Chapter Glossary

(ACS3)	Advanced Composite Solar Sail System
(ADCS)	Attitude Determination and Control System
(ADE)	Aerodynamic Deorbit Experiment
(ADR)	Active Debris Removal
(AFRL)	Air Force Research Laboratory
(BC)	Ballistic Coefficient
(CLEAR)	Clearing of the LEO Environment with Active Removal
(COPUOS)	Committee on the Peaceful Uses of Outer Space
(COSMIC)	Cleaning Outer Space Mission through Innovative Capture
(CRD2)	Commercial Removal of Debris Demonstration
(CSTT)	CubeSat Terminator Tape
(D3)	Drag Deorbit Device / D-Orbit Decommissioning Device
(DLR)	German Aerospace Center
(DOM)	Deorbit Mechanism
(EOL)	End-of-Life
(ESA)	European Space Agency
(ESEO)	European Student Earth Orbiter
(FAA)	Federal Aviation Administration
(FCC)	Federal Communications Commission
(GCD)	Game Changing Development
(GTO)	Geostationary Transfer Orbit
(HPS)	High Performance Space Structure Systems
(IADC)	Inter-Agency Space Debris Coordination Committee
(ISS)	International Space Station
(JAXA)	Japan Aerospace Exploration Agency
(LEO)	Low-Earth Orbit
(MSFC)	Marshall Space Flight Center
(NSTT)	NanoSat Terminator Tape

(ODMSP)	Orbital Debris Mitigation Standard Practices
(RPO)	Rendezvous and Proximity Operations
(SBIR)	Small Business Innovation Research
(SSO)	Sun-synchronous Orbit
(SSR)	Space Sustainability Rating
(SSTL)	Surrey Satellite Technology Ltd.
(STMD)	Space Technology Mission Directorate
(TES-n)	Technology Educational Satellite series
(TRL)	Technology Readiness Level
(TTP)	Thermosphere Test Probe
(UN)	United Nations
(UTIAS-SFL)	University of Toronto Institute for Aerospace Studies Space Flight Laboratory
(WEF)	World Economic Forum

13 Deorbit Systems

13.1 Introduction

Space debris, also known as orbital debris or space pollution, are derelict artificial objects left in space on purpose or accidentally that include larger nonfunctional spacecraft and rocket bodies, and smaller disintegrated mission-related objects such as lens caps, ejected bolts, or even paint flakes. Additionally, larger space debris are commonly broken up into even smaller fragments due to collisions, erosion, or expelled particles from spacecraft or rocket bodies. This presents a major problem in the space environment as spacecraft can be damaged or destroyed by space debris collisions due to the very high velocities of the debris objects, which then produces even more space debris.

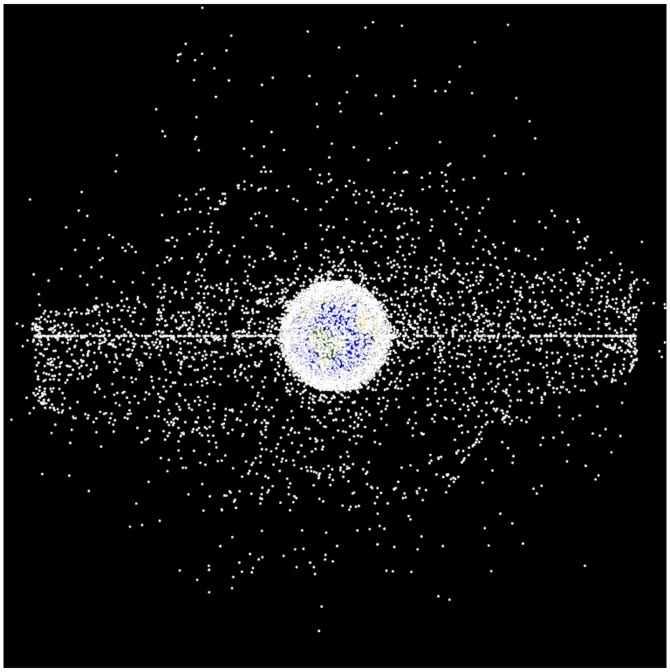

Figure 13.1: Orbital debris around Earth. Credit: NASA.

While space debris is present throughout space, there is a large accumulation around Earth, particularly in low-Earth orbit (LEO), where most space operations take place. This is also attributed to the increased launch cadence of small spacecraft and the recent surge in constellations over the past decade. Improved access to space has made LEO accessible and less expensive for more countries, organizations, and institutions to launch small spacecraft, which adds to the associated risks and threats of space debris. Estimates of the accumulation of orbital debris suggest approximately 1,100,000 objects with a diameter 1–10 cm, and over 36,500 pieces with diameters >10 cm, are in orbit between geostationary, equatorial, and LEO altitudes (1). Figure 13.1 shows a representation of the orbital debris around Earth. Additionally, the orbital lifetime of space debris can be extremely long since atmospheric drag is only effective at altitudes below ~250 km (2).

Due to the inherent problem of space debris, there are ongoing policy measures to establish the importance of mitigating and removing space debris. The general guideline is that spacecraft in LEO must deorbit, also known as decay, or be placed in a graveyard orbit within a maximum of 25 years after the completion of their mission (3). This standard spacecraft lifetime regulation has been recently updated to direct NASA and other national agencies to reassess current mitigation policies, especially regarding the potential advantages and cost implications resulting from limits on the orbital debris lifetime limits (4). These regulations have incorporated spacecraft decay capabilities into mission design.

The rate of spacecraft decay in LEO depends on several factors, including initial orbit parameters, the ballistic coefficient of the spacecraft, and solar weather conditions, all of which play a fundamental role in compliance with decommissioning regulations. Small spacecraft designers have examined various strategies for complying with decommissioning regulations to accelerate spacecraft decay post mission: spacecraft may be launched into lower orbits to enable natural decay within a few years, or equipped with deorbit systems to accelerate altitude decay and eventual reentry into Earth's atmosphere. Natural decay in <5 years can be achieved for most

SmallSats at altitudes <400 km, however several SmallSat missions must be in orbits beyond 400 km requiring the use of deorbit methods.

Spacecraft deorbit methods are either passive or active. Passive deorbit methods have gained maturity since the last iteration of this report, and there are more devices with high Technology Readiness Levels (TRL≥8) capable of satisfying current lifetime requirements. Traditionally, passive systems were the main option for deorbiting due to their increased simplicity, however recently active methods are gaining traction. Common active deorbiting approaches require attitude control and, in some cases, surplus propellant post-mission, such as a steered drag sail that relies on a functioning attitude control system, or on actuators for pointing the sail. Propulsion devices for deorbiting techniques are considered risky due to potential failure or malfunction of either the spacecraft, throughout its operational life, or the propulsive technology itself. Adequate attitude control and navigation capabilities after the mission for a controlled reentry are never a guarantee. Some of the new active deorbiting solutions include a separate spacecraft that can attach to the defunct satellite to bring it down to lower orbits where the satellites can complete deorbit using atmospheric drag.

The influx of small spacecraft in LEO has driven the development of space situational awareness and space traffic management data. For more information, please see the *Identification and Tracking Systems* chapter.

Chapter Organization

This chapter is organized as follows:

- Orbital Debris Regulations (13.2)
- State-of-the-Art – Passive Deorbit Systems (13.3)
- State-of-the-Art – Active Deorbit Systems (13.4)

Orbital space debris has been a known issue, and there has been ongoing research in this field. It is now a hot topic item, and the Orbital Debris Regulations section provides an overview of current policies for deorbit mitigations, their origins, and the organizations responsible for implementing orbital debris regulations. The Passive and Active Deorbit System sections contain technology descriptions, summary tables of devices, and previous, current, and planned missions. This chapter provides a comprehensive guide to existing commercial technologies and technology demonstrations for both methods, and the authors have attempted to highlight technology gaps and the current development status of each deorbit method.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status as discussed in open literature. Companies mentioned in this chapter are presented as informational only and do not represent an endorsement by NASA. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA. It should be noted that TRL designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of the technologies described.

