Бөлім 2 **Раздел 2** **Section 2**

Механика **Механика** **Mechanics**

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TETHER-ASSISTED SPACE DEBRIS REMOVAL WITH AN AEROBRAKE: PRELIMINARY ESTIMATION OF MISSION PARAMETERS

This paper investigates the application of an aerobrake in a tether system for space debris removal and provides a preliminary assessment of the key mission parameters. Tether system stability is analyzed using a one degree of freedom mathematical model. Corresponding drag requirements are determined. The results indicate that systems with longer tethers at higher altitudes would require higher drag coefficients to maintain stability. The relative motion of the target with respect to the tug following separation is examined using the Clohessy-Wiltshire equations. Based on the resulting trajectories, the relationship between maximum tether elongation and the target's initial velocity is established. The orbital motion of the tether system during the descent phase is studied through numerical simulations. The descent duration is evaluated for three tether system configurations with different aerodynamic coefficients at three initial altitudes. A $\pm 15\%$ variation in atmospheric density is applied to account for atmospheric density uncertainty. The results demonstrate that increasing the drag coefficient through an increase in surface area significantly reduces the descent duration across all investigated cases, demonstrating the potential of aerobraking to improve the de-orbiting performance of tether systems.
Keywords: active space debris removal, tether systems, aerobraking, orbital dynamics, space tug.

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Аэродинамикалық тежегіші бар тростық жүйені пайдалана отырып ғарыш қоқысын жою: миссия параметрлерінің алдын ала бағалануы

Бұл жұмыста ғарыш қоқысын орбитадан шығару үшін тростық жүйе құрамында аэродинамикалық тежегішті қолдану мүмкіндігі қарастырылып, миссияның негізгі параметрлеріне алдын ала бағалау жүргізіледі. Тростық жүйенің орнықтылығы бір еркіндік дәрежесі бар математикалық модель негізінде зерттеліп, оған қойылатын аэродинамикалық кедергі талаптары анықталды. Зерттеу нәтижелері трос ұзындығы үлкен және биіктігі жоғары орбиталарда орналасқан жүйелердің орнықтылығын қамтамасыз ету үшін аэродинамикалық кедергі коэффициентінің жоғары мәндері қажет екенін көрсетті. Бөліну үдерісінен кейін ұсталған ғарыш қоқысы фрагментінің буксирге қатысты салыстырмалы қозғалысы Клохесси–Уилтшир теңдеулері арқылы талданып, тростың максималды созылуы мен нысанның бастапқы салыстырмалы жылдамдығы арасындағы тәуелділік анықталды. Орбитаны төмендету кезеңіндегі тростық жүйенің қозғалысы сандық модельдеу әдісімен зерттелді. Аэродинамикалық кедергі коэффициенттерінің әртүрлі мәндері бар үш тростық жүйе конфигурациясы үшін үш бастапқы биіктіктегі орбитадан түсу ұзақтығына бағалау жүргізілді. Атмосфералық тығыздықтың белгісіздігін ескеру үшін оның $\pm 15\%$ шегіндегі өзгерісі қарастырылды. Нәтижелер аэродинамикалық тежегіштің беткі ауданын ұлғайту арқылы аэродинамикалық кедергі коэффициентін арттыру барлық қарастырылған жағдайларда орбитадан түсу ұзақтығын едәуір қысқартатынын көрсетті. Бұл аэродинамикалық тежеуді тростық жүйелердің көмегімен ғарыш қоқысын жою тиімділігін арттыру мақсатында қолданудың перспективалы тәсіл екенін көрсетеді.
Түйін сөздер: ғарыш қоқысын белсенді жою, тростық жүйелер, аэродинамикалық тежеу, орбиталық динамика, ғарыштық буксир.

