Chapter Contents

Chapter Glossary

(ADCS)	Attitude Determination and Control System
(AEOLDOS)	Aerodynamic End-of-Life Deorbit system for CubeSats
(AFRL)	Air Force Research Laboratory
(ARC)	Ames Research Center
(CRD2)	Commercial Removal of Debris Demonstration
(D3)	Drag Deorbit Device
(DOM)	De-orbit Mechanism
(EOL)	End-Of-Life
(FURL)	Flexible Unfurlable and Refurlable Lightweight
(GCD)	Game Changing Development
(GTO)	Geosynchronous Transfer Orbit
(HSC)	High Strain Composite
(IADC)	Inter-Agency Space Debris Coordination Committee
(ISS)	International Space Station
(JAXA)	Japan Exploration Space Agency
(MSFC)	Marshall Space Flight Center
(RODEO)	Roll-Out DeOrbiting Device
(SBIR)	Small Business Innovation Research
(SSO)	Sun-synchronous orbit
(STMD)	Space Technology Mission Directorate
(TRL)	Technology Readiness Levels
(UTIAS-SFL)	University of Toronto Institute for Aerospace Studies Space Flight Laboratory
(VESPA)	Vega Secondary Payload Adapter

13.0 Deorbit Systems

13.1 Introduction

The threats of space debris are increasing with the launch of multi-satellite constellations, particularly in low-Earth orbit (LEO). Currently, the general guideline is that satellites in LEO must deorbit or be placed in graveyard orbit within a maximum of 25 years after the completion of their mission (1). However, on September 29, 2022, the Federal Communications Commission (FCC) adopted a new rule to reduce this requirement to 5 years for US-licensed satellites, as well as those from other countries that seek to access the US market (40) (64). Therefore, spacecraft under 2000 km in altitude will have to deorbit as soon as it is applicable and no longer than 5 years after end of mission. This requirement will apply to spacecraft launched two years after the rule is approved. Up to the date of publication of this report, this rule does not specifically apply to NASA satellites that are not licensed through the FCC. As of November 2022, it is estimated that only a small percentage of NASA satellites launched every year may have to follow this rule. Current discussions at the agency and federal level are ongoing to determine the final policies (64).

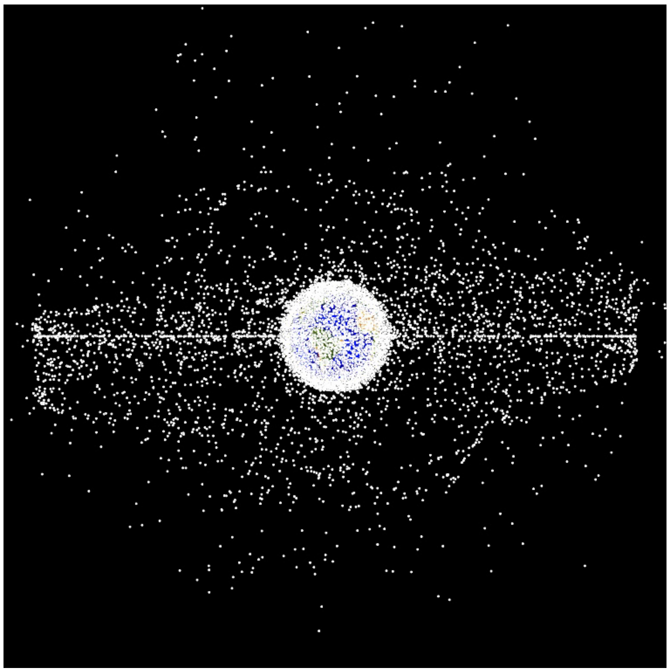


Figure 13.1: Illustration of all known space debris in orbit around Earth. Credit: NASA.

The rate of decay in LEO depends on several factors. In particular, the initial orbit allocation and the ballistic coefficient play a fundamental role on the ability to comply with the regulations. Estimates of the accumulation of orbital debris suggest approximately 500,000 objects with a diameter 1 – 10 cm, and over 25,000 pieces with diameters >10 cm, are in orbit between geostationary equatorial and low-Earth orbit altitudes (2). Of the 11,370 satellites that have been placed in orbit 60% are still in orbit and only 35% are still operational. As of November 2022, it is estimated that all the space debris in orbit exceeds a collective mass of 9000 metric tons (2)(63). Figure 13.1 is a representation of the debris around Earth. The objective of the NASA Orbital Debris Program Office along with the Inter-Agency Space Debris Coordination Committee (IADC) is to limit the creation of space debris. NASA requires that all spacecraft must either deorbit within 25 years or move into a graveyard orbit for safe storage, while the IADC is a non-binding recommendation (3). However, as explained earlier in this chapter, the new FCC rule will reduce this value to just 5 years (40) for most commercial spacecraft (64).

Small spacecraft missions typically stay in LEO, as it is a more accessible, less expensive orbit to reach, and there are rideshare opportunities from several commercial launch providers. Additionally, the proximity to Earth can relax spacecraft mass, power and propulsive constraints, and also the radiation environment in LEO is relatively benign for altitudes below 1000 km. Small spacecraft launched at or around the International Space Station (ISS) altitude (~400 km) naturally decay in under 5 years. However, at orbital altitudes beyond 500 km, there is no guarantee that a small spacecraft will naturally decay in 5 years to comply with the new FCC rule, due to potential low atmospheric density conditions and the differences in ballistic coefficient, as seen in figure 13.2. To ensure compliance with the 5-year requirement, satellites would need to increase their ballistic coefficient (or area to mass ratio). Deorbit technologies such as drag devices are important in this context since they can provide a way to effectively address this issue.

