TECHNOLOGIES TO SOLVE THE ORBITAL DEBRIS PROBLEM AND ITS EFFECTS ON THE FUTURE OF SPACE EXPLORATION

A THESIS

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Dedication

This thesis is dedicated to my grandmother, Marica W. Haddock, aka Pooh. There is nothing we cannot do. The sky was never the limit, and space is not either!

#BlackSTEMMatters forever and always

Abstract

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Words: 460

This thesis deals with the orbital debris problem and its impact on small satellites such as CubeSats. Currently there is approximately eighteen tons of space junk that are currently in Earth orbit of which 80% of this space debris is in Low Earth Orbit (LEO), which is where most spacecraft are launched into. A simplified orbital lifetime tool is used to analyze the impact of the exponential rise in small satellite launches into LEO. It is shown that unless proactive measures are taken, the orbital debris problem will become worse in the future. To this end, two proactive approaches are examined: active removal of technologies and space policy changes. With respect to active removal technologies, three solutions being considered are examined: laser removal, electrodynamic tethers, and deployable nets. Laser removal involves using a space based or ground-based laser to ablate material from space debris. The ablated material acts as a miniature thruster which decreases the semi-major axis of the debris' orbit. The second technology considered is electromagnetic tethers. The tethers are based on using the earth's magnetic field to generate an electromotive force which acts as drag and, thus, causes the orbit of a debris object to decay. Lastly, there is the concept of a deployable net. A net with flexible rods is deployable from a host satellite and captures multiple forms of debris and knocks it out of orbit. For this concept, there

is a closing mechanism to efficiently remove the debris. The advantages and disadvantages of all these technologies are analyzed.

Next policy changes that can take advantage of these coming orbital debris removal technologies as well as existing technologies are considered. As will be shown, current space policies do not effectively deal with the orbital debris problem. Many papers have discussed how it is the launcher's responsibility to remove their spacecraft from operational orbit. Since the creation of the Outer Space Treaty of 1967, countries know that space is deemed as an environment for exploration as opposed to property. National space policies are analyzed with focus on responsibility of removing orbital debris and keeping the space environment clean for future exploration. With the wording of some of the standing space policies conflicting with the current state of the space industry, these publications are discussed and reformed to align with the future of the space industry. Another policy reform that is considered is that of future design standards. Using CubeSats as an example, we explore what kind of changes in design standards can help mitigate the orbital debris problem. To this end, typical CubeSat subsystems are separately examined, Structures, Propulsion, Control, Power, Navigation, and Communication. The analysis also focused on how changes in the practice of designing these subsystems can be used to mitigate the orbital debris problem.

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1 Introduction

1.1 Motivation

Access to space is becoming easier and currently one can launch small spacecraft into Low Earth Orbit (LEO) for a few hundreds of thousands of dollars. As a case in point, let us consider CubeSats. CubeSats are small, modular spacecraft that fall in the category of micro- or nanosatellites. They are built by assembling basic 10 cm x 10 cm x 10 cm building blocks known as a *CubeSat Units* (1U for short). They are inserted into orbit using the standard Poly-Picosatellite Orbital Deployer (P-POD). By decoupling the satellite design from the launch vehicle, the CubeSat standardization provides inexpensive access to space. It is not surprising, therefore, that the number of CubeSats deployed for scientific, educational and commercial purposes has been increasing exponentially as shown in Figure 1 [1]. Thus, it is expected that CubeSats will continue to see widespread use in commercial and research applications. A case in point is that NASA's Space Launch System (SLS) is being designed to accommodate CubeSats "hitching" a ride into Earth's orbit or an initial trajectory into deep space.

Given the increasing demand for CubeSats, it is apparent that their construction and launch costs will continue to decrease. This is particularly true because a large industry has developed around CubeSats, which provides off-the-shelf solutions for fabrication. For example, one can purchase modular command and data handling computers with an integrated guidance, navigation, and control (GNC) system for LEO operations. Off-the-shelf

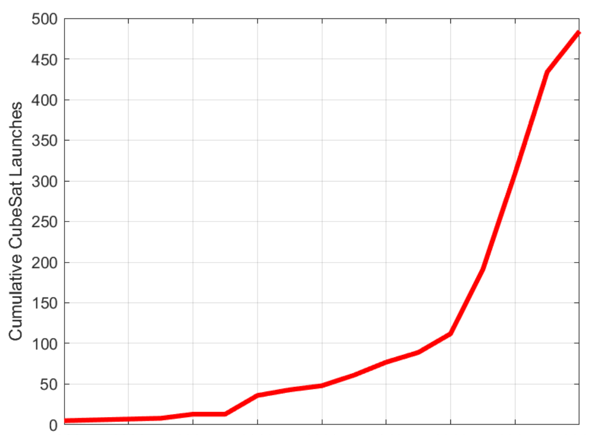

Figure 1: Cumulative number of CubeSat launches since 2001 [1]. The number of CubeSats being launched for scientific, educational, and commercial purposes is increasing exponentially.

propulsion and communication systems (including some very high-bandwidth radios for transmission of high definition video) are also available. While most launches to date have been 1U, 2U and 3U CubeSats, a significant number of larger CubeSats in 6U and 12U form factor will be launched soon. All of this points to the possibility of building a CubeSat that can accommodate the sensors and systems needed to make useful and precise measurements in hypersonic flight.

Currently, it is possible to design and fabricate a 3U CubeSat in several months for less than $100,000, and a commercial launch service provider can deliver a 1U CubeSat to Low Earth Orbit (LEO) for less than $85,000. All of this points to the following fact: LEO (altitudes less than 2000 km) is going to be a very crowded space in the next few years. Unless active measures are taken, the spacecraft (CubeSats) that have reached their end of life can end up cluttering the LEO environment. The measures can include policy changes as well as engineering and technical solutions related to how satellites need to be designed.

This thesis examines the orbital debris problem using CubeSats as a case study. It explores CubeSat design and the changes national space policies that may be required to accommodate many of these vehicles in Earth orbit without leading to an orbital debris crisis.

In this chapter, we will briefly examine the orbital debris problem by starting with orbital lifetime analysis, analysis of debris removal technologies, reform of current space policies and the problem statement which this thesis is designed to address. This chapter is concluded with this thesis' contributions and a description of the organization for the following chapters.

1.2 Orbital Debris Problem

According to the U.S. Space Surveillance, there are half a million space objects in Low Earth Orbit (LEO), and only 30,000 are actively tracked. 23,000 pieces of orbital debris are larger than 10 cm and provide more velocity when in orbit [2]. The estimated population of particles between 1-10 cm in diameter is approximately 500,000. There are 100,00,000 pieces of debris that are smaller than 1mm. The United States is responsible for 30% of all orbital space debris [3]. The debris is frequently in transit the orbits of hundreds of operational spacecrafts. Additionally, most of the debris were inserted into long-duration orbits, with orbital lifetimes imagined at multiple decades and centuries. Collisions can lead to huge investment efforts, including expensive fixes. There have been three major collisions since 2005 [4]. They all involve a large intact body, typically a satellite, colliding with smaller pieces. With these smaller pieces still in orbit, more collisions will occur, thus creating more space debris.

NASA’s *Handbook for Limiting Orbital Debris* is concerned with the issue of the orbital debris crisis and focuses on de-orbiting space devices as a solution [5]. The process of de-orbiting will decrease future production of space debris, focusing on the removal instead of the limitation. The focus will be on de-orbit objects or combustion after the completion of the mission. Disposal or de-orbiting of the spacecraft is a strategy that removes significant mass from the environment that could become debris in the future should an explosion or collision take place. Removal is the elimination of space objects by another system than those mentioned above, which for now is not an economically feasible option. Some studies have been done to target certain objects that may present the largest mass or largest risk of explosion. But the cost of actively retrieving the object, or a rendezvous such that a large object might be pushed to a lower orbit or reenter the atmosphere completely, is not a viable option. However, it is understood that in the future, this mechanism of debris mitigation may be employed. The first International Orbital Debris Conference will be hosted by the Lunar and Planetary Institute in hopes of limiting the orbital debris crisis caused by space exploration in early December 2019 [6].

1.3 Problem Statement

The work described in this thesis is an effort to examine possible technical solutions and policy reforms that can help mitigate ongoing orbital debris crisis.

Particularly, this thesis focuses on the efforts of CubeSats and how technological (design) and policy changes can contribute to mitigating this problem.

1.4 Thesis Contribution

This thesis' primary contribution is to describe possible technical solutions to the orbital debris problem. It will examine proposed removal technologies and possible policy changes that can mitigate the issue. The orbital debris problem will be evaluated through technical analysis and solutions, decision and risk management, and policy reform.

1.5 Thesis Organization

The remainder of this thesis is organized as follows: Chapter 2 describes a simulation study on the orbital lifetime of CubeSats in LEO. The objective of this chapter is to show that CubeSats or other small satellites travelling through LEO can, if care is not taken, results in being orbital debris. This motivates the need for orbital debris removal technology which is the subject of Chapter 3. Chapter 3 addresses various orbital debris removal technologies and how they can potentially solve the orbital debris problem. Chapter 4 presents policies focused on the preservation of the space environment. This starts with an overview of space policy throughout the United States and ends with a proposal for reform and recommendations for future CubeSat design. Chapter 5 presents a conclusion on the solutions to the orbital debris problem. It also outlines suggestion for future work related to the analysis of mega constellations and their impact to the future of space exploration.

2 Orbital Lifetime Analysis

2.1 Overview

This chapter considers the orbital lifetime problem to motivate the need for new design and public policy changes associated with small satellites. A point mass model used to simulate orbital lifetime of a CubeSat is described. The chapter starts with an overview of orbital mechanics and its basic elements to set the foundation for the simulation model used in the simulation. A survey of representative CubeSats mission and their associate lifetime is presented. The chapter closes with an orbital lifetime case study using a simple simulation model developed for this thesis.

2.2 Orbit Equation

Satellites traveling around Earth follow an orbit which is either an ellipse or a circle with the Earth's center of mass being the focal point of the orbit. The primary forces acting on a satellite in Earth orbit are gravity and drag. The orbit equations describe the motion due the forces of gravity.

The shape of an orbit (whether it is a circle or ellipse) is described by six parameters known as its orbital elements. The orbital elements are six parameters that describe the geometry (shape) of the orbit and its orientation relative to Earth. Since a circular orbit is a just a special case of an elliptical orbit, closed orbits are commonly described as an elliptical shape. As shown in Figure 1, the longest distance through the center of the ellipse is called the major axis. The semi-minor axis is longest line perpendicular to the major axis between two points on the ellipse The semi-major axis,a is one-half of the major axis and it is the first of the six orbital elements. The second parameter, its eccentricity, e,is the magnitude of the deviation of an orbit from circularity. The third orbital parameter is its inclination, i, and is the angular distance between an object's orbital plane and the Earth's equatorial plane, which serves as a reference plane. The periapsis is the point in an orbit that is closest to the focus of the orbit. The apoapsis is the opposite of the periapsis, which is the farthest point in the orbit. The fourth orbital elements, known as the argument of periapsis,ω is the angle from the orbit's ascending node (see Figure 2) to its periapsis, measured in the direction of motion. The fifth orbital element is the true anomaly, ν, is the angular distance from periapsis to the current position of the satellite in orbit. The ascending node is the angular position at which a celestial body passes from the southern side of a reference plane to the northern side. The sixth and final orbital element is the longitude of the ascending node or Ω, and is the angle between the ascending note and the first point of Aries ♈ ("the celestial prime meridian").

