ORBITAL DECAY ANALYSIS FOR DEBRIS DEORBITING CUBESATS IN LEO: A CASE STUDY FOR THE VELOX-II DEORBIT MISSION

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ABSTRACT

Since the launch of Sputnik 1 into space in 1957, humans have sent thousands of rockets and more than ten thousand satellites into Earth's orbit. With hundreds of more launched every year, in-space collisions and the creation of high-speed debris fragments are becoming increasingly likely, threatening future space missions. The term orbital debris comprises defunct satellites, spent upper stages, fragments resulted from collisions, etc., which pose a significant threat to many other operational satellites in their vicinity. With the advent of satellite mega-constellations in low Earth orbit (LEO), the LEO environment is becoming extremely crowded. In addition to the government space organizations, several private space agencies are also investing heavily in space launches in LEO. Due to all these, the low earth orbits are getting overpopulated, increasing the risk of collisions, which might set off a collision chain. Thus, it is necessary to monitor and remove space debris for the existence of future space operations. From a commercial deployment and economic point of view, it is viable to use small satellites, especially CubeSats to perform this task, when compared to the deployment of large satellites. As the orbital speeds in LEO are far greater than that of the speeds in GEO, at more than 7 km/s, it is indeed essential to track the debris and remove them. In this paper, we present the orbital decay analysis for a debris deorbiting CubeSat from LEO. We also aim to present the lifetime analysis for 6U, 12U, and 27U CubeSats removing space debris under the effect of solar radiation flux F10.7 cm, variable drag cross-sectional area, and drag coefficient. We also present a case study on the VELOX-II deorbit mission using a CubeSat equipped with a passive deorbit device, a drag sail. VELOX-II is a 6U CubeSat launched into a near-equatorial orbit at an altitude of 550 km, designed to demonstrate inter-satellite communication between a LEO and a GEO satellites, data downlink anywhere any time in orbit without passing the ground station, and precision navigation and fault-tolerant electronics. As VELOX-II is still orbiting the Earth post its intended mission life, it is recommended to deorbit this satellite within 25 years. Therefore, we explore and analyse the feasibility of the CubeSat-based debris deorbit mission. For VELOX-II, orbital decay for various drag surface area increments is analysed.

Keywords: Space debris; LEO; orbital decay; debris removal; VELOX-II; CubeSat.

1. INTRODUCTION

Space debris is any man-made object in orbit about the Earth that no longer serves a useful function. The Earth orbit is in serious danger caused by millions of these space debris. Since the beginning of the space age, more than 10,680 satellites have been placed into orbit [1]. Out of which 6,250 are still in the orbit and only 3,700 are operational, leaving an astonishing 2550 dead satellites in the orbit. Furthermore, more than 28,210 objects are currently being tracked and classified by the Space Surveillance Network (SSN).

There are over 34,000 pieces of space debris larger than 10cm and more than 128 million pieces smaller than 1 cm in size. Furthermore, close to a million bits of debris between 1 cm and 10 cm are estimated to be orbiting the Earth [1]. The space objects in LEO travel at speeds greater than 7 kilometers per second. At that speed, a little fleck of paint packs an equivalent punch of a 250-kilogram object travelling at 100 kilometers per hour. Such impact damages critical components such as pressurized items and solar cells besides creating new pieces of potentially threatening debris.

Thus, debris removal and collision avoidance are significant to ensure safe space exploration. A few methods have been proposed to capture and remove space debris in the past decade. Ground and parabolic flight experiments are ongoing to test the efficiency of these methods. As humans launch more and more objects, these numbers are further going up and turning Earth's orbits into a dangerous and crowded junkyard. To regulate space operations, all space organizations & industries are directed to follow the 25-year safety lifetime standard for spacecraft, which states that all the satellites that are functional in LEO, should lower their orbit and re-enter the Earth's atmosphere within 25 years of mission completion [2]. Therefore, removing or burning up this debris by deorbiting them is an essential task to facilitate future space missions.

