An Evaluation of CubeSat Orbital Decay Utilizing ADCS

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ABSTRACT

Since the early 2000s, the number of nanosatellites launched has shown an exponential trend. As Low Earth Orbit (LEO) is getting crowded with nanosatellites and small satellites, FCC's new "five-year rule" regulation requires space operators to plan disposal through re-entry into Earth's atmosphere in no more than five years after the mission's end. One way to decelerate and deorbit a satellite is by increasing the satellite drag area using active attitude control, which can be used to tactically deorbit satellites to satisfy the "five-year rule".

The atmospheric density in the upper atmosphere (LEO region) widely varies as a function of altitude, latitude, longitude, geomagnetic activity, solar cycle, seasons, and local time. One factor potentially within the control of the satellite operator is the drag associated with the satellite ram face. This is accomplished by controlling attitude which is especially effective for satellites with faces offering varying cross-sectional areas (e.g., 3U or 6U CubeSats).

In this paper, the authors present a feasibility study of how satellite drag can be predicted and controlled by managing the satellite attitude to increase or decrease the effective cross-sectional area of a satellite in consideration of variable factors, such as altitude, inclination, geomagnetic activity, solar cycle, variations in seasons, and local time.

INTRODUCTION

The rapid miniaturization of electronics has led to a surge in the deployment of nanosatellites, defined as satellites with a mass ranging from 1 to 10 kilograms. This trend, which has been accelerating exponentially since the early 2000s, is illustrated in Figure 1. Currently, approximately 1200 nanosatellites are orbiting Low Earth Orbit (LEO), with about a quarter of them inactive.[1] These inactive nanosatellites pose a significant collision risk, as they typically lack propulsion systems and, therefore, are incapable of maneuvering to avoid potential impacts.

