NASA/TP—2024–10001462

State-of-the-Art
Small Spacecraft Technology

Small Spacecraft Systems Virtual Institute

Ames Research Center, Moffett Field, California

February 2024

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National Aeronautics and
Space Administration

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February 2024

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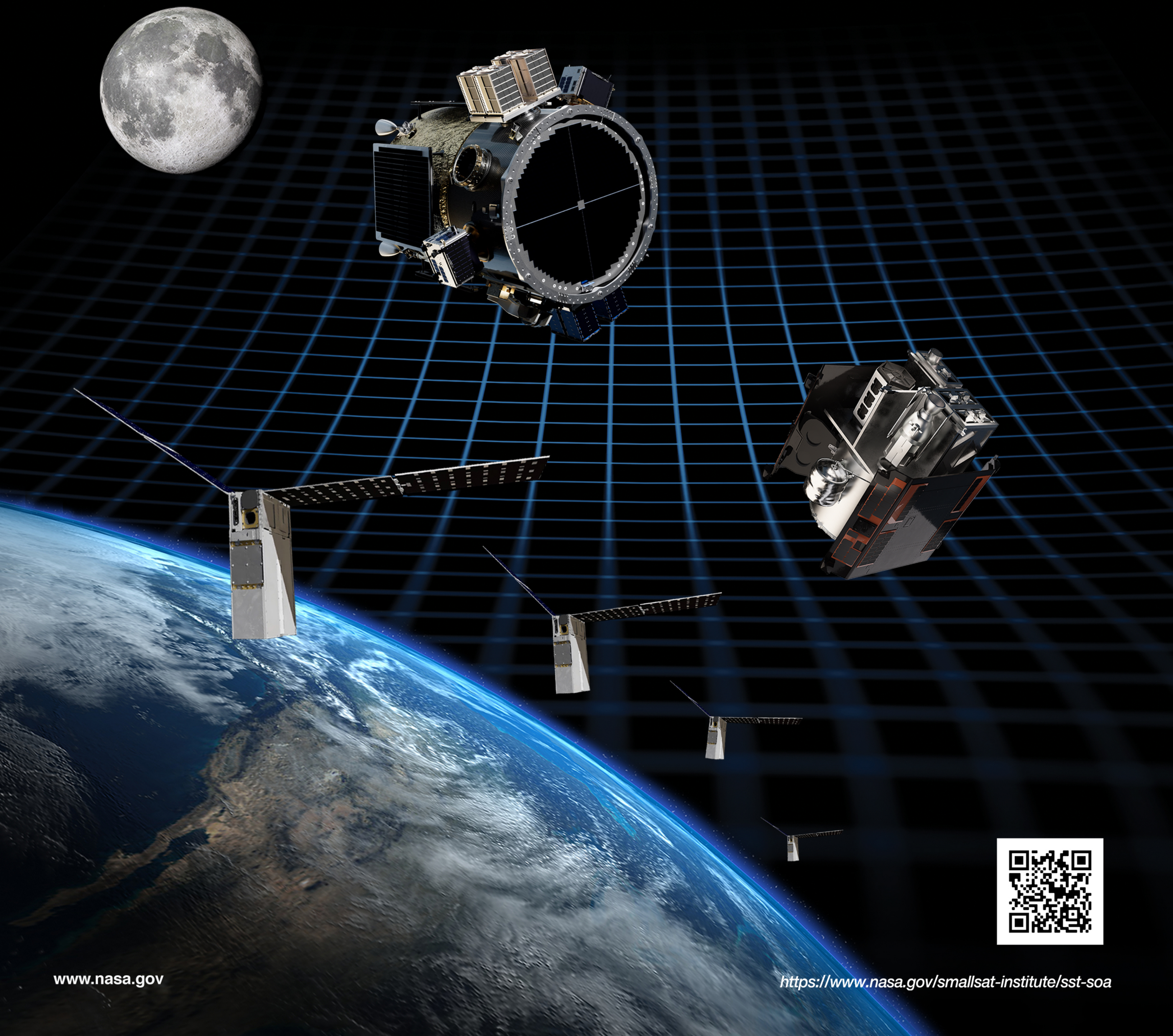
Small Spacecraft Technology
State-of-the-Art Report

2023 Edition



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Four Lower Spacecraft: Artist depiction of Starling CubeSat swarm
Credit: NASA

NASA Ames Research Center, Small Spacecraft Systems Virtual Institute

February 2024

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Helpful suggestions and contributions were also received from numerous people across NASA. In particular, the following are acknowledged for their participation as contributors or reviewers on the 2023 SOA report:

From NASA Ames Research Center: Craig Burkhard, Andres Dono, Julianna Fishman, Scott Miller, Marc Murbach and the TechEdSat team, Shang Wu, and Senior Technical Editor Teague Soderman

From NASA Glenn Research Center: Marc Abadie, Drew Ahern, Gabriel Benavides, Jonathan Valenzuela Brok, William Fabanich, James Gilland, Yao Kovach, Thomas Liu, Brian Reed

From NASA Goddard Spaceflight Center and Wallops Flight Facility: Rebekah Austin, Eric Golliher, Eliad Peretz, Luis Santos Soto, and David Steinfeld

From NASA Marshall Space Flight Center: Les Johnson, Jodi Turk, and Hunter Williams

From NASA Kennedy Space Center: Liam Cheney, Shaun Daly, Norman Phelps, Jorge Piquero

From NASA Langley Research Center: Laurence Thomsen

From NASA Headquarters: Lauri Newman

From Jet Propulsion Laboratory: Colleen Marrese-Reading and Frank Picha

From Bryce Space and Technology: Joseph Zimo and Anh Nguyen

The authors would like to also thank all of the companies, universities and organizations who provided information for this report.

Contents

Change Summary

Published Date	Edition	Chapter	Description of Changes
February 2024	2023	Complete Spacecraft Platforms	All technology tables updated.
		Power	The Solar Panel section in the Power chapter was updated.
		In-space Propulsion	All three major sections (Chemical, Electric, and Propellant-less) were updated to reflect the surge of commercial propulsion technologies.
		GNC	Edits pending next edition.
		Structures, Materials, and Mechanisms	The Mechanisms and Primary Structures sections updated.
		Thermal Control	New passive and active technology tables included.
		SmallSat Avionics	On-board Computing Systems table updated.
		Communications	Edits pending next edition.
		Launch, Integration, Deployment, and Orbital Transport	A new OMV section included with information on reusable in-space servicing vehicles.
		Ground Data Systems and Mission Operations	Updated content in Ground Segment Services, Ground Station Components, Ground Data and Supporting Systems sections.
		ID and Tracking	Minor edits throughout chapter.
		Deorbit Systems	New Orbital Debris Regulations section included; Drag Sail table and Passive and Active sections updated.

1.0 Introduction

1.1 Objective

The objective of this report is to assess and provide an overview of the state of the art in small spacecraft technologies for mission designers, project managers, technologists, and students, connecting current small spacecraft missions to available technologies. This report focuses on the spacecraft system in its entirety, provides current best practices for integration, and then presents the state of the art for each specific spacecraft subsystem. Certain chapters have a particular emphasis on CubeSat platforms, as nanosatellite applications have expanded due to their high market growth in recent years.

This report is funded by NASA's Space Technology Mission Directorate (STMD). It was first commissioned by the Small Spacecraft Technology (SST) program within NASA's STMD in mid-2013 in response to the rapid growth in interest in using small spacecraft for low-Earth orbit, low-cost missions. The report was subsequently updated in 2015, 2018, 2020, 2021, and 2022 to capture smallsat technology growth and maturation. In addition to reporting currently available state-of-the-art technologies that have achieved TRL 5 or above, a prognosis is provided describing technologies as "on the horizon" if they are being considered for future application.