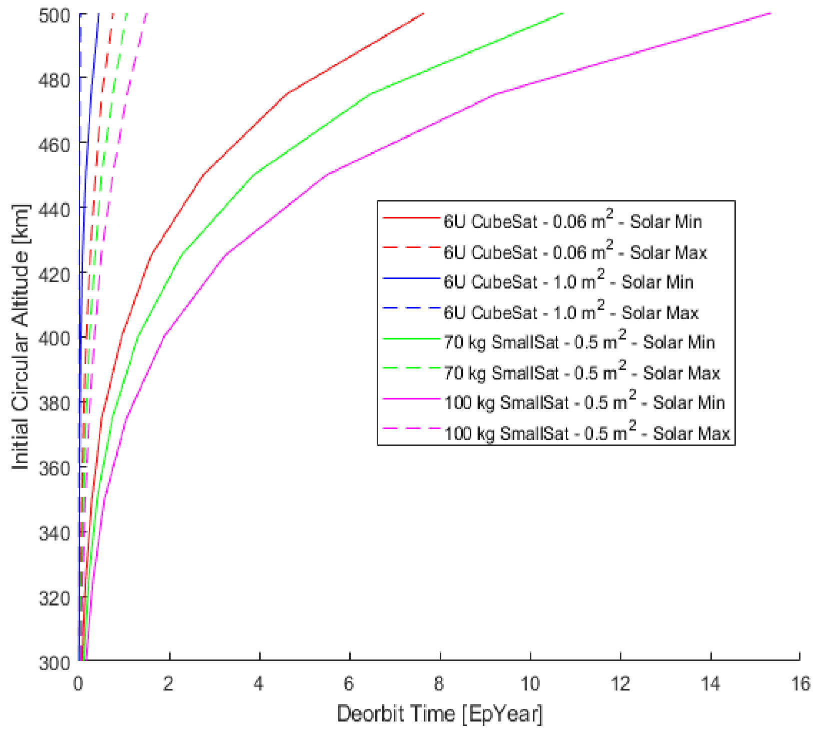


Figure 13.2: Initial orbit altitudes yield different lifetimes depending on the ballistic coefficient of the spacecraft. Three representative area-to-mass ratios are shown. Note that the propagation stops at 25 years, but the initial altitudes yield even longer times. Credit: NASA.

Figure 13.2 shows various representative small satellites with various masses, drag areas and initial orbits, under two atmospheric density conditions, near the maximum and the minimum solar cycle. For instance, a 6U CubeSat with 0.06 m^2 drag area and 14 kg of dry mass decays at a faster rate than a more massive satellite with 100 kg and 0.5 m^2 of drag area, showing the important effect the ballistic coefficient plays in the orbit propagation. The majority of launched small spacecraft do not carry on-board propulsion, making them unable to achieve graveyard orbits for decommissioning. Therefore, they need to rely on deorbit techniques such as increasing the drag area by rotating the spacecraft if they are in low altitudes. Some spacecraft, if their exposed drag area is not enough to meet the new 5-year requirement, can use deorbit devices such as drag sails (passive systems) or external deorbit services (active systems) to deorbit.

In addition, the varying solar weather conditions affect the deorbit performance for a given altitude. The drag force that satellites experience is increased when the Sun is at the maximum of the solar cycle, producing a faster decay. When the Sun emits extra energy in the atmosphere, higher density layers occupy LEO altitudes, producing a stronger drag force as a result (66). The solar maximum typically occurs every 11 years and can have a severe impact on orbital lifetimes, so some missions plan their launch periods around the solar cycle. With the new 5-year rule, more companies may want to consider the solar cycle for their launch plans as the deorbit time can be reduced by more than 10 years in some cases as seen in figure 13.2.

Passive deorbit systems have gained maturity since the last iteration of this report, and there are more devices with high Technology Readiness Levels (TRL ≥ 8) that are guaranteed to satisfy the stricter 5-year requirement. Several missions have demonstrated passive deorbit systems, and an increasing number of small spacecraft have been carrying these devices.

Traditionally passive systems were the main option for deorbiting due to their increased simplicity. However, recently active methods are gaining traction. On one hand, active deorbiting requires attitude control and, in some case, also 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. On the other hand, 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 the deorbit using their own drag decay. Some recent small spacecraft like the European RemoveDebris project have even implemented a variety of active and passive deorbit systems within the same mission. This technology demonstration mission included both active and passive systems such as a net experiment, a harpoon, and a more traditional drag sail. The mission tested these systems to prove feasibility of such technologies in space by deploying two separate 2U CubeSats from the main spacecraft to simulate space debris. After the mission was completed, the passive system was deployed and is currently deorbiting the main satellite to burn in the atmosphere.

Propulsive devices have also been used for deorbiting techniques; however, this approach is still considered risky due to potential failure or malfunction of either the spacecraft, up until its final stage of decommission, or the propulsive technology itself. Even if the spacecraft carries enough excess propellant for its own active decay approach, it may also need adequate attitude control and navigation capabilities after the mission for a controlled reentry. This method may require navigation and mission operation capabilities, making it inconvenient and more costly for some small spacecraft missions (4). Overall, active deorbiting methods are still challenging for small spacecraft, as this demand increases design complexity and uses valuable mass and volume. This report studies the state-of-the-art for both systems, excluding spacecraft that carry their own propulsive means. For those systems, please refer to the Propulsion chapter of this report.