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The remainder of the paper is organized as follows: Section 2 briefly discusses the orbital decay analysis using the drag equation and the orbital period decay expression. It also analyses the effect of variation in solar flux, drag surface area, and drag coefficient on LEO CubeSats. Section 3 presents the VELOX-II deorbit mission and the design details of a deobiter CubeSat. This section also presents the orbital decay results obtained for the deorbiter CubeSat using various drag sails. Conclusions are provided in Section 4.

2. ORBITAL DECAY ANALYSIS FOR CUBESATS IN LEO

The lifetime or orbital decay of space debris depends on three major parameters, namely solar radiation flux F10.7 cm, the drag coefficient of the surface, and the drag surface area. Therefore, for a satellite commissioned to deorbit space debris, these parameters define its lifetime during reentry. Out of all the regions of space, low Earth orbit (LEO) has higher debris density. With the increase in day-to-day launches, the debris density is further growing and eventually making some orbits unusable. Besides, the in-orbit collisions might initiate a chain reaction and damage all the operating satellites in their vicinity. Therefore, debris removal from LEO using satellites has become one of the important space missions nnowadays To perform this prime task, it is recommended to use smaller satellites than choosing larger satellites, to reduce the design and launch costs.

To address this issue, a miniature satellite design has been proposed in 1999, called a *CubeSat* [3]. CubeSats are miniature satellites that have been used extensively in LEO for the last two decades. The CubeSat standard and design was first proposed in 1999 by Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University, as primarily training tools for students to get acquainted with flight hardware design, building, testing, and operations. They are built to standard dimensions of 10 cm x 10 cm x 10 cm, defined as one U or a unit [40]. They can be 1U, 3U, 6U, 9U, 27U in size, and typically weigh less than 1.33 kg (3 lbs) per unit and often use commercial off-the-shelf components for their electronics and structural designs.

2.1. Drag and Orbital Decay Equations

Atmospheric drag is the frictional force exerted by the atmosphere acting opposite to the relative motion of an object [4]. When a spacecraft travels through an atmosphere it experiences a drag force in a direction opposite to the direction of its motion. The expression for the drag force is given by:

$$D = \frac{1}{2}\, \rho\, v^2\, A\, C_d. \tag{1}$$

Where D is the drag force, ρ is the atmospheric density, v is the speed of the satellite in the orbit, A is its cross-sectional area perpendicular to the direction of motion, and C_d is the surface drag coefficient. By substituting this drag force in Newton's second law together with orbital energy equations, we can derive an expression for the change in the orbital period of the satellite with time. The expression for the decay in orbital period ΔP due to atmospheric drag is given by:

$$\Delta P = -3\, \pi\, h\, \rho\, (A\, C_d/m_s)\, \Delta t. \tag{2}$$

Where P is the orbital period, h is the semi-major axis, Δt is the time step increment used for the simulation, and m_s is the mass of the satellite respectively. The MSISE-00 [5] empirical model has been used to obtain the atmospheric density in LEO, to compute the orbital decay. MSISE-00 is an empirical, global reference atmospheric model of the Earth from ground to space. was developed by Mike Picone, Alan Hedin, and Doug Drob [5].

The following sections emphasise the effects of the variation in solar flux F10.7 cm, drag surface area, and drag coefficient on satellite lifetime. Throughout this paper, the term *satellite lifetime* refers to the lifetime of the satellite deorbiting with the captured debris object.

2.2. Effects of Solar Radiation Flux F10.7cm

The solar radio flux at 10.7 cm is an important indicator of solar activity at a given time. Often called the F10.7 index, it is one of the longest-running records of solar activity by the NOAA, USA [6]. These radio emissions originate high in the chromosphere and low in the corona of the solar atmosphere. The F10.7 correlates well with the sunspot number as well as a number of UltraViolet (UV) and visible solar irradiance records. It has proven to be very valuable in specifying and forecasting space weather. From the atmospheric drag model equations, an increase in the F10.7 flux readings show an exponential decay in the satellite lifetime for a non-varying drag coefficient and drag surface area values. The F10.7 radiation varies w.r.t. the Sun's solar activity as per the 11-year solar cycle, which is continuous with time.