1.2 Scope

The SmallSat mission timeline began at NASA Ames Research Center with the launch of Pioneer 10 and 11 that launched in March 1972 and April 1973, respectively, where both spacecraft weighed < 600 kg. To address the increase in mass and associated cost with the high launch cadence, NASA initiated the Small Explorer (SMEX) program in 1988 to encourage the development of small spacecraft with masses in the range of ~60–350 kg. In 1998, Ames' SmallSat program then focused on lunar exploration and launched Lunar Prospector (< 700 kg), followed by the Lunar Crater Observation and Sensing Satellite (LCROSS), (< 630 kg) in 2009, and the Lunar Atmosphere and Dust Environment Explorer (LADEE), (~380 kg) which was launched in September 2013. In late 2010, NASA launched its first minisatellite called Fast, Affordable, Science and Technology Satellite (FASTSAT), which had a launch mass ~180 kg. This decrease in spacecraft mass, reduced overall cost, and increase in science capabilities ignited interest in miniaturization and maturity of aerospace technologies which have proven to be capable of producing more complex missions for less cost.

The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) payloads provided up to 180 kg mass allocation to six payload slots in 2012 when this report was first being written. As this report is focused on smaller platforms, the "180 kg mass limit" served as a good indicator to further classify the maximum "SmallSat" mass. SmallSats are generally grouped according to their mass, and this report adopts the following five small spacecraft mass categories (1):

- minisatellites are spacecraft with a total mass of 100 – 180 kg;
- microsatellites have a total spacecraft mass of 10-100 kg;
- nanosatellites have a total mass of 1 – 10 kg;
- picosatellites have a mass of 1 – 0.01 kg; and
- femtosatellites have a total spacecraft mass 0.01 – 0.09 kg.

Figure 1.1 offers examples of the various categorized spacecraft. On the lower mass end, there are projects such as KickSat-2, which deployed 100-centimeter (cm) scale "ChipSat" spacecraft, or Sprites, from a 2U femtosatellite deployer in March 2019. These femtosatellite ChipSats are the size of a large postage stamp and have a mass below 10 grams.

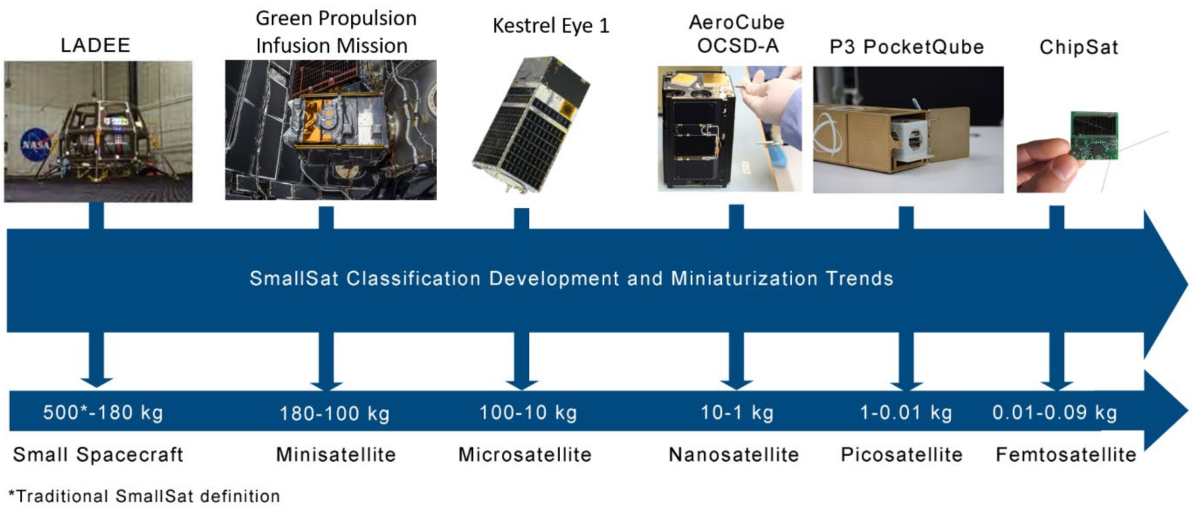


Figure 1.1: Overview of small spacecraft categories. Credit: NASA, SpaceX, Redwire Space, and Alba Orbital.

In 1999, a collaboration between California Polytechnic State University (Cal Poly) in San Luis Obispo and Stanford University in Stanford, California, developed a small educational platform called a "CubeSat" which was designed for space exploration and research for academic purposes. CubeSats are now a common form of small spacecraft that can weigh only a few kilograms and are based on a form factor of a 10 cm square cube, or unit (U) (1). The original CubeSat was composed of a single cube, a 1U, and it is now common to combine multiple cubes to form, for instance, 3U or 6U units as shown in figure 1.2. These larger CubeSat sizes have become more standardized and popular in the past five years as much more science can be achieved at less cost with the additional volume, power, and overall increase in capability.

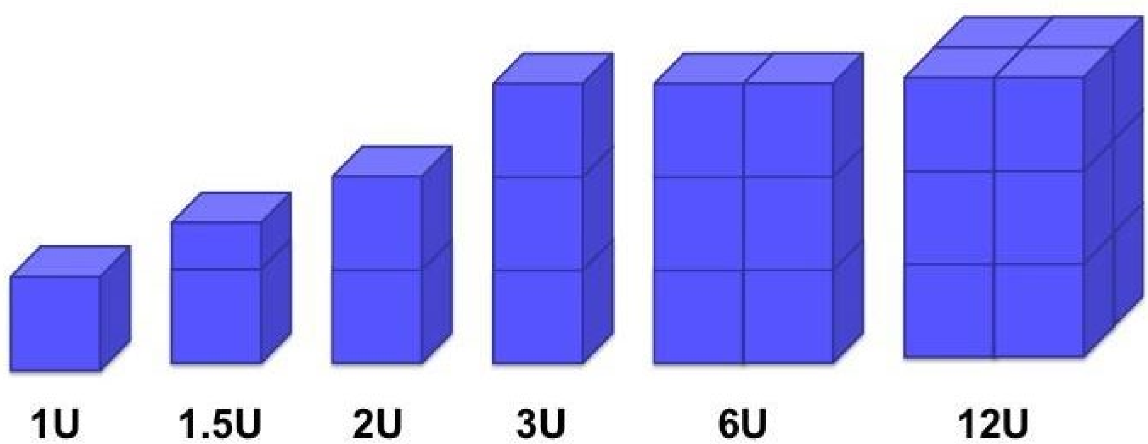


Figure 1.2: CubeSats are a class of nano- and microsatellites that use a standard size and form factor. Credit: NASA.

It is common to interchange the terms “CubeSat” and “NanoSat” (short for nanosatellite) as the original 1-3U CubeSat platforms fall under the nanosatellite category. Since the physical expansion of CubeSats in 2014 with the 6U form factor, CubeSats now fall into both nanosatellite and microsatellite categories, and this report refers to a nanosatellite as a spacecraft with mass under 10 kg; a microsatellite as a spacecraft with mass greater than 10 kg; and a CubeSat as the accepted form factor. Figure 1.3 illustrates the three smaller SmallSat categories: microsatellites, nanosatellites, and picosatellites.