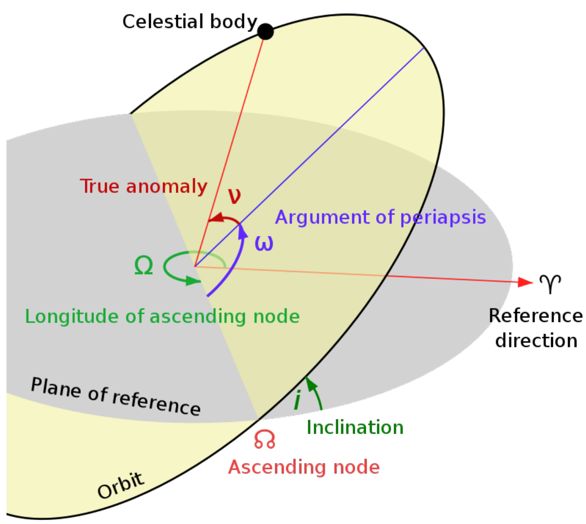

Figure 2. A visual description of the six major orbital elements.

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For the orbital lifetime analysis which is the subject of this chapter, we will only deal with a subset of the orbital elements contained in the orbital equation given below:

$$r = \frac{h^2}{\mu}\frac{1}{1+e\cos\theta} \tag{2.1}$$

Where r is the magnitude of the position is vector relative to the focus of the orbit (or Earth's center) and h is the relative angular momentum for the orbiting object or satellite. The variable. μ is the Earth's gravitational parameter. Without a loss of generality, we will focus on orbits that circular from now on. This is because the important and key points about the orbital debris problem can be examined, initially, considering circular orbits. With respect to Equation (2.1) above, a circular orbit would be one where $e = 0$. In what follows we will examine circular orbits a little more closely on our way to the orbital lifetime problem.

2.2.1 Circular Orbit

Generally small satellites occupy nominally circular, low-earth orbits ($r < 2000\, km$). Therefore, the parameters being used in this simulation display a circular orbit. If we set $e = 0$, the orbital equation becomes:

$$r = \frac{h^2}{\mu} \tag{2.2}$$

The orbital velocity, v, in turn, becomes:

$$v = \sqrt{\frac{\mu}{r}} \tag{2.3}$$

For circular orbit, the orbital period can be computed. The orbital period is the time it takes a satellite to complete a full orbit around the Earth. Due to the speed being constant, the orbital period can be calculated as

$$T = \frac{2\pi r}{\sqrt{\frac{\mu}{r}}} \tag{2.4}$$

The goal of the work in this chapter is to analyze the orbital lifetime. A satellite's orbital lifetime is how long it takes the satellite's orbit to decay. By decay we mean the time it takes for the satellite's orbital semi-major axis to decrease in size such that it eventually enters the atmosphere. The semi-major axis decreases (or the orbit decays) because the total kinetic energy of the satellite is decreased by atmospheric drag. The satellites specific energy, which includes potential and kinetic energy is given by:

$$\epsilon = \frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2r} \qquad (2.4)$$

Orbital decay occurs as the first term in Equation (2.4) decreased (due to drag) and the second term increased (due to gravity). In the next section we discuss how atmospheric drag reduces this first term.

2.3 Atmospheric Drag and Orbital Decay

Atmospheric drag is defined as the aerodynamic force that opposes a spacecraft's motion though the air. It has a significant impact on spacecrafts that operate in LEO. Although the air density in LEO is much lower than near the Earth's surface, it is still strong enough to produce drag which decreases the kinetic energy of the satellite. Atmospheric drag at orbital altitude is caused by frequent collisions of gas molecules with the satellite. These collisions between the gas molecules is a major cause to orbital decay which is defined as the reduction of the orbital semi-major axis of the satellite (or decrease in altitude). As the orbit decays, the aerodynamic drag cause heating which eventually leads to the burn up the satellite once it enters deep into the atmosphere. The formula for drag is based on the drag coefficient (C_D), the air density (ρ), the velocity (v), and the satellites sectional area (A) as follows:

$$D = \frac{1}{2} C_D \rho v^2 A \qquad (2.5)$$

While the magnitude of the drag force is a primary factor affecting orbital decay, the mass of the satellite also plays a role. Therefore, a non-dimensional quantity known as the ballistic coefficient, BC, is normally used in orbital decay calculations. The ballistic coefficient is the ratio of the satellite's mass to the product of its drag coefficient and frontal area (area perpendicular to the velocity vector) written as follows:

$$BC = \frac{m}{C_D A} = \frac{C_D A}{m} \tag{2.6}$$

The larger the ballistic coefficient, the less the impact of drag force on a satellite. As will be shown later in this chapter, as the ballistic coefficient increases, so does the orbital lifetime. Combining Equations (2.3), (2.5) and (2.6) gives the following equation for the drag on a satellite as a function of atmospheric density,ρ orbital semi-major axis,r and ballistic coefficient,BC:

$$D = \frac{\rho \cdot BC \cdot \mu}{2 \cdot m \cdot r} \tag{2.7}$$

As noted above, drag decrease the kinetic energy of the satellite. From elementary dynamics we know that the incremental change in kinetic energy,$d\varepsilon$ is related to the drag force as follows:

$$d\varepsilon = -D \cdot ds = -\frac{\rho \cdot BC \cdot \mu}{2 \cdot m \cdot r} \cdot ds \tag{2.8}$$

ds is incremental distance traveled by the satellite. If we divide by dt of both sides of Equation (2.8), noting that $v = \frac{ds}{dt} = \sqrt{\frac{\mu}{r}}$ we get:

$$\frac{d\varepsilon}{dt} = -\frac{\rho \cdot BC \cdot \mu^{\frac{3}{2}}}{2 \cdot m \cdot r^{\frac{3}{2}}} \tag{2.9}$$

The left-hand side of the equation above can be evaluated by taking a derivative of Equation (2.4). That is

$$\frac{d\varepsilon}{dt} = -\frac{d}{dt}\left(\frac{\mu}{2r}\right) = \frac{\mu}{2r^2}\frac{dr}{dt} \tag{2.10}$$

Combining Equations (2.9) and (2.10) and rearranging gives the following differential equation for the rate at which a satellites semi-major axis (or orbital radius for a circular orbit) changes with time as a function of ballistic coefficient:

$$\dot{r} = \frac{dr}{dt} = -\frac{\rho \cdot BC \cdot r^{\frac{1}{2}}}{2 \cdot m \cdot \mu^{\frac{1}{2}}} \tag{2.11}$$

For a given satellite, everything except density and radius, ρ and r , on the right-hand side of Equation (2.11) is constant. If we know how density changes with altitude or r , then we can numerically integrate Equation (2.11) to determine orbital lifetime. Therefore, in the next section we discuss how atmospheric density changes as a function of altitude.

2.3.1 Atmospheric Density Models

A reference atmospheric density model describes how the ideal gas properties (pressure, temperature, density) of an atmosphere change, typically as a function of altitude, and sometimes also as a function of latitude, day of year, etc. Our interest here is the change of density a function of altitude or orbital radius. The four most common atmospheric density models used in satellite orbit analysis are the exponential model [7], scale height exponential model , 3-zone model [8] and the Jacchia 1977 model [9]. The different models have different levels of fidelity with the Jacchia model being the most accurate. However, for our purposes here, a high-fidelity atmospheric model is not required. Therefore, for the work described in this thesis we used the scale height exponential density model.

A MATLAB script which solves Equation (2.11) using the scale height exponential atmospheric model was used to study the orbital lifetimes of CubeSats in orbit. We describe that study in the next section.

2.4 Survey of Representative CubeSat Missions

CubeSats are defined as a small "shoebox size" satellite that can be placed into orbit using a standardized dispenser whose standards were developed in 1999 from an initiative by California Polytechnic State University & Stanford University. These types of satellites are in the class of satellites known as nanosatellites which have a mass of less than 10 kg. The name "cube" comes from the satellites' basic form factor which is a 10 cm × 10 cm × 10 cm or 1000 cm^3 cube. This basic unit is called a "U" or a unit, which weighs about 1.33 kg. This size allows for the satellites to be packaged as a secondary payload on a launch vehicle. The basic sizes are 1U, 2U, 3U, 6U, and 12U and are shown in Figure 3 below.

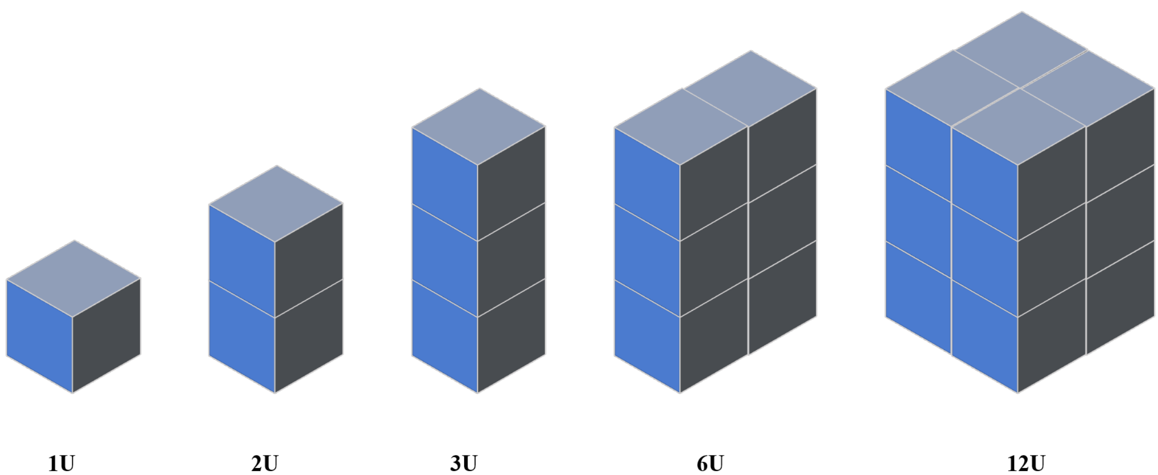

Figure 3. Basic CubeSat geometries.

The 6U and 12U form factors can be arranged in other ways than shown in this figure. For example, the TechEd Sat series of CubeSats from NASA Ames (See Table 1 below) have a 6U form factor which consists of two 3U CubeSats attached end to end.

