# IN-ORBIT LIFETIME OF SATELLITES

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## Abstract

This paper examines the in-orbit lifetime of satellites. The study encompasses different orbital regimes, General Mission Analysis Tool (GMAT) simulations and data to affirm the impact of factors in Low Earth Orbit on satellite decay.

Solar activity emerges as a critical determinant of satellite lifetime, impacting atmospheric drag experienced by satellites in Low Earth Orbit (LEO). The research substantiates correlations between drag factors (cross-sectional area and orbital altitude) and satellite lifetime, emphasising the need to optimise these factors for prolonging in-orbit operations as well as quick deorbiting subsequently.

This research seeks to contribute to the nuanced understanding of atmospheric drag factors and satellite dynamics.

## Introduction

Satellites have become an essential part of our modern world, providing a wide range of critical services, from communications and navigation to weather forecasting and Earth observation. However, satellites are not permanent fixtures in space. Particularly in LEO, satellites may gradually lose their orbital altitude due to the effects of atmospheric drag, tidal perturbation and solar effects, and eventually re-enter the atmosphere and burn up. The in-orbit lifetime of a satellite is therefore a critical factor in its design, operation and mission planning.

This paper is written within the context of the flourishing of many different space exploration related companies, both in Singapore and abroad, dubbed New Space 2.0. Marked by private ventures rather than nations funding such missions, New Space marks a paradigm shift in the exploration of space. The rise of New Space has brought both new challenges and opportunities to the in-orbit lifetime of satellites. On one hand, companies are choosing to launch smaller satellites with little or no propulsion (e.g. CubeSats) which naturally have shorter in-orbit lifetimes as they do not have any means to overcome orbital decay. On the other hand, New Space companies are also developing new technologies that can extend the in-orbit lifetime of satellites such as compact electric propulsion. A better understanding of factors that affect orbital decay can contribute to satellite design decisions such as whether or not to include a propulsion sub-system in order to achieve the desired, in-orbit lifetime.

This paper provides an overview of the factors that affect in-orbit lifetime of satellites, specifically with respect to orbital decay in LEO. I begin by discussing the types of orbits and factors that affect the in-orbit lifetime, including atmospheric drag, and solar radiation pressure. Finally, I discuss the future of the in-orbit lifetime of satellites, and the challenges and opportunities that New Space presents.

## Types of Orbits

The types of Earth's orbits encompasses a diverse array, each designed with distinct purposes and operational considerations. Low Earth Orbit (LEO), close to the Earth's surface at altitudes up to approximately 2,000 kilometres, serves as a vantage point for Earth observation and reconnaissance satellites, fostering faster revisits. In recent times, companies such as SpaceX (through Starlink) have been using satellite constellations in low-Earth orbit for low-latency coverage of even remote areas.

Near-Equatorial Orbit (NEO) features a low inclination, meaning the satellite spends most of its time close to or over the Equator, facilitating low revisit times of Equatorial regions.

Medium Earth Orbit (MEO), occupying altitudes between 2,000 and 35,786 kilometres, is widely used by global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) to provide ubiquitous coverage and precise positioning capabilities. The Molniya orbit, characterised by its eccentricity and high inclination, caters to telecommunication needs at high latitudes, ensuring extended dwell times over specific geographic regions.

Sun-synchronous orbits, meticulously synchronised with Earth's rotation and the position of the Sun, provide invaluable platforms for Earth observation missions, capturing consistent and well-illuminated imagery, by making a pass over a location at the same Mean Solar Time every day.

The highest regime is found at and beyond the Geosynchronous and Geostationary orbits, situated at an altitude of approximately 35,786 kilometres. The former, with a period equal to Earth's rotational period, facilitates persistent communication and meteorological observations. The latter, a special case of the former distinguished by zero inclination and eccentricity, and constant positioning over a specific longitude over the Equator, serves as an ideal location for communication satellites and weather monitoring systems. High Earth Orbit (HEO), extending beyond geosynchronous orbit altitude, accommodates satellites for astronomical observations and scientific research, using the vantage point for unobstructed celestial observation.

## Literature Review

The in-orbit lifetime of satellites is a critical aspect of satellite engineering to design optimal satellite mission durations and ensure the sustainable use of space resources. This literature review aims to provide an overview of the current state of research on the in-orbit lifetime of satellites as it relates to factors affecting orbital decay. This review aims to examine key studies and identify prevalent themes, debates, and knowledge gaps.

The exploration of in-orbit satellite lifetimes can be traced back to the early days of space exploration when satellites were primarily launched for short-duration missions. Early studies [1, 2 and 3] laid the foundation for understanding the factors influencing satellite longevity. Over the decades, advancements in satellite technology, propulsion systems, and materials have significantly extended in-orbit lifetimes. Notable contributions include studies on satellite design innovations and their impact on longevity [4], as well as on satellite engineering best practices [5].

A consensus among researchers is the multifaceted nature of factors influencing satellite lifetimes. Solar radiation exposure, micrometeoroid impacts, thermal cycling, and propellant depletion are recognized as key contributors to satellite degradation [6]. Recent studies delve into the intricate interplay of these factors, employing advanced modelling techniques to simulate satellite degradation over time [7]. Such research provides valuable insights into the complex dynamics of in-orbit environments.

The solar flux, representing the radiant energy per unit area emanating from the Sun, engenders several consequential effects on the satellite's orbital dynamics, thereby exerting an observable impact on its operational lifespan.

Primarily, solar heating of the atmosphere, especially during periods of high solar activity, causes an upward shift of air. This results in a higher density of air at higher altitudes than nominal baseline. Since drag force is proportional to density of medium, the drag force on the satellite increases, accelerating orbital decay [8].

