VERIFICATION AND DEMONSTRATION RESULTS OF ADEO DRAG SAIL SUBSYSTEMS

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ABSTRACT

The growing emphasis on deorbiting regulations has driven the need for reliable post-mission disposal solutions. HPS has developed the ADEO family of drag sails, which passively decelerate satellites for deorbiting using atmospheric drag in LEO. The ADEO system ranges from the compact 1.7 m² ADEO-P to the large 25 m² ADEO-L for diverse missions.

Notably, the ADEO-N2, deployed on D-Orbit's ION Satellite Carrier in 2022, provided critical flight data, validating ADEO's effectiveness. In December 2023, the ADEO-L completed its qualification campaign. Results from onboard telemetry and imaging confirm robust performance, supporting Zero Debris compliance.

Beyond deorbiting, ADEO shows potential for space debris detection. This paper presents in-flight performance, deployment dynamics, and lessons learned, contributing to the advancement of sustainable space operations and global space debris mitigation efforts.

1 INTRODUCTION

The current space debris environment poses a significant safety risk to operational spacecraft. In recent years, the number of satellites launched into Low Earth Orbit (LEO) has increased exponentially, driven by the growing interest in mega-constellations and the affordability of small satellites. This trend is expected to continue in the coming decades, raising the likelihood of collisions and emphasizing the need for effective deorbiting technologies.

Passive deorbit technologies share the key advantage of functioning independently of an operational spacecraft. This means they do not rely on an active propulsion system or guidance, navigation, and control (GNC) for deorbiting. Such systems are particularly beneficial for micro and small satellites that lack propulsion while also meeting casualty risk requirements. By using passive deorbiting solutions, these satellites do not need for a dedicated propulsion system to achieve controlled re-entry.

Additionally, small and medium satellites equipped with active propulsion may benefit from an autonomous "emergency" passive deorbit system to mitigate failure scenarios.

Drag augmentation devices, also known as dragsails, leverage the residual atmospheric drag present in LEO [1]. When deployed, the sail expands the satellite's effective drag surface, accelerating orbital decay. This system is inherently reliable and fully passive, requiring no active steering once the dragsail is deployed.

2 ADEO CONCEPT AND PRODUCT FAMILY

The Drag Augmentation Deorbiting System (ADEO) is a scalable deployable dragsail developed by High Performance Space Structure Systems (HPS) during different governmental funded and commercial programs. It can be applied in case of a satellite as the primary deorbit solution to reduce the deorbit time after end-of-business to less than 5 years, but could also be used as a backup solution to deorbit a dead satellite.

By using the ADEO dragsail, the area of the spacecraft will be increased. However, collisions with the sail material do not have any significant effect, and due to the shorter disposal phase, the overall collision risk is even reduced.

The product family includes various configurations of the ADEO sail: the ADEO-N series is designed for small satellite missions of 20-250 kg, while the ADEO-M and ADEO-L target larger satellites, 100-700 kg and 500-1500 kg. The ADEO-N series corresponds to sail sizes of 5±2 m^2, while ADEO-M covers areas within 15±5 m^2. Smaller versions are available as well for picosatellites (ADEO-P) with a sail size of 1.7 m², and CubeSats (ADEO-C) in particular with 3.4 m² sail, and with the option to configure the sail size according to customer needs.

The ADEO systems are designed to survive the harsh environmental conditions in space, including the UV, ATOX, and temperature environment.