Deploying CubeSats to LEO is become easier and easier. For example, NASA developed the CubeSat Launch Initiative (CSLI) in 2010 to enable universities and nonprofit organizations can launch CubeSats for educational usage and research opportunities [10]. CSLI uses various launch opportunities including private contractors such as NanoRacks for launch services. Outside of CSLI companies such as NanoRacks provide launch services for commercial and non-profit customers at relatively modest prices. An example of a 3U CubeSat built by an educational institution and launched by NanoRacks via the CSLI program is the University of Minnesota's Signal of Opportunity CubeSat Timing and Ranging Experiments (SOCRATES) shown in Figure 4 below. SOCRATES is a 3U CubeSat whose mission is to increase the technology readiness level of a novel x-ray and gamma ray spectrometer. It was deployed into LEO from the International Space Station (ISS) in February of 2020.

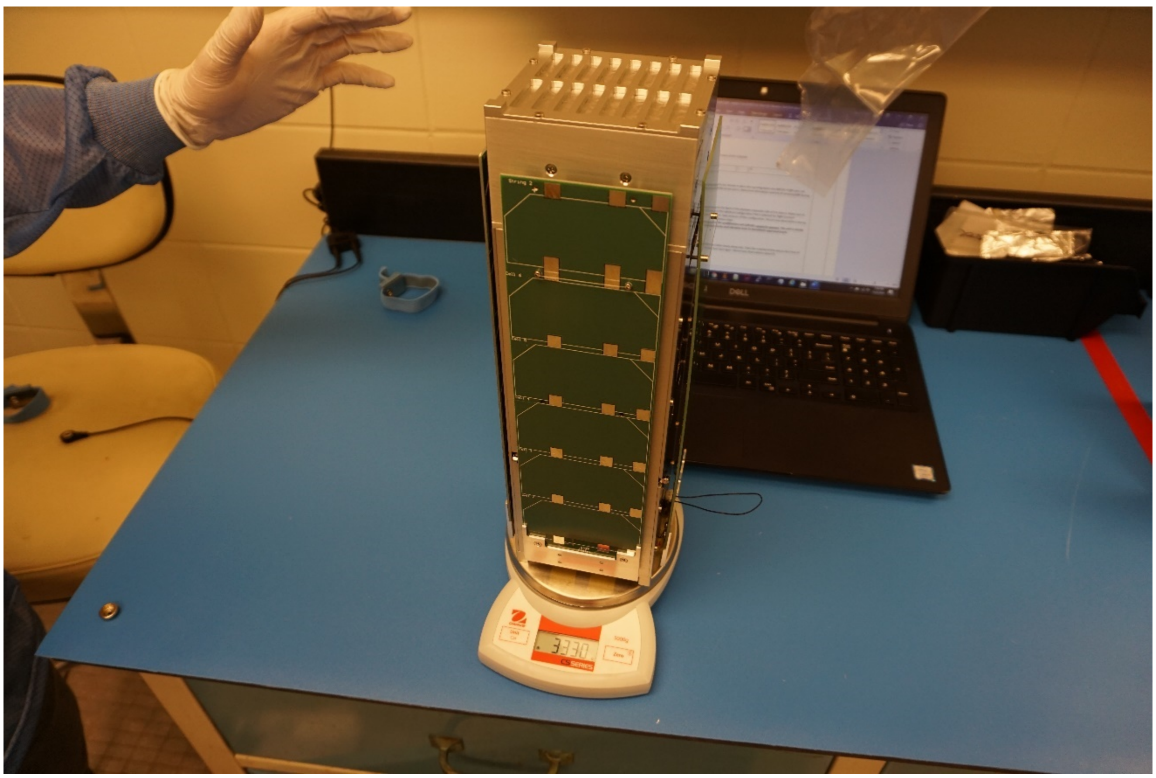

Figure 4 The Signal of Opportunity CubeSat Ranging and Timing Experiments (SOCRATES) CubeSat shown with its solar panels in the stowed configuration.

The effort to build and deploy SOCRATES demonstrates that it is becoming easier and easier to build and fly small CubeSats and, thus, the number of the in orbit is bound to increase with time. This point is made clearer by Table 1 below which is a listing of CubeSat that have been deployed in Earth orbit and their orbital lifetimes. As can be seen from the table most of these CubeSats have an orbital lifetime of less than 5 year (4.42 years = 1,616 days for hours is the maximum in Table 1).

All the CubeSat listed have an orbital altitude of less than 500 km. It can also be seen that their orbital lifetime is proportional to altitude: the higher the CubeSat the longer its orbital lifetime.

Name of CubeSat	Altitude (km)	Inclination (deg)	Frontal Area (cm^2)	Ballistic Coefficient (unitless)	Orbital Lifetime (days)
GeneSat-1	460	40.5	300	79.4	21
InflateSail	500	97.5	300	63.3	73
TechEdSat-6	400	51.6	300	63.3	153
Flock-2e-1	400	51.6	300	63.3	190
TuPoD	400	51.6	300	63.3	270
Lemur-2	400	51.6	300	63.3	491
Bevo-2	400	51.6	300	63.3	552
FireFly	500	40.5	300	63.3	1460
Horus	500	40.5	300	63.3	1616

Table 1. Orbital lifetime for representative 3U CubeSats in LEO

There are many envisioned plans for CubeSat-like satellites in higher orbits. There are also mega-constellations that are being planned which will use small satellites (not necessarily CubeSats) at higher orbits. Therefore, the question we want to answer in this chapter is will be the orbital lifetime of CubeSats deployed into higher and higher LEO?

2.5 Orbital Lifetime Simulation

In closing this chapter, we present the results of a simulation study to show the impact that higher altitudes will have on orbital lifetime and, thus, the orbital derbies problem for small satellites. To this end, we use a MATLAB simulation developed to solve Equation (2.11). We consider a CubeSat-like small satellite in an orbit with radius (semi-major axis) of 1200 km. This is representative of the orbits of some envisioned mega-constellation such as OneWeb [11]. We consider two ballistic coefficients: 67 and 200. A $BC = 67$ is representative of a CubeSat such as SOCRATES with deployed solar panels. A $BC = 200$ is representative of a 3U CubeSat with no deployable structure and flying with its small face lined up with the velocity vector. We assume that the CubeSat has an orbital attitude of 500 km and an re-entry altitude of 120 km.

Figure 5. Results from the COLS Simulation in MATLAB showing the relationship between Altitude and Orbital Lifetime for two different ballistic coefficients 67 and 200.

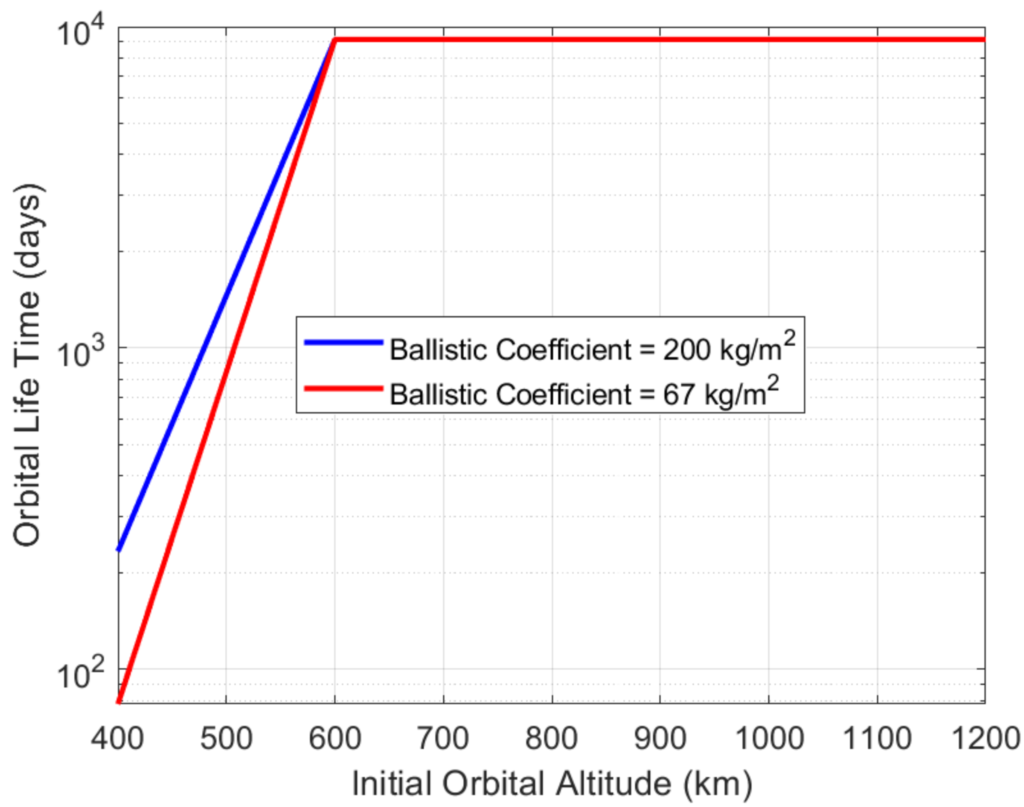

Figure 5 shows orbital lifetime vs. time for these two cases. At an altitude of 500 km. as can be seen the orbital lifetime for the satellite with $BC = 67$ is about 800 days. Similarly, the orbital lifetime for the satellite with $BC = 200$ is around 1000 days. This shows that small satellites like these in high LEO will continue to persist in orbit and be a debris hazard way after their useful mission life. This motivates the concern for the orbital debris problem and the need for a technology and policy solution to deal with this potential problem.

2.6 Chapter Summary

In this chapter we examined the orbital lifetime problem associated with small satellites. We showed that small satellites in high LEO (orbital semi-major axes on the order of 1000 km) will have orbital lifetimes on the order of years. Unless these satellites can be actively deorbited after their end-of-life, they can become a big problem from an orbital debris point of view. In the chapters that follow we will examine potential solutions for this problem. In Chapter 3 we will consider technology solution that are being proposed for removing debris from orbit. We will explore whether these technologies are suitable for removing small satellites such as CubeSats. In Chapter 4 we will consider policy and future design requirement-based solution to mitigate this orbital debris problem.

3 Orbital Debris Removal Technologies

3.1 Chapter Overview

The term “debris removal” implies taking *active* measures to remove something from orbit and not letting its orbit decay on its own. In this chapter we examine proposed technologies for performing active debris removal. The chapter examines three-removal technology concepts: Laser Solutions, Electrodynamic Tethers, and Deployable Nets. Each technology is analyzed conceptually to provide the proper physics behind its operation. Then the suitability of the technology for dealing with the orbital debris problem stemming from proliferation of small satellite (especially CubeSats) is briefly discussed. Before each technology for orbital debris removal is described, we will use material from Chapter 2 to describe the basic orbital mechanics behind orbital each of these active systems.