Similarly, solar flux imparts momentum to the satellite through solar radiation pressure. This effect is contingent upon the reflective characteristics of the satellite's surface, commonly expressed by the albedo term. The pressure differential induced by solar radiation pressure manifests as a slow drift in the satellite's orbital elements, notably the semi-major axis and eccentricity [9]. Consequently, alterations in the solar flux directly modulate the orbital parameters, thereby influencing the satellite's orbital evolution. Since this effect occurs at such a slow pace, its effect is relevant mostly for GEO/HEO satellites, as these are not as greatly affected by atmospheric drag at such high altitudes.

Furthermore, solar flux induces thermodynamic effects, contributing to the establishment of a thermal equilibrium within the satellite's internal components. The intricate interplay of solar irradiance and the satellite's radiative properties results in the generation of thermal expansion. Such thermal expansion, especially when coupled with thermal cycling as the satellite moves in and out of Earth’s shadow, may weaken the satellite’s structure depending on the material used [10].

The in-orbit longevity of satellites is also affected by gravitational interactions, particularly those arising from tidal forces.

Tidal forces, an outcome of gravitational gradients induced by celestial bodies (mainly interactions between the Sun, Moon and Earth, and to a much smaller extent other planets), materialise as perturbing influences upon satellite orbits. These perturbations influence the orbital elements of the satellite, including alterations in the semi-major axis and eccentricity, thereby causing temporal variations in the satellite's trajectory [11].

Moreover, tidal-induced perturbations introduce variations in the argument of perigee and nodal regression, thereby contributing to the overall complexity of satellite trajectories. Orbital perturbations may result in an increase in drag due to an increase in eccentricity and a lower perigee, accelerating the process of orbital decay [11]

Drag force, an inherent consequence of a satellite's movement through the Earth's upper atmospheric environment, arises from the interaction between the satellite and atmospheric particles. The principal mechanism underpinning this force is the transfer of momentum from the satellite to atmospheric particles, culminating in the gradual dissipation of kinetic energy and the consequent modification of orbital parameters [12].

The drag force, as represented by the ballistic coefficient, occurs in a direction opposite to the satellite's instantaneous velocity. This opposition causes a deceleration of the satellite's motion, inducing a reduction in its orbital energy and a commensurate degradation of orbital parameters over extended timescales. The most conspicuous manifestation of this deceleration is a gradual decrease in the semi-major axis of the satellite's orbit, i.e. orbital decay [12].

The atmospheric environment, another factor in orbital decay, is characterised by extremely variable density and composition. The atmospheric density, contingent upon factors such as solar activity and the satellite's altitude, is inversely proportional to the satellite's orbital altitude. Consequently, satellites in low Earth orbit are subjected to more pronounced drag forces due to their proximal exposure to the denser atmospheric strata, while those in higher orbits experience diminished atmospheric drag effects [13].

The seasonal and solar cycle-dependent variations in atmospheric density further underscore the complex relationship between the satellite's trajectory and atmospheric environment [13].

Moreover, the atmospheric composition contributes to the degeneration of satellites, with reactive elements such as atomic oxygen attacking and weakening exposed satellite structures [14].

Within the low Earth orbit (LEO) regime, characterised by altitudes ranging from approximately 180 to 2,000 kilometres, space debris poses a heightened risk due to increased particle density. The elevated prevalence of debris within this region amplifies the likelihood of collisions, thereby endangering the longevity of satellites orbiting within this altitude band. Intensifying this risk is the fact that the atmosphere induces strong disturbances within the trajectory of debris, complicating collision prediction and necessitating high-fidelity tracking. While in the long-run debris is likely to deorbit more quickly than MEO and GEO regimes, the short-term unpredictability at LEO poses a much greater risk to operations [15].

In the medium Earth orbit (MEO) and geostationary orbit (GEO) regimes, located at altitudes ranging from approximately 2,000 to 35,786 kilometres, the prevalence of space debris is comparatively diminished. However, the longer orbital lifetimes inherent to these altitudes render the trajectories susceptible to infrequent yet still present interactions with debris fragments. The absence of much atmospheric effects also means that the trajectories of debris are extremely predictable. However, this also means that the time to decay out of orbit is tremendously long, ranging from thousands to millions of years, meaning that buildup of debris in this regime is likely to be significant in the future. For now, the negative influence is much lower compared to LEO, yet remains a strong consideration for satellites within these mid and high-altitude regimes [15].

Propulsion systems may extend satellite lifetimes by providing a means to overcome the effects of atmospheric drag. Traditional chemical propulsion systems, though effective, have limitations in terms of fuel efficiency and mass constraints [16]. Emerging technologies, such as electric propulsion [17], are gaining attention for their potential to significantly extend satellite operational lifetimes as the feasibility, scalability, and cost-effectiveness of these technologies improve over time [18].

The exponential growth in the number of satellites deployed in orbit has raised concerns about space debris and its impact on in-orbit lifetimes. Sustainable practices and debris mitigation strategies are essential components of contemporary research agendas [19]. The concept of "space traffic management" is explored as a means to ensure the longevity of satellites while minimising collision risks [20]. However, the integration of such practices into international space policies remains a debated and evolving area.

Advancements in remote sensing and monitoring techniques play a pivotal role in assessing the health and performance of satellites in orbit. Satellite anomaly detection algorithms [21] and on-board sensor technologies enable real-time monitoring, enhancing our understanding of in-orbit degradation processes. The integration of artificial intelligence and machine learning approaches in these monitoring techniques [22] presents a promising avenue for future research, though challenges related to data accuracy and interpretability persist.

Despite significant progress, several knowledge gaps and emerging challenges persist within the current literature. The scarcity of long-term empirical data on satellite lifetimes, especially for GEO, and further, the slow evolution of their orbit, hinders the development of comprehensive predictive models. Additionally, the impact of space weather phenomena, such as solar flares and geomagnetic storms, on satellite lifetimes remains a relatively understudied area. Addressing these gaps is crucial for developing robust strategies to ensure the sustained functionality of satellites in orbit.