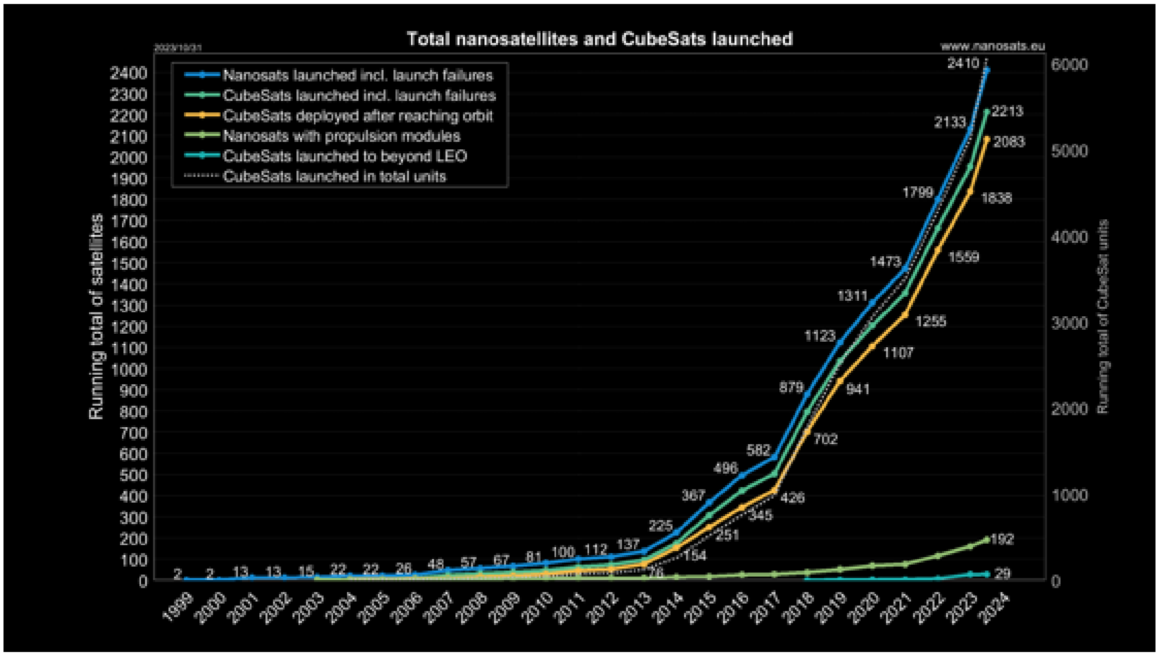

Figure 1: Nanosatellites launched since 1999

To mitigate the growing congestion in LEO, the Federal Communications Commission (FCC) has implemented a "five-year rule."[2] This regulation mandates that space station operators plan for the disposal of their satellites through uncontrolled reentry into Earth's atmosphere within five years after the mission's conclusion. Since the FCC's "five-year rule", satellite operators have had to be mindful of satellite disposal plans following the mission's operational lifetime. Plans for reentry can require carrying additional systems (i.e. fuel for propulsion systems, deorbiting systems) on the satellite, which could consume valuable space in the satellite that otherwise could be used by payloads and/or satellite bus subsystems. On the other hand, most satellites carry an attitude control system, which can be dual-purposed to control the satellite's attitude, but controlling the attitude can also be utilized to gradually decrease the satellite's altitude to meet the mission operational lifetime but also be mindful of disposing the satellite to reduce space junk.

One effective method to achieve compliance with the FCC mandate is by increasing the atmospheric drag on the satellite, thereby decelerating it and ensuring its reentry within the stipulated timeframe.

BACKGROUND

Drag on satellites is primarily caused by the interaction of the satellite with the Earth's atmosphere. As a satellite orbits the Earth, it encounters atmospheric particles. This drag force acts opposite to the satellite's velocity vector, decreasing its orbital energy and, consequently, reducing its altitude.

The importance of understanding and modeling the effects of atmospheric drag on satellites lies in its impact on their orbital dynamics. Over time, the drag force causes a reduction in the satellite's altitude and orbital energy, leading to orbital decay. This decay can ultimately result in reentry into Earth's atmosphere if the satellite is not reboosted or if there are no other means to counteract the drag-induced changes.

The governing equation for atmospheric drag force (F_d) on a satellite can be expressed as:

$$F_d = \frac{1}{2} C_d \rho A v^2$$

where F_d is the drag force; C_d is the drag coefficient (dimensionless); ρ is the atmospheric density; A is the effective cross-sectional area presented by the satellite; v is the relative velocity between the satellite and the atmospheric particles.

As shown in Figure 2[3], the drag force on a satellite is not constant due to varying solar wind conditions interacting with the Earth's upper atmosphere resulting in varying air density. The drag coefficient (C_d) depends on the shape and surface properties of the satellite. For a typical satellite, C_d can be assumed to be 2.2.[4] The atmospheric density (ρ) in the upper atmosphere is a function of altitude, latitude, longitude, geomagnetic activity, solar cycle, seasons, and daily effects. The effective cross-sectional area (A) is the apparent area as "seen" by the oncoming particles, and it also depends on the satellite's orientation relative to the incoming flow. The relative velocity (v) of the satellite changes dynamically as the altitude changes. Hence, a simple equation is often not enough to determine the drag force or lifetime of a satellite in LEO. Simulation with a dynamic atmospheric model is often used to determine the satellite's operational lifetime.