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Утилизация космического мусора тросовой системой с аэродинамическим тормозом: предварительная оценка параметров миссии

В работе рассматривается применение аэродинамического тормозного устройства в составе тросовой системы для удаления космического мусора и проводится предварительная оценка основных параметров миссии. Для оценки устойчивости системы разработана математическая модель с одной степенью свободы, позволяющая определить требования к коэффициенту аэродинамического сопротивления в зависимости от длины троса и высоты орбиты. Установлено, что системы с большей длиной троса на более высоких орбитах требуют повышенных значений коэффициента аэродинамического сопротивления для сохранения устойчивости. Относительное движение захваченного фрагмента мусора после отделения от буксира проанализировано на основе уравнений Клохесси–Уилтшира; выявлена зависимость максимального удлинения троса от начальной относительной скорости объекта. Орбитальное движение системы в процессе снижения орбиты исследовано методом численного моделирования. Продолжительность снижения оценивается для трёх конфигураций тросовой системы с различными значениями коэффициента аэродинамического сопротивления на трёх начальных высотах. Для учёта неопределённости атмосферной плотности рассматривается её изменение в диапазоне ±15%. Показано, что увеличение коэффициента аэродинамического сопротивления за счёт увеличения площади поверхности позволяет существенно сократить продолжительность снижения для всех рассмотренных случаев, что подтверждает перспективность применения аэродинамического торможения для повышения эффективности удаления космического мусора при помощи тросовых систем.
Ключевые слова: активная уборка космического мусора, тросовые системы, аэродинамический тормоз, орбитальная динамика, космический буксир.

1 Introduction

The increasing number of man-made objects in the Earth's orbit has made space debris one of the most significant challenges for current and future space activities. Today, satellites play a vital role in communication, navigation and Earth observation. Collisions with space debris can result in damage or loss of satellites and other spacecraft while generating additional hazardous debris. While the issue was not regarded as critical in the early years of space exploration, the rapid growth of space missions has changed the orbital environment. This development has intensified both the risks associated with space debris and the need for effective space debris removal methods.

Tether systems are among the most promising methods for space debris mitigation [1]. Such systems typically consist of an active spacecraft acting as a tug, a tether, a capturing device and a passive debris object. The debris object serves as the target to be captured and subsequently towed for removal. Several studies have investigated the dynamics of tether systems in orbit [2, 3]. However, attitude motion of the target introduces a significant complication that can disrupt stability of the system and has therefore been widely studied [4–6]. Further challenges occur during the towing phase, where control strategies have been developed to prevent tether slack [7] or tether libration [8]. Despite these advances, further research is required to ensure the reliable implementation of tether systems in operational space debris removal missions.

Previous studies have predominantly investigated tether systems with propulsion thrust [6,9–11]. This straightforward approach, however, requires onboard propellant and additional

thruster systems, which will increase the mass of the debris removal spacecraft. Alternatively, tethered debris removal can be performed through the use of aerobraking. Aerobraking is a manoeuvre that employs aerodynamic drag in the atmosphere to modify the spacecraft's orbit by reducing the orbital energy of the system. Aerobraking offers several advantages over conventional propulsive de-orbiting methods: (1) it reduces the spacecraft mass by eliminating or reducing the need for a propulsion system; (2) it lowers mission costs by eliminating the need for propellant during the de-orbit phase; and (3) the aerodynamic drag can be adjusted by varying the aerobrake surface area, providing flexibility for mission requirements. Under these conditions, atmospheric density becomes a critical factor in determining the duration of descent, as it varies significantly with altitude [12].

The practical implementation of aerobraking has been the subject of rigorous research in recent years. One of the most significant challenges in aerobraking for debris removal is the design of reliable deployment mechanisms that can safely and effectively increase surface area. A deployable structure was proposed to be mounted directly on the satellite and deployed at the end of the mission to facilitate the de-orbiting process [13–15]. A family of Drag Augmentation Systems was developed in Cranfield University and demonstrated successful deployment in the orbit [16]. In [17] aerobraking was combined with electrodynamic tether to take advantage of both methods. However, the application of aerobraking in tether systems requires further investigation.

This paper explores a tether-assisted space debris removal concept that combines a tether system with a deployable aerobrake to achieve propellant-free de-orbiting. Unlike conventional tether-assisted de-orbiting concepts, the proposed mission relies exclusively on aerodynamic drag generated by the aerobrake during the de-orbit phase, eliminating the need for onboard propulsion. Three mission phases are investigated: separation and tether deployment, tether system stabilization, and descent. During the first phase, the tug and the target, initially combined into a single module, separate while the tether is deployed. The tether system is subsequently stabilized along the local horizontal. Once the aerobrake is deployed, the system enters the final phase, during which it descends to lower altitudes, where aerodynamic heating caused by the increasing atmospheric density ultimately leads to its destruction.