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 for a particular small spacecraft subsystem. 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 described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

13.2 State-of-the-Art – Passive Systems

Passive deorbit methods require no further active control after deployment. Recent developments have increased the number of available options with flight heritage. This chapter will emphasize recent developments rather than past missions. In addition, the chapter aims to discuss devices used exclusively for deorbit purposes, excluding technologies such as solar sails that are used for other propulsive applications.

13.2.1 High TRL Drag Sails

Drag devices represent the most common deorbit device for satellites orbiting in low-Earth orbit. They present an advantage due to simplicity and by not occupying large volumes while stowed. 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 in compliance with the new 5-year requirement. Recently, 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 to the space debris problem for missions that do not have resources for an active system. Table 13-1 displays current state-of-the-art technology for passive deorbit systems. These are the most developed technologies for deorbiting systems as of 2022.

Product	Manufacturer	Mission host and launch mass (kg)	Device mass (kg)	Initial orbit (alt and inc)	Launch Year	Deployment Year	Drag area (m^2)	TRL	Ref
NanoSail-D2	NASA MSFC/ARC	FASTSAT (4.2 kg)	N/A	650 km 72 deg	2010	2011	10	7-9	(1)
Drag-Net	MMA Design	ORS-3 Deployed a Minotaur Upper Stage (100 kg)	2.8	N/A	2016	2016	14	7-9	(5)
Icarus-1	Cranfield Aerospace Solutions	SSTL TechDemoSat-1 (157 kg)	3.5	635 km	2014	2019	6.7	7-9	(6)
Icarus-3	Cranfield Aerospace Solutions	Carbonite-1 (80 kg)	2.3	650 km 98 deg	2015	Future (in-orbit)	2	7-9	(6)
DOM	Cranfield Aerospace Solutions	ESEO (45 kg)	0.5	572 × 588 km 97.77 deg	2018	Future (in-orbit)	0.5	7-9	(6)
Terminator Tape	Tethers Unlimited, Inc.	Prox-1 (71 kg)	0.808	717 km 24 deg	2019	2019	10.5	7-9	(7)
DragSail	Surrey Space Centre	InflateSail (3.2 kg)	N/A	505 km 97.44 deg	2017	2017	10	7-9	(8)
Exo-Brake	NASA	TES-5 (3.4 kg)	TBC	405 km 51.5 deg	2014	2015	0.35	7-9	(9)
Exo-Brake	NASA	TES-7 (3 kg)	TBC	485 x 513 km 60.7 deg	2021	2021	1.2	8-9	(43)
Exo-Brake	NASA	TES-13 (4 kg)	TBC	505 km 45 deg	2022	2022	0.083	8-9	(43)
Exo-Brake	NASA	TES-15 (4.5 kg)	TBC	215 x 270 km 137 deg	2022	2022	0.087	8-9	(43)

Table 13-1: Launched Drag Sails

removeDebris	Surrey Space Centre	removeDebris (100 kg)	N/A	405 km 51.5 deg	2018	2019	16	7-9	(10)
CanX-7	UTIAS-SFL	3U CubeSat (3.6)	0.8 (4 modules of 0.2)	688 km 98 deg	2016	2017	4	7-9	(11)

Several small spacecraft missions have built and launched passive deorbit technologies in the past using a drag sail or boom. The NanoSail-D2 mission, which was deployed in 2011 from the minisatellite *FASTSat-HSV* into a 650 km altitude and 72° inclined orbit, demonstrated the deorbit capability of a low mass, high surface area sail. The 3U spacecraft, developed at NASA Marshall Space Flight Center (MSFC), reentered Earth's atmosphere in September 2011.

CanX-7, still in orbit at an initial 800 km Sun-synchronous orbit (SSO), deployed a drag sail in May 2017. The sail was developed and tested at University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS-SFL) (figure 13.3).

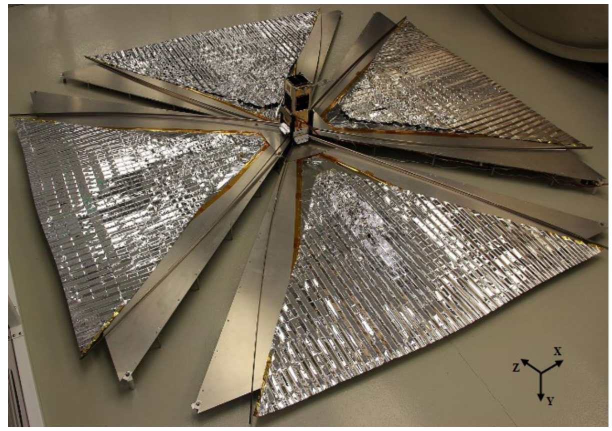


Figure 13.3: CanX-7 deployed drag sail during testing. Credit: Cotten et al. (2017).

The CanX-7 deorbit technology consists of a thin film sail that is divided in four individual modules that each provide 1 m^2 of drag area. These sail sections are deployed mechanically with spring booms, which help to preserve the geometry. Each module also has electronics for individual telemetry and command. This feature allows different sections to be controlled separately to mitigate risk of a single failure, and to allow custom adaptability to various spacecraft geometries and ballistic coefficient requirements for other missions. For the 2017 deployment, all four segments functioned successfully. The deorbit performance was measured after a month. The deorbit profile showed that the effects of the sail segments accounted for an altitude decay rate at the time of measurement of 20 km/year, which results in a significant increase from the previous 0.5 km/ year. These rates are expected to increase as the atmospheric density increases exponentially with lower altitudes (11).