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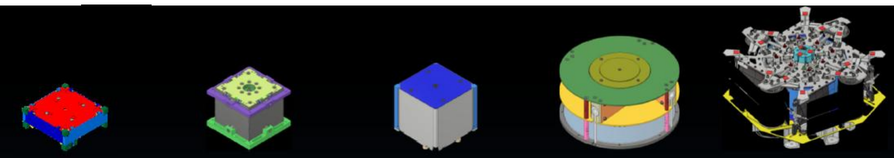

	ADEO-P(ico)	ADEO-C(ube)	ADEO-N(ano)	ADEO-M(edium)	ADEO-L(arge)
Satellite Masses	1 - 20 kg	5 - 50 kg	20 - 250 kg	100 - 700 kg	500 - 1.500 kg
ADEO Module Mass	0.45 kg	0.8 kg	0.8 kg	4.5 kg	9.5 kg
ADEO Module Size (stowed)	10 x 10 x 3.9 cm³	9.5 x 9.5 x 7.2 cm³	10 x 10 x 10 cm³	Diameter 29 cm Height 13.4 cm	40.6 x 40.6 x 26 cm³
Sail Area	1.7 m²	3.4 m²	5.0 m²	15 m²	25 m²
Deployment Mechanism	Spring-based	Spring-based	Spring-based	Controlled continuous deploym. with spring	Electrical motor
Activation System	Pyro Cutter	Pyro Cutter	Pyro Cutter	Pyro Cutter	Release Nut
Mechanical Interface	4 x M4 through holes Ø4,3 mm	CubeSat Standard	4 x M5 thread (diam. 8.2 cm)	8 x M6 thread (diam. 27.5 cm)	8 x 7.0 mm hole (diam. 28/29 cm)
Electrical Interface	2 Wires (free ends)	4 Wires (free ends)	2 Wires (free ends)	4 Wires (free ends)	3 Connectors D-Sub HD15, RS-422
Electrical Power	12V @1A – 10 msec	>1V @3A - 25 msec	12V @1A – 10 msec	>1V @3A - 25 msec	24-38 V

Figure 1: ADEO Product Family

3 ADEO-N2 MISSION

3.1 The Mission

The goal the ADEO-N2 IOD mission was to demonstrate and verify the functionality of ADEO-N (1U envelope, 3.6 m² sail, about 800 g) in orbit and thus, reach TRL 9. The mission ADEO-N2 is a part of the S/C mission Wild Ride of the S/C ION-SCV003 by D-Orbit, named Dauntless David, on which the ADEO-N2 PFM is mounted (Figure 2, Figure 3). The spacecraft was launched with the Transporter-2 mission (SpaceX Falcon 9).

