Drag-enhancing deorbit devices for spacecraft self-disposal: A review of progress and opportunities

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ABSTRACT

Attention to the need to deorbit spacecraft at end-of-life will only intensify as space-faring nations grapple with the problems of increasingly crowded orbits. The use of drag devices for spacecraft self-disposal in low Earth orbit (LEO) merits review now. Drag-enhancing deorbit devices can be used to offset propellant reserved for deorbit operations and to extend mission life. Drag devices offer increase compliance with debris mitigation standards and can also offer other system-level advantages such as mass savings.

We analyze the "trade-space" for spacecraft that are best suited to make use of this technology with specific examples. Our findings suggest that drag devices are well suited for both small *and* mid-sized LEO spacecraft. The suitability and feasibility of drag devices for small spacecraft (<200 kg) are proven and we review what has been achieved in this regard. Many mid-sized spacecraft are likely to burn-up during reentry and thus likely to meet the less-than-1-in-10,000 casualty risk requirement. We address recent progress in this area; showing that only moderate increases in cross-sectional area (~ tens of square meters) are necessary to apply this technology to mid-sized spacecraft to reduce the orbital lifetime below the prescribed 25-year limit. Drag devices with such areas have been demonstrated, albeit not on mid-size spacecraft. We address requirements for drag devices for the larger classes of spacecraft, along with developmental and research opportunities to expand the technology beyond the demonstration phase.

1 INTRODUCTION

For spacecraft in LEO, atmospheric disposal within 25 years after edn-of-life (EOL) is seen as the most effective method of meeting orbital debris mitigation standards. "The residual atmosphere present at orbital altitudes causes orbital decay that, at sufficiently low operating altitudes, will naturally deorbit a spacecraft well within the prescribed 25-year period. At higher altitudes, the natural decay may be insufficient and a drag-enhancing deorbiting device may be used to increase the spacecraft's cross-sectional area, thus increasing the aerodynamic drag and shortening its natural decay below the 25-year limit (*i.e.,* self-disposal)." [3]

The proliferation and variety of drag devices either demonstrated or in development merits review at this time. Here, we first review current debris mitigation guidelines to provide context and motivation (Section 2); analyze the role of deorbit drag devices in terms of "trade-space" available and estimated market (Section 3); address the current state-of-the-art for spacecraft self-disposal, with emphasis on drag devices (Section 4); address the emerging consensus on drag device design guidelines, benefits and challenges (Section 5) and, based upon emerging research and interest, project future drag device utilization (Section 6).

2 DEBRIS MITIGATION STANDARDS

The distressing growth of orbital debris—along with the associated collision risk—has motivated the international space-faring community, primarily via the Inter-Agency Space Debris Coordination Committee (IADC), to promulgate debris mitigation and remediation guidelines [1]. In most space-faring nations, these have become national policy and new spacecraft designs are required to comply [2].

Spacecraft designers are expected to build in compliance such that the spacecraft can be passivated and safely disposed of at EOL. For LEO spacecraft, disposal consists of either boosting the spacecraft out of the popular

operational orbits to an orbit above 2000 km (graveyard orbit), or deorbiting using an atmospheric disposal within 25 years of its EOL. An approximate ΔV comparison between a graveyard disposal and a direct deorbit for a mid-sized spacecraft is found in [3], illustrating that in terms of ΔV, a direct atmospheric disposal is more efficient below ~1300 km.

2.1 The role of drag devices for debris mitigation

The required ΔV can be reduced or offset by utilizing the atmospheric drag present at orbital altitudes. The spacecraft can naturally deorbit well within 25 years at sufficiently low altitudes. At higher altitudes, intervention is needed.