Definitions

- *Disposal* refers to removal of spacecraft from the orbital environment.
- *Deorbit* refers to lowering spacecraft's orbital altitude, also referred to as *decay.*
- *Decay* refers to a gradual decrease of the distance between a spacecraft and the Earth.
- *Atmospheric Drag* refers to molecular collisions with the spacecraft body.
- *Drag Area* refers to the spacecraft surface area experiencing atmospheric resistance.

- *Orbital Lifetime* refers to the total time a spacecraft remains in orbit.

13.2 Orbital Debris Regulations

Space debris has been a concern for several decades, but with visible sightings of reentry fragments of spacecraft and rocket bodies, the urgency to address space debris has grown. NASA's Orbital Debris Program Office[1] was created in 1979, and the Air Force Space Debris Research Program was initiated in the 1980s. NASA was among the first organizations to implement plans for mitigation and remediation of space debris in the early 1990s, and in 1993 the Inter-Agency Space Debris Coordination Committee (IADC) was founded as an international body.

NASA collaborated with the Department of Defense in 1997 to develop the U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP) (5). The agency's most recent orbital debris guidelines can be found in NASA NPR 8715.6B "NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments" (6) and NASA Standard 8719.14C "Process for Limiting Orbital Debris" (3). These technical documents describe the processes and requirements to limit orbital debris for all NASA spacecraft missions. The guidelines, among other considerations, include a limit on the risk of potential human casualties caused by reentering debris, which shall not exceed 1 in 10,000 (5). Of the three spacecraft disposal methods identified – direct retrieval, atmospheric re-entry, and maneuvering into a storage orbit – atmospheric reentry was deemed the most feasible for most spacecraft missions. Therefore, a maximum 25-year post-mission orbital lifetime (no longer than 30 years after launch or relocation to a graveyard orbit for safe storage) was established for all U.S. spacecraft. The rationale for this specific orbital lifetime was based on the minimum propellant required to maneuver to a lower orbit, as predicted by orbital debris models (7).

The IADC is an entity formed by national and multi-national space agencies, including NASA, ESA, JAXA, and several others, and is widely recognized by the international community as the technical authority on space debris. In 2002, the IADC established the Space Debris Mitigation Guidelines to address orbital debris. Their findings and procedures are submitted to the United Nations (UN), as space debris has been one of the main interests of the UN Committee on the Peaceful Uses of Outer Space (COPUOS). In 2007, mitigation guidelines based on the IADC procedures were accepted by the COPUOS and endorsed by the UN (5). The IADC adopted the 25-year orbital lifetime guideline for space objects in LEO.

The U.S. Federal Communications Commission (FCC) regulates all radio communication across the U.S. and all U.S. spacecraft must be licensed for space communications. Since the early 2000s, the FCC has deliberated over how best to mitigate orbital debris from FCC-authorized space activities and formally adopted debris mitigation regulations (2) in 2004. These FCC regulations include orbital debris mitigation plans as part of license applications, and require applicants to disclose "the design and operational strategies that they will use, if any, to mitigate orbital debris," and to "identify particular methods by which a proposed satellite system will mitigate orbital debris" (2). The FCC adopted the ODMSP 25-year lifetime guideline as well and commented that the 25-year "rule" should be tightened, as this no longer adequately addresses current orbital debris issues arising from the launch of large constellations and the expected increase in future LEO space activity. In September 2022, the FCC adopted a new rule for all FCC-licensed satellites within the LEO region (<2000 km) to reduce the lifetime requirement to 5 years post-launch (8). There are ongoing discussions at the agency and federal level to determine the final policies.

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[1] https://www.orbitaldebris.jsc.nasa.gov/

Since this updated “5-year lifetime rule” by the FCC, there has been increased focus on space debris removal activities. In April 2023, the FCC created a new Space Bureau responsible for the regulation of satellites and space debris (9). The World Economic Forum (WEF) released the “Space Industry Debris Mitigation Recommendations” document in June 2023 to standardize a series of recommended behaviors for satellite operations. One of these listed recommendations is to target five years or less after end-of-life for spacecraft removal. The document was signed by several companies including Airbus, The Aerospace Corporation, SES, and Planet. The WEF collaborated with ESA, the MIT Media Lab, and other stakeholders to establish a Space Sustainability Rating (SSR) system to provide a measurable score to characterize spacecraft mission compliance with international space debris mitigation guidelines (10)(11).

The Federal Aviation Administration (FAA) announced in September 2023 a proposal to create a new rule to limit the growth of debris from commercial launch vehicles to reduce collision risk and limit space debris in populated LEO environments (12). The new regulation will give commercial launch operators specific options for orbital debris countermeasures, requiring disposal of their rocket upper stages by performing a controlled reentry within 30 days after mission completion, moving them to a less congested or graveyard orbit (within 30 days), placing them in an Earth escape trajectory (within 30 days), retrieving them with active debris removal within five years after launch, or performing an uncontrolled atmospheric disposal within 25 years.

13.2.1 Considerations for Orbital Lifetime Requirements in LEO

Small spacecraft launched at or around 400 km altitude naturally decay in under five years, however at orbital altitudes beyond 500 km, there is no guarantee the spacecraft will deorbit within that timeframe, and some may not deorbit within 25 years. This is due to low atmospheric density and its effect on ballistic coefficient, as seen in Figure 13.2. This graph displays various cases of SmallSats with distinct masses, drag areas, and initial orbits, under atmospheric density conditions corresponding to solar cycle maximum and minimum over the 11-year solar cycle.

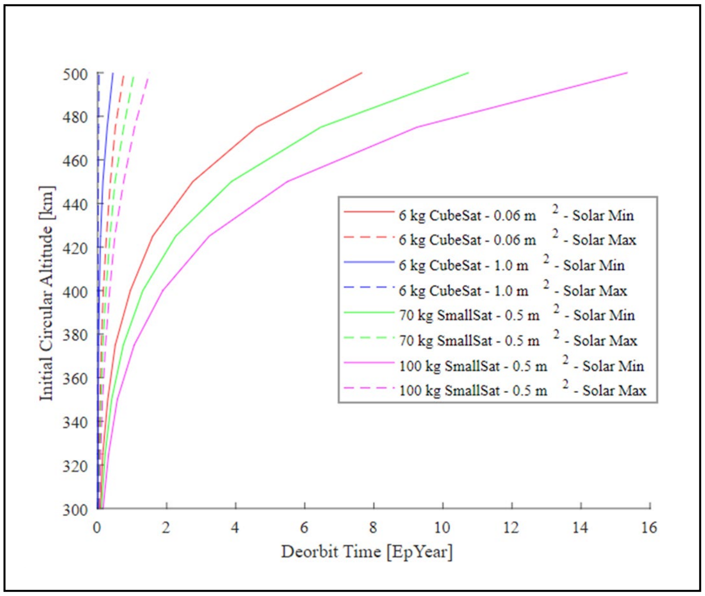


Figure 13.2: Initial orbit altitudes yield different lifetimes depending on the ballistic coefficient of the spacecraft. Three representative area-to-mass ratios are shown. Note that the propagation stops at 16 years, but the initial altitudes yield even longer times. Credit: NASA.

The varying solar weather conditions can affect the deorbit performance for a given altitude and can have a significant impact on orbital lifetimes. The atmospheric drag force that satellites experience is increased during solar maximum, resulting in a faster decay. In this situation, the Sun emits extra energy into the atmosphere and creates higher density layers in LEO that produce stronger drag forces on satellites (13). It is common for some missions to plan their launch periods around the solar cycle; if the stricter 5-year orbital lifetime requirement becomes widely accepted, more operators may consider this approach, as the deorbit time can be reduced by more than 10 years as seen in Figure 13.2.