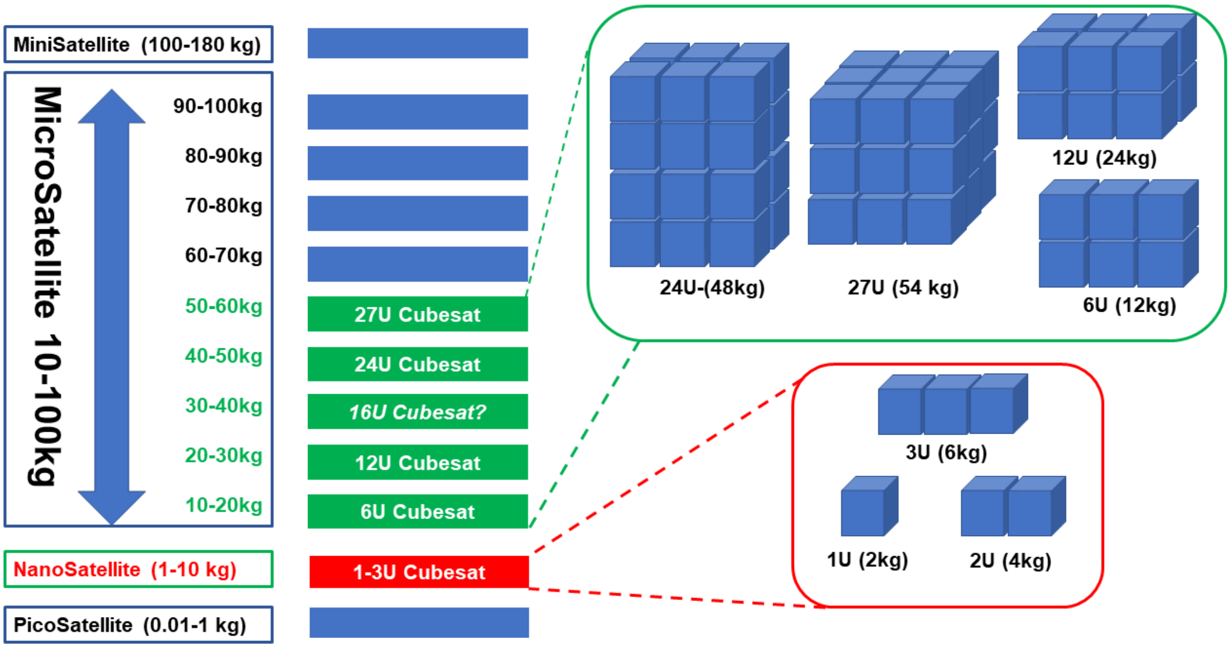


Figure 1.3: Nanosatellite sizes compared to CubeSat containerized sizes. Credit: NASA.

1.3 Assessment

While “state-of-the-art” may be defined as the most recent development stage of technology, this report considers NASA’s Technology Readiness Level (TRL) scale (figure 1.4) when assessing SmallSat technology. A technology may be deemed state-of-the-art whenever its TRL is larger than or equal to 5. A TRL of 5 indicates that the component and/or brassboard with realistic support elements was built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas. Success criteria include documented test performance demonstrating agreement with analytical predictions and documented definition of scaling requirements. Performance predictions are made for subsequent development phases (2).

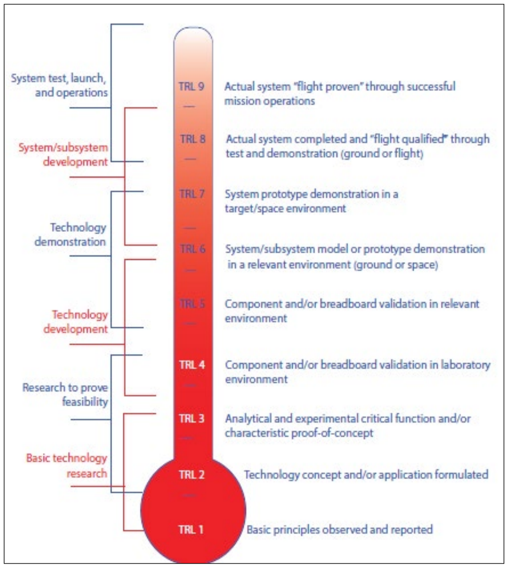


Figure 1.4: NASA’s standard TRL scale. Credit: NASA.

An accurate TRL assessment requires a high degree of technical knowledge on a subject device, and an in-depth understanding of the mission (including interfaces and environment) on which the device was flown. TRL values vary depending on design factors for a specific technology. For example, differences in TRL assessment based on the operating environment may result from mechanical loads, mission duration, the thermal environment, or radiation exposure. The authors believe TRLs are most accurately determined when assessed within the context of a program's unique requirements. If a technology has flown on a mission without success, or without providing valid confirmation to the operator, such claimed "flight heritage" is discounted. Some older technologies may still be well suited to certain mission needs and still be regarded as "state-of-the-art." For a technology to be considered obsolete, "retired", or no longer "state-of-the-art", it's performance must have been surpassed by newer technology such that it is no longer used.

While a technology with a TRL value lower than or equal to 4 may not be state of the art, in some cases these technologies may considered "on the horizon." A TRL of 4 is defined as a component and/or breadboard validated in a laboratory environment with documented test performance demonstrating agreement with analytical predictions and a documented definition of the relevant environment. These promising technologies may soon be considered state-of-the-art for small spacecraft.

NASA standard TRL requirements for this report edition are stated in the NPR 7123.1C, Appendix E, which is effective through February 14, 2025. The criteria for selection of appropriate TRL are described in the NASA Systems Engineering Handbook 6105 Rev 2 Appendix G: Technology Assessment/Insertion. Please refer to the NASA Online Directives Information System (NODIS) website https://nodis3.gsfc.nasa.gov/ for NPR documentation. The following paragraphs in sections 1.3.1 and 1.3.2 of this introduction are excerpts from the NASA Engineering Handbook 6105 Rev 2 (pp. 252 – 254). They highlight important aspects of NASA TRL guidelines in hopes of eliminating confusion on terminology and heritage systems.

1.3.1 Terminology

"At first glance, the TRL descriptions in figure 1.4 appear to be straightforward. It is in the process of trying to assign levels that problems arise. A primary cause of difficulty is in terminology, e.g., everyone knows what a breadboard is, but not everyone has the same definition. Also, what is a "relevant environment?" What is relevant to one application may or may not be relevant to another. Many of these terms originated in various branches of engineering and had, at the time, very specific meanings to that particular field. They have since become commonly used throughout the engineering field and often acquire differences in meaning from discipline to discipline, some differences subtle, some not so subtle. "Breadboard," for example, comes from electrical engineering where the original use referred to checking out the functional design of an electrical circuit by populating a "breadboard" with components to verify that the design operated as anticipated. Other terms come from mechanical engineering, referring primarily to units that are subjected to different levels of stress under testing, e.g., qualification, protoflight, and flight units. The first step in developing a uniform TRL assessment (see figure 1.5) is to define the terms used. It is extremely important to develop and use a consistent set of definitions over the course of the program/project."