The goal of this study is to evaluate the feasibility of tether-assisted debris removal using an aerobrake and to provide preliminary estimates of the key mission parameters. The following objectives are addressed:

1. To determine the drag required for tether-system stabilization and to analyze how altitude and tether length affect the resulting drag coefficient.

2. To investigate the relative trajectory of the target during tether deployment and assess the influence of target separation velocity on the trajectory.

3. To estimate the corresponding descent time for different initial conditions by performing numerical simulations of the orbital motion of a tether system.

The organization of this paper is as follows. Sec. 2 presents the mathematical model of a simplified one degree of freedom tether system and provides estimates of the drag coefficient required for tether stability. Sec. 3 describes relative motion of the tug after tether deployment. Sec. 4 investigates the descent phase of the tether system through numerical

simulations of its orbital motion. Lastly, the discussion and conclusions are presented in Sec. 5.

2 Tether Stability Analysis

We begin with the tether system stabilization phase to determine the aerodynamic drag required to maintain alignment along the local horizontal. In this section, the equation of motion for the tether system in orbit is derived and the corresponding stability criteria are presented. A simplified tether system consisting of a tug, a target, and a tether is considered (Fig. 1).

The main assumptions are as follows:

1. Atmospheric density as a function of altitude is obtained from the U.S. Standard Atmosphere [18], with a ±15% variation applied to account for uncertainty in atmospheric density.

2. The system's center of mass (CoM) follows a nearly circular orbit, and the orbital eccentricity is assumed to be sufficiently small that its effect on tether stability is negligible.

3. Both the tug and the target are modeled as point masses [9].

4. The tether is assumed to be always tensioned and is therefore modeled as a rigid rod [9, 11, 19].

5. The tether is considered massless, as its mass is negligible compared to that of the tug and the target [8, 20].

6. The drag force acting on the target is negligible.

These assumptions enable a simplified mathematical model that captures the primary dynamics of the tether system. The effects of spacecraft attitude dynamics, tether flexibility and mass, and orbital eccentricity are therefore neglected.

The origin of the Local Vertical/Local Horizontal (LVLH) frame is located at the center of mass of the tether system, which moves with velocity V. The tether forms an angle α with the local horizontal. The drag force D acting on the tug is given by

$$D = qA_{\mathrm{r}}C_D \tag{1}$$

where $q = \rho V^2/2$ is the dynamic pressure, C_D is the drag coefficient, and A_{r} is the reference area. The equation of motion is [11]

$$\alpha'' = -a\sin\alpha + \frac{3}{2}\sin 2\alpha. \tag{2}$$

where $(\ )'$ means differentiation with respect to the true anomaly, which is used as dimensionless time. The parameter a was introduced in [21] and can be interpreted as dimensionless thrust:

$$a = \frac{D}{Lm_2n^2} \tag{3}$$

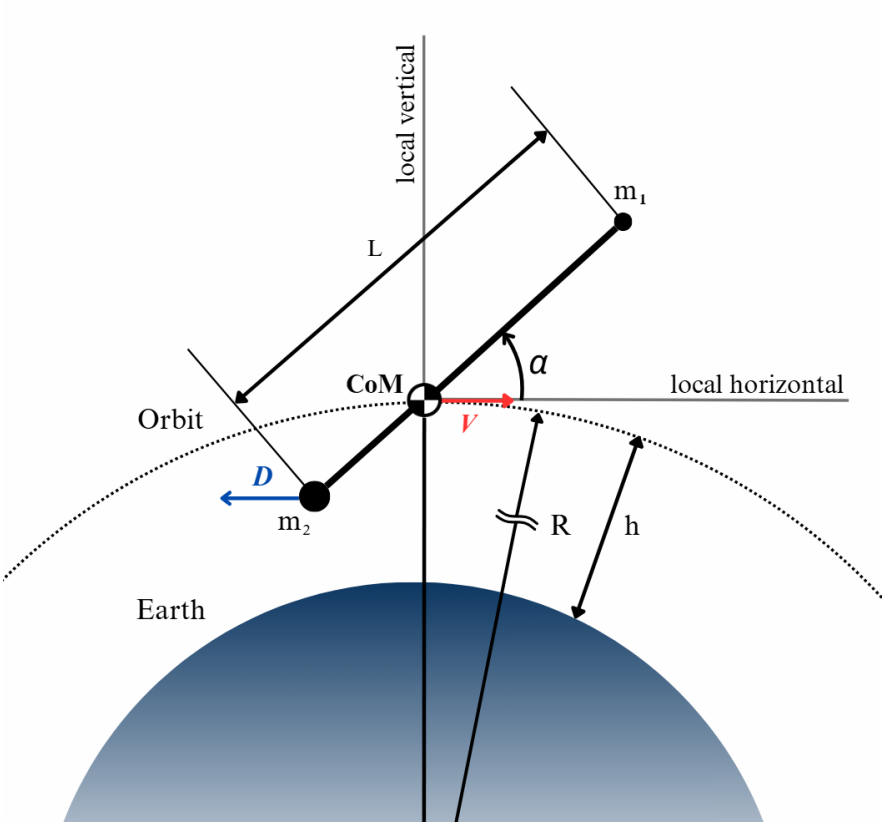


Figure 1: Tether system.

where $n = \sqrt{\mu/R^3}$ is the mean motion, R is the orbital radius, μ is the gravitational parameter of the Earth.

The potential energy of the tether system is

$$U = -a\cos\alpha + \frac{3}{2}\cos^2\alpha. \tag{4}$$

The equilibrium points are obtained from the condition:

$$\frac{dU}{d\alpha} = 0. \tag{5}$$

Solving this equation yields the equilibrium positions:

$$\alpha = 0 \quad \text{or} \quad \alpha = \pm\arccos\left(\frac{a}{3}\right) \tag{6}$$

where the second set of solutions exists only for $a \leq 3$. The equilibrium configuration aligned with the local horizontal corresponds to the first solution ($\alpha = 0$). Stability requires the second derivative of the potential energy to be positive:

$$\left.\frac{d^2U}{d\alpha^2}\right|_{\alpha=0} = a - 3 > 0. \tag{7}$$

From Eq. (7), it follows that the potential energy has a minimum at $\alpha = 0$ only when $a > 3$ [11]. By expressing the drag force in terms of the parameter a and substituting it into Eq. (1), the minimum drag coefficient required to achieve stable position along the local horizontal is obtained as

$$C_D = \frac{a_* L m_1 n^2}{q A_\mathrm{r}} \tag{8}$$

where L is the tether length and $a_* = 3$ is the critical value of the parameter a obtained from the stability criterion (7). The target and the tug are assumed to be a 1U CubeSat with mass $m_1 = 1.3$ kg and a 2U CubeSat with mass $m_2 = 2.6$ kg, respectively. The reference area corresponds to that of a 1U CubeSat and is taken as $A_\mathrm{r} = 0.01$ m^2.

Fig. 2 illustrates how minimum drag coefficient required to achieve stable position along the local horizontal increases linearly with tether length. The slope of this relationship grows with altitude, suggesting that increased surface area is required to maintain sufficient drag in the rarefied atmosphere at higher altitudes. Moreover, as the tether length increases, the effect of the altitude on drag coefficient becomes more pronounced.