Another important factor that affects orbit propagation in LEO is the spacecraft's ballistic coefficient (BC). Spacecraft BC is defined in this chapter as the mass to area ratio multiplied by the inverse of the drag coefficient, assumed to be 2.2. By this definition, a spacecraft with a lower ballistic coefficient will decay faster due to lower mass-to-area ratio. As shown in Figure 13.2, a 6U spacecraft with an area of 0.06 m^2 and an assumed mass of 6 kg has a ballistic coefficient of 45, which is significantly lower than that of a 100 kg spacecraft with an area of 0.5 m^2 and a BC of 90.

Since timing the launch for a particular solar weather scenario may not be feasible, another strategy for satellite operators to comply with orbital lifetime requirements is to decrease their spacecraft ballistic coefficient or mass to area ratio. Deorbit technologies such as drag devices can effectively increase the spacecraft's drag area and may play an increasingly important role in LEO operations.

13.3 State-of-the-Art – Passive Deorbit Systems

Passive deorbit methods require no further active control after deployment, relying only on natural perturbations and forces to deorbit the spacecraft. They are popular for their minimal mass, power, and cost constraints, and high reliability characteristics. Passive methods consist of a deployed structure, such as a drag sail, boom, or electromagnetic tether, to reduce the spacecraft's ballistic coefficient. This raises atmospheric drag on the spacecraft, accelerating the reentry process. These techniques have greatly matured in the last ten years, and recent developments have made passive deorbit technology well understood and space-ready.

This section provides information on drag sails, deployable booms, and electromagnetic tethers. In the last decade, there have been several SmallSat missions that have demonstrated passive deorbit capabilities with a deployed sail, boom, or tether. Some notable deorbit missions led by academic programs, research institutions and government organizations, and commercial entities are described under *Missions* for each deployed structure.

13.3.1 High TRL Drag Sails

Drag devices are the most common deorbit technology for satellites orbiting in LEO. They are advantageous due to simplicity and small stowed volumes. For certain area-to-mass ratios in altitudes equal to or lower than 800 km, drag devices can be deployed to increase the drag area for faster deorbiting to meet emerging 5-year requirements. This technology has been implemented in several small spacecraft missions, and several companies and institutions are developing prototypes that are increasingly more mature, providing solutions for missions that lack the resources for active deorbit systems.

Many mission designers are discovering that drag sails do not need to be complicated in material or shape to be effective. It is important to note that some missions described below are better documented due to publicly available data. Table 13-1, located at the end of this section, summarizes state-of-the-art passive deorbit systems. Solar sail technology development and mission information are found in the *In-Space Propulsion* chapter.

Missions

In January 2011, the NanoSail-D2 mission successfully demonstrated a drag sail to deorbit the spacecraft from a 650 km altitude and 72° inclined orbit. NanoSail-D2 was deployed from the minisatellite FASTSat–HSV to demonstrate the deorbit capability of a low-mass, high surface area sail. The 3U spacecraft, developed at NASA Marshall Space Flight Center (MSFC) and Ames Research Center (ARC), reentered Earth's atmosphere in September 2011.

CanX-7 started at an initial ~700 km Sun-synchronous orbit (SSO), deployed a drag sail in May 2017 and re-entered April 2022. The thin film sail—developed and tested at University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL)—consists of four modules, each providing 1 m^2 of drag area (see Figure 13.3). Each sail section deployed mechanically with spring booms, preserving geometry and incorporating separate electronics for individual telemetry and command to mitigate risk of single-point failures. This is useful for custom adaptability to various spacecraft geometries and ballistic coefficient requirements for other missions (14).

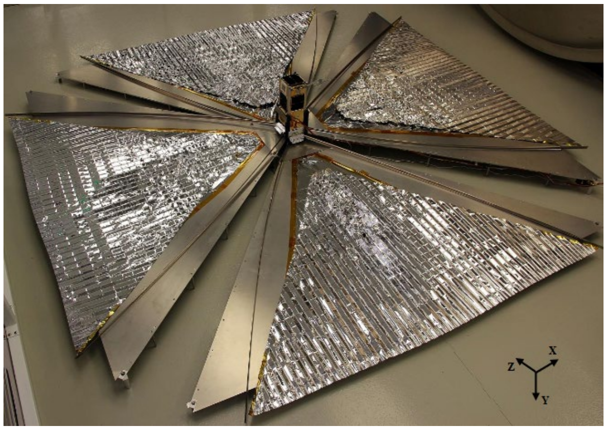


Figure 13.3: CanX-7 deployed drag sail during testing. Credit: Cotten et al. (2017).

The Surrey Space Centre, based in the United Kingdom, developed DragSail technology that was implemented in a family of missions. Funded by the European Commission QB50 program and the DEPLOYTECH partnership that included the German Aerospace Centre (DLR) and NASA Marshall Space Flight Center, among others, the Inflatesail 3U CubeSat first demonstrated the DragSail in 2017 and included a mast/drag-sail technology that successfully deorbited the satellite in just 72 days. This achievement was the first time a spacecraft has deorbited using European inflatable and drag-sail methods (15).

The RemoveDebris mission, developed under the European Commission FP7 program by a consortium of several institutions such as Airbus and the Surrey Space Centre, consisted of a 100 kg spacecraft, deployed from the ISS in 2018. One of the experiments it carried was a passive drag augmentation device consisting of a sail. The sail was deployed in March 2019, however, trajectory data indicated only partial deployment, as no significant altitude change was observed. The lessons learned from this incident were implemented in another version for the Space Flight Industries' SSO-A mission that incorporated two of these sails. In that case, the assembly did not include an inflatable boom (15).

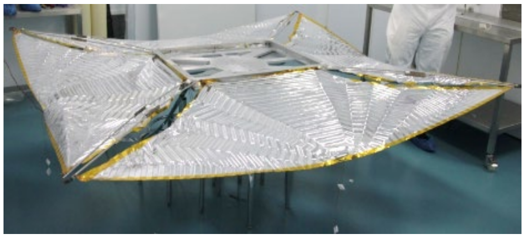


Figure 13.4: Icarus-3 drag sail implemented in the Carbonite-1 mission. Credit: Cranfield Aerospace Solutions.

As part of the ESA CleanSat program, Cranfield Aerospace Solutions developed a variety of drag augmentation systems called Icarus which are similar to other drag devices where drag is increased by deploying a membrane sustained by rigid booms. The first demonstration was the Icarus-1 sail that flew on the TechDemoSat-1 mission from SSTL launched in 2014 and re-entered May 2019. Another version also flew on the Carbonite-1 spacecraft, also built by SSTL and launched in 2015. The Icarus sail is a thin aluminum structure located around the satellite side panel that contains four stowed Kapton trapezoidal sails and booms. The Icarus-1 sail system had a mass of 3.5 kg for about 5 m^2 of sail area, and the Icarus-3 sail had a mass of 2.3 kg for 2 m^2 sail area (Figure 13.4). Another technology developed by Cranfield Aerospace Solutions is a de-orbit mechanism (DOM) device like the Icarus drag sail but in a smaller cuboid outline. The mechanical system varies from Icarus since the sails are triangular and the booms work as tape springs themselves. This system flew on the European Student Earth Orbiter (ESEO) that was a

45 kg satellite with several student payloads launched in March 2018. The DOM module has a mass of 0.5 kg and will deploy a sail with an area of 0.5 m^2 to deorbit ESEO after decommissioning (16).

The Spinnaker product line of drag sails that focus on low size, weight, power, and cost (SWaP-C) and a reliable approach to meeting FCC deorbit requirements by Applied Aerospace & Defense (acquired Vestigo Aerospace in 2026). Launched in March 2025, the Sphinx mission consisted of a 32 kg Astro Digital Corvus-Micro microsatellite and deployed an 18.8 m² Spinnaker 3 drag sail intended to dramatically shorten orbital lifetime and generate engineering telemetry and imagery of deployment (17). This demonstration is to support upcoming tests of deorbiting upper rocket stages.