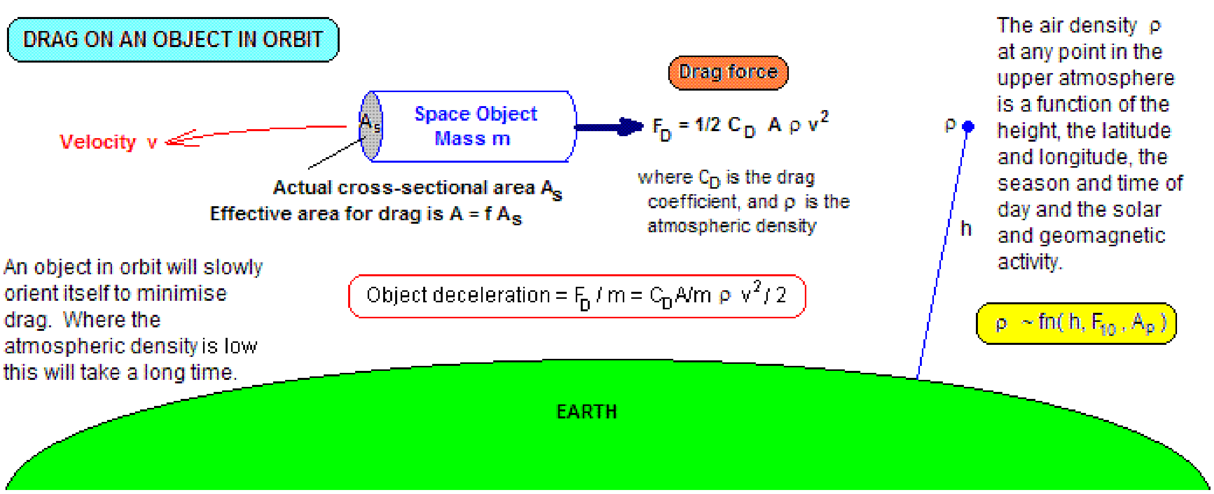

Figure 2: Governing equation for drag force on a spacecraft

METHODOLOGY

To demonstrate satellite lifetime variabilities for varying atmospheric conditions and apparent cross-sectional area in the ram direction, a simulation is performed in the ANSYS Systems Tool Kit (STK). STK's Satellite Lifetime Tool is used to predict the satellite's orbital decay. The Lifetime tool estimates the amount of time a satellite can be expected to remain in orbit. It assumes the satellite has decayed when the height of its perigee drops below 150 km. Due to variability in atmospheric densities caused by varying solar activity (which cannot be predicted accurately), predicted satellite lifetime estimates tend to have a 10% error (compared to actual lifetime).[5] A simulation study is performed for a 3U CubeSat with a mass of 4kg and with one of the 3U faces as nadir-pointing using Lifetime Tool. The software allows for user-defined settings of satellite characteristics, such as drag and solar radiation pressure. In this work, typical drag and solar radiation pressure coefficients of $C_d = 2.2$ and $C_r = 1$, respectively, are chosen. To evaluate the drag performance of a spacecraft based on attitude, two different configurations, 1U (0.01 m^2) and 3U (0.03 m^2) faces in the ram direction (drag area), are considered. The area exposed to the sun is 0.03 m^2 from the zenith-pointed 3U face. Although various atmospheric density models are available, from a previous study, An Evaluation of CubeSat Orbital Decay[4], Oltrogge and Leveque found the NRLMSISE2000 to be one of the more accurate models for CubeSats in LEO. The CelesTrak Space Weather Data is used for Solar Data to obtain solar flux and geomagnetic conditions data which uses various models.[6] Since the solar cycle has an 11-year periodicity where solar max and min are experienced as shown in Figure 3, the simulation was performed for satellites launched in Jun 2001, Dec 2013, and Dec 2024 (predicted) for solar max and Jun 2008 and Jun 2019 for solar min. A wide range of orbit altitudes and inclinations are available in LEO; for this study, we are evaluating spacecraft launched at altitudes of 400, 500, 550, and 600 km in sun-synchronous orbit with LTDN 12:00 hrs.