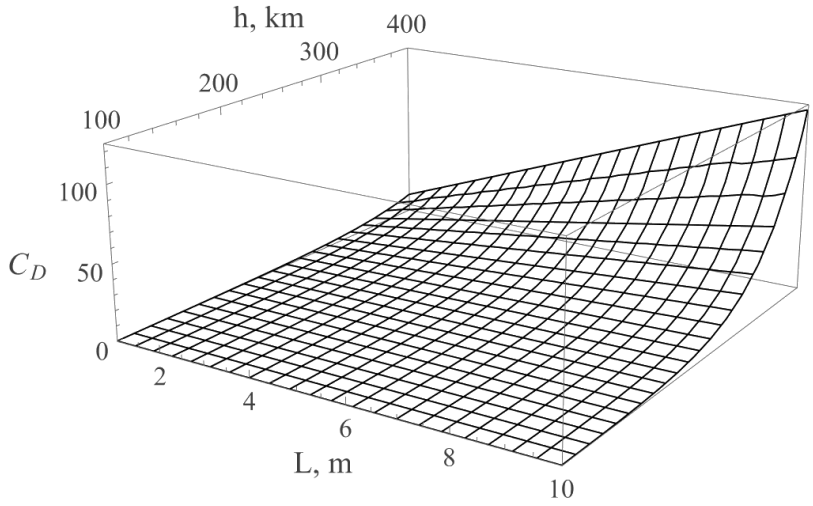


Figure 2: Drag coefficient as a function of tether length and altitude.

These results characterize the relationships between drag coefficient, tether length, and altitude. It can be seen that increasing altitude and tether length both lead to an increase in the drag coefficient required to maintain the position along the local horizontal. Based on these findings, the following procedure can be applied to define the configuration of a tether system that remains stable along the local horizontal and can proceed to the descent phase: (1) the target altitude is specified; (2) the tether length is determined, while also satisfying safety requirements, since excessively short tethers may increase the risk of collision between the tug and the target; (3) the required drag coefficient that ensures stable alignment along the local horizontal is evaluated.

3 Separation Phase Examination

During the separation phase, the tether system must approach alignment with the local horizontal to achieve a stable position. This requirement implies a minimum tether length, as the tether must remain slack until the target reaches its final relative position. This section analyzes the relative motion of the target following separation from the tug and assesses how the separation velocity influences the target's trajectory. Using the tether length determined in Sec. 2, the corresponding separation velocity can then be evaluated.

The relative motion of the target with respect to the tug is described using the planar Clohessy-Wiltshire equations [22]. The equations are formulated in the LVLH reference frame, with the origin located at the position of the tug. x and y denote the radial and along-track relative positions of the target, respectively:

$$\begin{aligned} \ddot{x} &= 3n^2 x + 2n\dot{y}, \\ \ddot{y} &= -2n\dot{x}. \end{aligned} \tag{9}$$

At the initial time the target is separated from the tug with initial velocity in the along-track direction, opposite to the orbital motion. The initial radial velocity is assumed to be zero. The corresponding initial conditions are

$$\begin{aligned} x(0) &= 0, \quad y(0) = 0, \\ \dot{x}(0) &= 0, \quad \dot{y}(0) = \dot{y}_0. \end{aligned} \tag{10}$$

The solutions of Eqs. (9) for the relative position of the target as a function of time are given by

$$\begin{aligned} x(t) &= 4x_0 + \frac{2\dot{y}_0}{n} - 3x_0 \cos(nt) - \frac{2\dot{y}_0}{n}\cos(nt) + \frac{\dot{x}_0}{n}\sin(nt), \\ y(t) &= -6ntx_0 - \frac{2\dot{x}_0}{n} + y_0 - 3t\dot{y}_0 + \frac{2\dot{x}_0}{n}\cos(nt) + 6x_0 \sin(nt) + \frac{4\dot{y}_0}{n}\sin(nt). \end{aligned} \tag{11}$$

Fig. 3 presents the relative trajectories of the target during one orbital period following separation from the tug. Once the target reaches its final relative position, the tether system aligns with the local horizontal and is ready to proceed to the descent phase. As indicated by the trajectories, the target's initial velocity and therefore the required tether length depend strongly on the target's final position.

This section establishes the relationship between the separation velocity, $\dot{y}_0$, and the final relative position, which is determined by the maximum tether length. The required separation velocity can be evaluated based on the tether system configuration defined by the stability analysis in Sec. 2. After separation and subsequent stabilization along the local horizontal, the system is ready to begin the descent phase.