In conclusion, the literature on the in-orbit lifetime of satellites reflects a dynamic and evolving field of research. From cutting-edge propulsion systems to sustainable practices and advanced monitoring techniques, researchers have made significant strides in understanding and extending satellite operational lifetimes. However, challenges and knowledge gaps persist, prompting the need for further interdisciplinary collaboration, empirical data collection, and the development of innovative solutions. As the demand for satellite services continues to grow, a holistic and sustainable approach to satellite operations is imperative for the future of space exploration and utilisation. The goal of this project was to contribute to a nuanced understanding of atmospheric drag factors and satellite dynamics that affect the in-orbit lifetime of satellites.

## Methodology

The research methodology devised for this investigation into the factors impacting the in-orbit lifetimes of satellites employs the General Mission Analysis Tool (GMAT) developed by the Goddard Space Flight Centre at NASA.

GMAT is a software that provides a platform for simulation of the satellite. This representation encompasses intricate details of the satellite, ranging from its physical attributes such as drag coefficients to propulsion system specifications and orbital parameters. The in-built features such as atmospheric and solar radiation pressure modelling allows for more precise simulation of the in-orbit environment, boosting the reliability of acquired data.

For the purpose of this study, the satellite drag coefficient was fixed at 2.2, which is the generally accepted value where further ray-tracing based models and characterisations are unavailable [23]. The satellite mass was also fixed at 850kg, which corresponds to a medium size satellite. The satellite’s orbital inclination and eccentricity were set to 0, for simplicity of this study.

The end point of the simulation is set at 100km, corresponding to the Karman line, which is generally accepted to be the conventional boundary between Earth's atmosphere and outer space.

## Solar Activity

To model variance in solar activity, the average solar flux at 10.7cm (a common indicator used to study solar activity) was varied from 75 to 300 sfu at 25 sfu intervals (the typical range across the solar cycle) for each simulation at an initial altitude of 700 km. The minimum and maximum sfu values were referenced from the NOAA which correspond to solar minimums and maximums (i.e. geomagnetic storms) respectively [24].

## Drag

To model drag variance with altitude, a spacecraft of the following parameters was used. Initial altitude was varied from 300 km to 700 km in 200 km intervals, except between 500-700 km where 50km intervals were used.

To model drag variance with cross sectional area, orbit simulation was carried out at 500 km, and default flux. Cross-sectional area was varied from 5m² to 60m². These values were chosen based on satellites commonly seen in LEO.

After results were obtained as CSV files, they were analysed by means of Python code, which can be found in Appendix 1.