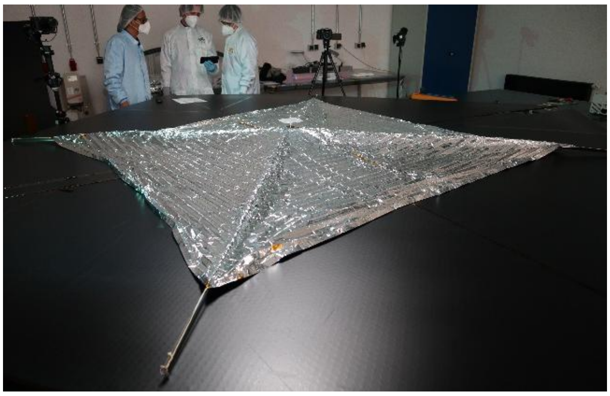

Figure 2: ADEO-N2 after successful ambient deployment test

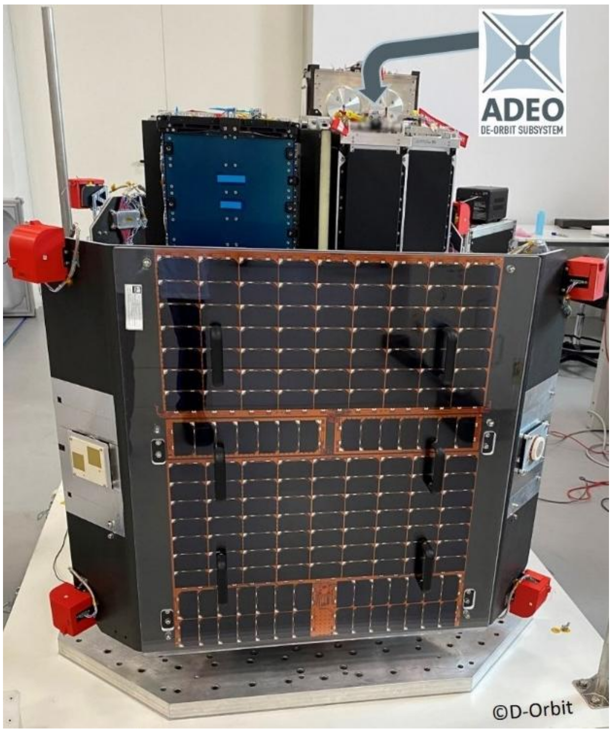

Figure 3: ION-SCV003 by D-Orbit with ADEO-N2 onboard

3.2 Test Activities

ADEO-N underwent a full qualification campaign, consisting following tests:

Table 1:Performed tests and models of ADEO-N

Partial Ambient Deployment Test	PFM
Vibration	PFM
Partial Ambient Deployment Test after Vibration	PFM
TVAC Cycling	PFM
TVAC Cold deployment	PFM
TVAC Hot deployment	PFM
Partial Ambient Deployment Test after TVAC	PFM
Shock Test	EM
Partial Ambient Deployment Test after Shock test	EM

The qualification campaign took place at DLR-IRS in Bremen. This had the benefit, that all required equipment and test facilities were at one location. An additional advantage was the available size of the TVAC-chamber, which allowed a partial deployment under vacuum conditions at the maximum and minimum qualification temperatures. The qualification campaign followed the test-as-you-fly approach and started with an ambient deployment test, followed by vibration and TVAC testing. In between each environmental test, an ambient deployment test took place, to verify the functionality of ADEO-N.

The test loads were defined based on reference missions and the IOD/IOV mission, ensuring the module's qualification for all standard launch vehicles.

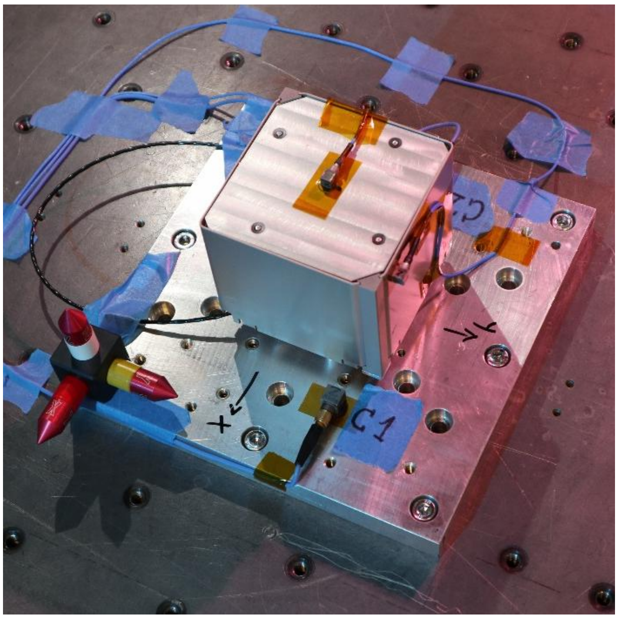

Figure 4: ADEO-N2 mounted on shaker

After an extensive period of testing, all tests were successfully completed and ADEO-N was ready for its in-orbit demonstration, launched in 2021.

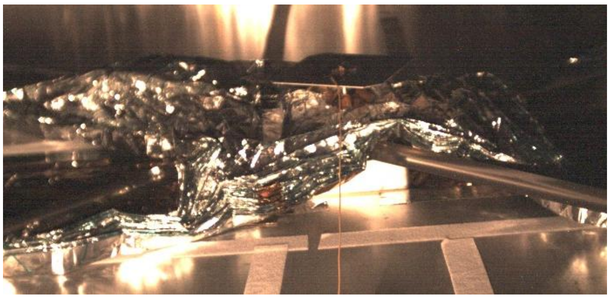

Figure 5: ADEO-N2 PFM after a successful deployment under thermal-vacuum conditions (hot case 70°C)

3.3 IOD Results

ADEO-N2 was launched on June 30, 2021 on Transporter-2 by SpaceX from the Space Launch Complex 40 at Cape Canaveral Space Force Station. The initial phase of the ADEO-N2 mission, titled “Show Me Your Wings,” aimed to demonstrate the dragsail deployment after withstanding launch loads and being stored on board in LEO. One and a half years later, on December 15, 2022, after all other payloads on the 210 kg heavy Dauntless David completed their tasks, ADEO-N2 deployed its 3.6 m² as planned at an altitude of 506 km (Figure 6).