4 Descent Parameters Evaluation

During the descent, the tug accelerates the de-orbiting of the target through aerobraking. However, the duration of the tether system's descent must be evaluated to ensure a feasible

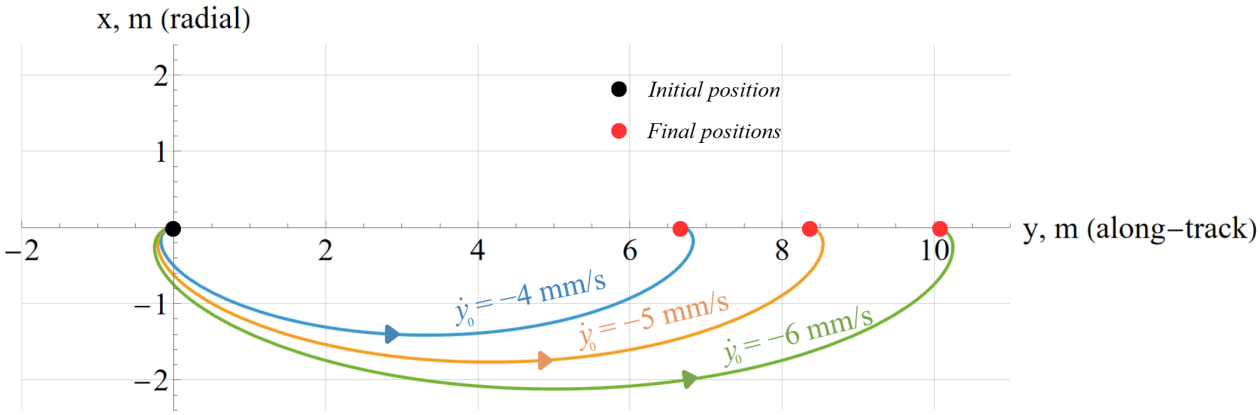


Figure 3: Relative motion of the target after separation.

mission timeline. This section presents a mathematical model describing the orbital motion of the tether system during this phase. The model is developed under the following assumptions: the only perturbing force acting on the tether system is the aerodynamic drag, D, defined by Eq. 1, and the tether system is modeled as a point mass, since its length is small compared to the orbital radius. Planar orbital motion of the tether system is described using Gauss Planetary Equations [23]:

$$\dot{H} = r\, p_s, \tag{12}$$

$$\dot{e} = \frac{H}{\mu} \sin\theta\, p_r + \frac{p_s}{\mu H} \left[(H^2 + \mu r) \cos\theta + \mu e r \right], \tag{13}$$

$$\dot{\theta} = \frac{H}{r^2} + \frac{1}{eH} \left[\frac{H^2}{\mu} \cos\theta\, p_r - \left(r + \frac{H^2}{\mu} \right) \sin\theta\, p_s \right] \tag{14}$$

where H is the specific angular momentum of the orbit, e is the eccentricity, θ is the true anomaly, p_r, p_s, and p_w are respectively the radial, transverse, and normal perturbations due to atmospheric drag, all expressed in the LVLH frame:

$$p_w = 0, \tag{15}$$

$$p_r = -\frac{\mu D}{mVH}\, e\, \sin\theta, \tag{16}$$

$$p_s = -\frac{HD}{mVr} \tag{17}$$

where m is the mass of the tether system. Orbital radius, r, and velocity, V, can be obtained from

$$r = h_a + h_p + 2R_E, \tag{18}$$

$$V = \sqrt{\left(\frac{\mu}{H} e \sin\theta\right)^2 + \left(\frac{H}{r}\right)^2}. \tag{19}$$

where R_E is the Earth's radius. The perigee h_p and apogee h_a altitudes are given by [23]

$$h_a = \frac{H^2}{\mu(1-e)} - R_E, \tag{20}$$

$$h_p = \frac{H^2}{\mu(1+e)} - R_E. \tag{21}$$

The total mass of the tether system is taken as the sum of the masses of the tug and the target, $m_{\text{total}} = m_1 + m_2 = 3.9$ kg. The initial true anomaly is taken as zero, which places the tether system at perigee. Three cases with different initial perigee and apogee altitudes were investigated and are presented in Tab. 1.

Table 1: Initial altitudes.