MMA Design LLC patented the dragNET de-orbit system, which is a 2.8 kg module (Figure 13.5 [top]) featuring four stowed thin membranes that deploy through a single heater-powered actuator. The sail has an area of 14 m^2 that can effectively deorbit a 180 kg spacecraft at an altitude of 850 km within 10 years (18). The dragNET was a part of the ORS-3 Minotaur Upper Stage and facilitated its deorbit 2.1 years after launch in November 2013. In October 2022, the dragNET deorbit system was launched as part of the General Atomics GAzelle satellite, as seen in the lower image of Figure 13.5, and is still operational (19).

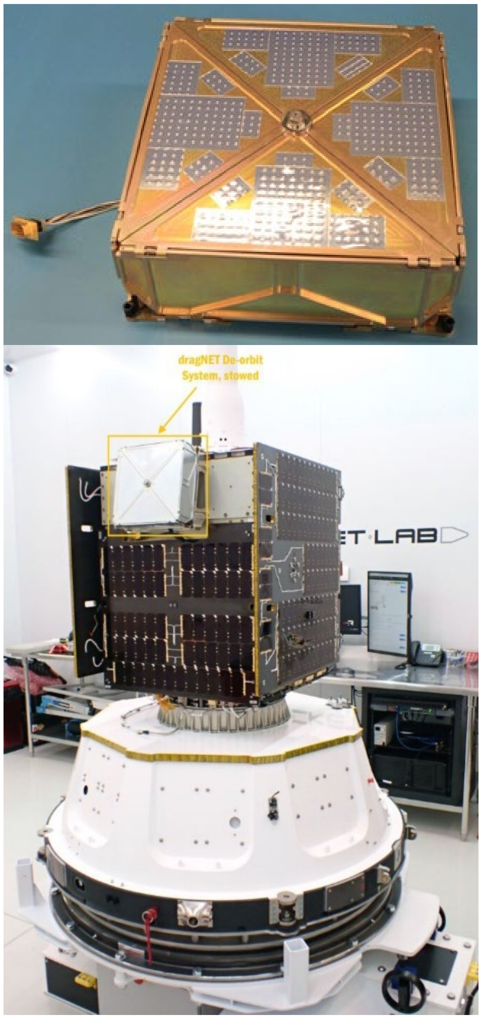


Figure 13.5: [top] The dragNET module. [bottom] dragNET module attached to the GAzelle satellite prior to launch. Credits: MMA design.

NPC Spacemind developed and launched a series of CubeSat missions that demonstrated their ARTICA deorbit system, which consists of a deployable 2.1 m^2 drag sail. The total size of the deorbiting system is 0.3 U which makes it suitable for CubeSats as small as 1U (20). In November 2022 and in January 2023, the DanteSat 3U CubeSat, and the Future-SM3 6U CubeSat, Futura-SM3, were respectively launched and successfully operated with an ARTICA system onboard. These two new missions extend the ARTICA flight heritage after the earlier UrsaMaior, 1-Kuns, and Alpha missions, launched in 2017, 2018 and 2020 respectively (21).

The Planetary Society's LightSail-2 was a 3U CubeSat mission with a solar sail launched in June 2019 and deployed from the Prox-1 satellite once in orbit. The mission demonstrated that solar sail technology can be used in LEO by modifying its orbital altitude over the course of the mission. The 32 m^2 sail was able to extend the mission lifetime by reducing orbital decay and on some occasions, it was also able to overcome drag entirely. In late November 2022, the mission successfully re-entered the atmosphere according to orbital predictions (22).

The Drag Augmentation Deorbiting System (ADEO) is a scalable drag sail developed by High Performance Space Structure Systems (HPS). There are various configurations of the ADEO sail: the ADEO-N series is tailored for small satellite missions of 20-250 kg, while the ADEO-M and ADEO-L target larger sizes, 100-700 kg and 500-1500 kg respectively. The ADEO-N series corresponds to sail sizes of 5±2 m^2, while ADEO-M covers areas within 15 ± 5 m^2. There are other smaller versions as well for picosatellites (ADEO-P) and CubeSats (ADEO-C) in particular, and the option to configure the sail size according to customer needs. Various configurations of the ADEO-N product family have been tested already (23). The NABEO-1, launched in 2018, attached to the center of a Rocket Lab Electron rocket Kick Stage and the sail was deployed 90 minutes after launch (24). In late December 2022, the ADEO-2 sail was deployed with a 10x10x10 cm package from the D-orbit ION-2 satellite carrier (Figure 13.6). For more information, contact ADEO@hps-gmbh.com.

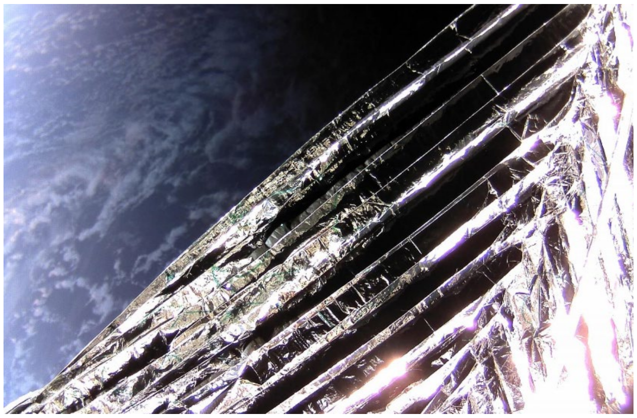


Figure 13.6: The ADEO-2 system deployed in LEO in December 2022, picture captured by the D-orbit's ION spacecraft carrier. Credits: HPS GmbH, Germany (www.hps-gmbh.com).

Gama launched its first spacecraft mission, a 6U CubeSat named Gama Alpha, in January 2023 into a ~550 km LEO and is currently still in orbit. This first technology demonstration mission aims to test the deployment and control of their 73.3 m^2 solar sail, and the final phase of the mission will use the sail to rapidly deorbit the satellite (25).

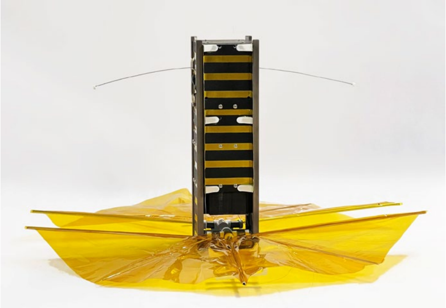


Figure 13.7: SBUDNIC CubeSat with drag sail made from Kapton polyimide film. Credit: Brown Univ.

SBUDNIC, shown in Figure 13.7, and designed and built by Brown University students with support from D-Orbit, AMSAT-Italy, La Sapienza-University of Rome, and NASA Rhode Island Space Grant, demonstrated a practical, low-cost method to cut down on space debris. Rather than taking debris out of orbit after it becomes a problem, this $30 drag device made from Kapton polyimide can be added onto satellites to radically reduce how long they're in space. SBUDNIC was launched on a SpaceX rocket May 2022 as part of the Transporter 5 ridesharing mission. The plastic drag sail was deployed at about 520 kilometers and the satellite re-entered August 2023, about five years ahead of schedule (26).

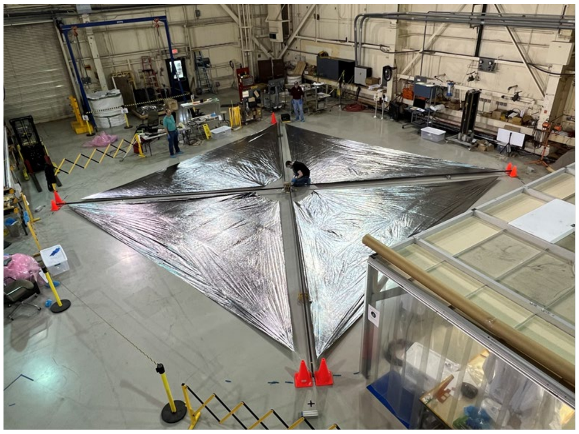


Figure 13.8: The ACS3 sail fully deployed during its pre-integration fit test. Credits: NASA Langley.