3.2 Orbital Mechanics of Active Debris Removal

The objective for all removal technology is to cause a change in velocity (Δv) of an object and thus cause it to change its orbit. Equation (2.4) shows that changing velocity will cause a change in specific energy of the object in orbit. In the limiting case where the orbital velocity is reduced to zero, the object will only have gravitational potential energy and, thus, “fall” back to Earth. Thus, de-orbiting of the debris is mainly focused on using different mechanism for changing orbital velocity. This is done by applying a force (or impulse). The three technologies considered are different in the way they impart this force or impulse. The lased-based approaches impart this force or impulse in a contactless fashion. Electrodynamic tethers are objects that are deployed from or attached to an object that will result in forces being applied to it form Earth magnetic field. Nets on the other hand apply this force by physical contact with the object.

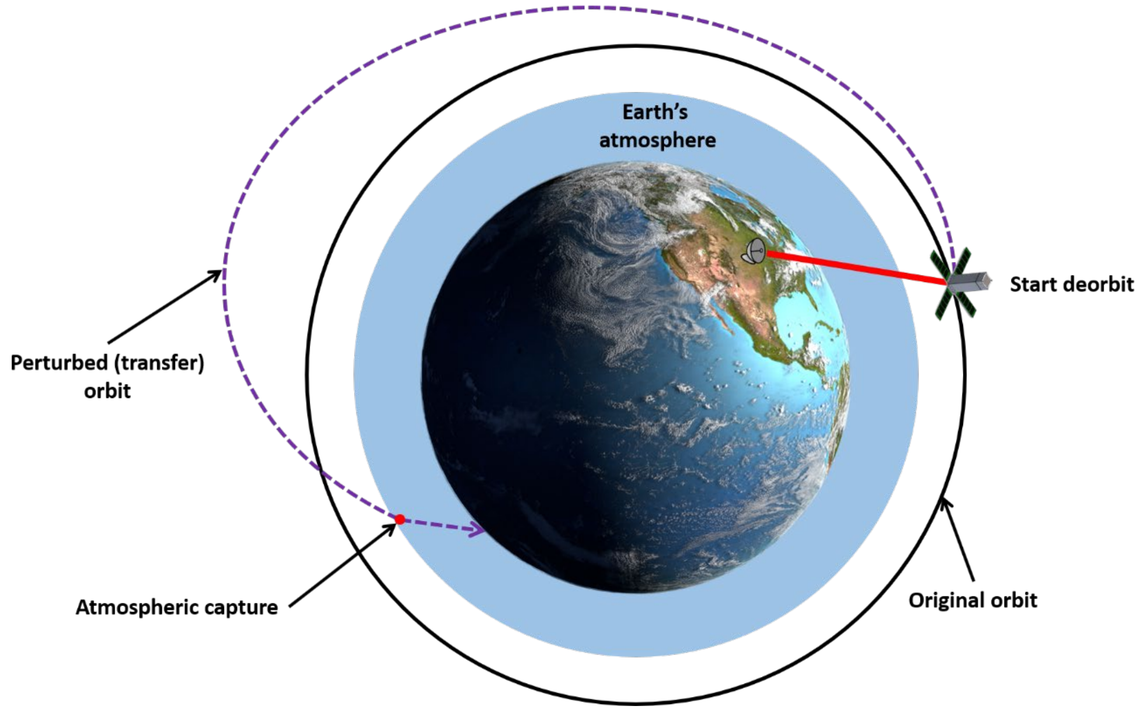

Figure 6. Basics of active orbit debris removal.

All three of the orbital debris removal systems discussed in this chapter effectively perturb the original orbit of the object so that it eventually gets captured by the atmosphere.

Figure 6 shows the basic idea behind active debris removal. Without a loss of generality, what is shown in Figure 5 is a laser debris removal system, but the idea extends to the other methods discussed in this chapter. As shown in the figure, we assume that a satellite or any other object that we want to remove is initially in a circular orbit around Earth. What the debris removal system does is to perturb the orbit by applying a force or impulse to the object. The applied force or impulse perturbs the objects orbit and puts into a new orbit. The new orbit is effectively a transfer orbit whose periapsis is a point in the dense part of the atmosphere. Thus, once the debris is on the transfer orbit is will eventually encounter the dense part of the atmosphere in which the drag on it will be very high. This will slow down the object and the aerodynamic heating resulting from the increased drag will cause it to burnup high in the atmosphere.

The three debris removal systems discussed in this chapter effectively perturb the orbit of a satellite and result in a re-entry and burnup as shown in Figure 3.1. The difference from each other in how they apply the force or impulse to the object that is to be removed from orbit.

3.2 Laser Orbital Debris Removal

Laser orbital debris removal (LODR) is one of the proposed solutions to solving the orbital debris crisis within the low Earth orbit (LEO). LODR is a contactless method in that applying a force or impulse to the object to be de-orbited does not require to physically contact it. The system uses a laser either on Earth or in orbit to shone on the object that is to be deorbited. As will be described below, this leads to force or impulse that results in a change of orbital velocity or Δv .One of the earliest proposed use of LODR was by NASA in 1996 with Project Orion [12]. Project Orion was created as a “laser broom” to remove all pieces of debris less than 10 cm under 1100 km in two years. This LODR as used a pulsed laser.

The LODR solution is considered successful, especially for larger debris. With having the ability to capture debris from the ground and in space, researchers can explore a solution with multiple options. There are concerns with this laser orbital removal technology capturing the smaller pieces (less than 1mm).

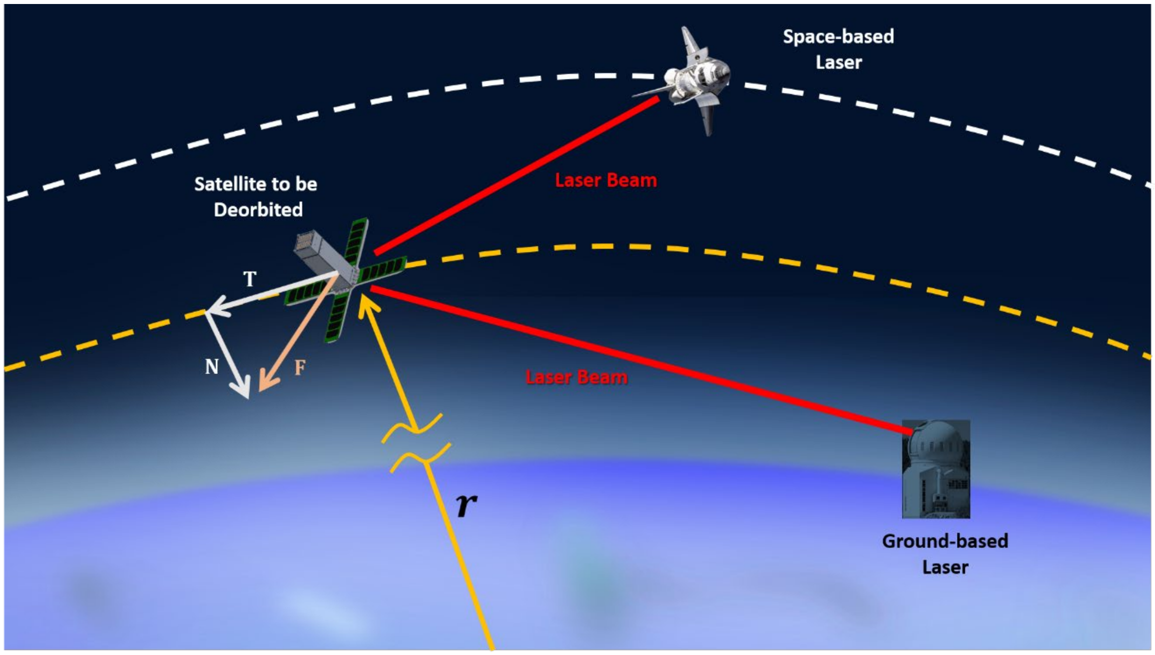

Figure 7. Concept of operation (CONOP) of the Laser Orbit Debris Removal (LODR) system.

The laser which is either a ground- or space-based one applies a force $\boldsymbol{F}$ to the debris. This in turn changes the orbital speed and eventually orbital radius r.

Figure 7 shows the concept of operation or CONOP for the LODR system. The system uses either a ground-based or space-based laser to apply a force or impulse to the object to be deorbited. The total force imparted to the debris is $\mathbf{F}$ and can be resolved into its tangential component $\mathbf{T}$ and radial/normal component $\mathbf{N}$. As will be discussed below, the magnitude of $\mathbf{T}$ and $\mathbf{N}$ depend on many factors including the orientation (attitude) of the debris. The force applied by the laser beam causes a change in the debris orbital velocity which puts it into a transfer orbit with a perigee deep in the dense part of the atmosphere ash shown in Figure 6. The mechanism by which a force is applied to the debris is discussed next.

3.2.1 Mechanics of LODR

Figure 7 shows a very simplified depiction of the operations of LODR. All removal technologies need to be able to provide a change in orbital velocity. The laser deposits energy into the material of the debris which causes ablation of the material. The ablation products leave the debris at a high speed and carry with them some of the momentum of the debris. In effect, the ablation products are acting as a miniature thruster that is applying an impulse to the debris. The net thrust that is imparted by the ablation products depends on the orientation of the debris. As show shown in Figure 7, if the flat part on which the laser shines is not perpendicular to the original velocity vector, the resulting force will have both a tangential component **T** and a normal component **N**.

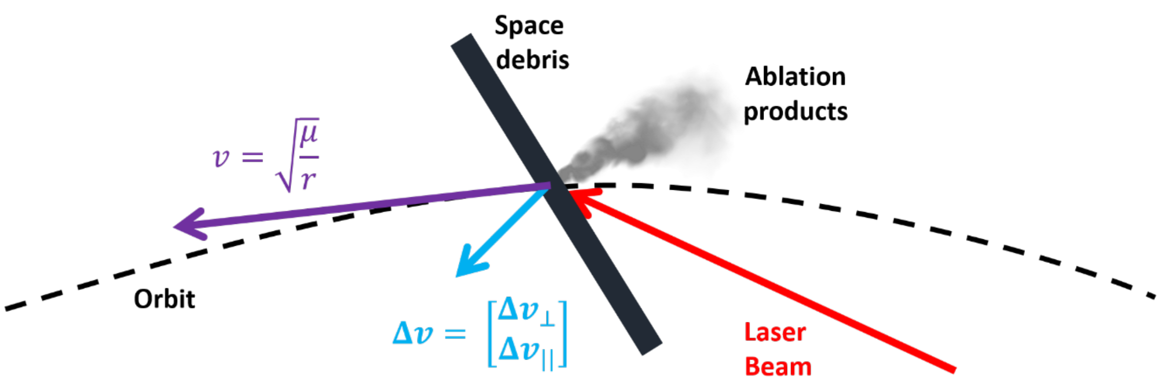

Figure 8. Impact of debris orientation on Δv generated by LODR. The direction of the normal to the surface of the debris relative to the laser beam affects the magnitude and direction of the applied Δv.