The Technology Educational Satellite, also known as TechEdSat-n (TES-n), program 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. 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. The Exo-Brake deorbit system is an atmospheric braking system that distinguishes itself from other drag devices since it is more akin to a parachute instead of a solar sail due to its primary tension-based elements. This becomes fundamental for accurate deorbit targeting since the device must retain its shape without collapsing during those critical reentry moments occurring at the atmosphere interface altitude of 100 km, known as the Von Karman line (12). The Exo-Brake has been used as both a passive and a controlled active deorbit system, therefore it is included in both sections.

The Exo-Brake development is funded by the Entry Systems Modeling project within the NASA Space Technology Mission Directorate's (STMD) Game Changing Development (GCD) program. The Exo-Brake was first implemented as a passive deorbit device on the TechEdSat missions TES-3, TES-4, and TES-5. Recent CubeSats have also used it for controlled mission deorbiting. Two of the four TechEdSat spacecraft using a passive Exo-Brake were TES-5 and TES-7, while TES-13 and TES-15 also used variations of the TES-7 design. TES-5 was deployed from the ISS in March 2017 and demonstrated this deorbiting capability after 144 days in orbit with the Exo-Brake deploying at 400 km. TES-7, a 2U CubeSat that launched January 2021, onboard Virgin

Orbit's LauncherOne rocket, was placed into orbit at 500 km (13) and decayed May 2022. TES-13 was launched January 2022 with other CubeSats on the third successful Virgin LauncherOne flight and carried an Exo-Brake onboard to demonstrate autonomous navigation and reentry over specific Earth locations. TES-15 was launched October 2022 aboard a Firefly Aerospace Alpha Launcher. Its primary objective was to test an Exo-Brake designed to sustain much higher temperatures than in previous missions. The satellite also included a simple ablator in the nosecap that is expected to last deeper into the atmosphere before burning up. After this experiment, TES-15 should be able to validate higher heating rates and the flight dynamics ability to target an Earth entry point (43). The satellite reentered on October 7, 2022, and the team is analyzing the data to study the performance of this latest flight (44).

The Surrey Space Centre based in the United Kingdom has developed the DragSail technology, which was implemented in a family of missions. The Inflatesail 3U CubeSat first demonstrated this technology. The European Commission QB50 program and the DEPLOYTECH partnership that included German Aerospace Centre (DLR) and NASA Marshall Space Flight Center, among others, funded it. This mission was launched 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 (8).

The RemoveDebris mission was developed under the European Commission FP7 program by a consortium of several institutions such as Airbus and the Surrey Space Centre. The mission consisted of a 100 kg small spacecraft that was 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 showed it only partially deployed since no significant altitude change was measured. 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 (10).

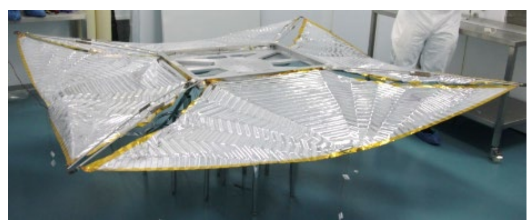


Figure 13.4: Icarus-3 drag sail implemented in the Carbonite-1 mission. Credit: Cranfield Aerospace Solutions.

As part of the ESA CleanSat program, Cranfield Aerospace Solutions in the United Kingdom has also developed a variety of drag augmentation systems. The first demonstrated technology was the Icarus-1, which flew in the TechDemoSat-1 mission from SSTL, launched in 2014. Another version also flew in the Carbonite-1 spacecraft, launched in 2015. The concept is similar to other drag devices in which the drag increases by deploying a membrane sustained by rigid booms. The Icarus technology consists of a thin aluminum structure located around the satellite side panel that contains four stowed Kapton trapezoidal sails and booms. The mass of the system is 3.5 kg for about 5 m^2 of sail area for the Icarus-1, and 2.3 kg for 2 m^2 for the Icarus-3 (figure 13.4). Both sails deployed successfully and are expected to deorbit both spacecraft in less than 10 years. The second technology developed by Cranfield Aerospace Solutions is a de-orbit mechanism (DOM) device which consists of a version of the drag sail presented 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 in the European Student Earth Orbiter on a 45 kg satellite that carried several student payloads. Among them, the Cranfield University DOM module will deorbit the spacecraft after decommissioning. The sail has an area of 0.5 m^2 with a mass of 0.5 kg (6).

MMA Design LLC, a company from Colorado, has patented the dragNET de-orbit system. The 2.8 kg module (figure 13.5) deorbited the ORS-3 Minotaur Upper Stage in 2.1 years after launch in November 2013. DragNet features 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 in less than 10 years (5).

Redwire Space holds an exclusive license for the Flexible Unfurlable and Refurlable Lightweight (FURL) solar sail developed and tested by the Air Force Research Laboratory (AFRL). FURL extends and retracts with four booms stored around a common hub. Small satellites can employ solar sails to control attitude, change planes or remain in their proper orbits and then retract the sail once it reaches its destination. This technology could be applied to deorbit applications as well.