# Results

## Solar Activity

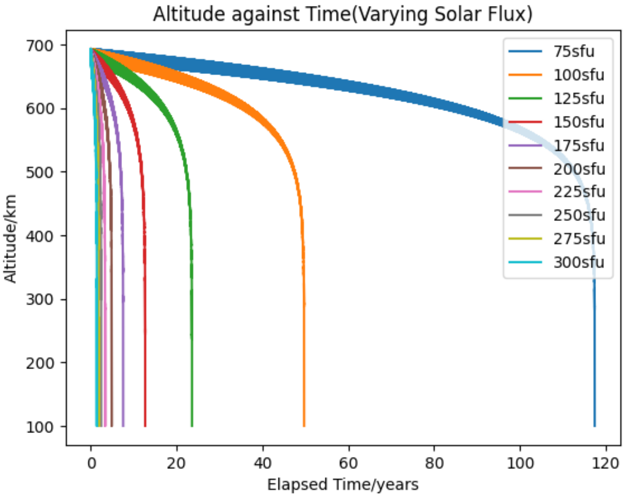


Figure 1. Altitude against time for varying solar flux

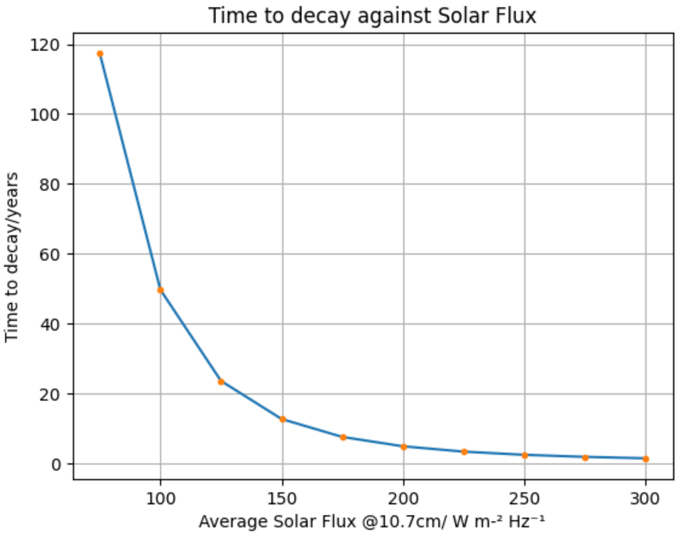


Figure 2. Time to decay to 100km against solar flux

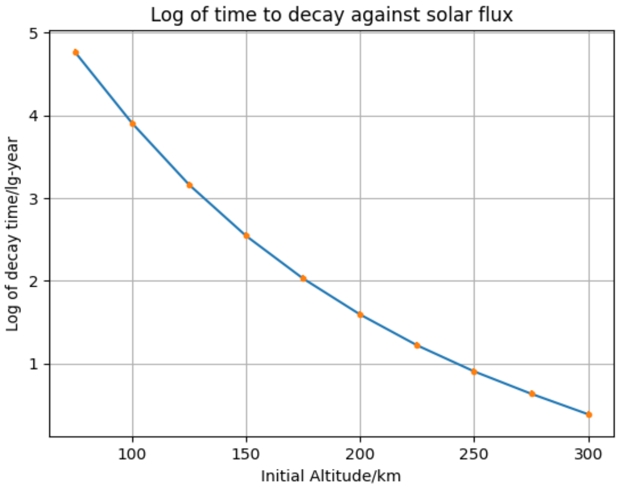
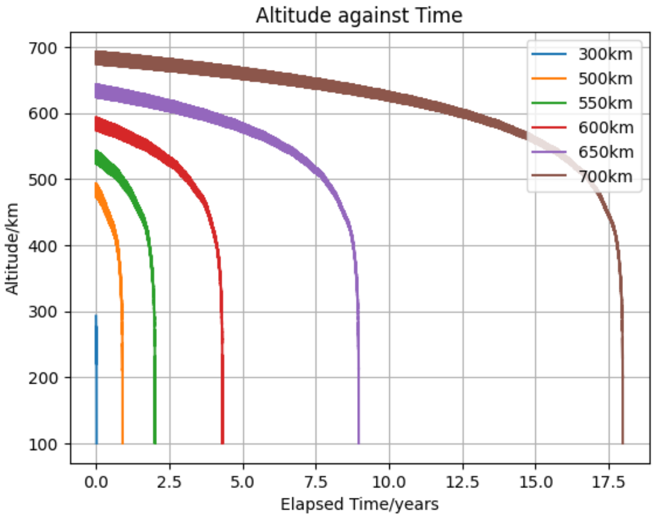


Figure 3. Logarithm of time to decay to 100km against solar flux; showing the exponential relation between decay and solar activity(logarithm is natural)

## Initial Altitude



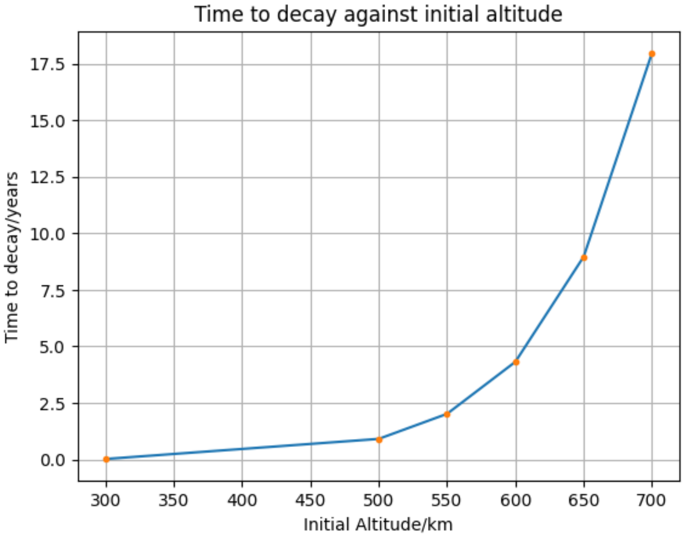


Figure 4. Altitude against time for varying altitude

Figure 5. Time to decay to 100km against initial altitude

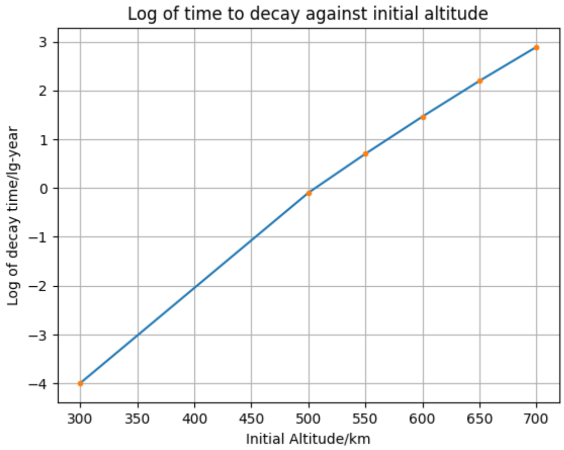


Figure 6. Logarithm of time to decay to 100km against initial altitude; showing the exponential nature of time to decay against initial altitude(logarithm is natural)