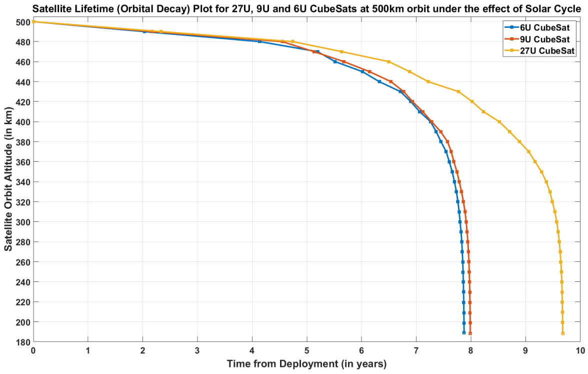

Figure 1. Lifetime of 27U, 9U and 6U CubeSats from 500km altitude under the effect of 11-year solar cycle.

Figure 1 illustrates the effect of day-to-day variation in F10.7 on the lifetime of a 27U CubeSat in 30x30x30 cm^3 configuration, a 9U CubeSat in 30x30x10 cm^3 configuration and a 6U CubeSat in 30x20x10 cm^3 configuration.

2.3. Effects of Debris Surface Area Increment

The drag surface area is one of the most important parameters, which has a drastic effect on the satellite lifetime. With the increase in the exposed drag surface area of the satellite, the resulting drag force acting on a space object increases and thereby reduces the satellite orbital lifetime. It is evident from Eq. 1, where the drag force D is directly proportional to the drag surface area A.

Many methods exist in the literature to deorbit satellites or debris from LEO. The deorbit mechanisms are broadly categorized into two: active and passive deorbit devices. In Active deorbit systems, propellents or thrusters are used to perform orbit reduction or lowering the altitude of the satellite. This ensures a controlled reentry into the atmosphere using active control. On the other hand, passive deorbit systems use mechanisms to increase the exposed drag surface area of the satellite, thereby increasing the net drag force acting on the satellite to achieve faster reentry. Devices such as space balloons, sails (drag, solar, electric, and magnetic), drag nets, terminator tapes, deployable booms, exo-brake parachute systems, etc. fall into this category. Figure 2 shows the CanX-7 3U CubeSat [7] equipped with a deployable drag sail.

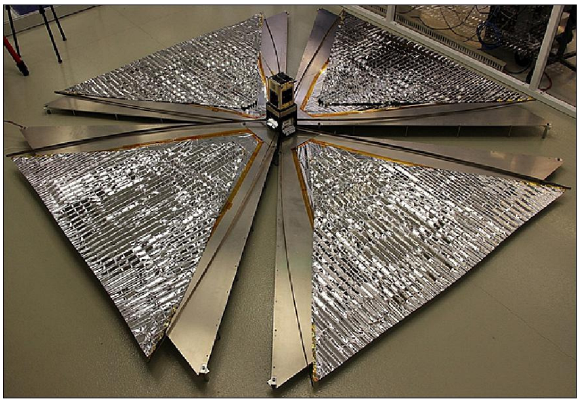

Figure 2. CanX-7 CubeSat with a drag sail [7].

Passive deorbit systems are economical and easy to design & test on the ground. However, the only drawback of these devices is the uncontrolled reentry. Nonetheless, passive deorbit systems are quite effective in reducing the satellite lifetime to meet the mandate of 25 years lifetime requirements. In this study, we assume that the CubeSat is equipped with a passive deorbit device, namely a drag sail. Figures 3, 4 and 5 illustrate the effect of the variation in the drag surface area on the lifetime of a 6U CubeSat. It is clear from these plots that the lifetime of the satellite is inversely proportional to the surface area.