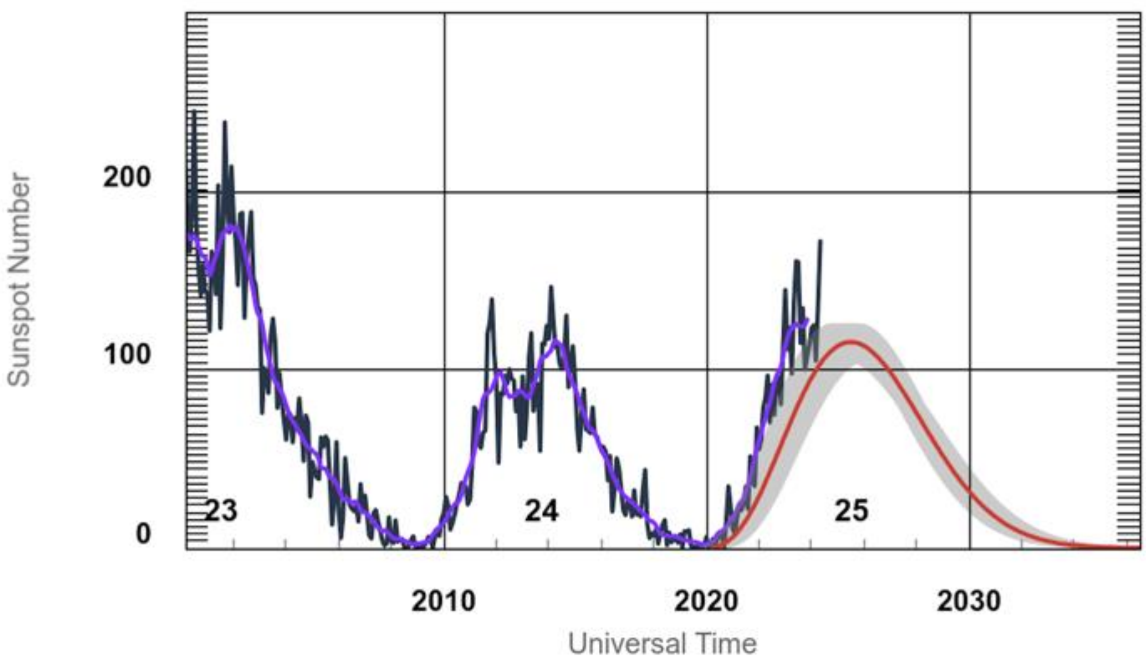

Figure 3: Recent Solar cycle progression

RESULTS

Figure 4 illustrates the orbital lifetime of satellites launched during the 2001 solar max at various altitudes with 1U and 3U face in the ram direction. A clear trend emerges, orbital lifetimes increase exponentially with an increase in altitude. During the 2001 solar max, satellites with a 1U drag area generally experienced a 3 to 4 times longer lifetime than those with a 3U drag area, with an exceptional increase of approximately 7.5 times for satellites launched at 500km. This anomaly can be attributed to the satellite's slower initial orbital decay at higher altitude during solar max, followed by a transition to the solar min about 3 years later, resulting in decreased atmospheric densities and a slower orbital decay rate.