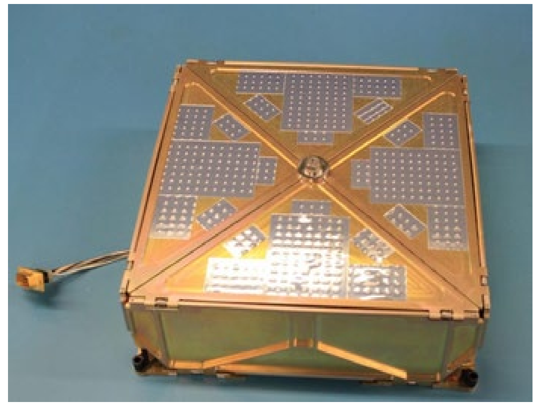


Figure 13.5: DragNet module. Credit: MMA Design LLC.

Purdue University has developed a drag device with a pyramid geometry that can deorbit a satellite placed in a geosynchronous transfer orbit (GTO). The Aerodynamic Deorbit Experiment (ADE), developed jointly with CalPoly and Georgia Tech, will consist of a 1U CubeSat technology demonstration deployed from a Centaur upper stage in a future Atlas V rocket from United Launch Alliance. Once deployed, the device will occupy an area of about 1 m^2 to decrease the ballistic coefficient of the spacecraft and reduce the perigee altitude during each pass. Consequently, the expected lifetime of the ADE mission will be 50 – 250 days instead of the estimated seven years (21). The technology has been licensed to Vestigo Aerospace which is commercializing the drag device with their Spinnaker series of drag sails and has been awarded funding from NASA's Phase II Small Business Innovation Research (SBIR) Program (37). The company, which is licensing the technology through Purdue University, expects to start sales in 2023 for small satellites. An initial flight test was attempted in September 2021 aboard the first Firefly Aerospace Alpha rocket. The Spinnaker3 concept sail consisted of a 18 m^2 sail, and was supposed to deorbit the upper stage of the launch vehicle, however the launch ended with an explosion shortly after liftoff (45). Vestigo is developing two main products, a sail targeted for small satellites that has a surface area of 1.77 m^2 and a larger 18 m^2 sail for objects weighing up to 1000 kg (46).

In June 2022, China launched a Long March 2D rocket that carried a 25 m^2 drag sail attached to the payload adapter on the rocket upper stage. The 300 kg object could deorbit within two years due to this technology (48).

BAMA 1 was a 3U CubeSat developed by the University of Alabama that carried a drag sail module to rapidly deorbit the satellite. It was launched aboard the Astra Rocket 3.3 but was unable to reach orbit due to launch failure (49).

13.2.2 Deployable Booms

Deployable booms, while not strictly a deorbit device themselves, compose a vital part 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 Chapter 6: Structures, Materials, and Mechanisms.

In 2019, the first ROC-FALL drag-based deorbit device was launched on the General Atomics OTB-1 spacecraft (38). Built by Redwire Space, the ROC-FALL device consists of a rectangular sail supported by a High Strain Composite (HSC) boom that is co-wrapped on a spool and restrained with a strap for stowage. The ROC-FALL system is scalable both in width and length to accommodate a variety of spacecraft sizes, and the heritage system sail measures 3.8 x 0.45

m in deployed area and rolls to a 0.04 x 0.45 m tube + supporting mechanism. The ROC-FALL is tip-rolled and passively deployed from the spacecraft. Redwire Space offers a variety of deployable boom technologies with a wide range of applications on small spacecrafts including open lattice mast, rollable tubes, and telescopic booms that can be applied on small spacecraft.

The University of Florida has developed the Drag Deorbit Device (D3) 2U CubeSat which provides attitude stabilization and modulation of the satellite drag area at the same time, making the overall solution an alternative to regular ADCS units. 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 (18) (19). Figure 13.6 shows two images of the final design. The mission was selected by NASA through the CubeSat Launch Initiative, which included eligibility for placement on the ELaNa-45 launch manifest (20). On September 6, 2022, D3 was succesfully placed in orbit by the NanoRacks NRCSD CubeSat deployer that is located on the International Space Station (47).

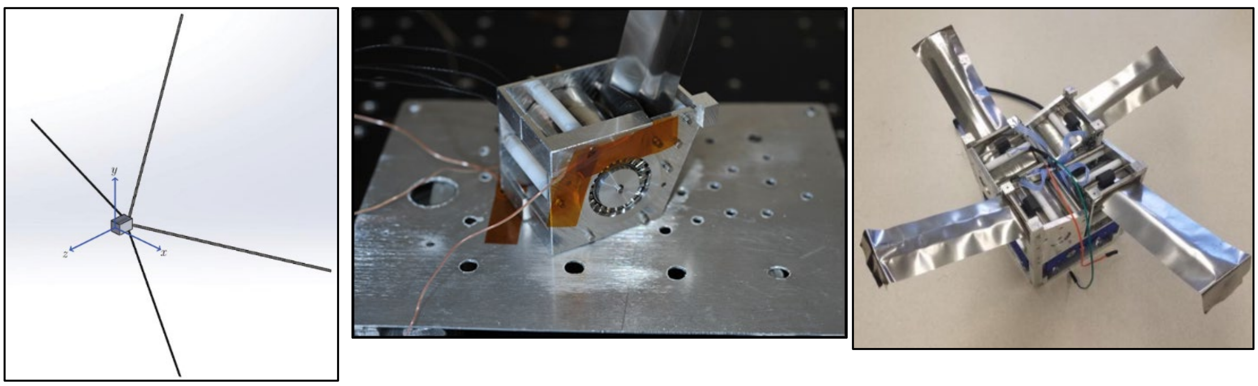


Figure 13.6: D3 CAD design (left), boom inside thermal vacuum chamber (center), and prototype design (right). Credit: Omar et al., 2019, and Martin et al., 2019.