Case	Initial perigee altitude $h_p(0)$	Initial apogee altitude $h_a(0)$
1	367 km	369 km
2	417 km	419 km
3	467 km	469 km

The corresponding initial angular momentum and eccentricity are calculated for each case using Eqs. (22) and (23) [23]:

$$e(0) = \frac{h_a - h_p}{h_a + h_p + 2R_E}, \tag{22}$$

$$H(0) = \sqrt{\mu\, r(0)(1 + e(0))}. \tag{23}$$

Three configurations of the tether system were analyzed. The aerodynamic coefficients for each configuration were calculated using the in-house developed software based on the analytical approach proposed by Schaaf and Chambre [24]. The first configuration employed a drag coefficient of $C_D = 3$, corresponding to a 3U CubeSat at zero angle of attack, and represents a tether system with a malfunctioned aerobrake. The second employed a drag coefficient of $C_D = 30$, representing a partially deployed aerobrake. The third configuration used a drag coefficient of $C_D = 115$, corresponding to a tether system with a successfully

deployed aerobrake. The tether length in these configurations will depend on the initial altitude and can be derived from Eq. 8

Fig. 4 shows the decrease in apogee altitude with time for three configuration at three initial altitudes. The simulations were terminated at 100 km, since below this altitude the atmospheric density becomes sufficiently high for significant heating and structural breakup of the module. To assess the effect of atmospheric density uncertainty on the descent duration, a ±15% variation in atmospheric density was introduced. The shaded regions represent the range of apogee decay corresponding to the upper and lower bounds of the assumed atmospheric density uncertainty. The results indicate that atmospheric density uncertainty has only a minor effect on the descent duration across the investigated initial altitudes.