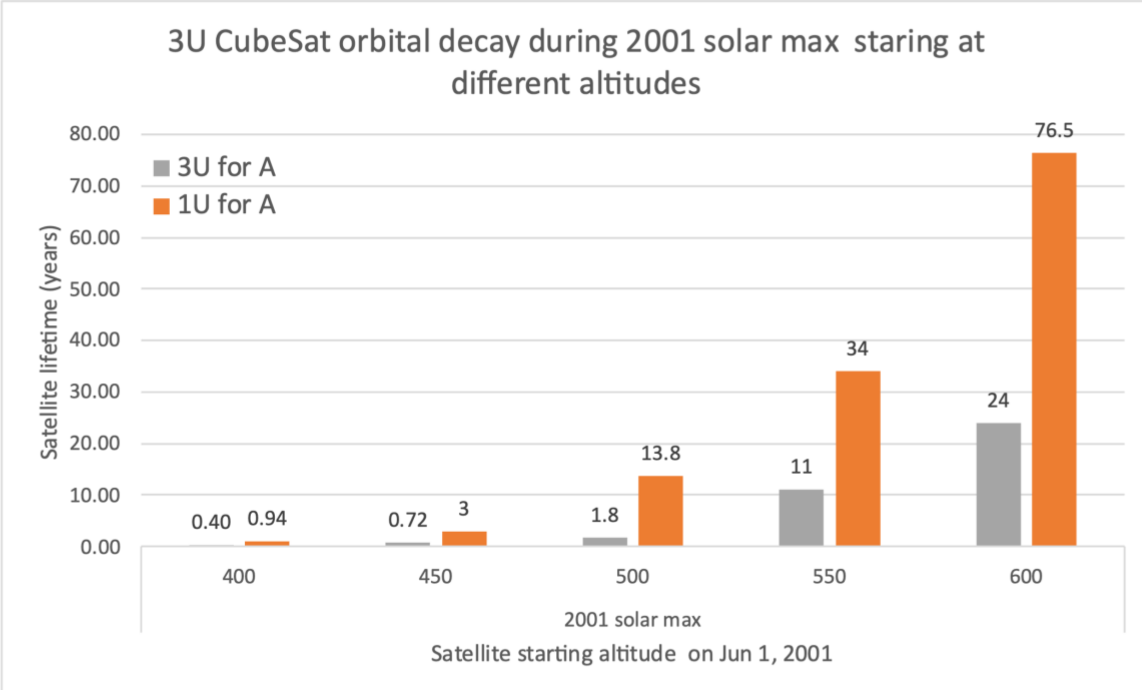

Figure 4: Comparison of satellite orbital decay launched during the 2001 solar max

Figure 5 presents a similar comparison to Figure 4 but for the 2008 solar min. Here, the satellite with a 1U drag area consistently exhibits about a 2 to 3 times longer lifetime than the satellite with a 3U drag area.