Reference [3] examines the relationship between a spacecraft's orbital lifetime, operational altitude, and ballistic coefficient. In this study, the effects of solar radiation pressure (SRP) were neglected; however, above 850 km SRP is estimated to be 10 times stronger than drag—assuming that the entire spacecraft is an ideal reflector. In this orbital regime, the disturbances due to SRP are significant enough such that the orbital lifetime is dependent on the spacecraft vs. solar geometry. The analyses performed in [3] and [7] reveal that "*the decay time is particularly sensitive to the rate of decay during the initial stages of the decay*." Examining the timing between the onset of orbital decay and fluctuations in solar activity, particularly the bounding cases of before a solar maximum and before a solar minimum, led to a critical conclusion for spacecraft EOL planning. "Above the altitude where the natural decay is above 25-year requirement, the spacecraft must be proactive and take action. For spacecraft with on-orbit propulsion capabilities the current practice is to reserve propellant for a final deorbit burn (for either a targeted or untargeted reentry). Spacecraft without propulsion must find other means to meet the debris mitigation requirements" [3]. To ensure meeting the prescribed 25-year orbit life limit requirement, a drag device can deploy at EOL—"consequently increasing the spacecraft's cross-section area, decreasing its ballistic coefficient, and shortening its decay" [3].

Following the methods of [3], Figure 1 illustrates the potential role for drag devices. Plotting ballistic coefficient vs operating altitude provides insight into the "trade space" where drag devices could prove beneficial. Region 1 (in green) is the regime where spacecraft will naturally decay within the required time period; above this in Regions 2 and 3, spacecraft will not meet decay requirements without intervention. As in [3], Region 3, above 850 km, is where SRP is large in comparison to atmospheric drag. Also note that the boundary between Regions 1 and 2 is not a line, but region where we see the effects of variation of atmospheric density due to the solar cycle (the lines demark solar maximum, mean, and minimum for the start of orbital decay). As highlighted in Figure 1, Region 2 is "the regime where drag devices could prove most useful". This region spans a range of ballistic coefficients likely to encompass spacecraft larger than seen in Table 1 (see Section 4) that would still demise upon reentry.

Several existing spacecraft are shown for illustrative purposes in Figure 1. Ballistic coefficients are taken from [11], with the exception of EO-1, which is taken from [3]. While the ballistic coefficient for individual spacecraft may span orders of magnitude [3, 11] depending on the spacecraft area and orientation to the drag force, in each case here, we use the average ballistic coefficient and assume a tumbling spacecraft [41]. As decaying spacecraft are often not under active control, this is a reasonable assumption for trade-study purposes.

Starting on the left, the Hubble Space Telescope, at over 12,000 kg, is currently operating at a relatively low altitude and is expected to reenter the atmosphere late in this decade; without intervention it will not meet the casualty risk requirement [29, 30]. Drag devices don't alleviate the problem of dense components on these large spacecraft surviving atmospheric reentry. At the far right of the figure, Landsat-1 is at the highest altitude. It ceased function in 1978 but remains on orbit [43]. Two other non-functioning sattelites, EO-1 and ERS-1, are shown in region 2, where drag devices could prove useful. ERS-1 experienced a failure and was decommissioned in 2000, but remains on-orbit. EO-1, decommissioned in 2017, had on-board propellant remaining for deorbit, but mission managers decided to use the fuel to extend the mission [31]. EO-1 is thus non-compliant with the 25-year rule, and is expected to remain in orbit until the 2050's [3]. As illustrated by the arrow in Figure 1, the working principle of a drag increase is shown for EO-1. Before the drag-increase the lifetime is above 25 years. After the presumed drag device deployment, which increases the area and decreases the ballistic coefficient, the orbital lifetime is reduced below 25 year limit.

We acknowledge the same limitations as Reference [3]: that the conclusions offered are not applicable to all situations given the atmospheric variability and the diversity of spacecraft's ballistic coefficients and orbits. Moreover, the analysis is limited to spacecraft in circular orbits as a matter of convenience.

2.2 The area-time product and its limitations

The debris mitigation standards are meant to halt, and in the worst case, delay, the increase in the overall debris population—especially in already croweded and sought-after orbital bands. The goal is to limit the creation of new debris by fragmentation, either due to collisions or break-up. The risk of break-ups is reduced by passivation at EOL. The 25-year disposal rule is a means to reduce the collision risk, based on the understanding that the longer an object is in orbit, the more likely it is to collide with another object.