### Cross sectional area

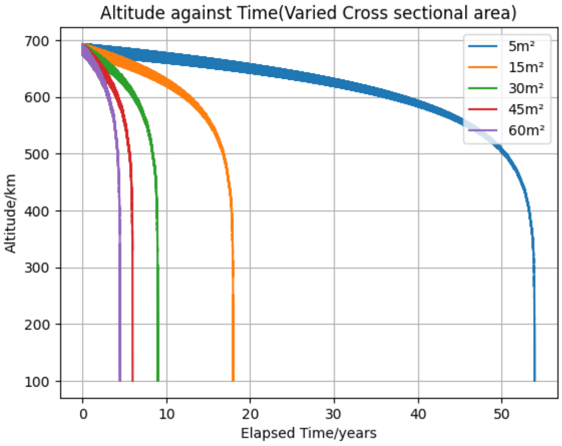


Figure 7. Altitude against time for cross-sectional area

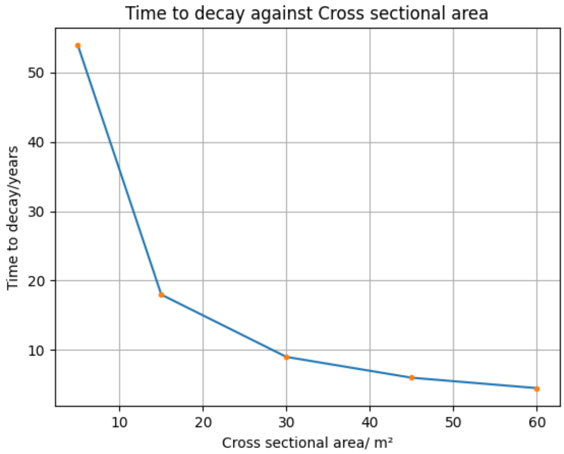


Figure 8. Time to decay to 100km against cross sectional area

## Discussion

### Solar Activity

In the context of my research on the in-orbit lifetime of satellites, a crucial aspect that emerged in prior studies is the correlation between satellite lifetime and solar activity. My investigation aligns with the hypotheses proposed in our study, affirming that greater solar activity (represented by solar flux) results in the faster decay of satellite orbits (Figures 1-3). This correlation is principally attributed to the impact of solar activity on atmospheric heating, which subsequently results in higher atmospheric density at higher altitudes.