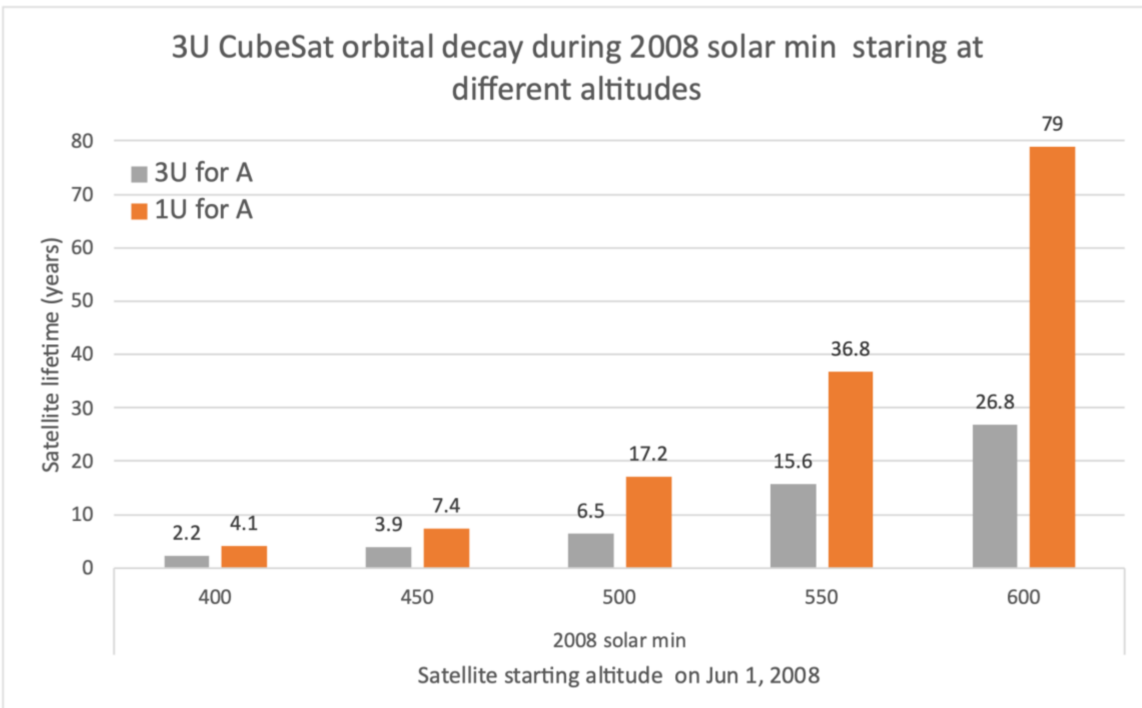

Figure 5: Comparison of satellite orbital decay launched during the 2008 solar min

Figure 6 presents a similar comparison but for the 2013 solar max The trend of satellites with 1U compared to 3U drag area having about 2 to 3 times longer lifetime persists, with an outlier at 450 km showing about 7 times increase in lifetime. This anomaly resembles the one seen in the 2001 solar max, explained by the satellite's slower initial decay and the subsequent transition to a solar min.

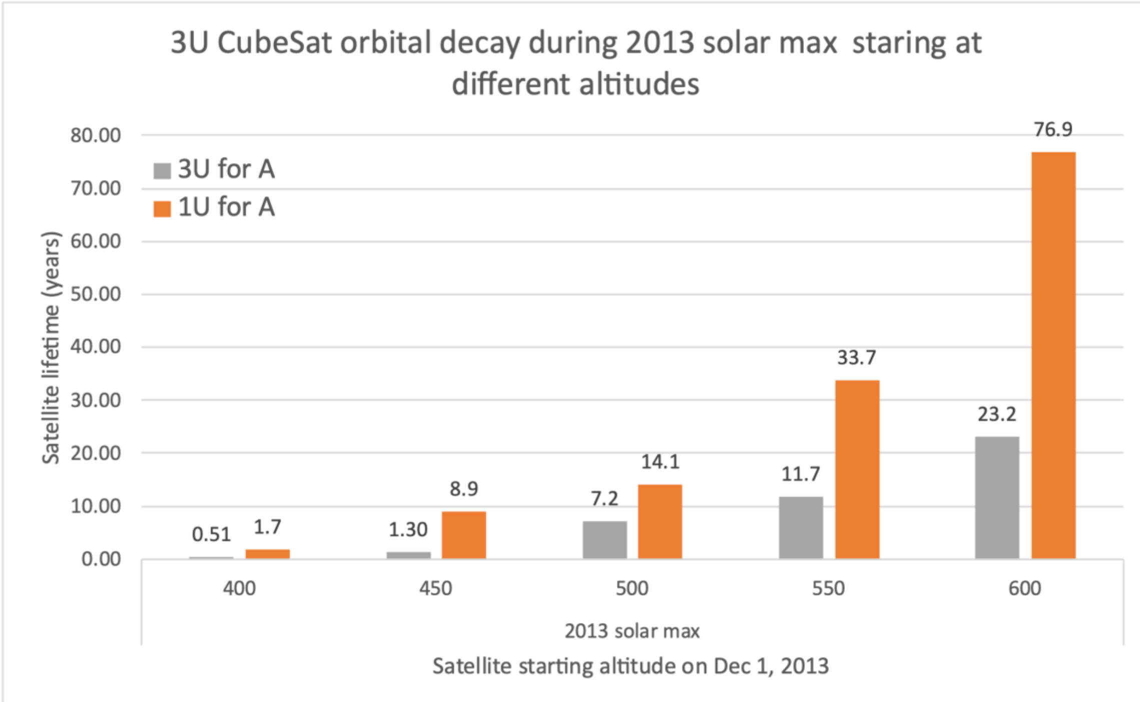

Figure 6: Comparison of satellite orbital decay launched during the 2013 solar max

Figure 7 presents a similar comparison but for the 2019 solar min. The trend of satellites with 1U compared to 3U drag area having about 2 to 3 times longer lifetime persists. The lifetime gap widens to about 4 times for satellites launched at 550 and 600km altitude.