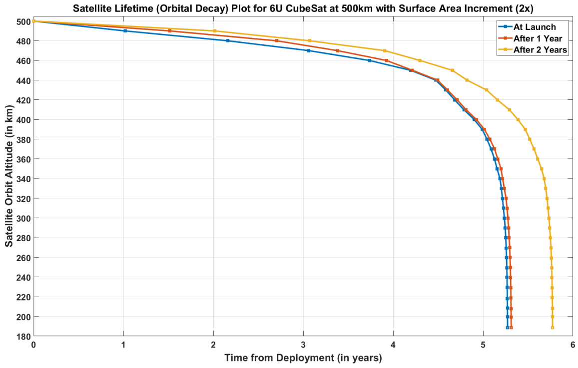

Figure 3. 6U CubeSat with 2x increment in the drag surface area A initiated at various time instances during its lifetime in the orbit.

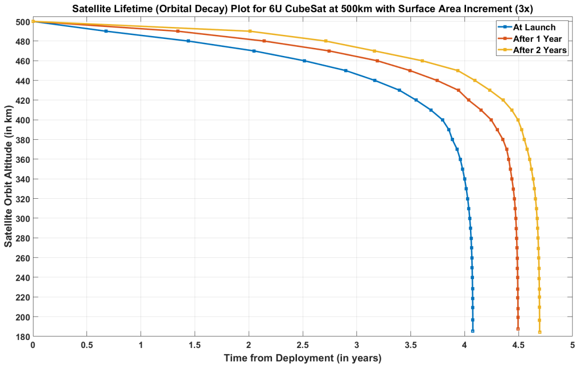

Figure 4. 6U CubeSat with 3x increment in the drag surface area A initiated at various time instances during its lifetime in the orbit.

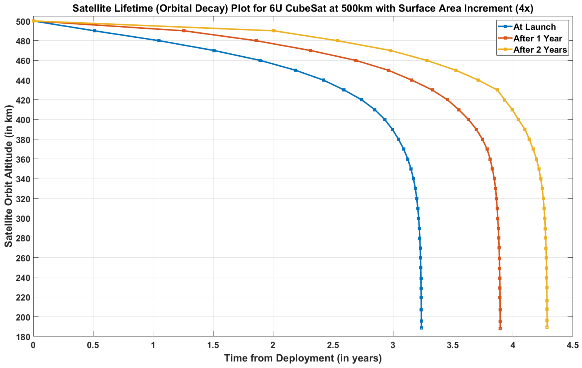

Figure 5. 6U CubeSat with 4x increment in the drag surface area A initiated at various time instances during its lifetime in the orbit.

2.4. Effects of the Drag Coefficient

The drag force acting on a satellite relies on the exposed drag surface area and the drag coefficient C_d of the spacecraft. In eq. 1, the drag force is directly proportional to C_d and inversely proportional to the satellite orbital decay time. Thus, a higher drag coefficient C_d results in more drag force on the satellite and results in a faster deorbit.

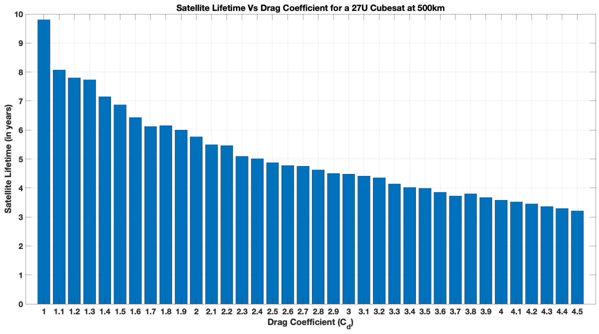

Figure 6. Lifetime of a 27U CubeSat from 500km altitude for variable drag coefficient C_d.

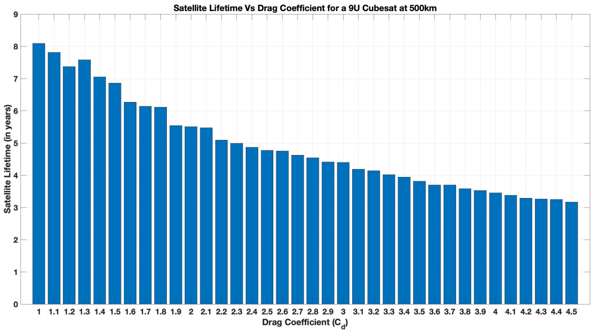

Figure 7. Lifetime of a 9U CubeSat from 500km altitude for variable drag coefficient C_d.