1.3.2 Heritage Systems

"Note the second box particularly refers to heritage systems (figure 1.5). If the architecture and the environment have changed, then the TRL decreases to TRL 5—at least initially. Additional testing may need to be done for heritage systems for the new use or new environment. If in subsequent analysis the new environment is sufficiently close to the old environment or the new

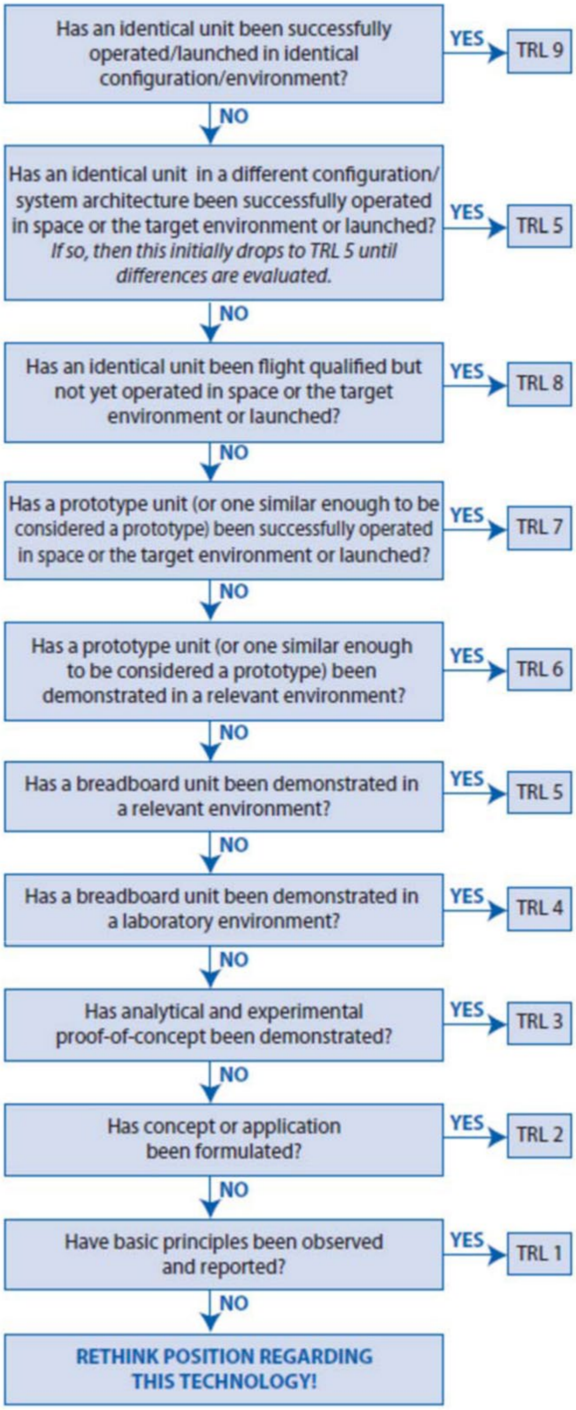


Figure 1.5: Technology Maturity Assessment (TMA) thought process. Credit: NASA.

architecture is sufficiently close to the old architecture, then the resulting evaluation could be TRL 6 or 7, but the most important thing to realize is that it is no longer at TRL 9. Applying this process at the system level and then proceeding to lower levels of subsystems and components identifies those elements that require development and sets the stage for the subsequent phase, determining the new TRL."

References

(1) NASA. What are SmallSats and CubeSats? February 26, 2015. Revised August 6, 2017. https://www.nasa.gov/content/what-are-smallsats-and-cubesats

(2) NASA Systems Engineering Handbook. NASA/SP-2016 6105 Rev. 2. https://www.nasa.gov/feature/release-of-revision-to-the-nasa-systems-engineering-handbook-sp-2016-6105-rev-2

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

Space debris, also known as orbital debris or space pollution, are derelict artificial objects left in space on purpose and 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 the 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, and thus producing even more space debris.

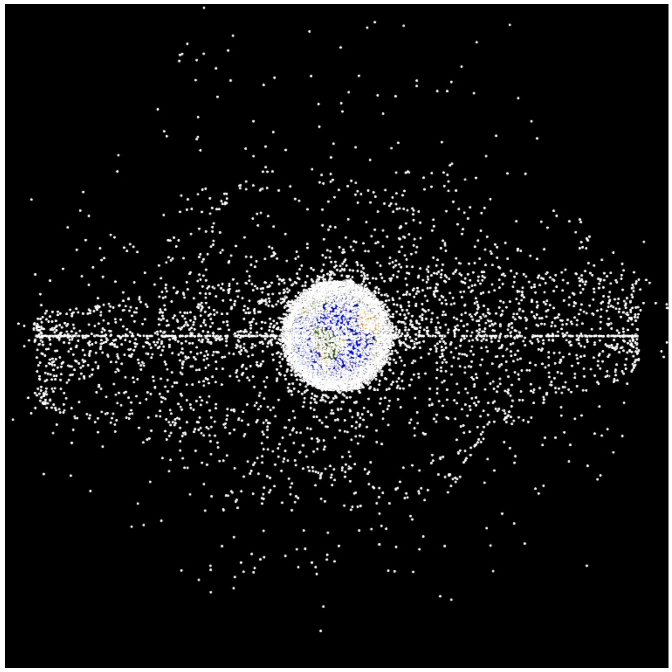


Figure 13.1: Orbital debris around Earth. Credit: NASA.

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 in the past decade. Improved access to space has made LEO accessible and less expensive for more countries, organizations, and institutions to launch a small spacecraft mission which only adds to the associated space debris risks and threats. Estimates of the accumulation of orbital debris suggest approximately 100,000,000 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 really helpful at <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 graveyard orbit within a maximum of 25 years after the completion of their mission (3).This standard spacecraft lifetime regulation has been recently updated that directs NASA and other national agencies to reassess current mitigation policies, especially regarding the potential advantages and cost implications resulting from limits on the space debris orbit lifetime (4). These regulations have incorporated spacecraft decay capabilities into mission design.

The rate of spacecraft decay in LEO depends on several factors, including the initial orbit insertion, the ballistic coefficient of the spacecraft, and solar weather conditions, which all play a fundamental role in the ability to comply with decommissioning regulations. Small spacecraft designers have examined various strategies for complying with decommissioning regulations to accelerate spacecraft decay post mission: spacecraft are launched in a lower orbit for a natural decay within a few years or equipped with deorbit systems to encourage altitude decay and ultimately reenter and burn up in the 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 making them susceptible to use 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) that are guaranteed to satisfy 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 requires 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, up until its final stage of decommission, 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 the deorbit using their own drag decay.

The influx of small spacecraft in LEO has also developed space situational awareness and space traffic management data. For information on this, please see the *Identification and Tracking Systems* chapter.

13.1.1 Chapter Organization

This chapter is organized as follows:

- Orbital Debris Regulations (13.2)
- Passive Deorbit Systems (13.3)
- Active Deorbit Systems (13.4)

Orbital Debris Regulations provide the reader with a comprehensive understanding of the current policy regulations for deorbit mitigations, when they were initiated, and the organizations that implement space orbiting debris regulations. The Passive and Active Deorbit System sections contain technology description, summary table 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 within existing deorbiting capabilities and current development status on 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. 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.

Definitions

- *Disposal* refers to removal of spacecraft from 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 two orbiting bodies.
- *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 total time spacecraft is 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 was created in 1979, 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 internationally.

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 updated 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 be greater than 1 in 10000 (5). Of the three spacecraft disposal methods identified – direct retrieval, atmospheric re-entry, and maneuvering into a storage orbit – atmospheric reentry was deemed as the most feasible for the majority of spacecraft missions. Therefore, a maximum 25-year post-mission orbital lifetime (no longer than 30 years after launch or a move into a graveyard orbit for safe storage) was established for all US spacecraft. The rationale for this specific orbital lifetime was based on the least amount of propellant required to maneuver to a lower orbit as predicted by various 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, space debris mitigations 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. On September 29th, 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 after launch (8). As of 2023, there are discussions at the agency and federal level to determine the final policies.

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 that can characterize spacecraft mission compliance with the international space debris remediation guidelines (10)(11).

The Federal Aviation Administration (FAA) announced on September 20th, 2023, a proposal to create a new rule to limit the growth of debris from commercial launch vehicles in order 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 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 the 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 have trouble deorbiting in under 25 years. This is due to potential low atmospheric density conditions and the effects on various ballistic coefficients, as seen in figure 13.2. This graph displays various cases of SmallSats with distinct masses, drag areas, and initial orbits, under the atmospheric density conditions during the 11-year solar cycle maximum and minimum.