Composite Technology Development, Inc. has developed the Roll-Out DeOrbiting device (RODEO) that consists of a lightweight film attached to a simple, ultra-lightweight, roll-out composite boom structure (figure 13.7). This is a self-deploying system where the stored strain energy of the packaged boom provides the necessary deployment force. It was successfully deployed on suborbital RocketSat-8 (138 kg) on August 13, 2013 (14).

Figure 13.7: RODEO stowed. Credit: Composite Technology Development, Inc.

13.2.3 Electromagnetic Tethers

In addition to drag sails, an electromagnetic tether has 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. 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 (7). 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 just 0.083 kg. Figure 13.8 shows an image of both systems respectively (16). The 70 m long NSTT has been implemented in the 71 kg Prox-1 satellite, launched in mid-2019 by AFRL.

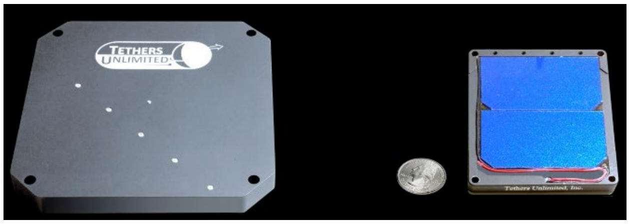


Figure 13.8: Image of the NSTT (left) and the CSTT modules. Credit: Amergint Technologies.

DragRacer, an experiment jointly developed by Tethers Unlimited, Millennium Space Systems, RocketLab, and TriSept Corp., consisted of a satellite (Alchemy) with the terminator tape, and another satellite (Augury) without it, to characterize the tape performance (17). Alchemy reentered in July 2021 while Augury is still in orbit.

The AeroSpace Corporation 2 kg and 1.5 AeroCube 5A and 5B CubeSats, launched in 2015, also incorporated a version of the terminator tape.

13.3 State-of-the-Art – Active Systems

Several companies have been increasingly offering active spacecraft-based deorbit systems. Space startups such as AstroScale, ClearSpace, and D-orbit have long-term plans and have already started initial technology demonstration missions. These systems consist of separate, dedicated spacecraft that attach to decommissioned satellites to place them into decaying or graveyard orbits. In December 2019, Iridium stated that they would like to pay for an active deorbit system to remove 30 of their defunct satellites (22). In addition, for NASA missions, the NASA STD-8719.14C document stipulates that all spacecraft using controlled reentry processes, the designed trajectory must guarantee that no remaining debris that could impact with a kinetic energy greater than 15 Joules is nearer than 370 km from foreign landmasses, or within 50 km from any territory of the United states and the permanent ice pack of Antarctica (10) (65).

This section covers some of the main stakeholders in the industry that are working towards the implementation of active space debris removal, as well as some other promising technologies that can potentially be used for actively deorbiting spacecraft in the future.

13.3.1 TechEdSat Series Exo-Brake

The Exo-Brake introduced earlier in the passive systems also has active control capability. The TES-6 mission was the first to implement this technology with a 3.5U CubeSat with a mass of 3.51 kg that deployed its Exo-Brake from the rear of the satellite. It targeted a reentry over Wallops Flight Facility by modulating the drag device to adjust the ballistic coefficient as orbital determination about the satellite state became available over time. The Iridium gateway enabled the command of the brake, which proved to significantly affect the reentry time and consequently, the location of the Wallops target area. The spacecraft overshot the intended target range slightly as shown in the second image, since it could not achieve a lower 4 – 5 kg m^{-2} ballistic coefficient configuration, which would have yielded suitable results if placed at 300 km (see figure 13.9).

Figure 13.9: Targeting of the TES-10 Exo-brake is achieved by modifying the drag area of the modulating Exo-brake. (Left) The plot includes actual GPS readings and the approximate ballistic coefficient achieved at different parts of the mission. (Right) The simulated reentry location of TES-10. The spacecraft overshot but still demonstrated the capability to target a particular location by modifying its ballistic coefficient. Credits: Jose Alvarellos et al. 2021/Sanny Omar/NASA.

Figure 13.10: TES-10 deployment from the ISS in July 2020. Credit: NASA.

However, the mission successfully demonstrated the reentry experiment and the command/control capability by overflying Wallops right before reentering. This technology was going to be demonstrated again in the TES-8 mission, although a power system failure occurred before the targeting process. It should be noted that the Exo-Brake was successfully deployed on TES-8, an improved version of the previous TES-5 and TES-6 devices. The TES-8 ballistic coefficient range was wider (6 – 18 kg m^{-2}), and enabled better control authority for targeting. TES-10 and upcoming TES-11 are also incorporating this design (12). TES-10 (figure 13.10) marked the second targeted deorbit flight test and successfully overflew NASA Wallops Flight Facility much like TES-6 (33). TES-15 reentered seven days after deployment, and the team is evaluating the data to determine the performance of a new version of the Exo-Brake.