Referring to Figure 8, the magnitude of the tangential velocity change $\Delta v_{||}$ applied to the debris is described by the following equation:

$$\Delta v_{||} = \frac{\eta_c C_m \Phi}{\mu} \tag{3.1}$$

The efficiency factor η_c accounts for the combined effects of improper thrust direction on the target, target shape and tumbling. The term Φ is the laser fluence which is a measure how much energy is contained in the laser. The mechanical coupling term C_m measures how much of how effectively the laser energy is converted into momentum change of the debris. The last term in this equation μ is the debris areal mass density and is a description of the debris' geometry.

Equation 3.1 shows, the change in orbital velocity achieved by LODR depends on many factors including the laser being used as well as the geometry and construction of the debris' host spacecraft. Below is the result of simulations from [13] [14] used to show what ablation laser requirements are needed for various materials, particularly materials found on spacecraft.

Debris Material	Laser Fluence Required (J/m^2)	Mechanical Coupling Coefficient
Aluminum (Al)	11.70	3.94E+29
Gold (Au)	16.90	2.20E+36
Carbon (C)	15.68	3.20E+27
Iron (Fe)	13.00	1.19E+32
Lithium (Li)	10.40	1.05E+23
Molybdenum (Mo)	5.20	5.46E+36
Tungsten (W)	20.80	2.48E+38

Table 2. Characteristic of LODR on common materials that are used on spacecraft.

3.2.1 Advantages and Disadvantages of for LODR

In view of the proceeding discussion, LODR has some very attractive features when it comes to orbital debris removal. One of these is the fact that is contactless and thus does not require interaction with space debris that can be potentially hazardous. Furthermore, lasers can work with most materials that are commonly used to make spacecraft (as shown in Table 2. Characteristic of LODR on common materials that are used on spacecraft. above). This implies that there is no cost upfront associated with designing a spacecraft that can be removed later by a LODR system.

In terms of disadvantages, Figure 7 shows the difficulty associated with using LODR. The Δv imparted by LODR depends on the orientation of the debris. This means that a very good situational awareness of space debris is required because application of LODR to an object with an unfavorable orientation can lead to exacerbating the problem by putting into an orbit that is harder to remove from or necessitating more application of LODR to get it to deorbit. The solution and diagram discussed only works when the object's primary surface is facing the laser system.

3.3 Electrodynamic Tethers (EDT)

Electrodynamic Tethers (EDT) are systems that take advantage of Earth's magnetic field to generate an electromotive force which can be used apply a positive or negative Δv to an object in orbit. Tethers are long strands of fibers that are used to connect or couple objects together to operate as one system. In space, tethers are typically launched or directed into Earth's orbit and will align with the movement of Earth's magnetic field [15]. Some tethers will convert potential energy to kinetic energy while others act as motors. Thus, they can be used as a deorbiting system or a "boost" system for changing the orbit of Earth orbiting objects. In other words, some tethers will convert potential energy to kinetic energy while others act as motors. This solution has been predicted better for mega-constellations due to the amount of electrodynamic drag they possess. There have been several EDT demonstrations missions most the TSS-1 and TSS-1R mission [16], Plasma Motor Generator (PMG) experiments [17] and NASA's Propulsive Small Expendable Deployer System or ProSEDS mission [18].

3.3.1. Mechanics of EDT

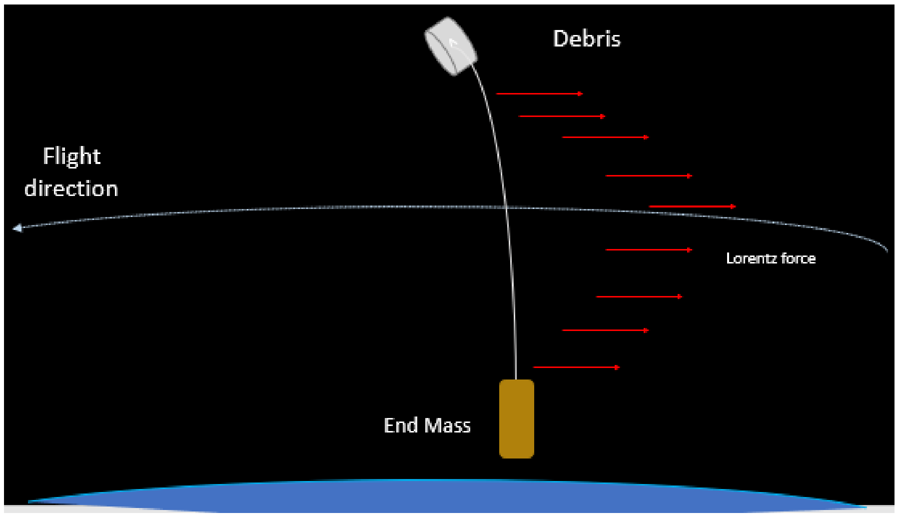

Figure 9. Principle of EDT demonstrated with experiment using EDT solution HTV-KITE from JAXA.

Figure 9 shows the principle of an electrodynamic tether solution for removing orbital debris. The tether was deployed and is shown orbiting around the Earth with an end mass. Current runs through the tether, working along with the geomagnetic field of the planet. The bare side of the tether attaches itself to the orbital debris using a hooker or connecter. After capture, the end mass allows the system to rotate and release the tether and orbital debris. The system then deorbit itself and burns up into the atmosphere, removing the debris overall. This concept is used in the KITE experiment from JAXA. Previous studies show that debris objects that should be removed from crowded orbits can re-enter the Earth's atmosphere within one year. Having a system with at least a 10-km tether on a host satellite should be able to eliminate that [19].

The basic principle behind EDT is captured by the well-known equation relating magnetic force $\mathbf{F}$ on a conducing wire moving with some velocity $\mathbf{v} = \frac{d\boldsymbol{\ell}}{dt}$ in a magnetic field $\mathbf{B}$ carrying a current I. That is, the force on a differential length $d\boldsymbol{\ell}$ of the conducting wire is given by:

$$d\mathbf{F} = I d\boldsymbol{\ell} \times \mathbf{B} \tag{3.2}$$

In the case of objects in orbit, the field in question is the Earth's magnetic field. Thus, if a space craft can deploy a long cable of length L cable of carrying an electric current, then as it orbits the interaction between Earth's magnetic field and the cable will generate a force given by:

$$\mathbf{F} = \int_0^L I \, d\boldsymbol{\ell} \times \mathbf{B} \tag{3.3}$$

Figure 10 below shows a simplistic diagram of the relationship between the orientation of the cable and the force $\mathbf{F}$ that would be generated by a deployed cable in orbit. The result force will be orthogonal to both the cable and Earth's magnetic field. As such, it acts in the direction opposite to the velocity vector of the object that deployed the cable. Thus, it is effectively delivering negative Δv to the space craft and causing its orbit to decay.

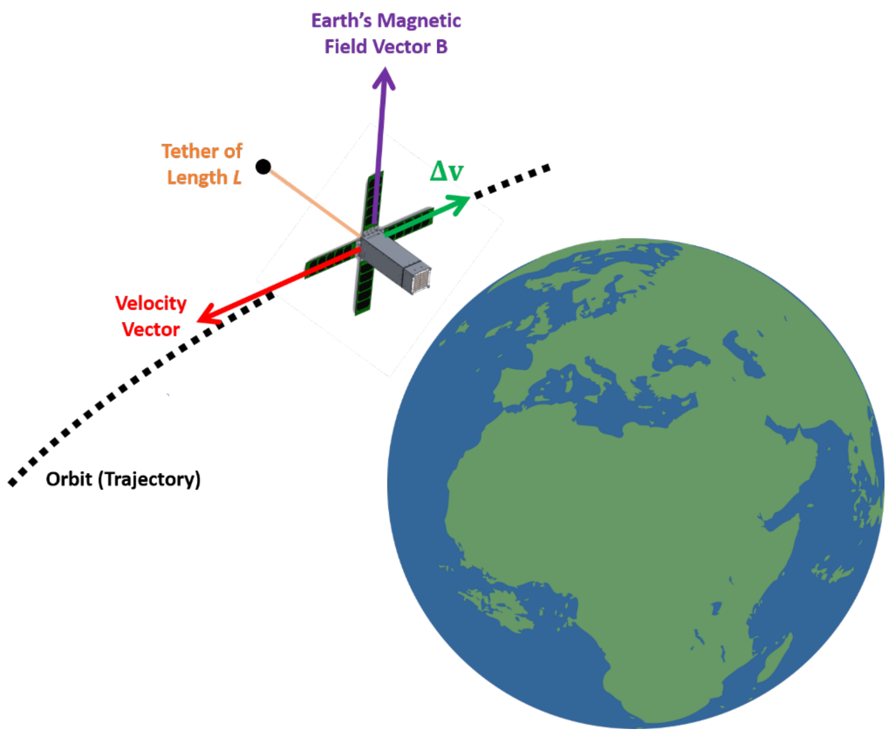

Figure 10. Operation of an electrodynamic tether for de orbiting of a small satellite in Earth's orbit

3.3.2. Advantages and Disadvantages of EDT

As described above the EDT is rather simple and passive device. This means that it can be easily installed on many small satellites. While the mechanism used for reeling out the cable can be difficult to design, they can be made to be rather compact and fit in most small space vehicles including CubeSats. For example, the company, Millennium Space, has fitted such systems on a pair of small CubeSats set to launched soon [20]. Another advantage of the EDT is that is a dual-use system. That is, it can be used not only to de-orbit a small spacecraft but also as for increasing their orbital altitude as well. Yet another advantage is that it can be used to generate electrical power which can be used to charge batteries thereby supplementing the function of solar panels. Unlike solar panels, however, they can generate power regardless if the sun is in view or not. Therefore, it is possible that a small CubeSat can be power positive for its entire orbit if it is equipped with an EDT.

A disadvantage is the interaction between the tether and material of the debris. The tether would be limited to what material it could capture depending on the conductivity, debris area, resistivity levels. There is also a larger orbital debris impact risk since the length of the tether can interfere with other pieces of debris when deployed. Another disadvantage of this system is that it only works on objects that have it designed and built into them. This means that it cannot be used on random space debris unless there is a way to attach a compact and self-contained EDT system to the debris on orbit. What we mean by the term "random space debris" are object that are the result of collisions or unintended separations (falling off) from satellites. This can be incredibly challenging in that the interaction between the tether and material of the debris is key for the EDT to operate well. As noted above, the tether would be limited to what material it could capture depending on the conductivity, debris area, resistivity levels. It is not clear that this can be accomplished with any random orbital debris that is not part of integrated and well-designed small satellite in the first place.

3.4 Deployable Nets

Deployable nets are perhaps the easiest to understand technology that has been proposed for orbital debris removal. The idea is to deploy something akin to a fisher's net called a tether-net from a chaser spacecraft (still connected to the net) in the proximity of an orbital debris that needs to be removed from orbit. The tether-net is deployed ahead of the debris to be removed. The debris slowly drifts into and gets tangled by the tether net. Then the chaser spacecraft fires thrusters to change the orbit of both itself and the debris in the net such that they will reenter Earth's atmosphere and burn.