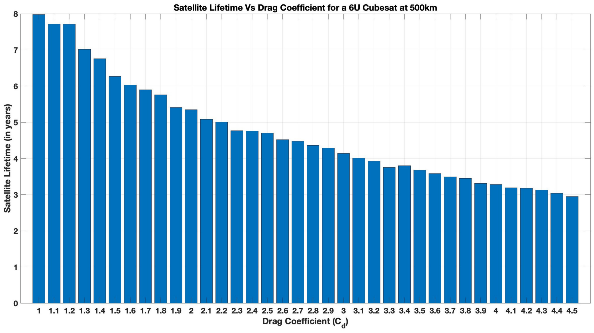

Figure 8. Lifetime of a 6U CubeSat from 500km altitude for variable drag coefficient C_d.

Figures 6, 7 and 8 represent this effect of drag coefficient on the CubeSat lifetime. It is evident from these plots that the lifetime of the satellite goes down rapidly by coating the satellite surface with a material of a higher drag coefficient.

2.5. Cumulative Effect of Solar Flux F10.7 cm, Drag Surface Area and Drag Coefficient

In Sections 2.2, 2.3 and 2.4, we have illustrated the effect of some of the vital environmental parameters, such as solar flux, drag surface area change, drag coefficient on the CubeSat lifetime. In this section, we present the simulation results obtained for the cumulative effect of the average variation in the solar flux F10.7cm, variable drag surface area for various drag surface area increments. It is clear from these results that the satellite lifetime (deorbiting the debris) will be greatly reduced through a careful selection of the drag surface area, and drag coefficient. Based on the predefined mission completion time, a suitable combination of these parameters can be selected.

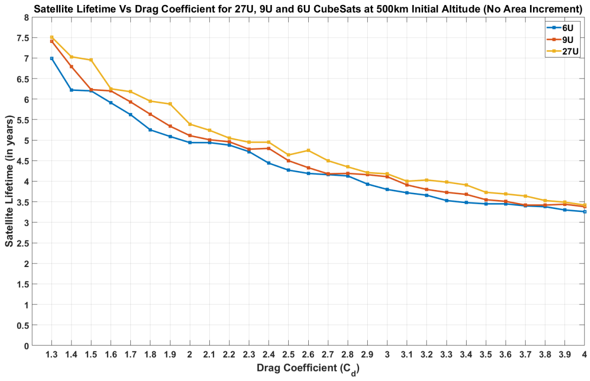

Figure 9. Lifetime Plots for 27U, 9U and 6U CubeSats under the effect of solar cycle, variable drag coefficient C_d with no increment in the drag surface area A.

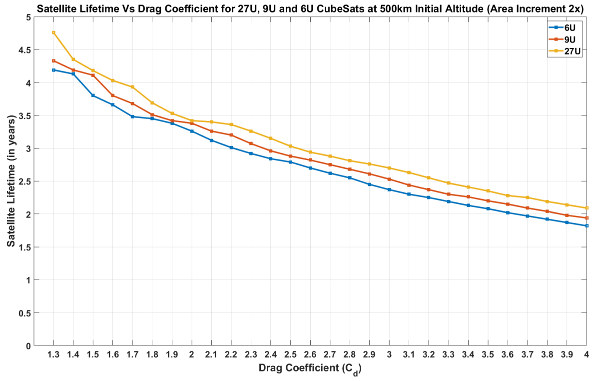

Figure 10. Lifetime Plots for 27U, 9U and 6U CubeSats under the effect of solar cycle, variable drag coefficient C_d with 2x increment in the drag surface area A.