Actions taken to comply with the 25-year rule can also result in an increased collision risk, thus becoming rather counterproductive. Increased cross-sectional area (*A)* can increase the risk of collision per unit of time. To adress this concern, the guidance is to verify that the area time product ($A \cdot t$) is reduced as well [6]. Where time *t* is defined as the time the spacecraft spends from EOL to entry interface. This area time product (ATP) is thus a proxy for collision risk.

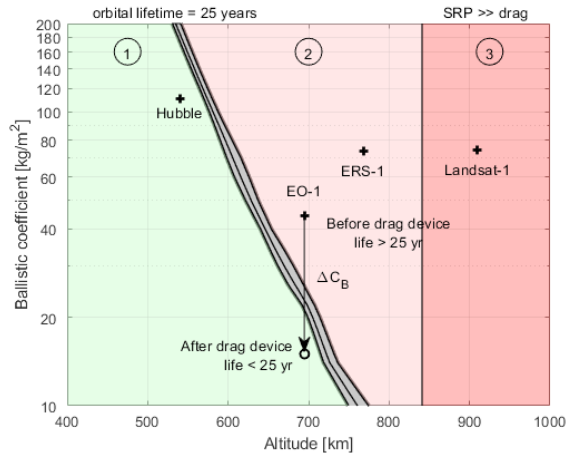

Figure 1. Drag device effect and typical ballistic coefficient for small, mid, and large size spacecraft

A recent analysis [7] points out the limitations of the ATP approach, and that the ATP approach can overestimate collision risk, leading to a less favorable conclusion regarding drag device effectiveness. Further, the ATP approach overlooks two significant effects: first, the variations in decay time due to the solar cycle discussed above; and second, the nature of the assumed collision impact. That is, debris collisions from small objects are more likely and have a high probability of "passing through" drag sail materials rather than generating more debris. The authors recommend taking advantage of the solar cycle by timing a deorbit near a solar maximum; as well as sizing a drag device large enough to deorbit a spacecraft *within* a solar cycle.

2.3 Compliance with standards

While debris mitigation standards have been gradually adopted since their promulgation two decades, it is recognized that some spacecraft launched either prior to or during this period would not be compliant. We note with dismay that current reporting, e.g., [8] indicates that compliance is still remarkably low. This fact drives demand for simple, inexpensive and reliable deorbit technologies.

3 SELF-DISPOSAL STRATEGIES: ROLE OF DRAG DEVICES

3.1 Traditional deorbit approaches

Spacecraft with on-board propulsion traditionally perform a deorbit burn at EOL, and propellant must be reserved for this action. If the spacecraft is expected to survive reentry this deorbit burn must be targeted, i.e., it must perform the reentry burn such that deorbit occurs over an unpopulated area (typically the south Pacific Ocean, see [9] [10]) so that the casualty risk is below the required 1:10,000. The ΔV required to execute this maneuver is analyzed in [10].

The required casualty risk is naturally met regardless of the reentry location if the spacecraft is predicted to fully demise (*i.e.,* burn up).Moreover, the deorbit burn only needs to lower the perigee so that the new orbital lifetime is below 25 years, and this option is more efficient in terms of ΔV, and since no targeting is needed, is also less complex.

3.2 Utility of drag devices

From Figure 1, we see that a self-disposal action is necessary when a spacecraft is expected to reach EOL at an operating orbit where the natural decay cannot be counted upon to achieve the required 25 years. Here, a drag device may either completely replaced or partially off-set a propulsive deorbit burn. At EOL a drag device would deploy to decrease the spacecraf ballistic coefficient and shorten the orbital lifetime to meet requirments.The arrow in Figure 1 illustrates the difference additional drag could have made in the case of this mid-sized (~500 kg) spacecraft. An increase of approximately 6 m^2 of drag area, well within current technological capabilities, could make this class of satellite compliant [3].

3.3 Market for drag devices

LEO is recognized as the most densely populated orbital region and also experiencing the largest satellite population growth. Palla and Kingston [12] addressed the size of the market for drag devices using the schedule projections in the SpaceTrak^{TM} database [13]. They examined launches planned for the 2015-2020 timeframe and excluded satellites larger than 1000 kg. They found large numbers of planned satellites that will be non-compliant without self-disposal strategies. Satellite population increases were concentrated in particular orbits, as would be expected. The largest population of projected non-compliance (without self-disposal strategies) was found to be in the 500-1000 kg mass class, in agreement with the expected ballistic coefficients for satellites from Figure 1.