13.3.2 RemoveDebris Consortium Partners

The RemoveDebris mission carried two 2U CubeSats that were ejected from the mothership to simulate space debris and demonstrate active deorbit capabilities. The first CubeSat, known as DebrisSat-1, deployed at a very low velocity from the main spacecraft and subsequently inflated a balloon that provided a larger target area. A 5 m diameter net was ejected from the main spacecraft just 144 seconds after deployment, capturing the CubeSat at a distance of ~11 m from the mothercraft. The object, once enveloped in the net, re-entered the atmosphere in March 2019 (10). The RemoveDebris mission also carried another active debris technology consisting of a harpoon. In this scenario, a target platform attached to a boom was deployed from the main spacecraft. The mothership then released the harpoon at 19 m/s to hit the platform in the center. Once that occurred, the 1.5 m boom that connected the two objects snapped on one end. However, a tether secured the target in place, avoiding the creation of new debris. This resulted in the first demonstration of a harpoon technology in space. The harpoon target assembly had a dry mass of 4.3 kg (10).

13.3.3 Astroscale

Astroscale is a company founded in Japan with offices in the UK, the US, and Singapore. Their two main objectives are to provide services to address the end-of-life (EOL) scenario of newly launched satellites, and to proactively remove existing space debris. They collaborate with a variety of governmental and international organizations around the world (such as the US government, ESA, the European Union, or the United Nations) to position themselves as leaders of a more sustainable low-Earth orbit environment.

As part of the EOL campaign, the ELSA-d mission, which launched on March 22, 2021, consists of two spacecraft, with one acting as a 'servicer' and the other as a 'client' (29). They have launch masses of ~175 kg and ~17 kg respectively. The concept of operations is to perform rendezvous maneuvers by releasing the client from the servicer repeatedly to demonstrate the capability of finding and docking with existing debris. The technology demonstrations include search and inspection of the targets, as well as rendezvous of both tumbling and non-tumbling cases (29). 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 (41). The ELSA-M spacecraft will leverage the lessons learned and technology demonstrated in this precursor mission to support a range of future satellite operators that may carry a compatible magnetic capture mechanism such as the Astroscale Docking Plate. The ELSA-M in-orbit demonstrator is planned to launch by the end of 2024 (54). It is important to note that several science missions undertake extensive efforts to make their spacecraft magnetically neutral, which may be a concern for this method and its application in some cases.

Regarding their active debris removal campaign, Astroscale is also working with national space agencies to incorporate solutions to remove critical debris such as rocket upper stages or defunct satellites. This campaign started with a partnership with the Japanese Space Agency (JAXA) in February 2020. This collaboration will result in the implementation of the Commercial Removal of Debris Demonstration project (CRD2) which consists of the removal of a large space debris object performed in two mission phases. Astroscale will be involved in both phases. The first phase consists of a satellite that identifies and acquires data from a JAXA rocket upper stage. The Active Debris Removal by Astroscale-Japan (ADRAS-J) satellite which will complete this first phase is scheduled to launch aboard a Rocket Lab Electron rocket in 2022 (42). Once deployed, the satellite is supposed to rendezvous with the upper stage to demonstrate proximity operations and obtain images to better understand the space debris environment (51). In August 2022, Astroscale was also selected to participate in the Phase II of the CRD2 project. The company will be responsible for the Front-Loading Technology Study which will focus on the ground test of hardware and software for close proximity operations and the capture mechanism design. This study is a requirement for satellite providers in the CRD2 Phase 2 mission (51).

Astroscale announced in May a $3.5 million funding award from OneWeb, the global communications network, to further develop their technology with the goal of commercial services starting in 2024. The next iteration consists of the ELSA-M satellite which will be capable of deorbiting multiple satellites per mission. OneWeb has also committed to including a docking plate on their satellites that would facilitate future deorbit missions (31). In September 2022, Astroscale secured funding from the UK Space Agency to keep developing the latest mission phase of the Cleaning Outer Space Mission through Innovative Capture (COSMIC). This mission will be an evolution of the Astroscale ELSA-M platform with a goal of removing two defunct British satellites by 2026 (55).

13.3.4 ClearSpace

ClearSpace is a Swiss company founded as a spin-off from the Ecole Polytechnique Federale de Lausanne research institute. Their plans also include service contracts for active debris removal.

One of their proposed missions, ClearSpace One, which has been backed by ESA, will find, target, and capture a non-cooperative, tumbling 100 kg Vega Secondary Payload Adapter (VESPA) upper stage. The chaser spacecraft will be launched into a 500 km orbit for commissioning and initial testing before raising its altitude to the VESPA's 660 km orbit, where it will attempt rendezvous and capture. ClearSpace One will use a group of robotic arms to grab the upper stage, and then both spacecraft will be deorbited together to a lower orbit for final disintegration in the atmosphere. The mission is planned to launch in 2025 to help establish a market for in-orbit servicing and debris removal (25).

In October 2021, the UK Space Agency commissioned ClearSpace to develop a feasibility study to remove at least two UK defunct satellites. The study was successfully completed in March 2022 and a new contract was awarded to perform a second phase of the project, which will finish with the preliminary design review in 2023 of the Clearing of the LEO Environment with Active Removal (CLEAR) mission. This mission plans to remove two UK objects that have been in orbit for more than 10 years in an altitude of over 700 km, with a deorbit time longer than a hundred years (53).

13.3.5 Momentus

Momentus is a company founded in 2017 and based in California that operates space transportation systems that can propel or deorbit other spacecraft. Their Vigoride platform can carry satellites with masses up to 250 kg. With a wet mass of 215 kg, it can provide up to 1.6 km s^{-1} for 50 kg payload, through a water plasma propulsion system (26). Although the main objective of this system is to provide enhanced propulsive capability to their customers, the platform is suitable for active deorbiting. Momentus launched its first Vigoride transfer vehicle on May 25, 2022, and successfully deployed three satellite payloads to their respective orbits as of September 2022 (56).