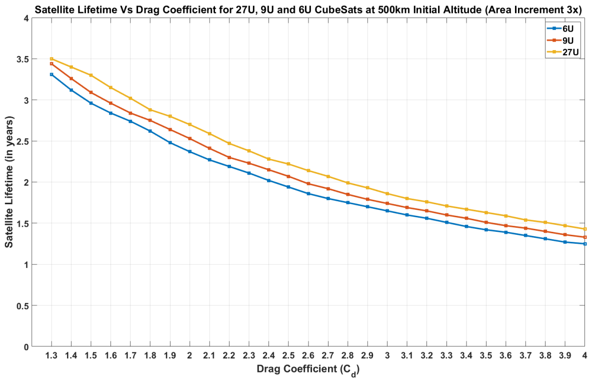

Figure 11. Lifetime Plots for 27U, 9U and 6U CubeSats under the effect of solar cycle, variable drag coefficient C_d with 3x increment in the drag surface area A.

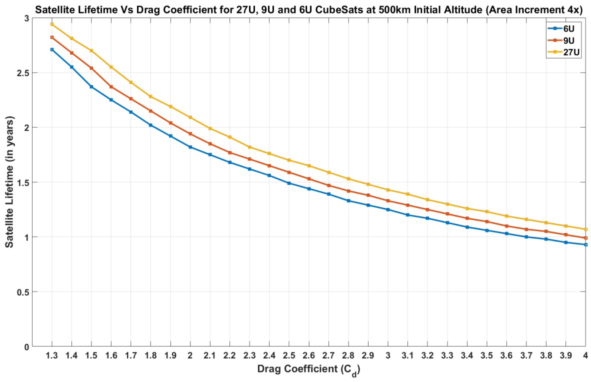

Figure 12. Lifetime Plots for 27U, 9U and 6U CubeSats under the effect of solar cycle, variable drag coefficient C_d with 4x increment in the drag surface area A.

Figures 9, 10, 11, and 12 illustrate this cumulative effect of solar flux variation as per the 11-year solar cycle and the drag cross-sectional area increment on the CubeSat lifetime. Therefore, a required satellite decay can be achieved through a careful selection of drag cross-sectional area and the drag coefficient. The next section details the VELOX-II deorbit mission and its orbital decay analysis.

3. VELOX-II DEORBIT MISSION

VELOX-II is a 6U nanosatellite built by the NTU/SaRC (Nanyang Technological University / Satellite Research Center), Singapore [8], as shown in Figure 13. It was launched into a near-equatorial orbit at 550 km on December 16, 2015, with one year of intended mission life. If no deorbit mission is commissioned, it would require more than 25 years to deorbit VELOX-II by itself. Therefore, we propose a CubeSat-based deorbit mission for VELOX-II using a 6U CubeSat equipped with all the debris removal payloads, and a drag sail to deorbit it.

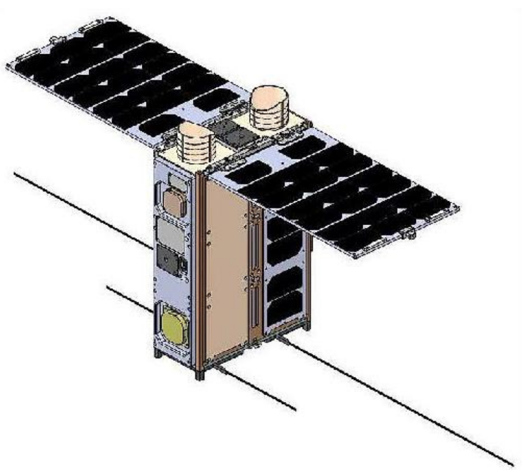

Figure 13. Illustration of the VELOX-II CubeSat [8].