As the sun undergoes varying degrees of activity, characterised by fluctuations in solar radiation, it influences the Earth's atmosphere. The consequential heating of the atmosphere then contributes to heightened atmospheric density at high altitudes of around 100-500km. Thus, satellites in low Earth orbit (LEO) and beyond experience the effects of an increase in atmospheric drag. This effect is generally expected to be exponential.

My empirical findings align with the correlation seen in the literature review, showcasing a consistent pattern of accelerated, exponential orbital decay (Figure 3) and diminished satellite lifetime during periods of heightened solar activity. As such, missions, especially those in LEO, should plan timelines to either avoid these periods of high solar activity, anticipate shorter mission lifetimes, or factor these considerations into the satellite’s design.

### Orbital altitude

Additionally, orbital altitude also has a significant impact on the orbital decay of satellites (Figures 4-6). Our findings align with the literature, affirming that satellites traversing orbits at lower altitudes are subject to increased atmospheric drag, due to greater atmospheric density, thereby hastening their descent and reducing their operational lifetime. This relationship is exponential in nature, as shown by Figure 5. Operators intending to put their satellites in lower orbits must thus prepare for more frequent station-keeping

## Cross-sectional area

Within the realm of my investigation into the in-orbit lifetime of satellites, an important factor observed in the discussion centres on the correlation between satellite lifetime and drag factors. My research substantiates the hypotheses set forth earlier, affirming the well-established association between these drag factors and the rate of decay of satellites in the LEO environment.

The cross-sectional area is one of the drag factors that significantly influences the atmospheric drag experienced by satellites. My findings align with the established literature, highlighting a direct correlation between these drag parameters and the observed trends in satellite lifetime. As hypothesised, a larger cross-sectional area contributes to heightened atmospheric drag, thereby accelerating the orbital decay of satellites (Figures 7 and 8).

The cross-sectional area of a satellite emerges as a key factor influencing atmospheric interactions. Satellites with larger cross-sectional areas present a greater surface for atmospheric particles to act upon, intensifying the drag forces they experience. My research corroborates this relationship, reinforcing the understanding that cross-sectional area is a crucial parameter in determining the pace of satellite orbital decay.

## Conclusion

In conclusion, this work has contributed to a nuanced understanding of the factors influencing the in-orbit lifetime of satellites, with a particular focus on the correlation between atmospheric drag factors and satellite dynamics. The study agreed with the hypotheses based on existing literature, emphasising the significance of drag parameters such as cross sectional area and altitude, as well as secondary factors such as solar activity.

One of the strengths of this research lies in its validation of theoretical concepts, providing evidence that supports the correlations between drag factors and satellite orbital decay. The alignment between my findings and established knowledge bolsters our ability to make informed decisions in satellite mission planning.

Looking ahead, there remain many avenues for further studies to advance our understanding of satellite behaviour in orbit. A notable direction is the need for a more comprehensive characterization of the Earth's atmosphere. Improving our understanding of atmospheric variations, particularly at different altitudes and under varying solar conditions, would significantly enhance the precision of predictive models and contribute to more accurate assessments of satellite lifetimes.

Moreover, the integration of artificial intelligence (AI) presents a promising frontier for the optimization of satellite operations. The potential for AI to automate station-keeping manoeuvres while making intelligent decisions based on vast datasets is a compelling area for future exploration. Machine learning algorithms could leverage extensive data on atmospheric conditions, solar activity, and satellite performance to adjust trajectories and optimise station-keeping strategies, thereby extending the operational lifetimes of satellites in a more adaptive manner.

The continual refinement of our understanding of atmospheric interactions, coupled with the integration of cutting-edge technologies like AI, holds the potential to revolutionise satellite operations and contribute to the sustainable and efficient utilisation of Earth's orbital space.

## Acknowledgements

I extend my appreciation to those whose unwavering support and guidance have been instrumental in shaping this research paper. Foremost, my gratitude goes to my mentors, Lee Xun Yong and Samuel Joo. Their expertise, counsel, and encouragement have been pivotal in navigating the complexities of this research, enriching my understanding and refining the quality of my work.

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## Appendix 1: GMAT Code and other relevant code

This appendix provides the detailed GMAT (General Mission Analysis Tool) code and data visualisation code utilised in this research study. The GMAT code serves as the backbone for simulating satellite trajectories and evaluating various factors influencing satellite operational lifetimes.

https://github.com/hi-bye125/Research-Paper-Appendix-1

Explanation:

The GMAT scripts initiate the simulation by defining a spacecraft with specified orbital elements, including the semi-major axis, eccentricity, inclination, right ascension of ascending node, argument of perigee, and true anomaly. The propagator is configured with the relevant gravitational, atmospheric, solar flux, and tide models to simulate the impact of environmental factors on the satellite's trajectory. The simulation is executed until the satellite reaches an altitude of 100km above ground and the resulting orbit data is recorded in a csv file.

This CSV file is then imported into a python Jupyter notebook using the Pandas library, followed by data visualisation using MatPlotLib. All GMAT Simulation files and data analysis code is made available at the link above. For raw data, please contact us separately.