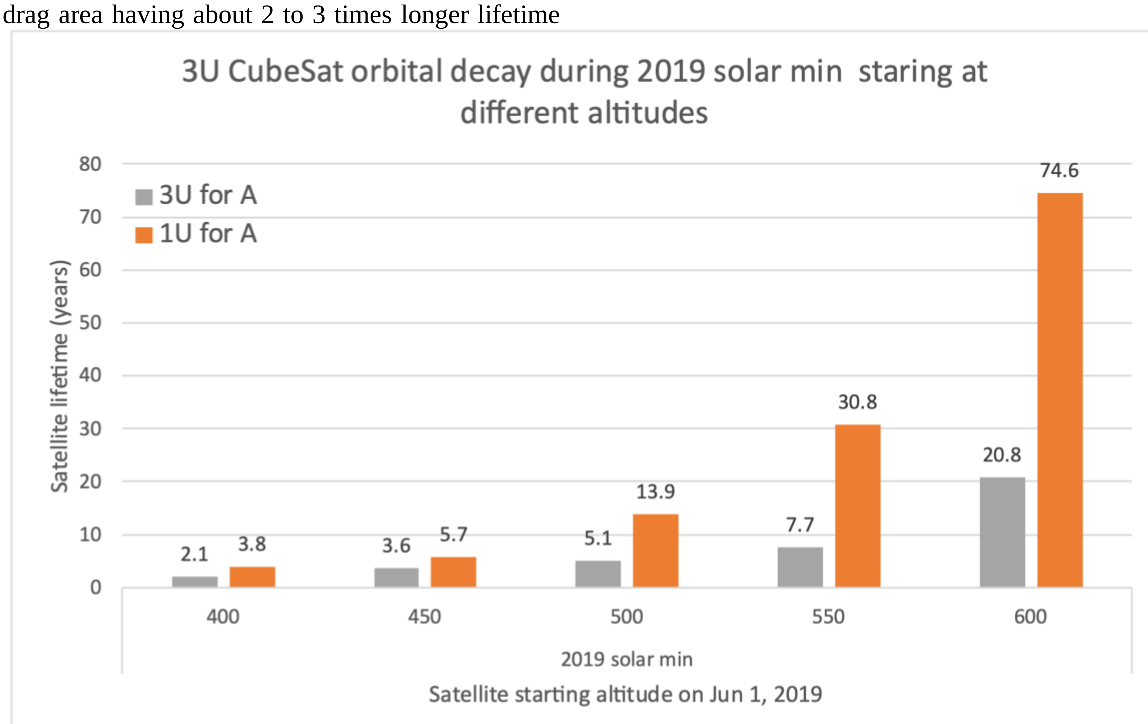

Figure 7: Comparison of satellite orbital decay launched during the 2019 solar min

Figure 8 offers a predictive analysis for the 2024 solar max. The trend of satellites with 1U compared to 3U drag area having about a 3 to 4 times longer lifetime holds, with an outlier at 500km showing about 5.5 times increase. This anomaly aligns with those seen in the 2001 and 2013 solar max scenarios, explained by the satellite's slower initial decay and the solar cycle's transition to solar min.