The Advanced Composite Solar Sail System (ACS3) was a mission developed at NASA Langley and NASA Ames that consisted of a spacecraft that deployed an 81 m^2 solar sail in a 1000 km sun-synchronous orbit (see Figure 13.8). The sail, composed of a combination of composite materials with distinct properties, was deployed using lightweight booms from a 12U CubeSat bus, developed by NanoAvionics. ACS3 launched in April 2024 (27). Although the main objective of the mission to show the propulsive capabilities of the solar sail were not achieved, the sail was successfully deployed prior to decommissioning in 2026.

TechEdSat (Passive) Exo-Brake Series

The Technology Educational Satellite program, also known as TechEdSat-n (TES-n), at NASA Ames Research Center (ARC) has contributed significantly to the development of drag devices. It consists of a series of nanosatellite technology demonstrations in collaboration with several universities including San Jose State University and the University of Idaho (28). One of the main goals of the program is to test and improve deorbiting techniques and develop a unique targeting capability with their own drag device design known as the Exo-Brake. Being used as both a passive and a controlled active deorbit system, the Exo-Brake is an atmospheric braking system that is distinguished from other drag devices with its parachute qualities rather than solar-sail behavior due to its tension-based structural elements (see Figure 13.9). This is fundamental for accurate deorbit targeting since the device must retain its shape without collapsing during those critical reentry moments near the atmosphere interface (~100 km altitude), known as the Von Karman line (32). Development of the Exo-Brake is funded by the Entry Systems Modeling project within the NASA Space Technology Mission Directorate's (STMD) Game Changing Development (GCD) program.

Figure 13.9: TechEdSat-10 aft-imaging captures Exo-Brake deployment July 2020 (29). Credit: NASA.

The Exo-Brake was first implemented as a passive deorbit device on TES-3 and TES-4, and then on TES-5 and TES-7. In comparison to other objects without a disposal device, the TES-7 flight is shown with other objects deployed from the same carrier, as seen in Figure 13.10. With a low ballistic coefficient induced by the deployed Exo-Brake, TES-7 re-entered in approximately 1.3 years from an initial 500 km orbit. This design incorporated a compact, low volume gas-generator cartridge to inflate the Exo-Brake struts.

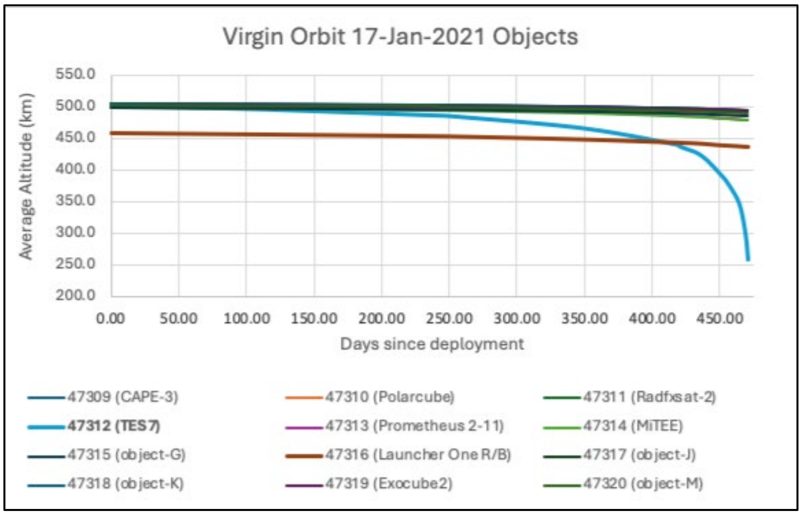


Figure 13.10: TES-7 deorbit compared to other deployed objects from the same carrier. Credit: NASA/Virgin Galactic

More recently, a simpler mechanical deployment scheme was developed (patent pending) that improves packaging performance by increasing the deployed-drag-area-to-stowage-volume ratio, as applied to TES-11. This has been further miniaturized for TES-22 which was launched in January 2025 as a test for a proposed future Thermosphere Test Probe (TTP) to be part of a small cohort during solar coronal events. The passive Exo-brake (not drag-modulated for deorbit targeting) has advanced recently for disposal activities to meet the new 5-year deorbit lifetime requirement. Table 13-1 provides a comprehensive overview of TES-n missions with passive Exo-Braking capability.

Table 13-1: Passive TechEdSat-N Spacecraft

TES-n mission (Volume)	Deployment (month, year)	Deorbit Duration Reentry Year	Nominal Drag Area (m^2)	Deployed Orbit Alt. & Inc.	Technology Tested Notes (ref)
TES-1 (1U)	October 2012	May 2013	NA	412 km, 51.7°	(33)
TES-2 (1U)	April 2013	April 2013	NA	223 km, 51.6°	First test of Iridium (34)
TES-3 (3U)	November 2013	January 2014	0.35	413 km, 51.6°	Original Passive Exo-Brake
TES-4 (3U)	March 2015	April 2015	0.35	398 km, 51.6°	Upgraded Exo-Brake design
TES-5 (3.5U)	March 2017	July 2017	0.35	403 km, 51.6°	Two-state Drag Modulated Exo-Brake for targeted re-entry (35)
TES-6 (3.5U)	November 2017	May 2018	0.564	402 km, 51.7°	Variable Exo-Brake settings (36)
TES-7 (2U)	January 2021	May 2022	1.2	499 km, 60.7°	High Packing Density Exo-Brake (37)
TES-9 (3U)	Planned	TBD	-	-	Automatic deorbiting using the Exo-Brake system
TES-11 (6U-W)	July 2024	February 2026	0.790	508 km, 97.4°	Advanced disposal Exo-Brake mechanism

Table 13-2: Drag Sail Missions

Product / Mission	Manufacturer	Mission host and launch mass	Device mass (kg)	Initial orbit (alt and inc.)	Launch Year	Deployment Year	Drag Area (m^2)
NanoSail-D2	NASA MSFC/ARC	FASTSAT (4.2 kg)	N/A	650 km 72 deg	2010	2011	10
Drag-Net	MMA Design	ORS-3 Deployed a Minotaur Upper Stage (100 kg)	2.8	N/A	2016	2016	14
Drag-Net	MMA Design	General Atomics GAzelle Satellite	2.8	N/A	2022	TBC	14
Icarus-1	Cranfield Aerospace Solutions	SSTL TechDemoSat-1 (157 kg)	3.5	635 km	2014	2019	6.7
Icarus-3	Cranfield Aerospace Solutions	Carbonite-1 (80 kg)	2.3	650 km 98 deg	2015	2018	2
DOM	Cranfield Aerospace Solutions	ESEO (45 kg)	0.5	572 × 588 km 97.77 deg	2018	2020	0.5
Terminator Tape	Tethers Unlimited, Inc.	Prox-1 (71 kg)	0.808	717 km 24 deg	2019	2019	10.5
DragSail	Surrey Space Centre	InflateSail (3.2 kg)	N/A	505 km 97.44 deg	2017	2017	10
Exo-Brake	NASA	TechEdSat 5 (3.4 kg)	N/A	405 km 51.5 deg	2014	2015	0.35
Exo-Brake	NASA	TechEdSat 7 (3 kg)	N/A	485 x 513 km 60.7 deg	2021	2021	1.2
Exo-Brake	NASA	TechEdSat 13 (4 kg)	N/A	499 x 509 km 45 deg	2022	2022	0.083
Exo-Brake	NASA	TechEdSat 15 (4.5 kg)	N/A	215 x 285 km 137 deg	2022	2022	0.087
removeDebris	Surrey Space Centre	removeDebris (100 kg)	N/A	405 km 51.5 deg	2018	2019	16
CanX-7	UTIAS-SFL	3U CubeSat (3.6 kg)	0.8 (4 modules of 0.200)	688 km 98 deg	2016	2017	4
NABEO-1	HPS	1U CubeSat (attached to Rocket Lab Kick Stage)	0.85	500 km	2018	2018	2.5
ADEO-2	HPS	1U CubeSat (attached to the D-orbit ION carrier)	3.4	N/A	2021	2022	3.6