While conceptually simple the design of the nets themselves and the debris removal operation using them can be complex. For example, proposed nets are a collection of elastic rods connected. The rods can be connected by knots, or elastic joints, or without them. As a deformable body, the elastic rod can bend and form around the target to secure and capture it. Most nets considered for orbital debris removal are cosserat nets. Cosserat nets consist of a network of elastic rods and elastic joints that link together to create a deformable body [21].

Furthermore, nets need to have a closing mechanism to allow satellite to release net once debris is captured. These can also be complex to design and operate in space.

3.4.1. Mechanics of Deployable Nets

The deployable net solution can be explained using the practices of fishing Fishermen handle large amounts of fish using nets. When fishing, fishermen will throw out a massive net from a ship to capture schools of fish. Fisherman locate the fish and eject a net from a safe distance. The net comes with a closing mechanism to secure capture and reel the net back up to the surface.

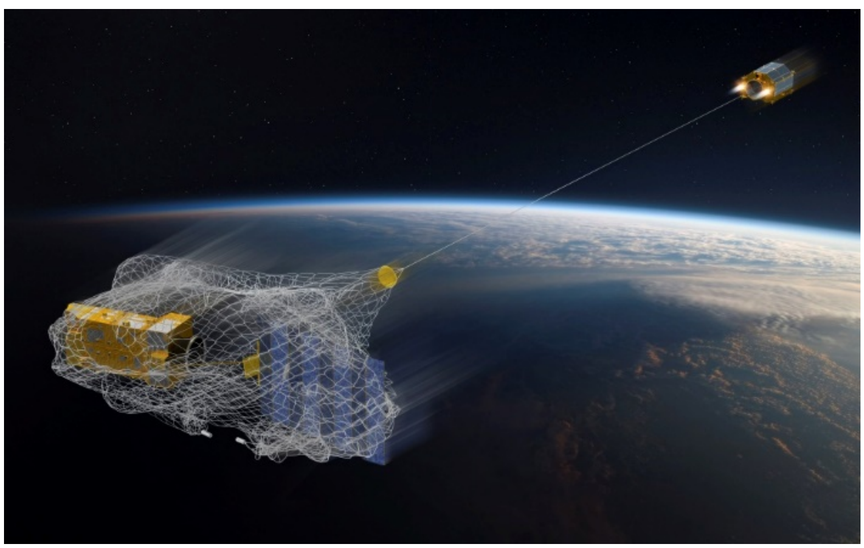

Figure 11. Image of proposed space debris removal using deployable net from the European Space Agency (ESA) in 2024. Courtesy David Ducros/ESA

Figure 11 shows the similar concept occurring with the deployable net solution in space. The net is transported into space on a host satellite in a container. Once the satellite is at desired altitude, the net is deployed and captures targeted debris using its closing mechanism. The closing mechanism would be the end points on the corners of the net to ensure proper capture. The satellite will then travel to a lower altitude and cut the net with the attached debris for it to de-orbit and burn up in the atmosphere.

3.4.2. Advantages and Disadvantages of Deployable Nets

Unlike the other solutions, deployable nets can capture a large group of debris at one time. This would be an ideal solution after a collision due to the amounts of debris that are created at that instance. This also makes it one of the more cost-efficient solutions. A disadvantage is that the net needs proper spatial awareness for proper capture. Multiple proposed net based solutions include the addition of a tether to assist with accurate positioning when deploying the net. Without proper attitude and control practices from the host satellite, this would be difficult for the net to capture the debris. Another concern is the net possibly getting stuck onto the host satellite. This can cause issues in its operation, thus failing the mission before it can occur.

3.5 Chapter Summary

In this chapter we examined the technology that has the potential to solve the orbital debris problem. We showed the mechanics of LODR, electrodynamic tethers, and deployable nets. As we have showed, all these methods are just different ways of being able to impart a force or moment to an object in orbed based on the equations discussed in Chapter 2. Each of the debris removal method was examined on how well they would solve the problem based on past results and specific characteristics. In Chapter 4 we will consider policy and future design requirement-based solution to mitigate this orbital debris problem. This might help inform future design of spacecraft with efficient, end-of-life deorbiting technologies built into them so that, in the future, active measures like the ones described int his chapter are used only as a last resort for debris removal.

4 Policies Focused on the Preservation of Space Environment

4.1 Chapter Overview

Chapter 4 presents policies focused on the preservation of the space environment. As shown in the previous chapter, while there are technologies being proposed to remove debris from orbit, it seems prudent to actually start designing future spacecraft so that they do not contribute to the debris problem in the future. This can happen by policy changes that affect how spacecraft operate but also by changes to design practices for fabricating spacecraft. This chapter examines both alternatives. It starts with an overview of space policy throughout the United States and ends with a case study of current CubeSat design practices. It concludes with some suggested paths forward for change to design practice for CubeSats (or CubeSat-like vehicles) which are expected to proliferate the space environment in the future.

4.2 Timeline of United States Space Policy

The United Nations Committee on the Peaceful Uses of Outer Space was established in 1959 to review the scope of international cooperation in the peaceful uses of outer space [4]. The committee was formed in response to the launching of Sputnik. The Outer Space Treaty signed by the United States in 1967 established that space shall be free for exploration and it is able to be explored by all nationalities. The treaty does not ban military activities within space, military space forces or the weaponization of space. However, the State that launches a space object retains jurisdiction and control over that object. The State is also liable for damages caused by its space object, which is resulted from orbital debris and orbital collisions [5]. Multiple states of the United Nations have developed their own Orbital Debris Mitigation guidelines, such as Russia, China, Japan, the nations of Europe, and the United States.

In 1988, the United States created an official policy to minimize the creation of new orbital debris. A set of U.S. Government Orbital Debris Mitigation Standard

Practices was developed in 1997 and approved in 2001 [6]. The 2010 National Space Policy addressed the importance of preserving the space environment, including orbital debris mitigation. NASA and the Department of Defense pursue research and development of technologies and techniques to mitigate and remove on-orbit debris, reduce hazards, and increase the understanding of the current and future debris environment. According to the 2010 National Space Policy, "Orbital debris poses a risk to continued reliable use of space-based services and operations and to the safety of persons and property in space and on Earth. The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space to preserve the space environment for future generations." [7]

The most recent space policy document from June 2018, Space Policy Directive-3 (SPD-3), the National Space Traffic Management Policy states "Orbital debris presents a growing threat to space operations. Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris." The SPD-3 further states that "The United States should develop a new protocol of standard practices to set broader expectations of safe space operations in the 21st century [8]. This protocol should begin with updated ODMSP, but also incorporate sections to address operating practices for large constellations, rendezvous and proximity operations, small satellites, and other classes of space operations. These overarching practices will provide an avenue to promote efficient and effective space safety practices with U.S. industry and internationally.

The United States Space Command is the current state that handles all space operations. The United State Space Command is under the United States Air Force. Its role is to control space forces and develop the tactics, techniques, and procedures for military space operations [9]. The Trump administration re-established the National Space Council back in 2017. They launched a joint review by the National Space Council and National Security Council of existing space operational authorities for meeting national security objectives. A creation of collaborative mechanisms with the Intelligence Community to improve unity of effort for the development of space capabilities and operations. This led to the creation of the Space Development Agency to ensure Americans in the Space Force have cutting-edge warfighting capabilities. The Space Force has been proposed as a separate and distinct branch of the military whose mission will be to organize, train, and equip combat space forces.

In the United States, multiple agencies and stakeholders play a role in space policy. NASA, National Oceanic and Atmospheric Administration (NOAA), Federal Aviation Administration (FAA), National Security Agency (NSA), DoD, and Federal Communications Commission (FCC) serve space policies depending on the topic [22]. For example, NASA focuses on policies that relate to the scientific observation of the space environment, including the orbital debris migration crisis. Therefore, we conclude that both mission restrictions and the scientific observation of orbital debris, can lead to the development of a sole entity that focuses all space policy, along with space operations.

4.3 Risk Assessment

The orbital debris problem has caused risk and hazard for technical and legal issues. A hazard is something that has the potential to cause harm. Risk is the measurement the likelihood of harm from a hazard. The continuous increase of orbital debris poses a threat to the future of space exploration. With more spacecrafts being launched into orbit, more debris will follow the competition of respected missions. *If launchers meet the current requirement for launching objects into space, the orbital debris will continue to increase and be an issue on the preservation of environment.* This observation is the motivation for our discussion of CubeSat design practices at the end of this chapter.

One of the main hazards to the orbital debris crisis are the pieces of orbital debris and their interaction with other spacecrafts and devices in orbit. These debris can be generated, as noted earlier, by satellite explosions or spacecraft/orbiting body collisions. With over 67,000 collisions documented annually, 22% of breakups from collisions are unknown [19]. Even though many of the space debris objects are small, their high velocity makes them potentially dangerous. Recall, for purposes of context, the orbital velocity of objects in LEO is approximately 17,400 mph which is on the order of 8 times greater than the muzzle velocity of semi-automatic rifle. Therefore, from the point of view of kinetic energy transfer, the impact of satellites encountering the smallest space debris is equivalent to someone actively shooting them with a semi-automatic rifle. An example of such damage of a space device is the damage a piece of orbital debris to the Hubble Telescope. In 1997, a hole was found on the disk of the Hubble Telescope and had to be repaired [3]. The Hubble Telescope is the first major optical telescope to be placed in space. It is used to observe the solar system and has been in operation for thirty years. It long and useful service could have been terminated by an encounter with a small space debris.

Another major hazard orbital debris has results from the design of spacecrafts. There is currently no active technology that will refuel or repair satellites in orbit. Vehicles on Earth have the benefit to be repaired and treated. This is seen with cars, boats, motorcycles, bikes, etc. There are gas stations to refuel cars and motorcycles at the need of the driver. On boats, there are portable containers on deck for fueling in case that boat runs out. While satellites are in orbit, there is no system like portable fueling or gas stations. Satellites must be designed to fulfill its mission using the technology the launcher equips it with. Dealing with orbital perturbation that result from encounter with space debris adds on the economic risks of cost to have satellites. For example, this may require carrying more fuel or power in attitude control system to able to deal with unplanned attitude upsets.

Orbital debris adds on to the risks of space travel for launchers. According to the NOAA, intense geo-magnetic storms and space weather are major contributes to risk. A geomagnetic storm is an exchange of energy from solar wind to the Earth's magnetosphere. This causes changes in the radiation belt, changes in thermosphere, and may result to an array of magnetic distances surrounding the Earth [12]. The experiences of space weather affect satellite communication due to loss of signal from the disturbances. With the GPS system and Internet broad system being operated in LEO, such disturbances can initiate signal loss.

