in DLR's Space Simulation Chamber. Note, that a full deployment without gravity compensation and within the chamber is not possible.

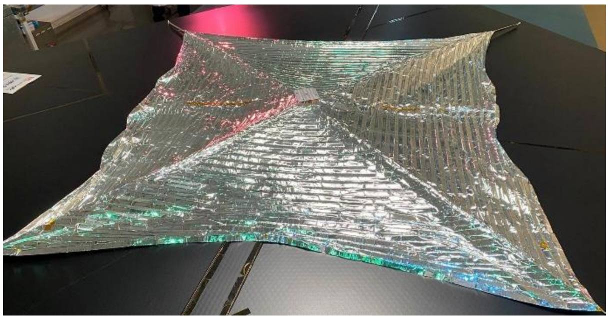

Figure 8: ADEO-N2 PFM after ambient deployment test in DLR's Integration Laboratory (ISO8).

4. IOD/IOV MISSION

4.1 D-ORBIT'S ION SCV "DAUNTLESS DAVID"

The ION SCV 003 satellite is a free-flying CubeSat deployer and propulsive platform for technology demonstration. The predecessor was ION SCV 002 "Laurentius" and D-Orbit is already preparing the next mission with ION SCV 004, "DASHING THROUGH THE STARTS" which is planned for the last quarter of 2021.

Figure 9 shows an artist's impression of ION in orbit during CubeSat deployment.

The name of the satellite carrier is "ION SCV Dauntless David", a combination of the acronym "ION", which stands for "InOrbit NOW", the acronym "SCV," which stands for "Space Carrier Vessel," and the satellite's first name. This format follows the naming conventions of naval vessels used in navies around the World. The name "Davide," translated into its Latin equivalent, was drawn at random from a bowl containing the names of all D-Orbit's employees. The company will continue to follow this procedure in the future to honour the skills, energy, passion, and commitment of its people.

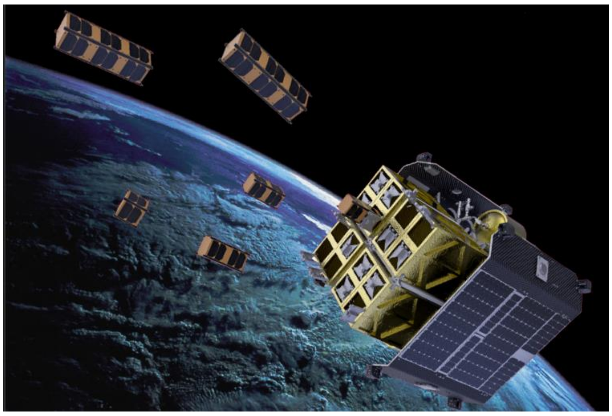

Figure 9: Artist's impression of D-Orbit's ION SCV "Dauntless David" in orbit during CubeSat deployment

4.2 MISSION OVERVIEW "WILD RIDE"

ION Satellite Carrier lifted off on June 30th, 2021, at 9.31 pm CEST, atop a SpaceX Falcon9 rocket from the Space Launch Complex 40 at Cape Canaveral Space Force Station, Florida. On the same day, 60 minutes after lift-off, the vehicle was successfully deployed into a 500 km sun synchronous orbit.
Over the course of the WILD RIDE Mission, ION SCV Dauntless David will deploy six satellites into distinct orbits and perform the in-orbit demonstration of 12 hosted payloads. The mission serves clients from 14 different nationalities and brings the total number of payloads launched by D-Orbit up to 63.
The mission manifest includes international clients like the Spanish Elecnor Deimos, the Bulgarian EnduroSat, and the Kuwaiti Orbital Space, which will launch the country's first radio amateur satellite. Also on board, under contract with ISILAUNCH and integrated into a QuadPack from Dutch satellite manufacturer ISISPACE, are Finnish Reaktor Space, Marshall Intech Technology from UAE, and the Royal Thai Airforce.
The mission will go through four phases: satellite deployment, in-orbit demonstration of the payloads hosted onboard, testing of D-Orbit's advanced services, and decommissioning.