Table 13-2: Drag Sail Missions

Product / Mission	Manufacturer	Mission host and launch mass	Device mass (kg)	Initial orbit (alt and inc.)	Launch Year	Deployment Year	Drag Area (m^2)
ADEO-Cube series	HPS	1-50 kg	0.5	LEO	N/A	N/A	2
ADEO-N series	HPS	20-250 kg	0.8	LEO	N/A	N/A	5±2
ADEO-M series	HPS	100-700 kg	4	LEO	N/A	N/A	15±5
ADEO-L series	HPS	500-1500 kg	9.5	LEO	N/A	N/A	20±100
ARTICA (ALPHA)	NPC Spacemind	1U CubeSat	0.285 (0.3U)	5865 Km, 70.16 deg	2020	2020	2.2
ARTICA (FUTURA SM 3)	NPC Spacemind	6U CubeSat	0.285 (0.3U)	N/A	2023	N/A	2.2
ARTICA (DANTESAT)	NPC Spacemind	3U CubeSat	0.285 (0.3U)	415 km	2022	2022	2.2
ARTICA (URSA MAIOR)	NPC Spacemind	3U CubeSat	0.285 (0.3U)	450 km, 97.1 deg	2017	2019	2.2
ARTICA (1KUNS)	NPC Spacemind	1U CubeSat	0.285 (0.3U)	N/A	2018	2019	2.2
LightSail – 2	The Planetary Society	3U CubeSat	N/A	720 km	2019	2022	32
ACS3	NASA	12U CubeSat	1 (6U)	1000 km SSO	2024	2024	81
Gama ALPHA	Gama	6U CubeSat	N/A	550 km	2023	N/A	73.3
NANO dragsail (28)	Frond Space Systems	2U-12U CubeSat	0.25	<650 km	2025	N/A	1
MICRO dragsail (29)	Frond Space Systems	50-100 kg spacecraft	<1600	<650 km	2025	N/A	10

13.3.2 Deployable Booms

Deployable booms, while not strictly a deorbit device themselves, are a vital component of many deorbit systems. They are structural components that can be stowed during launch, then deployed once in space to provide the support structure required for various drag sail designs. More specific information regarding deployable booms can be found in the *Structures, Materials, and Mechanisms* chapter.

Missions

The University of Florida developed the Drag Deorbit Device (D3) and De-Orbit Control System 2U CubeSat that provides both attitude stabilization and modulation of the satellite drag area at the same time, making the overall solution an alternative to regular ADCS units. This technology was licensed exclusively to Orbotic Systems who have changed and Trademarked the product title “D3 De-Orbit Drag Device". Four 3.7 m long tape-spring booms form the D3, which can deorbit a 15 kg satellite from an altitude of 700 km. A final design has already been tested and simulated, including thermal-vacuum and fatigue testing (38). Figure 13.11 shows two images of the final design. The mission was selected by NASA through the CubeSat Launch Initiative, and on September 6, 2022, D3 was successfully placed in orbit (39).

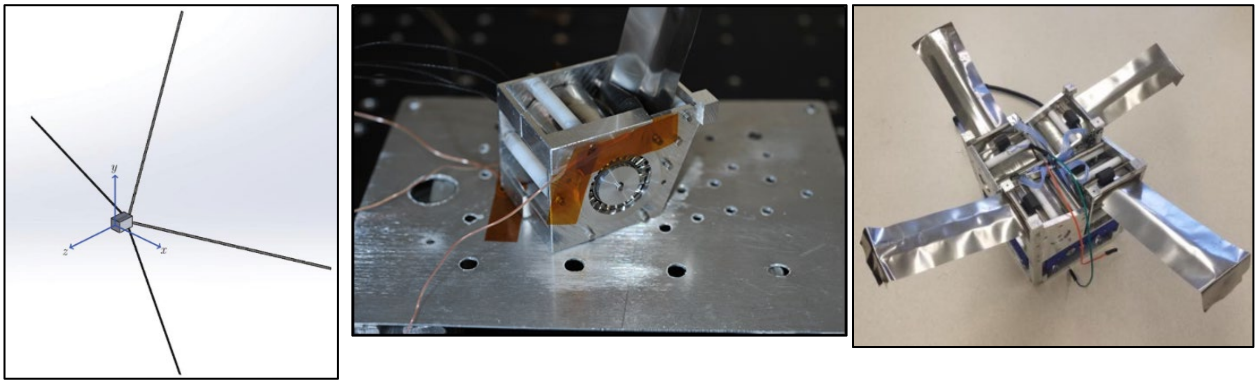


Figure 13.11: D3 CAD design (left), boom inside thermal vacuum chamber (center), and prototype design (right). Credit: Omar et al., 2019, and Martin et al., 2019.

13.3.3 Electromagnetic Tethers

In addition to drag sails, electromagnetic tethers have proven to be an effective deorbit method. This technology uses a conductive tether to generate an electromagnetic force as the tether system moves relative to Earth’s magnetic field.

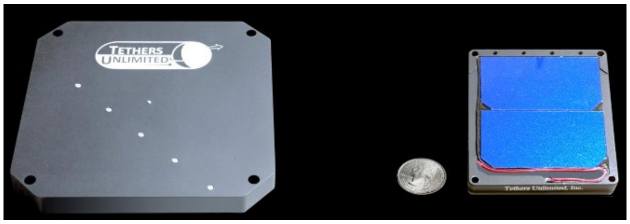


Figure 13.12: Image of the NSTT (left) and the CSTT modules. Credit: Tethers Unlimited.

Missions

Tethers Unlimited (now Amergint Technologies) developed Terminator Tape that uses a burn-wire release mechanism to actuate the ejection of the terminator’s cover, deploying a 70 m long conductive tape at the conclusion of the small spacecraft mission. There are currently two main modules. The first, NSTT for NanoSats, has a mass of 0.808 kg. The second, CSTT, is made for CubeSats and has a mass of 0.083 kg. Figure 13.12 shows an image of both systems. The 70 m long NSTT has been implemented in the 71 kg Prox-1 satellite, launched in mid-2019 by AFRL (40). DragRacer, an experiment jointly developed by Tethers Unlimited, Millennium Space Systems, RocketLab, and TriSept Corp., consisted of one satellite (Alchemy) equipped with

Terminator Tape and another (Augury) without it, to characterize the tape performance. Alchemy reentered in July 2021 while Augury is still in orbit (41).

13.3.4 Natural Deorbiting Highways

Finally, analysis has shown that there exists a natural network of what may be called “deorbiting highways or corridors” (42). Judicious injection into specific orbits in LEO may result in relatively rapid natural orbital decay. There exist dynamical resonances associated with solar radiation pressure, lunisolar perturbations and Earth's gravitational harmonics. In turn, these dynamical resonances are associated with natural deorbiting corridors; furthermore, their effectiveness is proportional to the spacecraft’s area-to-mass ratio. These LEO dynamical resonances are expressed as a network of specific orbital initial conditions. For example, for a nearly circular initial orbit at an altitude of 700 km, and assuming a typical value of the area-to-mass ratio, a spacecraft with an initial inclination of approximately 41 degrees will have a shorter lifetime in orbit than an identical spacecraft with an initial inclination of 20 degrees. The former example is an example of leveraging a natural deorbit corridor associated with these dynamical resonances. The downside of using this approach is that small satellites (a) often go as “piggyback” payloads to larger missions and do not have the luxury of picking an orbit, and (b) often go to sun-synchronous orbits which for typical area-to-mass ratio values are not dynamically close to these natural deorbiting corridors.

13.4 State-of-the-Art – Active Deorbit Systems

While it is still less common to design an active deorbiting system on a spacecraft directly due to mass, size, and power constraints, other methods enable active decommissioning. Several companies, such as Astroscale and ClearSpace, offer active spacecraft-based deorbit services and have already started initial technology demonstration missions to advance their deorbit systems. These deorbit systems consist of separate, dedicated spacecraft that attach to decommissioned satellites to place them into decaying or graveyard orbits. This niche is quite appropriate for the growing number of constellations that are planned to launch over the next few years.