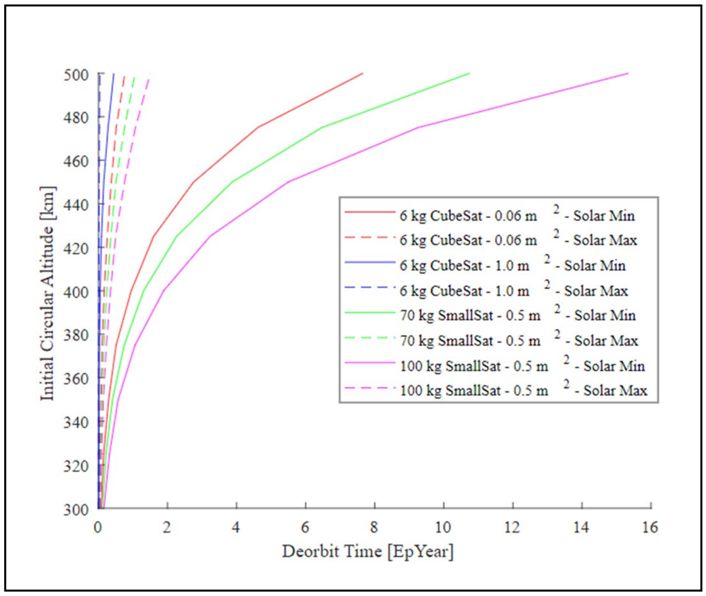


Figure 13.2: Initial orbit altitudes yield different lifetimes depending on the ballistic coefficient of the spacecraft. Three representative area-to-mass ratios are shown. Note that the propagation stops at 16 years, but the initial altitudes yield even longer times. Credit: NASA.

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 in the atmosphere and creates higher density layers in LEO altitudes that produce a stronger drag force on the satellites (13). It is common for some missions to plan their launch periods around the solar cycle, and if the stricter 5-year orbital lifetime requirement becomes widely accepted, more companies may want to consider this, 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). The BC is defined in this chapter as the mass to area ratio multiplied by the inverse of the drag coefficient, that is assumed to equal 2.2. By this definition, a spacecraft with a lower ballistic coefficient will decay faster due to the smaller 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 a 100 kg spacecraft of 0.5 m^2 with 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 become even more important for spacecraft operations in LEO.

13.3 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.

13.3.1 High TRL Drag Sails

Drag devices are the most common deorbit device 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 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.

Table 13-1: Drag Sails									
Product/Mission	**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	(3)
Drag-Net	MMA Design	ORS-3 Deployed a Minotaur Upper Stage (100 kg)	2.8	N/A	2016	2016	14	7-9	(14)
Drag-Net	MMA Design	General Atomics GAzelle Satellite	2.8	N/A	2022	TBC	14	7-9	(15)
Icarus-1	Cranfield Aerospace Solutions	SSTL TechDemoSat-1 (157 kg)	3.5	635 km	2014	2019	6.7	7-9	(16)
Icarus-3	Cranfield Aerospace Solutions	Carbonite-1 (80 kg)	2.3	650 km 98 deg	2015	Future (in-orbit)	2	7-9	(16)
DOM	Cranfield Aerospace Solutions	ESEO (45 kg)	0.5	572 km × 588 km 97.77 deg	2018	Future (in-orbit)	0.5	7-9	(16)
Terminator Tape	Tethers Unlimited, Inc.	Prox-1 (71 kg)	0.808	717 km 24 deg	2019	2019	10.5	7-9	(17)
DragSail	Surrey Space Centre	InflateSail (3.2 kg)	N/A	505 km 97.44 deg	2017	2017	10	7-9	(18)
Exo-Brake	NASA	TechEdSat 5 (3.4 kg)	N/A	405 km 51.5 deg	2014	2015	0.35	7-9	(19)
Exo-Brake	NASA	TechEdSat 7 (3 kg)	N/A	485 x 513 km 60.7 deg	2021	2021	1.2	8-9	(20)
Exo-Brake	NASA	TechEdSat 13 (4 kg)	N/A	505 km 45 deg	2022	2022	0.083	8-9	(20)
Exo-Brake	NASA	TechEdSat 15 (4.5 kg)	N/A	215 x 270 km 137 deg	2022	2022	0.087	8-9	(20)
removeDebris	Surrey Space Centre	removeDebris (100 kg)	N/A	405 km 51.5 deg	2018	2019	16	7-9	(21)

CanX-7	UTIAS-SFL	3U CubeSat (3.6 kg)	0.8 (4 modules of 0.200)	688 km 98 deg	2016	2017	4	7-9	(22)
NABEO-1	HPS	1U CubeSat (attached to Rocket Lab Kick Stage)	0.85	500 km	2018	2018	2.5	8-9	(23)
ADEO-2	HPS	1U CubeSat (attached to the D-orbit ION carrier)	3.4	N/A	2021	2022	3.6	9	(24)
ADEO-Cube series	HPS	1-50 kg	0.5	LEO	N/A	N/A	2	7	(25)
ADEO-N series	HPS	20-250 kg	0.8	LEO	N/A	N/A	5±2	9	(26)
ADEO-M series	HPS	100-700 kg	4	LEO	N/A	N/A	15±5	6	(27)
ADEO-L series	HPS	500-1500 kg	9.5	LEO	N/A	N/A	20±100	7	(25)
ARTICA (ALPHA)	NPC Spacemind	1U CubeSat	0.285 (0.3U)	5865 Km, 70.16 deg	2020	2020	2.2	7-9	(28)
ARTICA (FUTURA SM 3)	NPC Spacemind	6U CubeSat	0.285 (0.3U)	N/A	2023	N/A	2.2	7-9	(29)
ARTICA (DANTESAT)	NPC Spacemind	3U CubeSat	0.285 (0.3U)	415 km	2022	2022	2.2	7-9	(29)
ARTICA (URSA MAIOR)	NPC Spacemind	3U CubeSat	0.285 (0.3U)	450 km, 97.1 deg	2017	2019	2.2	7-9	(28)
ARTICA (1KUNS)	NPC Spacemind	1U CubeSat	0.285 (0.3U)	N/A	2018	2019	2.2	7-9	(28)
LightSail - 2	The Planetary Society	3U CubeSat	N/A	720 km	2019	2022	32	9	(30)
ACS3	NASA	12U CubeSat	1 (6U)	1000 km SSO	2024	2024 (expected)	81	8	(31)
Gama ALPHA	Gama	6U CubeSat	N/A	550 km	2023	N/A	73.3	8-9	(32)

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).

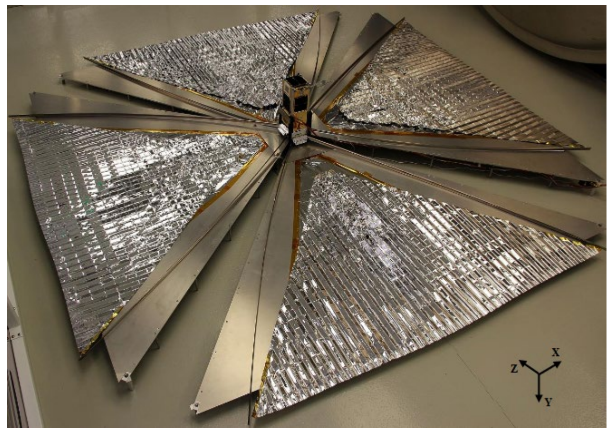


Figure 13.3: CanX-7 deployed drag sail during testing. Credit: Cotten et al. (2017).