4.4 Orbital Debris Mitigation

With the debris problem at an all-time high, national government organization are working to lead efforts of mitigation. According to NASA, “Mitigation measures can take the form of curtailing or preventing the creation of new debris, designing satellites to withstand impacts by small debris, and implementing operational procedures such as using orbital regimes with less debris, adopting specific spacecraft attitudes, and even maneuvering to avoid collisions with debris.” [14]

4.4.1. International Efforts

Many international space organizations focus on various solutions for orbital debris removal. JAXA, the Japanese Space Agency, has developed a technology to remove space debris with electrodynamic tethers. For example, as noted in Chapter 3, the system, Kounotori Integrated Tether Experiments (KITE), is an experimental deployable electrodynamic tether which is equipped with 20 kg end-mass. The primary objective of the KITE mission was to demonstrate key technologies of electrodynamic tether in preparation for the near future debris removal applications. During the approximately seven days from the end of integrated operation until reentry. The mission includes having the tether latching onto the debris and the spacecraft dragging the debris into the Earth’s atmosphere [23]. The European Space Agency (ESA) created the RemoveDEBRIS CubeSat, which has various space debris removal experiments. The RemoveDEBRIS mission plan is to test the efficacy of several active debris removal (ADR) technologies on mock targets in low Earth orbit [24].

For satellite operators based in the United States, all space activities need to be licensed. NASA and the Department of Defense have issued requirements governing the design and operation of spacecraft and upper stages to mitigate the growth of the orbital debris population. The Federal Aviation Administration, the

National Oceanic and Atmospheric Administration, and the Federal Communications Commission also consider orbital debris issues in the licensing process for spacecraft and upper stages under their auspices. Any activities "which are intended to conduct in the United States a launch of a launch vehicle, operation of a launch or reentry site, re-entry of a re-entry vehicle" needs a license to operate in outer space. This license needs to be applied for by "any citizen or entity organized under the laws of the United States, as well as other entities, as defined by space-related regulations, which are intended to conduct in the United States… should obtain a license from the Secretary of Transportation" compliance is monitored by the FAA, FCC and the Secretary of Commerce” [25].

4.4.2. United States’ Efforts

The Obama Administration created a new section of space policy titled, “Preserving the Space Environment” in the 2010 National Space Policy. This is the first space policy document to focus on active debris removal and space collision warnings:

> Foster the Development of Space Collision Warning Measures. The Secretary of Defense, in consultation with the Director of National Intelligence, the Administrator of NASA, and other departments and agencies, may collaborate with industry and foreign nations to: maintain and improve space object databases; pursue common international data standards and data integrity measures; and provide services and disseminate orbital tracking information to commercial and international entities, including predictions of space object conjunction [26].

After the release of this policy, the Joint Space Operations Center began to screen potential on orbit collisions. Warnings were provided to all satellite operators with data on conjunctions to implement proper maneuvers in orbit. The Data Sharing Program resulted in 128 avoidance maneuvers while warning almost 1,500 active satellites as of 2016 [27]. NASA focuses on policies that relate to the scientific observation of the space environment, including the orbital debris migration crisis. For both aspects, launch and mission restrictions and the scientific observation of orbital debris, that needs to be one, sole entity that focuses all space policy, along with space operations.

4.4.3. Orbital Collisions

Some scientists believe that the primary solution to the orbital debris crisis is to focus collision avoidance. The Air Force tracks almost 67,000 collisions annually. In 1996, the first unintentional collision occurred between the Cerise military satellite and debris from an Ariane rocket launched in the late 1970's. The collision was projected to produce almost a hundred pieces of debris, mostly small pieces. Most collisions occur from the smaller pieces (1-10cm) colliding into operating bodies. Due to their size, these pieces travel at a higher velocity, increasing the risk of collusion. The United States had a major collision occur in 2009, when the Iridium 33 satellite collided with the Russian satellite Cosmos 2251 [19]. Both satellites hit at about 22,300 mph and created thousands of orbital debris pieces. Other collisions result from destruction tests, low speed failures, and interaction between active satellite and orbital debris.

4.4.4. Rise in Space Tourism

The space industry is worth about $320 billion as of 2015. The space industry will be worth $1.1 trillion by 2040. Private sectors have begun to launch their own space technologies. As stated earlier, both SpaceX and OneWeb have proposed to launch their own versions of broadband internet mega constellations within the next couple of years. Space is working towards lowering the cost of payloads within LEO. Private sectors are also in talks of providing space tourism opportunities to the public. Space tourism is any human space travel for recreational purposes.

This effort lead to establishing a public trust doctrine. A public trust doctrine protects the public's interests in common pool resources. It would need to identify commonalities between outer space and the public trust resources. This may also be an issue regarding space's identity as an environment as oppose to a property.

Private property is the emergence of technology to define those rights in an area that is without static geographic and political boundaries. Objects in space are deemed between private and common ownership. Developing a space public trust doctrine may conflict with the Outer Space Treaty and the moon treaty. In the Outer Space Treaty states,

"…shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."

Several publications have highlighted contradictions in both the Outer Space Treaty and the Moon Treaty. Without a new doctrine or change in treaty, the advancement of space technology and space property will stay at a halt. These issues need to be addressed because they also play a role into acts to cleaning the space environment.

4.5 Proposed Timeline for Policy Framework

A reform in policy framework is needed to address the orbital debris problem. Over the next few decades, the administration in the United States government needs to begin to develop action for the orbital debris problem. The recent Trump administration continues to highlight the problem, but the future administration must have an action plan to resolve it.

4.5.1. Policy Framework for Preserving the Ocean

There are many similarities to the ocean and space. Both pace and the ocean are considered "great expanses", areas that can be deemed as limitless. Both areas have been largely unexplored but house many technologies humans utilize in their everyday life. The ocean is used to transport goods and is home to several animals. Space holds the global positioning system and the International Space System. With them being heavily polluted, similar practices can be used to clean the space environment.

There are several laws that protect our oceans. In 1973, the Act to Prevent Pollution from Ships. This assist with the study of effects of improper disposal of plastics in the ocean. Volunteer groups are used to monitor floatable debris. There is also the Marine Debris Research, Prevention, and Reduction Act, which identifies, determines sources of, assess, reduce, and prevent marine debris.

4.5.2 Proposed Timeline

First, reforming the current space policies for the United States. The United States is at fault for almost a third of all space debris currently in orbit. Many of the current space policy frameworks interfere with preserving the space environment. Statements in the Outer Space Treaty considers space debris as abandoned property [28]. It is uncertain whether space objects, their component parts or fragments thereof can legally be dumped, nonetheless of their non-functional status. This is in violation of the treaty due to how it is word. A doctrine needs to be created to have proper literature and regulation that focuses on cleaning the space environment.

Next, there needs to be a separation in policy for both public and private sectors. With the issue of private property in the space industry increasing, policy reform is ideal. The steps would include dividing regulations for the launching of private and common ownership. Ownership and property will play a role with the “clean up” of space. The launcher of the spacecraft holds responsibility for any activity that occurs from their spacecraft, therefore this becomes a conflict of property. This also includes the limitation for the exploration of space tourism, due to the pollution of the space environment [29]. By developing policies pertaining to public and private sectors, this will keep the focus on cleaning and preserving space.

Within the next two decades, the creation of an international entity should regulate universal removal practices of orbital debris that does not interfere with country’s individual regulations. The United Nations Office for Outer Space Affairs created the Inter-Agency Space Debris Coordination Committee (IADC) as an international forum of national and international space agencies for the worldwide technical/scientific coordination of activities related to space debris in Earth orbit issues and provides technical recommendations [6]. They created guidelines to set the mitigation of space debris. The IADC has a primary purpose to identify debris mitigation options. The narratives being displayed from the IADC are more technical, research-based recommendations. The entity has also created a list of guidelines focused on the Orbital Debris Mitigation. One of the guidelines focuses on the limit of the long-term presence of spacecraft and launch vehicle orbital stages in the LEO region after the end of their mission [5]. Member states of the United Nations are encouraged to take measures, but there are no policies placed for punishment if more debris is produced. The guidelines are not legally binding, so international regulation is necessary. Only 18 nations have ratified international agreements involving activities mined from asteroids. There needs to be an increase of space governance for both public and private sectors.

A brand-new space regulatory organization would allow for stricter government funding and policy advancement for international space policies. Both launch and mission restrictions and the scientific observation of orbital debris, that needs to be one, sole entity that focuses all space policy, along with space operations. The international regulation should center on orbital debris tracking, orbital debris removal practices, and collision punishments between different countries.

4.6 Proposal for Overall Reform

The preservation of space is considering an environmental issue in most countries. Like other environmental policies, our activity in space policies should be regulated to ensure the stability of the environment in outer space. Limiting orbital space debris will overall preserve the nature of outer space. Practices of orbital debris mitigation are outlined in the Orbital Debris Mitigation Standard Practices (ODMSP) by NASA [30]. It documents cleaning the pieces already in orbit to the regulation of new technologies to deorbit after the completion of a mission. In the 2019 update, the new guidelines focus on disposal options for immediate removal of structures from the near-Earth space environment, as well as implementing mitigation practices for middle Earth orbit (MEO) and geostationary orbit (GEO). With all the research being done on the crisis, regulation and punishment needs to be implemented to secure the nature of outer space and the future of space exploration.

4.5.1 Submission of Removal Technology for Failed De-Orbiting

Most of the orbital debris orbiting around the Earth are pieces that have fallen off spacecrafts or from collisions with another spacecraft or space object. As the launcher, it is their responsibility for any activity that occurs from their spacecraft. It should also be implemented that if the spacecraft creates orbital debris, there is a plan for removal. The plan of removal should be submitted with the mission requirements when requesting to be launched into space.

When submitting a removal process, the launcher should determine whether they will clean up the debris or contract another party to do so. Chapter 3 analyzes several active debris removal technologies being developed from multiple international space entities. Most of these technologies have not proposed how they will be used. With current space policies, one must not interfere with the technology of another country. This can cause war and disagreement between national space organizations [31]. Allowing these entities to collaborate in removal practices would be beneficial. Launchers would have to have documentation stating that they have contracted a technology outside of their country to remove their pieces if any were created. Having a secure plan for removal will reduce orbital debris and hold accountability to those who want to explore space but tend to produce trash in it.

4.5.2. Implementation of Debris Collision Fine

The launcher of the spacecraft should be responsible for any activity that occurs from their spacecraft, including failure, collisions, and falling parts. The Liability Convention defines the launching state as a state which launches or procures the launching of a space object or a state from whose territory of facility a space object. There is currently no punishment for causing more space debris. If there is a collision, the launcher should pay a fine that will go towards their country's space agency or regulator. For the United States, the fine money could be used to fund ADR technology launched from the Space Force to limit space pollution. For international causes, the fine money could go to the International Space Society and their R&D efforts to space mitigation.