The NASA STD-8719.14C document stipulates that all NASA-sponsored spacecraft using controlled reentry must have a designed trajectory to ensure that any remaining debris does not impact landmasses. Specifically, debris with a kinetic energy exceeding 15 Joules must stay at least 370 km away from any foreign landmass, or within 50 km from any territory of the United States or the permanent ice pack of Antarctica (3). This requirement implies that spacecraft must be equipped with improved active deorbit capabilities. There have been advances on deorbit technologies that can either be used on a specific mission or provided through commercial services.

This section highlights some of the main stakeholders that are working towards the implementation of active space debris removal services, and some promising technologies that can potentially be used for actively deorbiting spacecraft in the future.

13.4.1 Active Debris Removal Hardware

This section focuses on efforts to develop technologies for active debris removal. These include the active control of the Exo-Brake on the TechEdSat series for targeted re-entry, as well as potential and upcoming missions dedicated to actively removing orbital debris using drag sails, deployable booms, and electromagnetic tethers. In addition, some upcoming missions include orbiting vehicles to execute active operations to remove small satellites at end of life.

TechEdSat (Active) Exo-Brake Series

The Exo-Brake design has evolved from a fully passive device to one with active control capability that can target a specific reentry location by adjusting the drag device for the optimal ballistic coefficient based on the satellite's orbital determination. The TES-6 mission first implemented this technology with a 3.5U CubeSat and deployed the Exo-Brake from the rear and targeted reentry over NASA Wallops Flight Facility. Although the target area was overshot, analysis shows that a low 4–5 kg/m^2 ballistic coefficient configuration would have yielded suitable results if placed at 300 km (see Figure 13.13). TES-6 successfully demonstrated the reentry experiment and the command/control capability by overflying Wallops right before reentering.

The Exo-Brake targeting technology has been demonstrated on TES-6 and TES-10 missions and was going to be implemented on TES-8 except a power system failure occurred after Exo-Brake deployment but before targeting. The Exo-Brake on TES-10 was an improved version of the previous TES-5 and TES-6 devices with a wider ballistic coefficient range (6–18 kg m^2) to enable better control authority for a targeted deorbit flight test over Wallops (37). TES-13 and TES-15 used variations of the TES-7 design for active, controlled mission deorbiting (43). Table 13-3 provides a comprehensive overview of the different TES-n missions.

Table 13-3: Active TechEdSat-N Spacecraft

TES-n mission (Volume)	Deployment (month, year)	Reentry (month, year)	Nominal Drag Area (m^2)	Deployed Orbit Alt. & Inc.	Technology Tested Notes
TES-8 (6U)	January 2019	April 2020	0.5	406 km, 51.6°	Hot Exo-Brake; improved version of TES-5 and -6 designed for continued operation in high temperature environment
TES-10 (6U)	July 2020	March 2021	0.564	416 km, 51.6°	largest iteration Exo-Brake and performed targeting experiment
TES-13 (3U)	January 2022	July 2024	0.087	504 km 45°	Autonomous navigation and targeted reentry;
TES-15 (3U)	October 2022	October 2022	0.087	250 km, 137°	Hot Exo-Brake re-entry test; unable to complete full test
TES-22 (1U)	January 2025	TBD	2.00	~500 km	Rapid Disposal (Exo-Brake/Heliophysics Test Probe)
TES-23 (3U)	March 2026	TBD	-	-	Rapid Disposal (Exo- Brake), RADSET

RemoveDebris Consortium Partners

The RemoveDebris mission focused on testing several active debris removal experiments with different technologies on mock targets in LEO. In total, the RemoveDebris spacecraft carried two 2U CubeSats, a net, harpoon, laser ranging instrument, and a drag sail. One experiment deployed a 5 m net toward simulated space debris using one of the CubeSats, DebrisSat 1, and a balloon. Both DebrisSat 1 and the balloon were captured at ~11 m and maneuvered to a lower altitude, re-entering in March 2019 (44). Another active debris technology used a harpoon and a deployable target where the target platform attached to a 1.5 m boom was deployed from the main spacecraft, and a tethered harpoon was fired at 19 m/s to strike the center of the platform. Once that occurred, the boom that connected both harpoon and target platform joined the harpoon and target platform at one end. However, a tether secured the target in place, avoiding the creation of new debris. This resulted in the first space demonstration of harpoon-based debris—with a dry mass of 4.3 kg—capture technology.

13.4.2 Active Debris Removal / Spacecraft Reentry Services

This section focuses on commercial efforts to provide space debris removal services. This commonly involves a "servicer" spacecraft released from a host spacecraft that rendezvous with an object, captures it via attachment or docking method, and releases it in a lower altitude for reentry. Several core technologies, such as autonomous navigation, rendezvous and proximity operations (RPO), and robotics, are being developed by NASA and international space agencies, academics and researchers, and the commercial industry to boost the active debris removal service. Some deorbit removal services require the spacecraft to be fitted with a deorbit fixture for their servicer spacecraft to attach to. In response to the surge of small spacecraft constellations, deorbit fixtures are now being integrated into several new spacecraft constellations.

Some companies, like Momentus, are more focused on in-orbit servicing capabilities as a whole that include deorbit and removal applications. Those companies with a deeper affiliation with in-orbit servicing are featured in the Orbital Transfer / Maneuvering Vehicles (OTV/OMV) section of the *Integrated, Launch, Deployment, and Orbital Transfer* chapter.

Astroscale Holdings Inc.

Astroscale aims to provide services that will address the end-of-life (EOL) scenario of newly launched satellites and be proactively engaged in active debris removal. They are involved in collaborations with a variety of governmental and international organizations (such as the US government, ESA, the European Union, or the United Nations) that aim to address space debris removal. Since 2022, they are responsible for the Cleaning Outer Space Mission through Innovative Capture (COSMIC) mission design as part of the Active Debris Removal (ADR) mission with the UK Space Agency that will remove two defunct British spacecraft in 2028 (45).

Astroscale is collaborating with other efforts to implement their Generation 2 Docking Plate on future spacecraft for future removal activities or to remove critical debris such as rocket upper stages or defunct satellites (46). As part of JAXA's Commercial Removal of Debris Demonstration (CRD2) initiative—which focuses on the removal of large Japanese-made space debris in two mission phases—Astroscale developed the capture mechanism that enables close proximity operations on-orbit. Phase I consisted of a 150-kg Active Debris Removal by Astroscale-Japan (ADRAS-J) satellite that identified and characterized a rocket upper stage on-orbit. It was launched in July 2024 and maintained a constant distance of 50 m and began its decommissioning in early 2026 (47).

As part of their EOL campaign, the End-of-Life Services by Astroscale demonstration (ELSA-d) mission launched on March 22, 2021 and has successfully demonstrated EOL technologies in LEO with Astroscale's docking plate (48). ELSA-d consisted of two spacecraft: a "servicer" and "client" where the client spacecraft represented a piece of space debris that the servicer rendezvoused with and eventually attached to. With respective launch masses ~175 and ~17 kg, the servicer and client spacecraft repeatedly performed several complex demonstrations including magnetic capture and rendezvous operations of both tumbling and non-tumbling cases. In January 2022, the servicer spacecraft successfully released the client counterpart and initiated autonomous relative navigation over the course of multiple orbits as part of the mission plan. As of 2024, the servicer spacecraft is expected to re-enter in 3.5 years.

Planned for launch in 2026, the ELSA-M demonstration mission will leverage lessons learned for magnetic docking and autonomous navigation technologies demonstrated in the precursor ELSA-d mission. ELSA-M will dock with and remove a OneWeb spacecraft using Astroscale's compatible magnetic capture mechanism (49). OneWeb plans to have Astroscale's docking plate on their future spacecraft for this continued deorbit service (50). An important note is that several science missions are undertaking extensive efforts to make their spacecraft magnetically neutral, which may be a concern for magnetic docking methods.