4 STATE-OF-THE-ART OF DRAG DEVICES

The concept of drag devices is not new (*e.g.,* [21]) and they are generally classified as either drag sails, solar sails (that take advantage of SRP as well as atmospheric drag), or inflatables. Here we briefly review the current state-of-the-art based on the more recent on-orbit demonstrations. Drag devices are very appealing for small spacecraft that typically lack on-board propulsion to perform a deorbit burn. Drag devices provide a relatively simple, low-mass deorbit compliance method.

4.1 Drag sails and solar sails

The majority of the drag device designs consist of a deployable “drag sail” made of a thin film (the sail) that is deployed via extension mechanism(s). Table 1 summarizes drag sail flight experience to date. The feasibility of drag sails for small spacecraft has now been demonstrated on a number of missions. These missions have matured the technology, primarily deorbiting spacecraft that would have readily deorbited within the prescribed 25 years.

We include JAXA’s IKAROS solar sail spacecraft [15] which is notable for its large sail area. While solar sails are not designed to deorbit spacecraft, at low enough altitudes the atmospheric drag is large compared to the SRP, and thus a solar sail can become a drag sail. Thus, any feasible solar sail is a feasible drag sail and is relevant in our review. Others in this category include CubeSail [24], NanoSail-D [25], and LightSail-1 [26]. The technology was also reviewed in 2012 [36].

From Table 1, we can observe that drag sail demonstrations are progressing in sail area, payload size, and complexity. The Icarus-1 deorbited a 157 kg spacecraft earlier this year (largest payload to date). A commercial product, the dragNET^{TM}, deorbited a Minotaur 1 upper stage in 2016, and has the largest drag area to date, with the exception of the IKAROS solar sail. In principle, these devices could deorbit mid-size spacecraft.

Notably, there are a number of new designs in progress and nearing readiness for a flight opportunity [e.g., 37], or are already on-orbit awaiting deployment [17]. We don’t include a discussion of in-progress devopments here due to page restrictions, but hope to add these as they deploy in the near future.

Table 1: Summary of deorbit drag sails to date

Drag Sail Name	Sattelite, Size & Mass	Launch Year	Deployment Year	Drag Area (m^2)	Status	Reference
IKAROS	293 kg	2010	2010	196	Flown & deorbited	[15]
TechEdSat4 exo-brake	3U CubeSat	2014	2015	0.35	Flown & deorbited	[16]
Icarus-1	TechDemoSat-1 157 kg	2014	2019	6.2	Flown & deployed	[18]
Icarus-3	Carbonite-1 80 kg	2015	TBD	2	On orbit	[17]
Deorbitsail	3U Cubesat	2015	2015	16	Failed to deploy	[19]
dragNET™	~100kg Minotaur upper stage	2016	2016	14	Flown & deorbited	[20]
CANX-7	3U CubeSat	2016	2017	5	Flown & deorbited	[21]
DOM	ESEO 45 kg	2018	none	0.5	SC failed	[22]
removeDebris	100 kg	2018	2019	9	Flown & deorbited	[23]

4.2 Inflatables

Another way to increase drag at EOL is via inflatables, which are summarized in Table 2. Inflatable drag devices are appealing for their simplicity and because they can be partially stowed internal to the spacecraft. Their track record as drag devices indicates that a reliable implementation has been more difficult, although the recent success of InflateSail is encouraging. InflateSail combined an inflatable mast deployment with a 10 m^2 drag sail.