The CanX-7 deorbit technology consists of a thin film sail that is divided into 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 (22).

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 (33). 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 (34) 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 (20). The satellite reentered on October 7, 2022, and the team is analyzing the data to study the performance of this latest flight.

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 (18).

Figure 13.4: TechEdSat-10 deployment from the ISS in July 2020. Credit: NASA.

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 (21).

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 m2 with a mass of 0.5 kg (16).

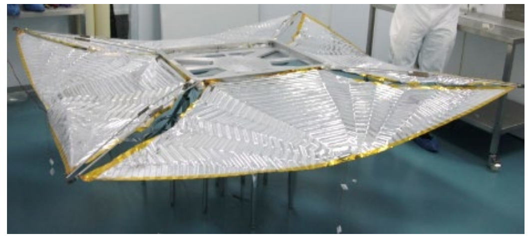


Figure 13.5: Icarus-3 drag sail implemented in the Carbonite-1 mission. Credit: Cranfield Aerospace Solutions.

MMA Design LLC, a company from Colorado, has patented the dragNET de-orbit system. The 2.8 kg module (figure 13.6) 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). In October 2022, the dragNET deorbit system was launched as part of the General Atomics GAzelle satellite, as seen in figure 13.6 (15).

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.

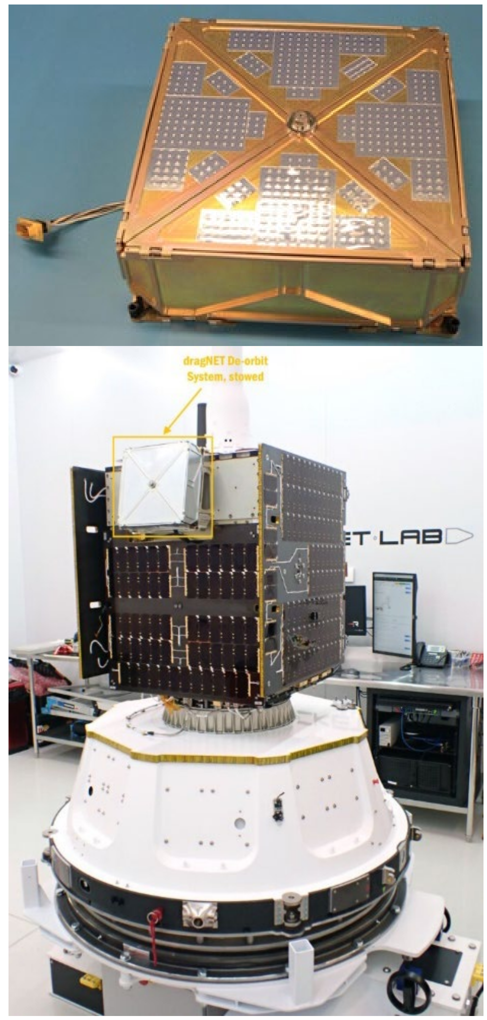


Figure 13.6: {top} The dragNET module. {bottom} dragNET module attached to the GAzelle satellite prior to its launch in late 2022. Credits: MMA design.

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 (35). 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. An initial flight test was attempted in September 2021 aboard the first Firefly Aerospace Alpha rocket. The Spinnaker3 concept sail consisted of an 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 (37). 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 (38). In 2023, Vestigo was awarded a NASA Phase II-S SBIR contract to contribute to the development of a technology demonstration mission to qualify the Spinnaker 2, a 8 m^2 sail for small satellites, and the Spinnaker 3, more targeted to orbital transfer vehicles and upper stages (39).

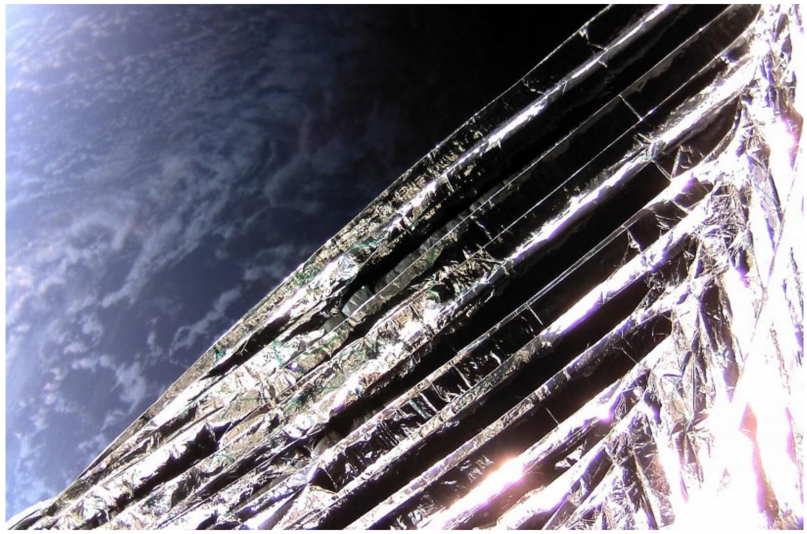


Figure 13.7: The ADEO-2 system deployed in LEO in December 2022, picture captured by the D-orbit's ION spacecraft carrier. Credits: ©HPS GmbH, Germany (www.hps-gmbh.com).

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 (40).

The Italian company NPC Spacemind has 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 (28). 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 (28).

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 orbit altitude along 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 reentered the atmosphere according to orbital predictions (30). The sail was intended to extend the mission lifetime of spacecraft in LEO, however the technology can be potentially use for deorbiting purposes as well.

The Drag Augmentation Deorbiting System (ADEO) is a drag sail developed by the German company High Performance Space Structure Systems (HPS). The sail is scalable, and HPS has launched already a set of missions increasing various configurations to TRL to 9. 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 missions have tested the ADEO-N product family already. The NABEO-1 was launched in 2018, attached to the center of a Rocket Lab Electron rocket Kick Stage. The sail was deployed as soon as 90 minutes after launch. There was an issue trying to measure if the drag sail was deployed initially, but optical ground observations confirmed the successful deployment and performance due to the expected change in semi-major axis (24). In late December 2022, the ADEO-2 sail was deployed from the D-orbit spacecraft carrier ION-2. The successful deployment was captured by the onboard camera from the ION carrier as depicted in figure 13.7.

In early 2023, JAXA selected Axelspace Corporation to develop the In-orbit Demonstration of Membrane Surface Deployable Deorbit Mechanism for Small Satellites (D-SAIL), together with Sakase Adtech Corporation, in Japan. D-SAIL consists of a deployable membrane mechanism to increase drag. The technology was part of the RAISE-3 satellite mission and it was launched in October 2022. However, the launch vehicle was not able to reach orbit. This new initiative results in a new opportunity to test the technology as part of the Innovative Satellite Technology Demonstration-4 mission (41).

In January 2023, the French company Gama launched its first spacecraft mission, a 6U CubeSat name ALPHA. This first technology demonstration mission aims to test the deployment and control of their 73.3 m^2 solar sail. The final phase of the mission will use the sail to rapidly deorbit the satellite (32).

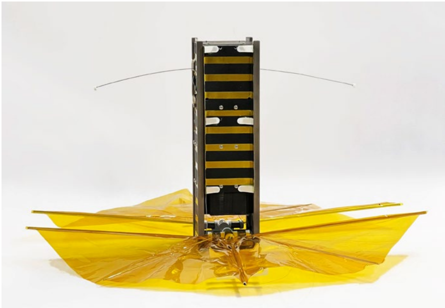


Figure 13.8: SBUDNIC CubeSat with drag sail made from Kapton polyimide film. Credit: Brown Univ.