ClearSpace

Another company that is solely focused on the design and execution of space debris removal is ClearSpace. By advancing robotics to support in-orbit servicing applications such as disposal, transport, inspection, assembly, manufacturing, repair, and recycling, ClearSpace aims to help establish a market for in-orbit servicing and debris removal. Collaborating with ESA, ClearSpace-1 is a space debris removal mission designed to locate and capture a non-cooperative, tumbling object via a four-armed robotic device (51). The object to be removed was originally a 100 kg VEGA upper stage, however in August 2023, it collided with another piece of space debris (52). The mission will now rendezvous with Project for On-Board Autonomy (PROBA)-1 —ESA's first spacecraft with fully autonomous technologies, launched 20 years ago—capture it with a group of robotic arms, and then both spacecraft will be deorbited together to a lower orbit for final disintegration in the atmosphere.

ClearSpace entered the preliminary design review in October 2023 of the Clearing of the LEO Environment with Active Removal (CLEAR) mission currently projected to launch in the second half of 2026. This study is designed to remove at least two UK non-operational satellites that have been in orbit for more than 10 years in a ~700 km orbit and have a natural deorbit time longer than 100 years (51). The CLEAR spacecraft features unfolding arms used to capture and release target objects.

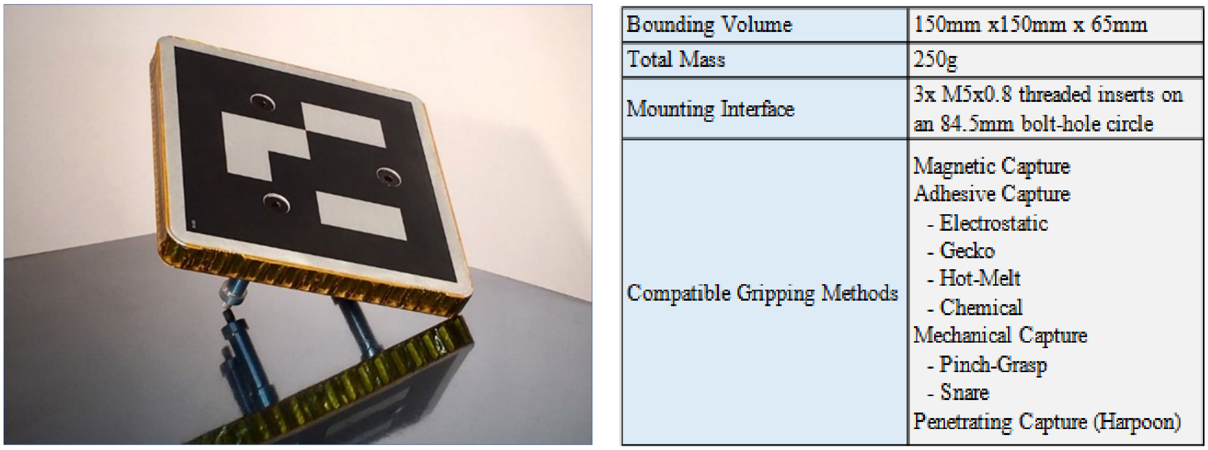
D-Orbit

Known for their transportation services onboard their ION CubeSat carrier platform, D-Orbit also provides an external solid motor booster specifically for deorbiting purposes. This independent module, known as D-Orbit Decommissioning Device (D3), shown in Figure 13.13, is a solution that is optimized for end-of-life maneuvers and was first demonstrated in 2017 (53). This technology would need to be added prior to launch and is activated from the ground or host spacecraft. More information on the ION is in *Chapter 10: Launch, Integration, Deployment, and Orbital Transport*.

Figure 13.13: D-Orbit D3 module. Credit: D-orbit.

Voyager Space

The main objective of Voyager Space is advancing humanity's presence in space and on Earth. They focus on space exploration and infrastructure, microgravity research, and technological innovations that will contribute to a sustainable space economy and enhance humanity's future. As part of their in-space servicing and assembly, they developed the DogTag, which is an inexpensive, lightweight, versatile, and advanced grappling interface. This fixture enables small spacecraft to be captured by various mechanisms such as magnetic grapples, mechanical arms, electrostatic or gecko adhesive, and even harpoons. This interface allows for spacecraft servicing or decommissioning and is compatible with other techniques to accommodate different mission needs (54). Figure 13.14 includes an image of the flight DogTags and a table of its main features. Since 2021, OneWeb includes the DogTags grappling fixture on their launched satellites to make space more sustainable (55). In total, over 500 DogTags have already been launched to space.



Bounding Volume	150mm x150mm x 65mm
Total Mass	250g
Mounting Interface	3x M5x0.8 threaded inserts on an 84.5mm bolt-hole circle
Compatible Gripping Methods	Magnetic Capture Adhesive Capture - Electrostatic - Gecko - Hot-Melt - Chemical Mechanical Capture - Pinch-Grasp - Snare Penetrating Capture (Harpoon)

Figure 13.14: DogTag prototype. Credit: Voyager Space.

Kall Morris Inc.

Another orbital debris research and solution development company with a focus on active debris removal techniques is Kall Morris Inc (KMI). They are developing a commercially viable system designed to capture and detumble an object— whether a client satellite at end-of-life or uncooperating debris object—and release it into a deorbit altitude (56). Their Laelaps spacecraft will rendezvous with and attach itself to a target object using a multi-armed, articulated robotic device called REACCH. As depicted in Figure 13.15 {left}, REACCH will capture, move, and release the object in a deorbit altitude. Gecko adhesion is incorporated on the REACCH tentacles in order to attach to the debris object and easily release the object when the tentacles retract.

With the assistance of the University of Southern California, by May of 2025 REACCH completed Astrobee-enabled International Space Station (ISS) testing sponsored through the Center for the Advancement of Science in Space (CASIS) 2025 (57). Laelaps in-space testing is anticipated in Q4 2027, with component ground testing leading up to that time. Figure 13.15 {right} is an image of REACCH on the ISS.

In 2027, the Space Machines Company's orbital transport vehicle will enter lunar orbit to rendezvous with and capture debris in lunar orbit. The Australian-built Optimus orbital transport vehicle (OTV) will rendezvous with, capture, and return hazardous debris from lunar orbit to Earth. Along the way, it will carry Australian payloads to lunar orbit for testing and development of lunar exploration communications and situational awareness infrastructure before returning them to Earth.

Figure 13.15: {left} REACCH interpretation and {right} REACCH during ISS Capture testing with Astrobee. Credit: Kall Morris Inc. Credits: Kall Morris Inc.

TransAstra was awarded a Phase 2 Small Business Innovation Research contract from NASA to continue developing their inflatable capture bag technology for space debris remediation. This device will be capable of enveloping and subsequently removing a non-cooperative object in orbit. A collaboration with ThinkOrbital, a company based in Colorado, includes the transport of the removed debris to an on-orbit processing plant.

13.5 Summary

Space debris regulations are becoming more stringent. Consequently, several deorbit technologies have matured significantly in recent years. Traditionally passive systems have been more common, have flown on various missions, and have reached TRL 9 following successful demonstrations. Drag sails are the main technology for passive systems, and several companies have already commercialized and brought these products to market. Other systems such as electromagnetic tethers, deployable booms, or the NASA TechEdSat series Exo-Brake have also been prototyped and demonstrated in space, now with navigation capabilities and increased reliability. The investment in active systems has also grown significantly. Several companies are offering transfer vehicles to remove debris or deorbit spacecraft at the end of their mission, and compatible systems for spacecraft rendezvous and removal are being developed in parallel. As an example, the RemoveDebris mission has successfully tested two different active methods: a net and a harpoon for potential future implementation in active debris removal operations. Companies such as Astroscale and ClearSpace are developing missions to remove defunct satellites and are launching precursor technology demonstration spacecraft in the initial stages of their roadmaps. In conclusion, the various deorbit technologies have seen a significant TRL increase since the last iteration of this report, and their robustness is expected to continue improving as demand for deorbiting services increases with additional launches and evolving regulations.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

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