Table 2: Summary of inflatable drag devices to date

Inflatable Name	SC Size/ Mass (kg)	Launch	Deployment	Drag Area (m^2)	Status	Reference
AeroCube-2	1U CubeSat	2007	No	0.05	Failed after launch	[27]
AeroCube-3	1U CubeSat	2009	Partial	0.28 fully inflated	Failed to sufficiently inflate	[27]
InflateSail (drag sail with inflatable mast)	3U Cubesat 3.2 kg	2017	2017	10	Flown & deorbited	[28]

4.3 Larger Spacecraft

As noted in Section 2, only moderate increases in drag area (~ tens of square meters) are needed to deorbit an example mid-size spacecraft. The required increases in cross-sectional area for large spacecraft grow very rapidly, as seen in Figure 1, and could be hundreds of square meters for moderately high-altitude orbits (~700 km).

The examples of larger spacecraft in Figure 1 (HST and Landsat-1) suggest that drag devices for large spacecraft remain impractical. Further undermining the potential use of drag devices on large spacecraft is the inability of drag devices to target the reentry location. Sizable pieces of debris from large spacecraft may survive reentry, necessitating a targeted reentry to reduce the risk of ground casualties to an acceptable level, as shown in the Hubble Space Telescope reentry survivability analysis [29] and the subsequent Hubble disposal study [30].

5 Design guidelines, benefits and challenges

5.1 Important design guidelines

A consensus has emerged regarding important considerations when designing, building and operating deorbit devices some of which is now appearing in commercial device promotions [20]. Here we summarize the most significant design guidelines appearing in the literature [e.g. 3, 37]:

- The device should avoid interfering with the primary mission. The device should remain stowed until commanded to release. To avoid inadvertent release, at least a single-fault tolerant release should be considered.
- The drag area should be sufficient to deorbit the spacecraft within 25 years using standard deorbit calculation tools (e.g., STELA [32] or DAS [33]). If the mission permits, consider an earlier disposal, taking advantage of the solar cycle (Section 2.2).
- The device deployment should be highly reliable, in keeping with the mission reliability requirements. Sufficient testing to assure reliability should be included in the test plan.
- The mass of the deorbit device should be minimized. A reasonable mass target is the mass of the propellant displaced for a deorbit maneuver if the deorbit device were not included.
- The deorbit device is expected to operate at the spacecraft EOL and survive to the entry interface altitude, so materials should be selected to endure the corrosive LEO environment (i.e., atomic oxygen , UV and MMOD attack).
- The device should be simple to integrate and operate. The pyramid configuration is favored for small spacecraft that have one side to dedicate to the deorbit device. Modular designs are favored for more complex spacecraft that may not have a single location available but could accommodate de-centralized sail areas [3, 21, 38].

5.2 Benefits

Here we enumerate the potential benefits of drag devices, after [3].

Single-purpose drag devices force compliance. Given the remarkably low level of compliance, this is perhaps the most important benefit. Propellant reserved for deorbit can be re-purposed to extend the mission or to offset the mass of the drag device. As noted in Section 2, having that propellant available can prompt mission managers to use it for mission extension rather than for deorbit purposes [31]. A drag device can eliminate this option, depending on whether it is commanded or a timer is embedded. It should be noted that a single-use solid rocket motor propulsion unit is now commercially available that also provides this capability [40].

Mass savings. Potential mass savings will depend upon the spacecraft propulsion needs:

- If the spacecraft needs propulsion only to perform the deorbit burn then a drag device displaces the propellant needed for that maneuver and also the mass of the propulsion system (*e.g.,* thrusters, tanks, plumbing, valves). For these cases drag devices are very compelling.

- If spacecraft that needs propulsion for the nominal mission, the drag device can displace only the propellant used for the deorbit maneuver. Reference [3] includes an analysis of the propellant mass consumed on a purely propulsive deorbit compared with the propellant mass consumed when a drag device is used.

"Greater tolerance to attitude determination and control failures. To perform a deorbit burn a spacecraft needs to point the thrust vector in the correct orientation and thus it needs a fully operational attitude determination and control subsystem. To deploy a drag device the orientation of the spacecraft is irrelevant (limits on the angular rates may still apply). Therefore, it is more likely that a drag device can deploy after an attitude determination and control failure. Since achieving reliability for attitude control systems akin to other spacecraft systems is currently elusive, this is an attractive feature." [3]

"Extended operational lifetime. This greater tolerance to spacecraft failures can help maintain the spacecraft beyond its original operational life more responsibly, knowing that if the attitude control system fails, the spacecraft can still be deorbited. Additionally, gauging the remaining propellant on the tanks is notoriously difficult. This difficulty may force operators to keep a propellant margin and thus perform a deorbit burn earlier than needed, leaving some of the precious mission-enhancing propellant unused." [3] Using a drag device allows operators to use all available propellant for the mission; a significant potential advantage.