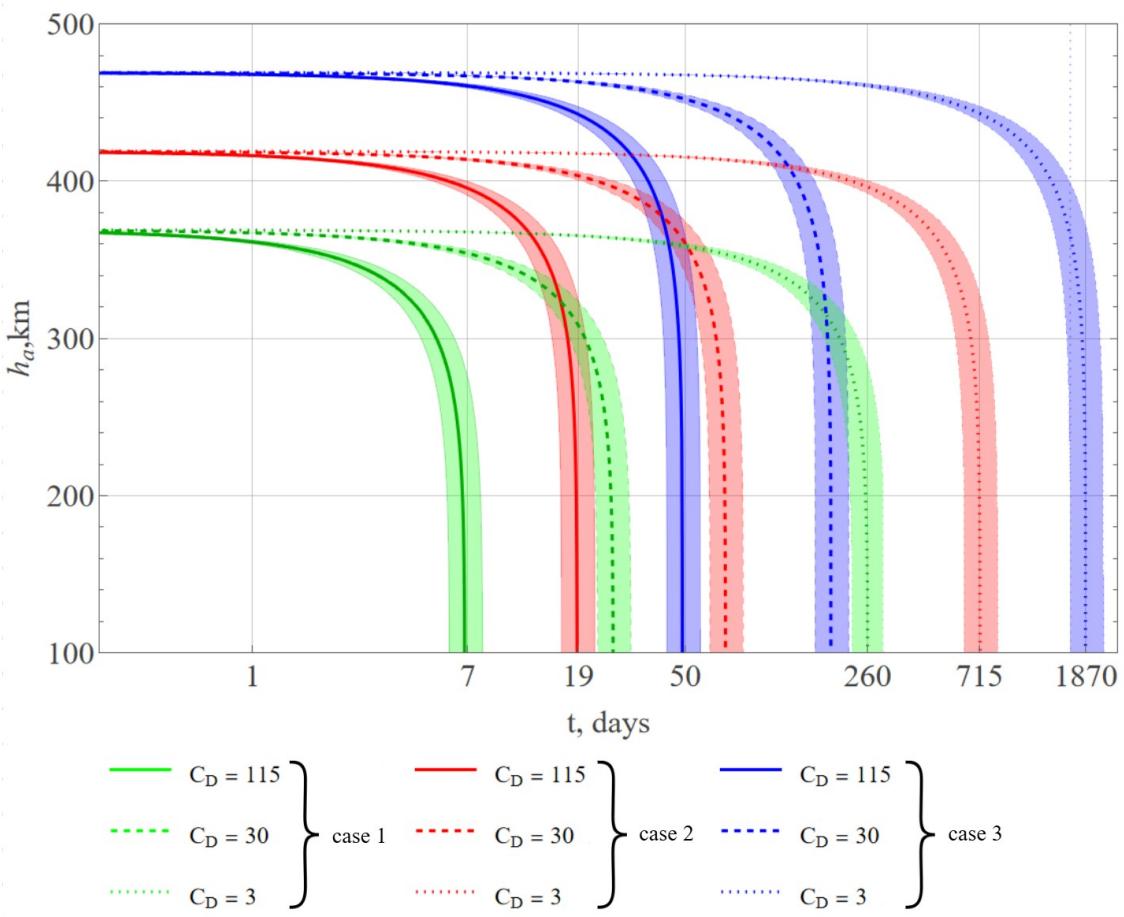


Figure 4: Decrease of apogee altitude over time for different initial altitudes.

It can be observed that increasing the drag coefficient of the tether system substantially reduces the descent time. It can be seen that in case 2, the configuration without an aerobrake requires nearly two years to descend. Deploying an aerobrake allows the tether system to reach an apogee altitude of 100 km 37 times faster, reducing the descent time to approximately 7 days. Even a partially deployed aerobrake significantly shortens the descent time, demonstrating that it remains effective despite incomplete deployment. This substantial improvement is consistently observed for all initial orbital altitudes considered in this study.

5 Discussion and Conclusions

This study demonstrates the feasibility of using an aerobrake in tether systems as a propellant-free de-orbiting device for space debris removal. A preliminary assessment of the proposed concept was carried out by investigating the stability, separation, and descent phases of the mission. The minimum drag coefficient required to maintain tether stability along the local horizontal was determined as a function of tether length and orbital altitude, providing a procedure for selecting these parameters. The relative motion during the separation phase was shown to depend strongly on the initial separation velocity, allowing the corresponding velocity to be determined for a given tether length. Finally, the descent performance was evaluated for three aerobrake configurations at three initial altitudes. The results demonstrate that increasing the drag coefficient significantly reduces the descent duration across all investigated cases.

The mathematical model was developed for a preliminary assessment of the proposed concept and therefore involves several simplifying assumptions. Modeling the tug and the target as point masses neglects spacecraft attitude dynamics, which may influence tether stability during the descent phase, while representing the tether as a rigid, massless rod neglects tether elasticity and vibration modes. The assumption of a circular orbit also simplifies the orbital dynamics. These effects should be incorporated into future higher-fidelity models to improve the accuracy of the proposed approach. Despite these simplifications, the proposed system offers a propellant-free alternative to conventional tether-assisted de-orbiting concepts that rely on onboard propulsion. By replacing propulsion with aerodynamic drag, the concept has the potential to reduce spacecraft mass and mission cost while allowing the de-orbiting performance to be adapted by varying the aerobrake surface area. These characteristics make the concept particularly attractive for low-cost CubeSat demonstration missions and future active debris removal missions in low Earth orbit. Its practical implementation, however, requires reliable tether and aerobrake deployment, attitude control, and tension control. Tether deployment must be performed without entanglement, excessive oscillations, or incomplete deployment; existing deployment technologies and strategies have been comprehensively reviewed in [26], while successful in-orbit tether deployment has been demonstrated by the RemoveDEBRIS mission [25]. Similarly, the aerobrake must deploy reliably while preserving its structural integrity and aerodynamic performance, and several deployable aerobrake concepts have been proposed and experimentally investigated [13–15]. During descent, attitude control is required to maintain the desired orientation of the aerobrake and maximize the effective drag area, for which several control strategies have been developed [4, 6, 27]. Finally, maintaining sufficient tether tension is essential to prevent collisions between the tug and the target, and several tension control methods have been proposed for tethered systems [9, 28, 29]. These existing developments indicate that the key implementation challenges associated with the proposed concept are actively being addressed.

The above discussion outlines several promising directions for future research on tether-assisted aerobraking systems. Future work should focus on the development of higher-fidelity dynamic models that incorporate tether flexibility, spacecraft attitude dynamics, and deployment mechanisms, together with more comprehensive simulations of realistic operational scenarios. In addition, further studies should investigate guidance and control strategies, deployment reliability, and experimental validation to assess the practical

feasibility of the proposed concept.

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