SBUDNIC, a CubeSat designed and built by Brown University students with support from D-Orbit shown in figure 13.8, 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 can be added onto satellites to radically reduce how long they're in space. SBIDNIC was launched on a SpaceX rocket May 2022 as part of the Transporter 5 ridesharing mission. The plastic drag sail made from Kapton polyimide was deployed at about 520 kilometers, well above the orbit of the International Space Station, which helped push the satellite back down to Earth quicker than anticipated-- about five years ahead of schedule-- reentering Earth's atmosphere on Aug. 8, 2023, burning up high above Turkey after 445 days in orbit, according to its last tracked location from U.S. Space Command (42).

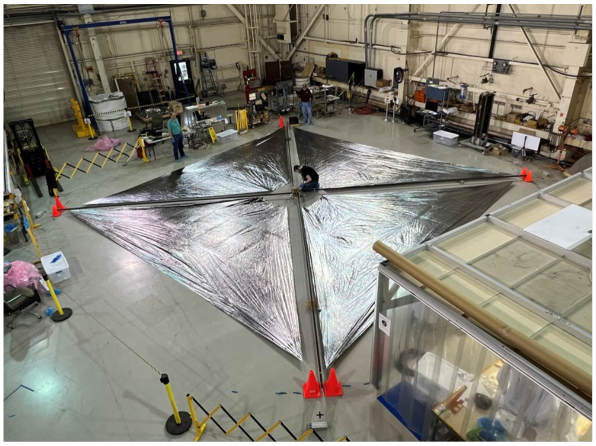


Figure 13.9: The ACS3 sail fully deployed during its pre-integration fit test. Credits: NASA Langley.

The Advanced Composite Solar Sail System (ACS3) is a mission developed at NASA Langley and NASA Ames that consists of a spacecraft that will deploy an 81 m^2 solar sail in a 1000 km sun-synchronous orbit (see figure 13.9). The main objective of the mission is to demonstrate that the solar wind can impulse the spacecraft to change the semimajor-axis and obtain a different orbit altitude. The sail will be composed of a combination of composite materials with distinct properties, and it will be deployed with lightweight booms from a 12U CubeSat bus, developed by NanoAvionics. The spacecraft will be launched aboard an Electron launch vehicle from Rocket LAB Launch Complex in New Zealand in 2024. Although the main objective of the mission is to show the propulsive capabilities of the solar sail, the device can be used for deorbiting purposes, and it may be used at the end of the ACS3 spacecraft lifetime for decommissioning (31).

13.3.2 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 the *Structures, Materials, and Mechanisms* chapter.

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 (43)(44). Figure 13.10 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 (45).

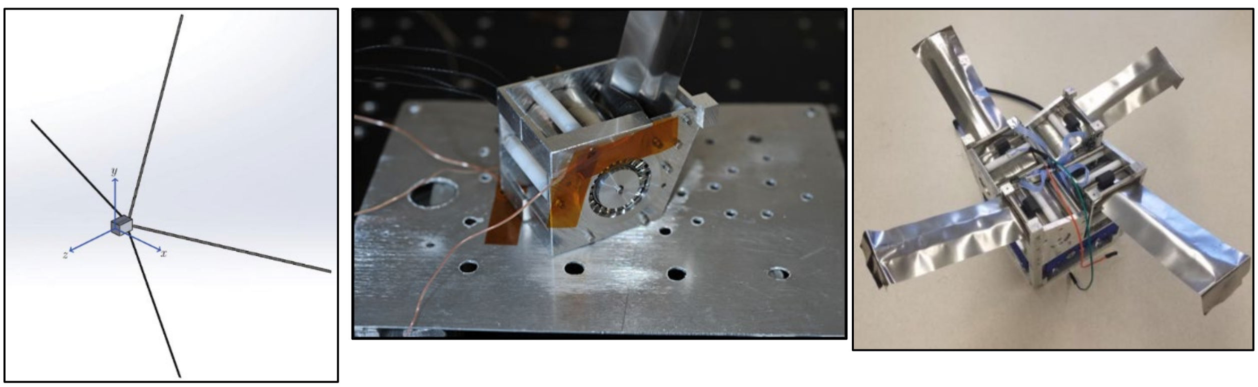


Figure 13.10: D3 CAD design (left), boom inside thermal vacuum chamber (center), and prototype design (right). Credit: Omar et al., 2019, and Martin et al., 2019.

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 13.11). 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 (46).

13.3.3 Electromagnetic Tethers

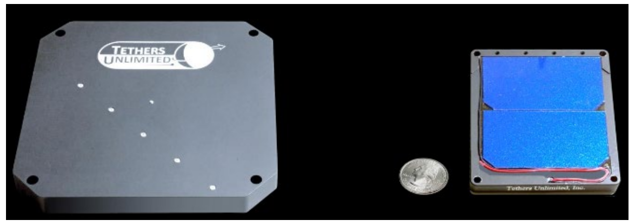


Figure 13.12: Image of the NSTT (left) and the CSTT modules. Credit: Tethers Unlimited.

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. 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 13.12 shows an image of both systems respectively. The 70 m long NSTT has been implemented in the 71 kg Prox-1 satellite, launched in mid-2019 by AFRL (17).

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 (47). Alchemy reentered in July 2021 while Augury is still in orbit.

13.4 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 (48). 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 (3).

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.

13.4.1 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 13.13).

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 (33). TES-10 (figure 13.13) marked the second targeted deorbit flight test and successfully overflew NASA Wallops Flight Facility much like TES-6 (49). 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.

13.4.2 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 (21). 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 (21).

13.4.3 Astroscale

Astroscale aims 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' (50). 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 (50). 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 (51). 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 be launched by the end of 2024 (52). 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 2023 (53)(54). The ADRAS-J spacecraft has a wet mass of 150 kg and it can maneuver with its 12 green monopropellant thrusters. The spacecraft payload includes a custom rendezvous system that includes several sensors and cameras. In late September 2023, the company announced the spacecraft is completely prepared for its rendezvous mission and is ready for launch (54)(56).

In August 2022, Astroscale was also selected to participate in 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 (55).

Astroscale announced in May 2021, 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 (57). 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 (53).

In July 2023, Astroscale announced a partnership with Astro Digital US Inc. to incorporate their Generation 2 Docking Plate into Astro Digital's modular satellite bus. The goal of this collaboration is to provide means for end-of-life servicing preparation. Having these devices on board will allow other servicing spacecraft such as ELSA-M to securely dock and achieve relocation or removal after mission completion (58).

13.4.4 ClearSpace

ClearSpace has plans include service contracts for active debris removal. One of their proposed missions, ClearSpace One, 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 (59).

ClearSpace developed a feasibility study to remove at least two UK defunct satellites and was successfully completed in March 2022. A new contract was awarded by the UK Space Agency 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 (60).

In September 2023, the object which was intended to be the target of the ClearSpace mission, the Vespa payload adapter, was hit by several space debris pieces, too small to be tracked. Vespa was intended to be removed after the ClearSpace scheduled launch in 2026. ESA is analyzing the impacts on the ClearSpace mission, which is going to continue its development according to the initial plan as of September 2023 (61).

13.4.5 Momentus Space

Momentus operates space transportation systems that can propel or deorbit other spacecraft. Their Vigoride platform can carry satellites with masses up to 250 kg, has a wet mass of 215 kg, and 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 (Vigoride-3) on May 25, 2022, successfully deployed three satellite payloads to their respective orbits as of September 2022 (63). As of 2023, Vigoride-5 and -6 have launched successfully. Their latest Vigoride-7 is slated for launch in 2024 (64).