"Storable and non-hazardous. A drag device can be easily stored on the ground and is easier to handle as it does not contain inherently hazardous materials such as hydrazine, the predominant propellant for on-orbit propulsion systems." [3]

5.3 Challenges

Reference [3] discusses challenges to incorporation of drag devices to a spacecraft. These are listed as: untargeted reentry, added complexity, and risk of early deployment. Targeted vs untargeted reentry is discussed below as an area of active research. The later two are discussed in Section 5.1 above via careful application of requirements to design.

6 FUTURE DIRECTIONS FOR DEORBITING DRAG DEVICES

Beyond small spacecraft. Despite the progress with drag devices and their increasing adoption among small spacecraft, the use of drag devices for spacecraft larger than 300 kg in LEO has yet to be demonstrated. There exists a range of spacecraft that would, if deorbited with a drag device, completely burn up on reentry as smaller spacecraft do [3, 12]. Moreover, the expected market in the 500-1000 kg size spacecraft is large [12].

Hybrid propulsion-drag deorbit. Additionally, larger spacecraft are more likely to have on-board propulsion due to more demanding missions, so that hybrid propulsive-drag device deorbit is also possible. On a fueled spacecraft in LEO or MEO, a deorbit burn can lower perigee below the re-entry interface threshold (i.e., 120 km) while targeting a specific reentry interface location. While these propulsive maneuvers produce a quick and controlled deorbit they require a significant fuel reserve and active control, thus limiting the spacecraft's operational life.

"If the spacecraft already has propulsion, the propulsive deorbit approach appears to be more mass efficient for a small range just above the altitude that naturally yields a 25-year decay. However, a deorbit approach with a drag device appears to be more mass efficient at higher altitudes. The point where the drag device becomes more mass efficient depends on the drag device mass and propulsion system efficiency (a higher specific impulse decreases the amount of propellant used). Note also that if the mass of the drag device is high enough, the drag device approach may be less mass efficient than a pure propulsive approach."[3]

Targeted vs Untargeted Reentry. To date, drag devices have been successful on untargeted reentries. Targeted reentries are much more complex, but coupled with a retractable or releasable drag device (see below), may be achievable. Under this scenario, large spacecraft that could survive reentry might also take advantage of drag devices to lower perigee to the point where disposal in an unpopulated area can be executed.

Active drag modulation. We note that work on targeted reentry using active drag modulation is appearing [34, 35]. Note that control of a drag device was recently attempted on the EOES but failed [39]. Drag devices could

potentially be integrated in attitude control algorithms, as well as rendezvous and proximity operations, thus extending the application of this technology past the traditional de-orbit problem set.

Retractable or releasable drag devices. Current drag devices are single-shot deployments—once they are deployed, there is no way of retracting the device. This poses several problems, including a lack of flexibility in performing maneuvers and non-ballistic behavior upon re-entry due to the large surface area. As space debris continues to be of concern with mega-constellations on the rise, an additional increase in the probability of a conjunction also poses additional risk. Future work undertaken at the Naval Postgraduate School includes studying the feasibility and demonstrating the use of retractable drag devices. If a passive or semi-passive drag element could be deployed at end-of-life and retracted prior to the final burn, non-mission-related propulsive requirements could be eliminated, enabling other spacecraft capabilities to expand.