3.1. Deorbiter CubeSat Design

To deorbit space debris from LEO, the most common solution is to launch a satellite onto the target debris orbit and remove it safely. From a commercial deployment and economic point of view, it is viable to use small satellites, especially CubeSats to perform this task, when compared to the deployment of large satellites. In this work, we propose the design of a 6U-sized deorbiter CubeSat to remove VELOX-II from its orbit. The required spacecraft avionics and on-board electronics can be packed within a 1U size form-factor, and the remaining 5U size can be used to pack the required debris removal mission components. A 1U form factor to accommodate the camera-based object tracking system, a 1U form factor for the Hall-effect thruster-based rendezvous sub-system, a 2U form factor to accommodate a debris capture sub-system, preferably a robot-gripper, a 1U size container for the drag sail, to passively deorbit the VELOX-II post the capture phase. The next sections detail the orbital lifetime analysis for the VELOX-II, assuming that all the other debris removal stages, tracking, rendezvous, and capture have been performed without any fail.

3.2. Lifetime Analysis for the VELOX-II Deorbiter CubeSat

The orbital decay of the deorbiter CubeSat, removing the VELOX-II has been analyzed using Eq. 2. We have investigated two different cases for this analysis, 1) lifetime analysis without using any sail, and 2) lifetime analysis using sails of various cross-sectional areas. Figure 14 illustrates the lifetime of the Deorbiter CubeSat without using any drag sail. It is clear from this plot that it would require more than 25 years to deorbit VELOX-II by itself or without the help of any deorbit mechanism.

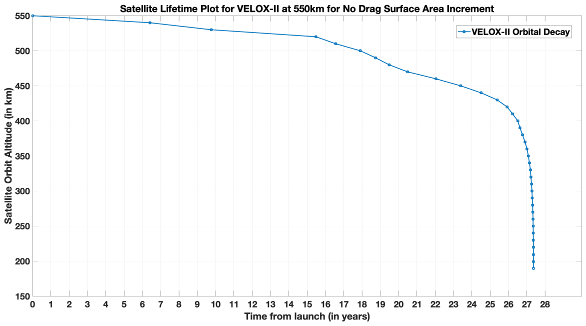

Figure 14. VELOX-II orbital decay without any sail.

Therefore, to reduce the satellite lifetime, or to accelerate the deorbit phase, there is a need for a passive/active deorbit mechanism. So, we have analysed the orbital decay of the deorbiter CubeSat using various drag sails of distinct cross-sectional areas, varying between 0.3 to 16 m^2.

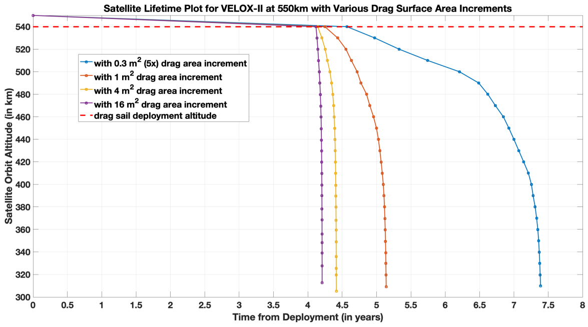

Figure 15. VELOX-II orbital decay using sails of various drag cross-sectional areas.

Figure 15 depicts the lifetime plots obtained for this scenario. It is evident from this plot that the target debris object, i.e. VELOX-II can be brought down in less than 8 years using a smaller sail, which can further be reduced by deploying a sail of a larger cross-sectional area.

4. CONCLUSIONS

In this paper, we have analyzed the orbital decay for 6U, 12U, and 27U CubeSats in LEO under the effect of solar radiation flux F10.7 cm, variable drag surface area, and drag coefficient. We have also presented a CubeSat-based debris removal mission for the VELOX-II using a passive deorbit device. A 6U-sized deorbiter CubeSat equipped with a drag sail has been proposed to deorbit the VELOX-II. The lifetime analysis for the VELOX-II deorbiting from its orbit at 550 km using a drag sail has also been presented under the influence of variable solar flux. It is evident from this analysis that VELOX-II can be deorbited within 7 years using a deorbiter CubeSat with a passive deorbit device. Potential future directions of work include the development of efficient rendezvous and debris capture sub-systems for small-sized deorbiter CubeSats in LEO.

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