13.3.6 D-orbit

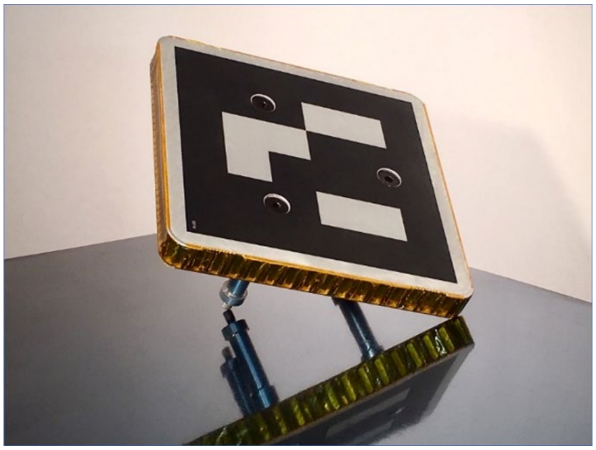
D-orbit is a space transportation company founded in 2011 in Italy, with subsidiaries in Portugal, the United Kingdom, and the United States. It provides transportation services onboard their ION CubeSat carrier platform that can provide precision deployment and is able to host satellites from 1 to 12U. The first mission Origin released 12 SuperDove satellites for the Earth-observation company Planet, deploying the first in September 2020 with the last SuperDove deployed about a month later (34). The most recent Pulse mission finished deploying 20 satellites May 11, 2021 (35). Future versions of this technology may consider other applications such as retrieving orbiting spacecraft to deorbit them. In June 2022, D-Orbit secured a contract with ESA to improve the performance and reduce the cost of its ION transfer vehicle. Over six flights, D-Orbit has already deployed over 80 satellites successfully into their orbits (57).

In addition, D-orbit provides an external solid motor booster specifically for deorbiting purposes. This independent module, known as D-Orbit Decommissioning Device (D3) shown in figure 13.11, is a proprietary solution that is optimized for end-of-life maneuvers (27). However, it is important to note that, as compared to some other technologies in this active systems section, this technology would need to be added prior to launch.

Figure 13.11: D-Orbit D3 module. Credit: D-orbit.

13.3.7 Altius Space Machines

In 2019, the satellite constellation company OneWeb signed a partnership with Altius Space Machines from Boulder, Colorado, to include a grappling fixture on all their future launched satellites in an effort to make space more sustainable. On January 14, 2021, it was announced that the first batch of DogTags were launched into space on OneWeb satellites (36). The Altius



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 13.12: Flight DogTags. Credits: T. Maclay, J. Goff, J.P. Sheean, and E.Han (2020).

DogTag consists of a universal interface for small satellites that is inexpensive and lightweight. The fixture design enables various grappling techniques to enable servicing or decommissioning. It uses magnetic capabilities as its primary capture mechanism but is also compatible with other techniques to accommodate other potential customers and act as a standard interface (28). More specifically, it is compatible with magnetic attraction, adhesives, mechanical, and harpooning captures. Figure 13.12 includes an image of the flight DogTags and a table of its main features. In February 2022, an ArianeSpace Soyuz launch vehicle carried 34 OneWeb satellites into orbit with corresponding Altius DogTags to mitigate future space debris. In total, over 300 DogTags have already been launched to space (50).

13.3.8 Other Transfer Vehicle Projects

Other companies are also developing their own the transfer vehicle technology for the LEO environment. These include UARX Space, based in Spain, which is developing its Orbit Solutions to Simplify Injection and Exploration (OSSIE) transfer vehicle. This spacecraft is designed to be modular and scalable to satisfy customer requirements by using either electric or chemical propulsion (52).

SpaceLogistics Inc., a subsidiary of Northrop Grumman announced the first flight of their Mission Robotic Vehicle (MRV) for 2024. The MRV will be aboard a SpaceX rocket and it will be equipped with a robotic arm (58).

Spaceflight Inc. has developed a complete family of transfer vehicles. The Sherpa-NG program is designed to minimize deployment times while maximizing mission assurance (59). Spaceflight Inc.'s Sherpa-LTC2 transfer vehicle was launched in September 2022 (60).

Inversion, a start-up founded in Los Angeles in 2022, plans to develop reentry capsules to bring cargo back to Earth from space. The capsules are compatible with any commercial launch vehicle, and are designed to de-orbit and land with a parachute (61). They have developed two designs, Ray and Arc, which are planned to be finalized by 2023 and 2025, respectively (62).

13.4 Summary

Space debris regulations are becoming more stringent. Consequently, several deorbit technologies have been matured significantly over the course of the last few years. Traditionally passive systems have been more common, have flown on various missions, and have increased to TRL 9 after successful technology demonstrations. Drag sails are the main technology for passive systems, and several companies have already commercialized and sold these products.

Other systems such as electromagnetic tethers, deployable booms, or the NASA TechEdSat series Exo-Brake have also already been prototyped and demonstrated in space, now with navigation capabilities and increased reliability. On the other hand, the investment in active systems has grown significantly. Several companies are offering transfer vehicles to remove debris or deorbit spacecraft at the end of their mission. Compatible systems to enable spacecraft rendezvous and removal are being developed in parallel as well. As an example, the RemoveDebris mission has successfully tested two different active methods, a net and a harpoon, for future implementation in active debris removal operations. Companies such as Astroscale or 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 the robustness of the technologies is expected to grow even further as demand for deorbiting services increases with additional launches and new 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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