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8 REFERENCES

1. Inter-Agency Space Debris Coordination Committee. *IADC Space Debris Mitigation Guidelines*. 2007, Technical Report, IADC-02-01, Revision 1
2. Committee on the Peaceful Uses of Outer Space. Compendium of space debris mitigation standards adopted by States and international organizations. 2018, A/AC.105/C.2/2016/CRP.16.
3. Alsup, KP, Anantachaislip, F., Komma, JL, Lobo, KB, Lovdahl, BL, Shapiro, JR, Rhatigan, JL, Romano, M, and Virgili-Llop, J. "Drag-enhancing deorbit devices for mid-sized spacecraft self-disposal" *IEEE Aerospace Conference*, Mar. 2019.
4. Saha, K. *The Earth's Atmosphere*: Its Physics and Dynamics. 2008, Springer.
5. Hanslmeier, A. *The Sun and Space Weather*, 2007, volume 347 of Astrophysiscs and Space Science Library. Springer.
6. U.S. Government. U.S. Government Orbital Debris Mitigation Standard Practices. 2001.
7. Visagie, L., Lappas, V., and Erb, S. "Drag sails for space debris mitigation" *Acta Astronautica*, 109 (2015) 65-75.
8. European Space Agency. *ESA's Annual Space Environment Report*. Technical Note. 2018, GEN-DB-LOG-00239-OPS-GR
9. European Space Agency. "ESA Space Debris Mitigation Compliance Verification Guidelines". 2015, ESSB-HB-U-002
10. Bacon, J. B. "Minimum dV for Targeted Spacecraft Disposal." *Proc. 7th European Conference on Space Debris*, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office.
11. Wertz, J. R., Everett, D. F., and Puschell, J. J., eds., 2011, *Space Mission Engineering: The New SMAD*, Microcosm Astronautics Books, Hawthorne, CA.
12. Palla, C. and Kingston, J. "Forecast analysis on satellites that need de-orbit technologies: future scenarios for passive de-orbit devices" *CEAS Space J* (2016) 8:191-200.
13. SpaceTrak: https://www.seradata.com/ accessed Oct. 2019.
14. Petro, A. J. Techniques for orbital debris control. *Journal of Spacecraft and Rockets*, 29(2), 1992, pp. 260-263.
15. Tsuda, Y., Mori, O., Funase, R., Sawada, H., Yamamoto, T., Saiki, T., ... & Kawaguchi, J. I. Flight status of IKAROS deep space solar sail demonstrator. *Acta Astronautica*, 69(9-10), 2011, pp. 833-840.