The second phase of the mission focused on verifying the accelerated deorbiting of ION. The spacecraft's orbital decay was continuously monitored and compared with simulation data. As NORAD data shows, the satellite descended smoothly until it finally re-entered on 08.12.2024. Therefore, this In-Orbit Verification (IOV) was successfully confirmed through the validation of the accelerated deorbiting profile. Without ADEO, the satellite still would have been at an altitude of about 480 km on the same day, as analysis with STELA suggests.

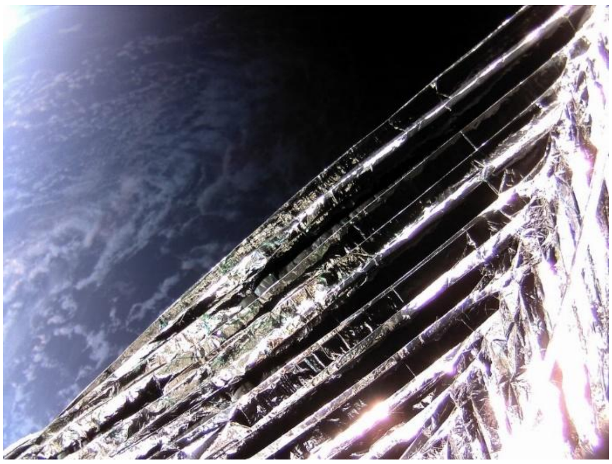

Figure 6: ADEO-N2 deployed in space

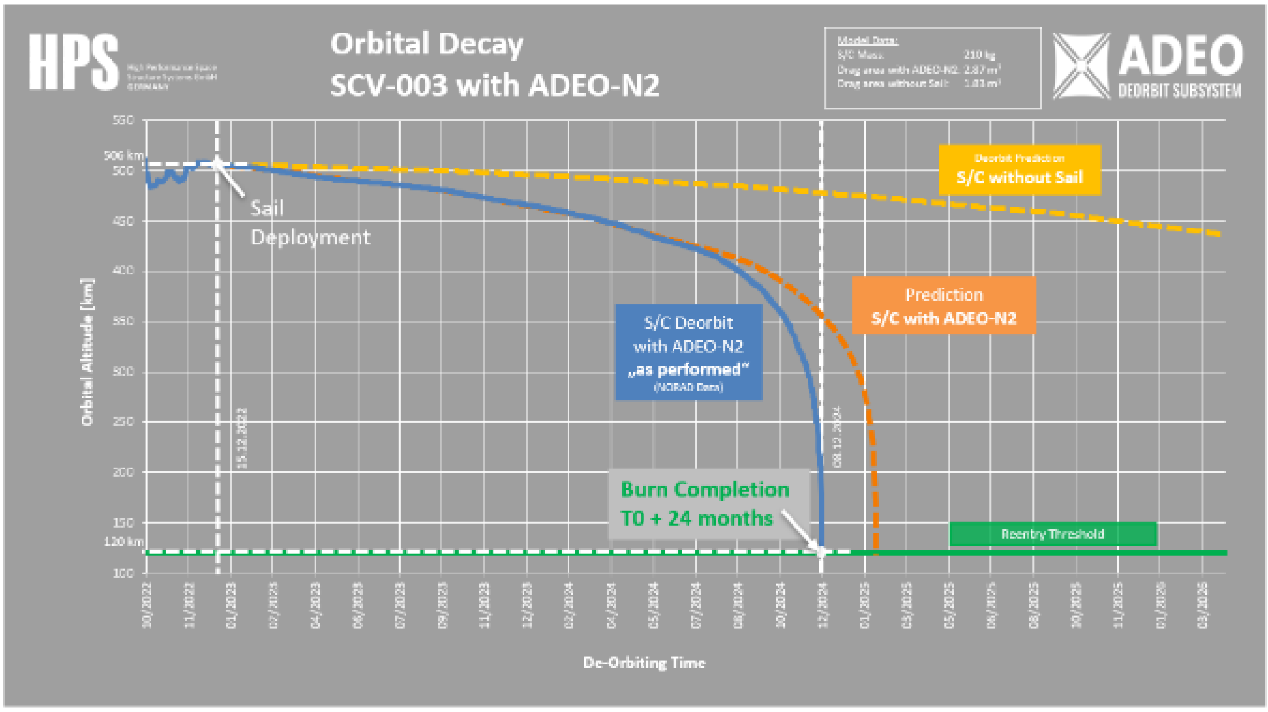

Figure 7: ADEO-N2 orbit propagation curves

4 ADEO-L Qualification

With 25 m², ADEO-L provides the largest drag area of the HPS drag sail family. ADEO-L was developed and qualified in the frame of project ADEO2, funded by ESA (GSTP) and follows ECSS standards. The qualification approach with a proto flight model (PFM) was used. Consequently, several breadboard (B/B) models with different functionalities were tested before design freeze in order to mitigate the risk of the PFM approach.

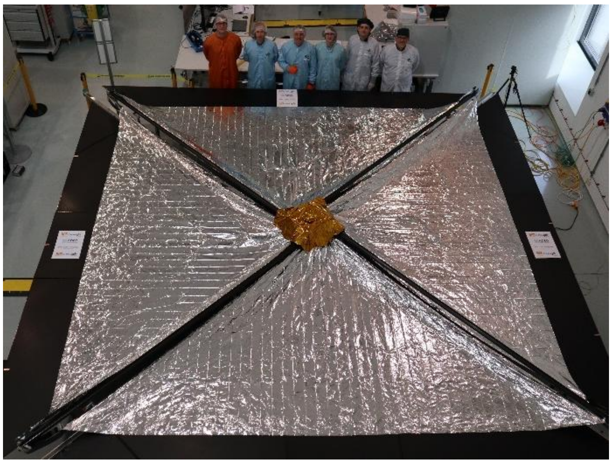

Figure 8: ADEO-L fully deployed during PFM test campaign

During the PFM test campaign, ADEO-L has seen three full deployments under ambient conditions (with and without MLI), vibration tests in all three axis and thermal cycling including partial deployment at worst hot and cold temperature level. Table 2 gives an overview about the tests which have been performed in the course of the project and the corresponding models.