4.5.3. Changes to Design Practice and Standards

One way the above noted policy changes can be implemented, in part, is by adapting new and improved practices and standards for the design of satellites. Changing design practices and standards is not a small undertaking and will require a considerable effort to and time to design and implement. However, we think it is instructive to consider a simple case limited to one class of spacecraft and examine what some of these changes would look like. To that end, in the next section of this chapter we consider, as a case study, the design practices for CubeSats and how that might change to accommodate orbital debris mitigation strategies.

4.6 Case Study of Design Standard/Practice Change

As described in Chapter 1, CubeSats are a class of nanosatellites that constructed by integrated a basic 1U element (a 10 cm $\times$ 10 cm $\times$10 cm cube). While there are some accepted standards and practice for designing these class of spacecraft, the current standard design of CubeSats does not have the capability to de-orbit on its own. They have mandated that all spacecraft either deorbit within a given amount of time or be placed into a graveyard orbit for safe storage. The lifetime requirement is 25 years post-mission, or 30 years after launch if unable to be stored in a graveyard orbit. ‘It is estimated that one of every five CubeSats launched between 2003 and 2014 is in violation of international guidelines calling for satellites to deorbit. Both by nature of orbit and by their operating on-board systems [32]. Recommendations are needed to alter the CubeSat design to add removal technologies or inherent de-orbiting capabilities into the standard CubeSat design.

In what follows, we examine the key subsystems found on most CubeSats and explore how they are currently designed and what types of standard changes can make them compliant with the philosophy of minimizing orbital debris.

The average CubeSat design cycle is an estimated to be a six-month process for professional organization (i.e.., not first-time CubeSat builders). The initial step in the design process including determining what systems and components are needed for the CubeSat to accomplish its mission [32]. The design should be as simple as possible. Without loss of generality we will assume for the case study that follows that the typical CubeSat contains the following subsystems: Structures subsystem, Propulsion subsystem, Attitude Determination and Controls subsystem (ADCS), Power subsystem, Navigation subsystems, and Communications subsystem. Currently, CubeSat design should comply with the CubeSat based Orbital Debris Mitigation Standard Practices. This requires that all CubeSats should be limited to an orbital lifetime of a maximum of twenty-five years and the total spacecraft object-time product should be less than 100 object-years per mission [33]. In what follows we examine each subsystem and identify what design practice changes will help enhance this orbital lifetime requirement.

4.6.1 Structure Subsystem

For CubeSats, there are two structural body to create its shape: primary and secondary. The primary structure is a generic, modular structure design to allow maximum possibility for mounting configurations. The parts of the primary structure include side frames and ribs connected through fasteners. Primary structures need to be adaptable, compatible, and lightweight to maintain its standard requirements. The secondary structure typically holds the inner workings of the Cubesat like the batteries, control subsystems, and the communication system. The parts of the secondary structure parts are typically shear panels and mounting elements.

When determining the development of levels of structure, the material being used most be discussed. For primary structures, alloys of aluminum are used. An alloy is defined as a metal made by combining two or more metallic elements to give strength, resistance, or tension. The three most common aluminum alloys are AL 5052, AL 6061, and AL 7075. For secondary structures, composite materials are used. These materials are typically a combination of carbon fiber and reinforced plastic. Having this material for the inside structure adds maximum resistance to breaking under tension through the stiffness of the material.

While CubeSat structure material selection requirement is already optimized for minimizing the hazard of materials surviving re-entry, increased use of composite materials in primary structure can further mitigate this hazard.

4.6.2 Propulsion Subsystem

A propulsion system is a system that produces thrust to push an object forward. They are not very common subsystems on CubeSats currently. However, the development of propulsion systems that is modular in design, permitting integration with multiple present and future small satellite platforms on the market will go a long way to potentially help mitigate the orbital debris problem. Currently, there are many efforts to propulsion system designs that can easily be scaled and optimized for a wide array of CubeSat mission by adjusting the volume of the tank to accommodate different propellant quantity needs. Common CubeSat propulsion systems include electrosprays, pulsed plasma thrusters, hydrazine thrusters, cold gas systems, ion engines, hall effect and solar sails. Most CubeSats do not have a propulsion system. They rely on external devices to assist with their de-orbit. After the completed mission, most CubeSats will eventually enter the graveyard orbit (SSO) after twenty-five years.

While the current practice it to design propulsion systems to meet mission needs and to include them to meet specific requirements for controlling their motion in space [34], if they can miniaturized sufficiently then they can potentially be included on most CubeSats. If the technology reaches that maturity level, then the recommendation for the propulsion subsystem design is to require propulsion and thrusters onto CubeSats. Requiring these satellites to have a propulsion system will assist with accurate de-orbiting, provide additional thrust to secure de-orbiting, and contribute low complexity to compliment simple design. Miniaturized and efficient (low fuel usage) propulsion system can be a game changes for the orbital debris mitigation problem.

4.6.3 ADCS Subsystem

The control system is the system that focuses on the attitude determination and control. Attitude determination is based on defining the position and orientation of the CubeSat.

The recommendation for the control system is to have the design comply with the propulsion system for ensured de-orbiting. Since the position and orientation of the CubeSat will determine how and where it is de-orbiting, the propulsion system must be able to produce the amount of force from that position to perform that task. This is particularly needed for a propulsion system with an integrated ADCS solution. The control system may need to be altered when implementing suggested orbital removal technologies. Furthermore, all the active debris removal methods discussed in Chapter 3 become more effective if the debris can cooperate and adjust its attitude. Thus, requiring that CubeSats can maneuver even at end of life will enhance the performance of active orbital debris removal. Thus, along with propulsion technology. miniaturized and efficient (small fuel usage) attitude control system can be potential game changers for orbital debris mitigation.

4.6.4 Power Subsystem

The power system focuses on the energy needed for the spacecraft to carry out the mission. For standard cubesat design, the power system is depicted as batteries or solar panels based on the mission of the satellite. The power system must be able to demonstrate power and meet all concerns for both the spacecraft mission and de-orbiting.

Changes to power systems may be required to accommodate changes in attitude control and propulsion systems. Thus, while no specific design standard changes are recommended for this subsystem, it should be noted that changes may be needed to accommodate other subsystem changes.

4.6.5 Navigation Subsystem

The navigation system identifying the position of spacecrafts. There are two types of navigation systems: onboard and ground base systems. An onboard system is on the system to track it. Onboard navigation systems are now standard thanks to the proliferation of Global Navigation Satellite Systems (GNSS) such as the global positioning system (GPS) or Galileo are standard on most CubeSats.

Because of the wide proliferation of accurate, onboard positioning the concept of transponders for satellites (align to what is done for ships and aircrafts) is being considered. The recommendation for the navigation system design is to implement onboard GPS transponders. A GPS transponder is a device that reports a spacecraft’s position. They also provide positive identification for a spacecraft and allow operators to maintain a lock on it, despite it being active or not. By providing more accurate position information, GPS transponders could significantly enhance the ability to compute the probability of collision—so operators would spend less time and fewer resources planning unnecessary avoidance maneuvers [35]. This will assist in an accurate collision risk assessment, will provide input for the current onboard navigation system, and will be an identifier.

4.6.6 Communication Subsystem

The communications subsystem commands the spacecraft and captures mission data to the end users. Opposed to large satellites, CubeSats communicate with a low data-rate to a limited number of receiver stations on the ground. This leads to constrained amounts of mission data that suffers from high latency, due to the long period between ground station accesses [36].

There is no recommendation for the communications subsystem. It does not need to be altered to assist in CubeSat de-orbit or to assist with removal technology.

4.7 Chapter Summary

In this Chapter we reviewed potential policy and design standard/practice changes that can take place in the future to ensure that the orbital debris problem does not become a crisis. As we have shown, while there are existing policy efforts to address this issue, more aggressive changes are required. A proper policy framework will need to be implemented to address the concerns of various space policy documentation. We also showed that, as the technology for small space craft improves, then design changes that leverage these new technologies can help in the mitigation of the orbital debris problem.

5 Conclusion and Moving Forward

5.1 Summary

In this thesis we showed that with so much orbital debris in orbit, we are at a point in time when technical and policy solutions need to be implemented to fix this problem. The long orbital lifetimes of objects in Earth orbit is a major factor contributor to the orbital debris problem. A simplified orbital lifetime tool was used to show how basic orbital mechanics of a spacecraft can be used to generate reasonable results of how long it can stay in orbit. It is shown that unless proactive measures are taken, the orbital debris problem will become worse in the future. We then explored three active removal technologies: laser removal, electrodynamic tethers, and deployable nets. Laser removal was analyzed from both a space based and a ground based perspective to evaluate similarities The tethers were analyzed using the earth's magnetic field to generate an electromotive force which acts as drag and, thus, causes the orbit of a debris object to decay. A net with flexible rods is deployable from a host satellite and captures multiple forms of debris and knocks it out of orbit. For this concept, there is a closing mechanism to efficiently remove the debris. The advantages and disadvantages of all these technologies are analyzed. While these approaches are effective and needed, we showed that they alone cannot solve the problem. Thus, space policy reforms such as adapting improved best-practices for design of spacecraft along with legal changes may be required.

Major policy reform can take advantage of these coming orbital debris removal technologies as well as existing technologies are considered. National space policies will be analyzed with focus on responsibility of removing orbital debris and keeping the space environment clean for future exploration. Future design standards of spacecrafts should be considered for reform. While we did not specifically address these here, something like the Federal Aviation Regulations (FAR), Part 23 and 25 may be a good example. Using a CubeSat as very simplistic but illustrative case study, we examined what kind of changes in design standards can help mitigate the orbital debris problem. To this end, typical CubeSat subsystems are separately examined, Structures, Propulsion, Control, Power, Navigation, and Communication. The analysis focused on how changes in the practice of designing these subsystems can be used to mitigate the orbital debris problem.

5.2 Future Work

With the new changes to the Orbital Mitigation guidelines, we can work towards improving the guidelines to affect various types of spacecrafts with policies and technical solutions. Each type of spacecraft should have requirements for their design and mission to prevent orbital debris through the mitigation guidelines. With proper de-orbiting practices and reform of policy, the amount of orbital debris can decrease, and space exploration will continue.

5.2.1 Mega Constellations

One of the main topics being discussed in the orbital debris crisis is the impact of mega constellations. A mega constellation is a group of hundreds, sometimes thousands of satellites, that function together under a single control to complete a task. Multiple mega constellations are set to be launched in low Earth orbit (LEO) due to the orbit having the speed needed for operation. A group of hundreds, sometimes thousands of satellites, that function together under a single control to complete a task.

Figure 12. Image of One Web’s mega constellation of an estimated 648 satellites

Figure 12 shows an example of a mega constellation. One Web is a company which has developed a mega constellation for expand broadband communications services globally. Examples of mega constellation proposals are the global positioning system (GPS), Internet broadband system, and communication systems. Although mega constellations will improve quality of life here on Earth, the amount of orbital debris will increase exponentially if proper protocols are not in place. Therefore, future work examining these mega-constellations will be necessary.

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