16. Murbach, M., Papadopoulo, P., Atkinson, D., Reuter, A., Mojica, J., Guarneros-Lun, A., ... & Bodmer, M. The TechEdSat NanoSatellites and Exo-Brake De-orbit Mechanism: Recent Flight Experience. In *11th International Planetary Probe Workshop*. 2014. (Vol. 1795).
17. Kingston, J., Hobbs, S., Roberts, P., Juanes-Vallejo, C., Robinson, F., Sewell, R., Patel, M. Use of CYPRES™ cutters with a Kevlar clamp band for hold-down and release of the Icarus De-Orbit Sail Payload on TechDemoSat-1. *Acta Astronautica*, 100, 2014, pp. 82-93.
18. https://www.sstl.co.uk/media-hub/latest-news/2019/techdemosat-1-on-board-camera-captures-drag-sail-d, (last accessed Oct 2019).
19. Hillebrandt, M., Meyer, S., Sander, M. and Huhne, C. Deployment Testing of the De-Orbit Sail Flight Hardware, *AIAA SciTech Forum*, 5-9 January 2015, Kissimmee, Florida.
20. https://mmadesignllc.com/product/dragnet-de-orbit-system/ (last accessed Oct. 2019).
21. Bonin, G., Hiemstra, J., Sears, T., & Zee, R.. The CanX-7 drag sail demonstration mission: enabling environmental stewardship for nano-and microsatellites. *27th Annual AIAA/USU Conference on Small Satellites*. 2013, SSC13-XI-9.
22. https://directory.eoportal.org/web/eoportal/satellite-missions/e/eseo#launch (last accessed Oct 2019).
23. Forshaw, J. L., Aglietti, G. S., Navarathinam, N., Kadhem, H., Salmon, T., Pisseloup, A., ... & Barraclough, S. RemoveDEBRIS: An in-orbit active debris removal demonstration mission. *Acta Astronautica*, 127, 2016, pp. 448-463.
24. Lappas, V., Adeli, N., Visagie, L., Fernandez, J., Theodorou, T., Steyn, W., & Perren, M. CubeSail: A low cost CubeSat based solar sail demonstration mission. *Advances in Space Research*, 48(11), 2011, pp. 1890-1901.
25. Johnson, L., Whorton, M., Heaton, A., Pinson, R., Laue, G., & Adams, C. NanoSail-D: A solar sail demonstration mission. *Acta Astronautica*, 68(5-6), 2011, pp. 571-575.
26. Biddy, C., & Svitek, T. LightSail-1 solar sail design and qualification. In *Proceedings of the 41st Aerospace Mechanisms Symposium* (pp. 451-463). 2012, Pasadena, CA: Jet Propulsion Lab., National Aeronautics and Space Administration.
27. Fuller, J. K., Hinkley, D., & Janson, S. W. *CubeSat Balloon Drag Devices: Meeting the 25-Year De-Orbit Requirement*. 2010. The Aerospace Corporation Report.
28. Viquerat, A., Schenk, M., Sanders, B., and Lappas, V. "Inflatable Rigidizable Mast for End-of-Life Deorbiting System," *Proceedings of the13th European Conference on Spacecraft Structures, Materials & Environmental Testing (SSMET)*, Braunschweig, Germany, April 1-4, 2014, ESA SP-727.
29. Smith, R., Bledsoe, K., Dobarco-Otero, J., Rochelle, W., Johnson, N., Pergosky, A., & Weiss, M. Reentry survivability analysis of the Hubble space telescope (HST). In *4th European Conference on Space Debris*, 2005, August. (Vol. 587, p. 527).
30. National Aeronautics and Space Administration. *Hubble Space Telescope Disposal Study Closeout Report*, November 2012.
31. National Aeronautics and Space Administration. End of Mission Plan for the Earth Observing-1 (EO-1) Satellite. Appendix B EO-1 Waiver, EO-1 Orbital Lifetime, 2007, System Waiver #: OD-07-05
32. Centre national d'études spatiales. Semi-analytic Tool for End of Life Analysis (STELA). https://logiciels.cnes.fr/en/content/stela (last accessed Oct. 2018).
33. NASA, Debris Assessment Software https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html (last accessed Oct 2019).
34. Josep Virgili, Peter C. E. Roberts, and Nathan C. Hara. "Atmospheric Interface Reentry Point Targeting Using Aerodynamic Drag Control", *Journal of Guidance, Control, and Dynamics*, Vol. 38, No. 3 2015, pp. 403-413. doi:10.2514/1.G000884

35. Sanny R. Omar, Riccardo Bevilacqua, David Guglielmo, Laurence Fineberg, Justin Treptow, Scott Clark, and Yusef Johnson. "Spacecraft Deorbit Point Targeting Using Aerodynamic Drag", *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 10 2017, pp. 2646-2652. doi:10.2514/1.G002612
36. Johnson, L. et al, Soalr Sails: Technology and Demonstration Status, *Int'l J. of Aeronautical & Space Sci.* 13(4), 421-427 (2012).
37. Long. A.C., and Spencer, D.A., A passively stable pyramid sail for the deorbit of small satellite constellations, *68th International Astronautical Congress (IAC)*, IAC-17-A6.5.2.
38. Palla, C., Kingston, J., and Hobbs, S., Development of commercial drag-augmentation systems for small satellites, *Proc. 7th European Conf. on Space Debris*, 2017, published by ESA Space Debris Office.
39. https://directory.eoportal.org/web/eoportal/satellite-missions/e/eseo#launch (last accessed Oct 2019)
40. https://www.wired.com/story/to-fix-the-space-junk-problem-add-a-self-destruct-module/ (last accessed Oct 2019).
41. U. S. Air Force, *SMC Standard SMC-S-022 End-of-Life Disposal of Satellites in Low-Earth Orbit*, 19 March 2010.
42. U. S. Geological Survey, https://www.usgs.gov/land-resources/nli/landsat/landsat-1?qt-science_support_page_related_con=0#qt-science_support_page_related_con (last accessed Nov 2019).