## Appendix 2: Enlarged graph images

### Solar Activity

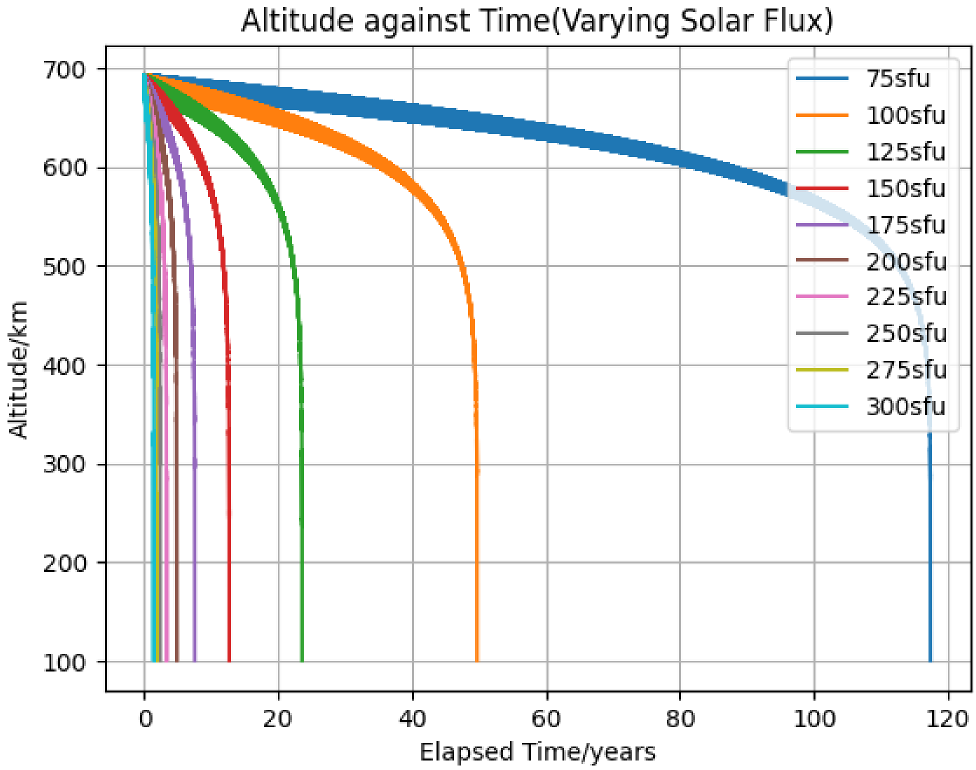

Figure 1. Altitude against time for varying solar flux

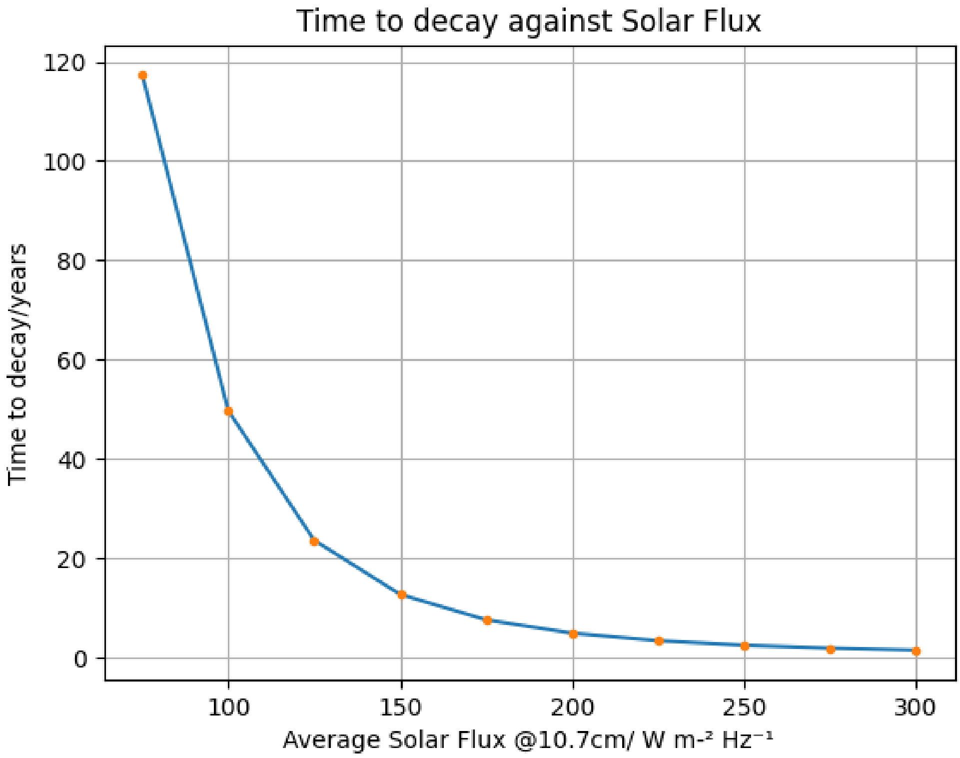

Figure 2. Time to decay to 100km against solar flux

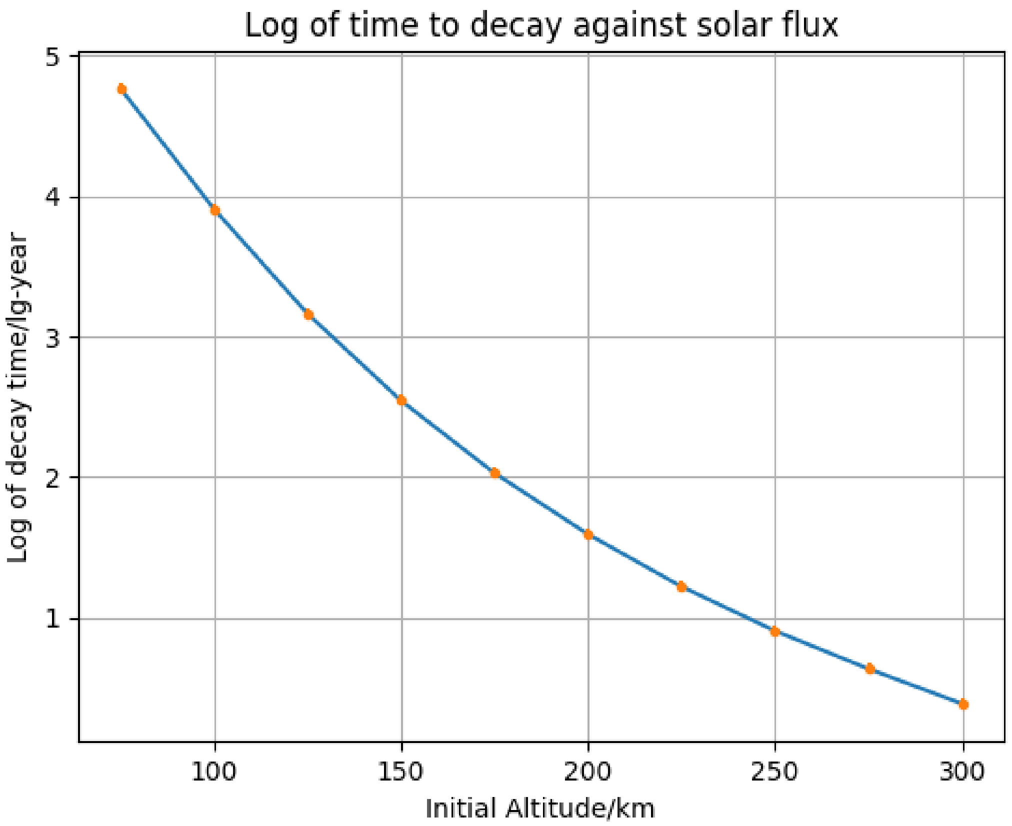

Figure 3. Logarithm of time to decay to 100km against initial solar flux; showing the exponential nature of time to decay against solar flux(logarithm is natural)

**Table 1:** Time to decay to 100km against solar flux

| **Solar Flux@10.7cm/W m$^{-2}$ Hz$^{-1}$** | **Time/years(5s.f.)** |
|---|---|
| 75 | 117.42 |
| 100 | 49.736 |
| 125 | 23.612 |
| 150 | 12.714 |
| 175 | 7.5881 |
| 200 | 4.9105 |
| 225 | 3.3822 |
| 250 | 2.4671 |
| 275 | 1.8827 |
| 300 | 1.4690 |