13.4.6 D-Orbit

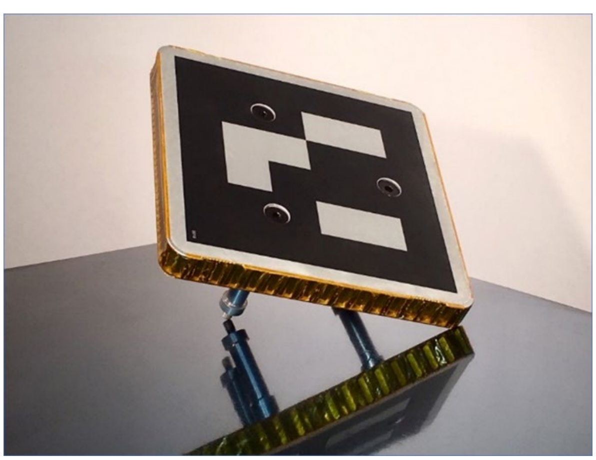
D-Orbit provides transportation services onboard their ION CubeSat carrier platform that can provide precision deployment and is able to host satellites from 1 to 12U. The first mission Origin released 12 SuperDove satellites for the Earth-observation company Planet, deploying the first in September 2020 with the last SuperDove deployed about a month later (65). The most recent Pulse mission finished deploying 20 satellites on May 11, 2021 (66). 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 (67).

Figure 13.14: D-Orbit D3 module. Credit: D-orbit.

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 13.14, is a proprietary solution that is optimized for end-of-life maneuvers (44). 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.

13.4.7 Voyage Space (Altius Space Machines)

In 2019, the satellite constellation company OneWeb signed a partnership with Altius Space Machines (acquired by Voyager Space in 2019) 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



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 13.15: DogTag prototype. Credit: Altius Space Machines.

announced that the first batch of DogTags were launched into space on OneWeb satellites (68). The Altius 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 (69). More specifically, it is compatible with magnetic attraction, adhesives, mechanical, and harpooning captures. Figure 13.15 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 (70).

13.5 Summary

Space debris regulations are becoming more stringent. Consequently, several deorbit technologies have 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. 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 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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Summary

This report provides an overview and assessment of state-of-the-art small spacecraft technologies publicly available as of September 2023. Technology maturation and miniaturization continues to expand small spacecraft capabilities, giving rise to more complex SmallSat mission designs. These improved capabilities have broadened the common SmallSat platform with larger CubeSats and smaller SmallSats; the traditional CubeSat platforms of 1U and 3U volume now include up to 16U form factors, and SmallSats once designed as <400 kg are now <100 kg with similar capability for less cost. The larger surface area of more capable SmallSat platforms can be more equipped with solar panels and subsystem arrangement options. The SmallSat industry is thinking outside the box to maximize usage of the full spacecraft volume and design increasingly complex future SmallSat missions.

While still fairly dominated by the traditional CubeSat form factor, this report is starting to reflect increased interest in the more capable SmallSat platforms. The surge in SmallSat launch opportunities and increased availability of services such as rideshares, hosted payloads, dedicated launchers, and orbital transportation is modernizing the SmallSat paradigm. Hosted payload services are increasingly available for larger SmallSats and other commercial satellites. Several SmallSat missions are actively working on rideshares (or dedicated rides) to destinations in years 2024-2026,and there is an increased interest in orbital maneuvering vehicles (OMV) that provide some autonomy from predetermined rideshares. Dedicated launches provide rapid integration and greater mission design flexibility, allowing spacecraft designers to better dictate mission parameters. A wide variety of integration and deployment systems are now available for constellations of small spacecraft, with SmallSat constellations recently launched by Starlink and OneWeb.

The pace of SmallSat technology advancement overall is rapidly accelerating and varies per subsystem. There has been significant subsystem growth in enhanced ground station support, improved technical efficiency, emerging sensor technology, and in rideshare opportunities. Recent flight missions have demonstrated innovative SmallSat technologies; the successful flights of Starling, CAPSTONE, PTD-3 and CLICK A spacecraft have each significantly contributed to SmallSat technology development. Starling successfully demonstrated intersatellite communication; CAPSTONE completed its six-month primary mission of testing the stability of the near-rectilinear halo orbit for Lunar Gateway; PTD-3 achieved a downlink of 200 gigabits per second via optical communication; and CLICK A tested the optical communication hardware that will be implemented on the second CLICK B/C mission, slated to launch later in 2024. DiskSat, expected to launch in 2024, with its revolutionary circular configuration and larger surface area will challenge the way SmallSat's are perceived. LiDAR sensor technology development is ongoing with applications for improved altimetry and relative navigation for rendezvous, docking, and formation flying. There has been particular consideration to deployment mechanisms for small spacecraft subsystems such as antennas booms, gravity gradients, stabilization, sensors, sails, and solar panels, and these technologies are gaining space heritage through operations. ACS3 is an ongoing NASA mission slated for launch in 2024 that will use a new composite boom solar sail in low-Earth orbit (LEO) for propellant-less propulsion. There is a spike in position, navigation, and timing technology progression in inertial sensors and atomic clocks, and magnetic navigation for near-Earth environments.

NASA's new Indefinite Delivery/Indefinite Quantity (IDIQ) mechanism–the Venture Class Acquisition of Dedicated and Rideshare (VADR) launch services–was developed to accommodate very low complexity CubeSats (up to more complex Class D missions) and provide FAA licensed launch services to deliver payloads to a variety of orbits. The 2023 NASA solicitation for Suborbital/Hosted Orbital Flight and Payload Integration Services included opportunities for hosted payloads on commercial orbital platforms (1). IDIQ contracts for these services will replace

existing Flight Opportunities IDIQ contracts when those expire, and are expected to be in place with commercial providers in early 2024. While the deadlines for the latest opportunities recently passed in Q4 2023, readers are strongly encouraged to subscribe to the Flight Opportunities newsletter in reference 1.

There are ongoing policy measures being developed to mitigate and remove space debris. In 2022, the FCC adopted a new “5 year“ rule to reduce the lifetime requirement for all FCC-licensed satellites in LEO to 5 years after launch. These new regulations have incorporated spacecraft decay capabilities into mission design. As of 2023, there are discussions at the agency and federal level to determine the final policies. To comply with new orbital lifetime requirements, satellite operators are employing strategies such as decreasing the spacecraft ballistic coefficient or mass to area ratio. Deorbit technologies such as drag devices that can effectively increase the spacecraft’s drag area may become even more important for future spacecraft operations in LEO.

NASA is working with several American companies to deliver science and technology to the lunar surface through the Commercial Lunar Payload Services (CLPS) initiative. Under the Artemis program, these commercial deliveries present SmallSat designers with opportunities to perform science experiments, test technologies and demonstrate capabilities to help NASA explore the Moon and prepare for human missions. NASA has initially selected 14 companies to deliver payloads for NASA, including payload integration and operations and launch services to the surface of the Moon. The NASA CLPS program will begin delivering science payloads to the Moon in 2024. CLPS contracts are indefinite delivery, indefinite quantity contracts with a cumulative maximum contract value of $2.6 billion through 2028. Companies of varying sizes can work with selected vendors and are encouraged to fly commercial payloads in addition to the NASA payloads (2).

This report will be updated annually as emerging technologies mature and become state of the art. Any current technologies that were inadvertently overlooked in this version may be included in subsequent editions. Updates to technologies listed in this report could be also modified in subsequent revisions. This report is also available online at: https://www.nasa.gov/smallsat-institute/sst-soa. Technology inputs, updates, or corrections can be made by reaching out to the editor of this report at arc-sst-soa@mail.nasa.gov.

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