Table 2:Performed tests and models of ADEO-L

Test	Model
Full deployment	B/B Model 1 + PFM
Vibration	B/B Model 1 + PFM
TVAC	B/B Model 1 + PFM
HDRM confidence life test	B/B Model 2
MLI vibration	B/B
Boom life	B/B
Sail segment deployment test	B/B
EMC	PFM

In terms of the thermal loads, the survival temperature range of the module is from -40°C to +85°C, while the operational temperature is -40°C to +75°C. ADEO-L consists multi-layer insulation (MLI), which is pushed open by the deployable booms during deployment. The duration of the full deployment using a release nut and an electric motor takes about 25 minutes.

The selected development approach of a PFM introduced technical challenges that were tackled effectively by intense testing of B/B models.

Flexibility and fast decision making during the development process led to a fully qualified system after completion of the environmental test campaign including full ambient deployment tests, vibration tests, TVAC tests, and EMC tests.

With that, the ADEO family of deorbit sails now offers flight heritage for its small systems and full ECSS qualification for its biggest system. ADEO-L is now ready for its IOD mission.

5 UPCOMING MISSIONS

At this time, HPS GmbH is integrating, testing and delivering several units of different ADEO modules to commercial and institutional customers in Europe and North America. All ADEO family modules are now commercially available and under production.