Deployment Phase

During the deployment phase, ION will deploy each satellite into a distinct orbit. The release of the six satellites onboard will follow a highly customized plan that defines the moment of release, and the direction and speed of ejection of each spacecraft.

In-Orbit Demonstration Phase

During the in-orbit demonstration phase, ION will operate LaserCube, by the Italian Stellar Project, a payload hosted onboard through an innovative plug-and-play system that streamlines the integration of instruments and experiments developed independently by third parties.

Testing of D-Orbit's Advanced Services

The third phase will be focused on testing Nebula, a payload at the core of D-Orbit's upcoming advanced services. The first iteration of Nebula, an on-demand, on-orbit cloud computing and data storage service being developed by D-Orbit UK, features Unibap's SpaceCloud iX5-100 radiation tolerant computing module. A range of innovative applications will be demonstrated using sophisticated, artificial intelligence/machine learning (AI/ML) techniques; some of these experiments will feature video compressing techniques from industry specialist V-Nova. Another Machine Learning payload, called "Worldfloods" and developed by the Frontier Development Lab has the ability to identify flooding and send down a flood map to emergency responders seconds after image acquisition.

Decommissioning

During the fourth and final phase, decommissioning, D-Orbit's operations team will deploy ADEO-N2.

The mission will also feature a SETI (Search for Extra-terrestrial Intelligence) experiment in collaboration with media artist Daniela de Paulis and INAF (Istituto Nazionale di Astrofisica). The experiment, which investigates the possibility to communicate with other kinds of life in the universe, consists in the transmission of simulated alien messages to be received and decoded by radio telescopes worldwide.
The entire mission, including operations on payloads, will be managed by D-Orbit's mission controllers through AURORA, the company's proprietary cloud-based mission control software suite that enables satellite operators to manage and control multiple payloads simultaneously, from any location in the World, saving all the expenses connected with software design, development, testing, deployment, and maintenance.

4.3 IOD

The first part of the mission for ADEO-N2 in orbit is

to demonstrate its sail deployment after sustaining the launch loads and the on-board storage in LEO. During the in-orbit operation phase, or stowage phase, ADEO-N2 is fixed inside a CubeSat deployer on board the ION spacecraft. As a final step before the deployment of ADEO, the CubeSat deployer allows the subsystem to move out of the spacecraft but remaining attached to it.
When ADEO-N2 is outside of the spacecraft envelope, the sail deployment is initiated.
The IOD for ADEO will be successful with the deployment of the sail. The ION spacecraft carries as standard 8 cameras on board and with successful deployment pictures and or videos of the deployed subsystem are planned. They will hopefully soon be available for the public.

4.4 IOV

The second part of the mission for ADEO-N2, during the decommissioning phase of ION, is the verification of its capability to accelerate the deorbiting of the spacecraft. During this phase the S/C will not be stabilized to simulate the behaviour of a “dead” spacecraft. Only for a few communication events the spacecraft will be stabilized, to allow transmission.
The orbital decay of the spacecraft will be tracked and continuously compared to simulation data. On the one hand simulation together with data from other missions allows to verify the accelerated deorbiting profile, on the other hand the data from this mission allows to refine simulations for future missions.
For “Dauntless David” a reduction of the time to deorbit by almost half with the deployment of ADEO-N2 is expected.

5. CONCLUSION

After more than 20 years of research and development the cooperation of DLR research facilities and HPS allowed a first step in the industrialisation of space sails for de-orbit systems.

With ADEO-N2 already in space and waiting for deployment the first hardware is about to reach TRL 9. With the following ADEO-L test campaign scheduled for the beginning of next year also the first bigger sail reaches TRL 8 and is then supposed to fly on another IOD/IOV mission with the launch planned in 2024.

Furthermore, HPS and DLR started further activities to enhance the sail design and reliability. One specific goal of the follow-on activities is to enhance the drag sail family to allow tailored solutions for each customer and to overall upgrade and improve the existing products with new materials and solutions.

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