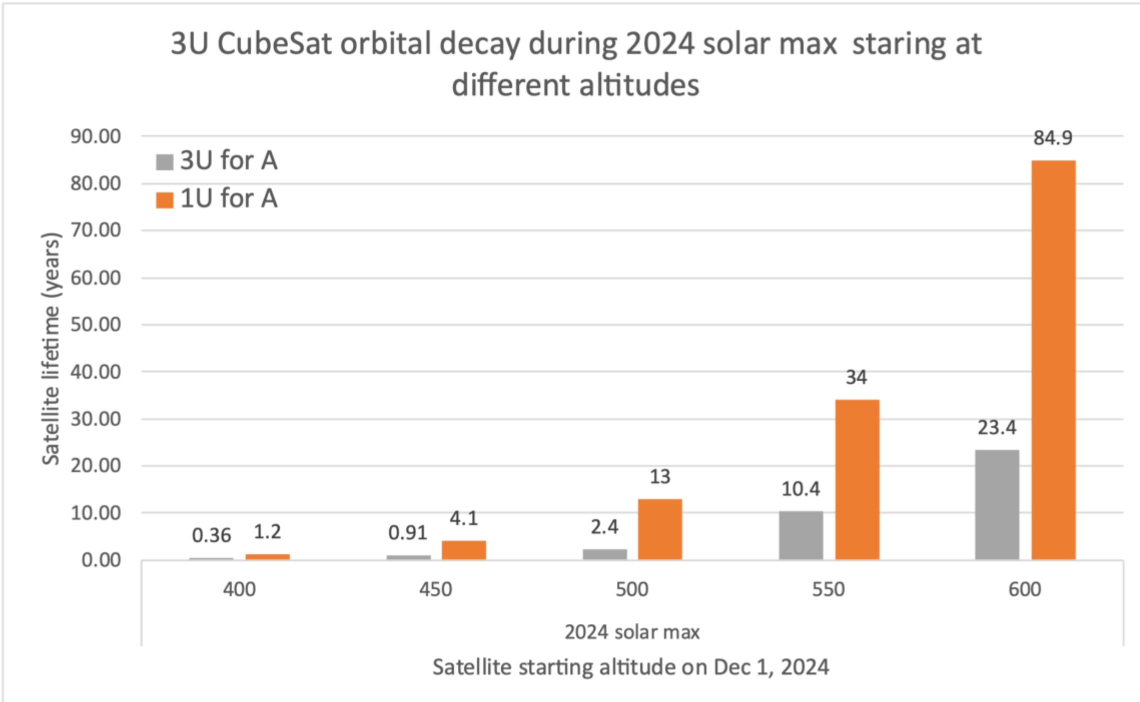

Figure 8: Comparison of satellite orbital decay launched during 2024 solar max

CONCLUSION

The results show that a small increase in the satellite's drag area can reduce a satellite's orbital lifetime when comparing satellites launched at the same altitude. At 550 km and 600 km, the lifetime difference between 1U and 3U configurations tends to be more pronounced, especially during solar min periods. Majority of the satellites launched in sun-synchronous orbit have an altitude between 500 and 550 km. Within this range, a satellite's lifespan can vary significantly, from approximately 2 to 37 years, depending on solar activity and drag area; albeit a CubeSat's operational lifetime typically lasts only 2 to 5 years. This wide range of lifetime can potentially congest LEO and increase space junk.

A 3U CubeSat shows itself to be a good candidate for attitude-based drag control and descent/decay, particularly with the 3U face in nadir pointing. The proposed methodology would be to incorporate an onboard (possibly autonomous) self-monitoring system to maintain/correct the satellite's altitude via attitude control with a plan to decay its orbit within 5 years from the end of the mission. The satellite would run a high-fidelity, on-board propagator (alternatively, receive ground-based status estimates depending on on-board computational capabilities). Although, solar and geomagnetic activity predictions can be uncertain, scheduled space weather model updates can improve atmospheric drag predictions. Increased drag area (for example, 3U face in ram direction) will likely also increase disturbance torques causing attitude instabilities. However, appropriate attitude maneuvers to increase drag during idling periods (where pointing capabilities can be compromised) can also be considered and implemented.

FUTURE WORK

In order to better understand the feasibility of monitoring and controlling orbital decay by controlling satellite attitude, further analysis is required to understand propagators' uncertainty, air density predictions based on space weather models, and the effects of drag on disturbance torques resulting in attitude pointing error.

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