The newest qualified child of the ADEO-family is the ADEO-Pico. It achieved its full qualification in January 2025 and will start to its first deorbiting mission in Q3 2025.

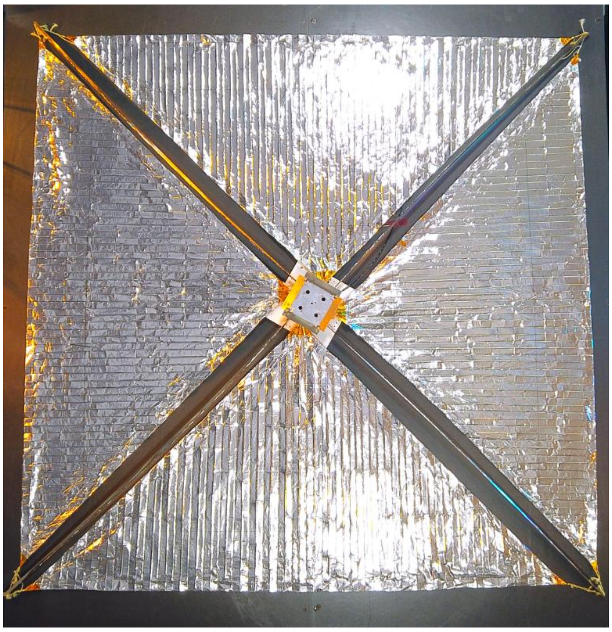

Figure 9: ADEO-P PFM deployment

Furthermore, the ADEO-Cube dragsail and the ADEO-Nx with customized 2 m² sail area are currently under development. The full qualification of these deorbiting devices is targeted for late 2025.

The ADEO subsystem is not limited to passive deorbiting; a new potential application is space debris measurement. While space debris is typically monitored using ground-based telescopes and in-orbit radar and optical instruments, these methods are only effective for objects larger than a few centimeters. However, smaller debris particles under 10 mm also pose a significant risk to spacecraft, and their impact is expected to become increasingly severe due to the Kessler effect.

Building on a previous study involving HPS and OHB from 2022, a novel approach proposes using two ADEO-L sails equipped with sensors with cameras positioned between them. This setup would allow for the detection and measurement of both large and small debris particles, capturing their impact, direction, and velocity. By employing this system, valuable data could be collected on the actual quantity of small debris in orbit and the severity of collision risks.

Currently, HPS is collaborating with C3S and University of Kent in a study to further explore the feasibility of using large ADEO sails for in-orbit debris measurement. This study, initiated at the end of May 2024, is part of the ESA Space Safety Program.

Another potential application of ADEO is active debris removal. In this scenario, ADEO could be attached to a spacecraft post-mission by another satellite, deploying immediately to speed up the deorbiting. While the preferred approach remains integrating ADEO onto spacecraft before launch, this method could serve as a viable solution for satellites that are already non-operational in orbit.

6 CONCLUSION

ADEO is a flight-proven deorbiting solution for a wide range of satellites in LEO by providing a reliable, cheap, small, and easy-to-install deorbiting subsystem. The commercial deorbiting sail subsystems provided by HPS can assure the timely deorbiting and hence enable the spacecrafts to meet the requirements of the latest regulations regarding clean space.

During the in-orbit demonstration of ADEO-N2, the deployment of the dragsail as well as the accelerated orbital decay was successfully verified by pictures of the deployed sail in orbit and telemetry data that is received from the satellite. The largest sized ADEO-L has been also qualified with the test campaign of ADEO2, and will fly on IOD/IOV mission. The smallest ADEO version, ADEO-P, was qualified and delivered for satellite integration.

The sail design and reliability are being continuously improved by ongoing development activities.

Furthermore, other applications for the ADEO dragsail system are being studied, like using the ADEO for the detection of space debris, but also for active deorbiting, by mounting ADEO on the spacecraft in orbit.

7 ACKNOWLEDGEMENT

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