**Initial Altitude**

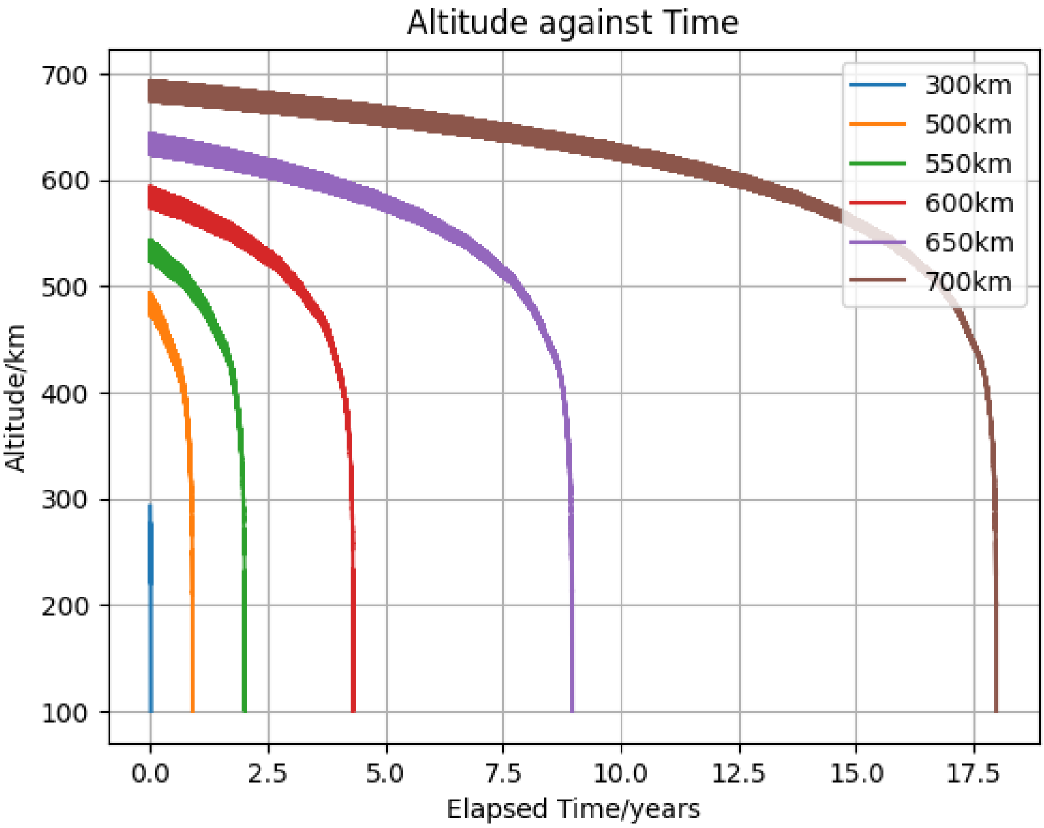

Figure 4. Altitude against time for varying altitude

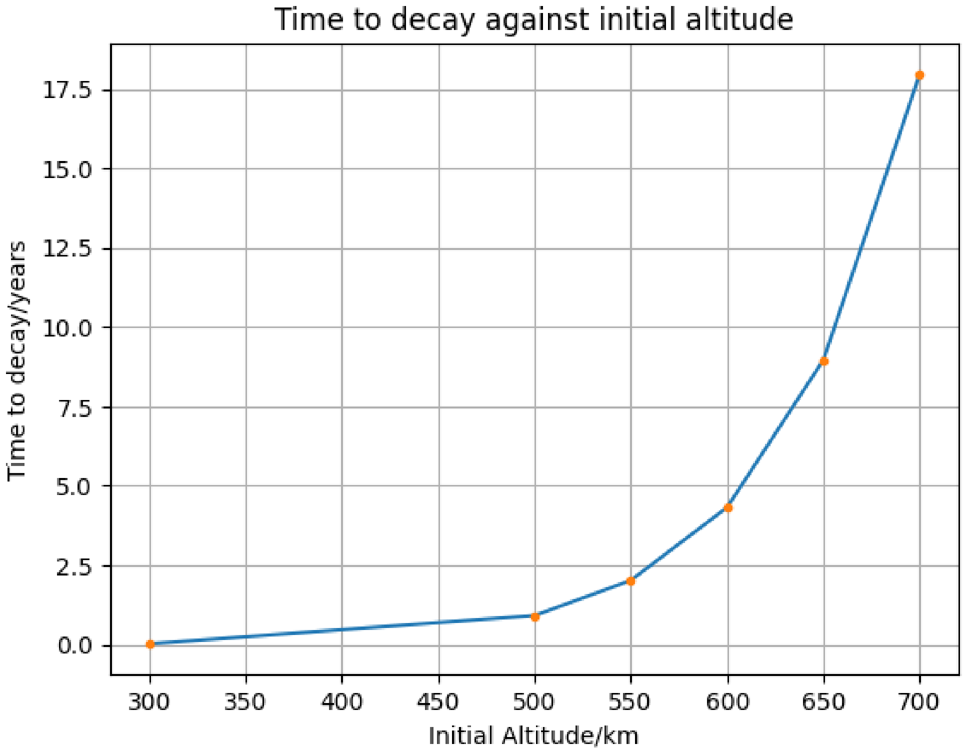

Figure 5. Time to decay to 100km against initial altitude

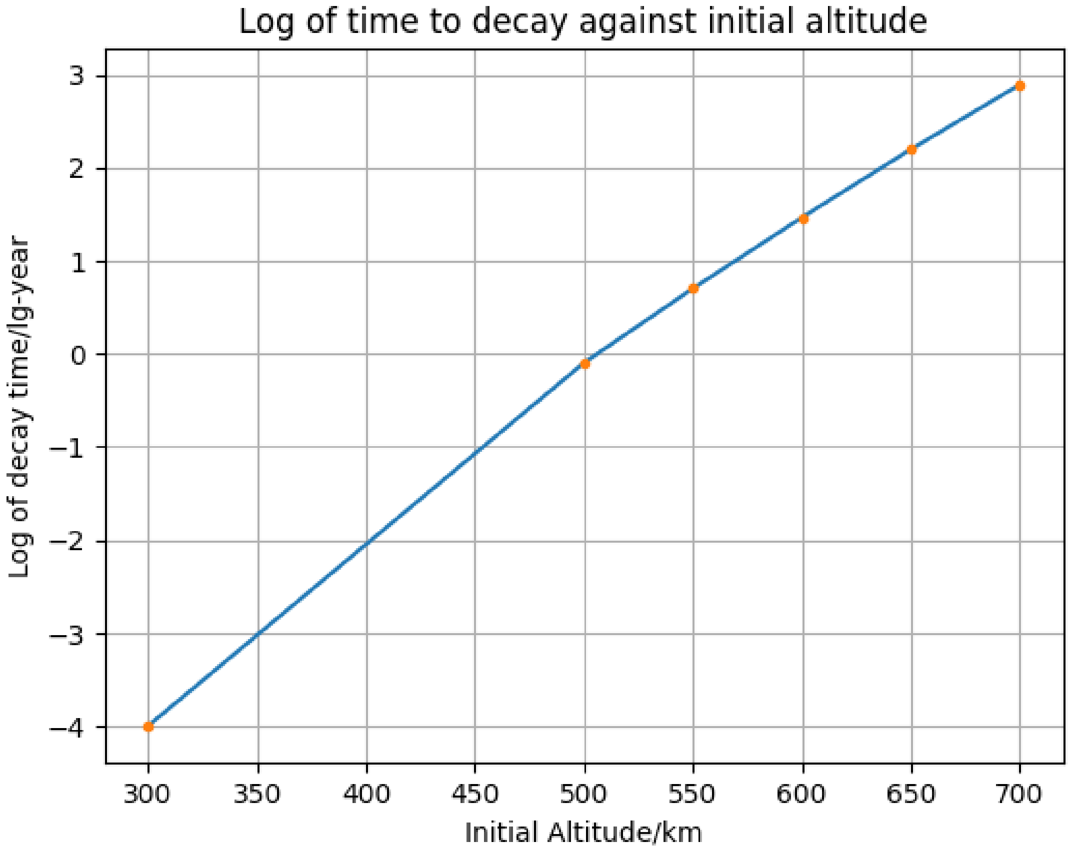

Figure 6. Logarithm of time to decay to 100km against initial altitude; showing the exponential nature of time to decay against initial altitude(logarithm is natural)

**Table 2:** Time to decay to 100km against initial altitude

| **Initial Altitude/km** | **Time/years(5s.f.)** |
|---|---|
| 300 | 0.018388 |
| 500 | 0.90643 |
| 550 | 2.0134 |
| 600 | 4.3152 |
| 650 | 8.9657 |
| 700 | 17.977 |

**Cross sectional area**

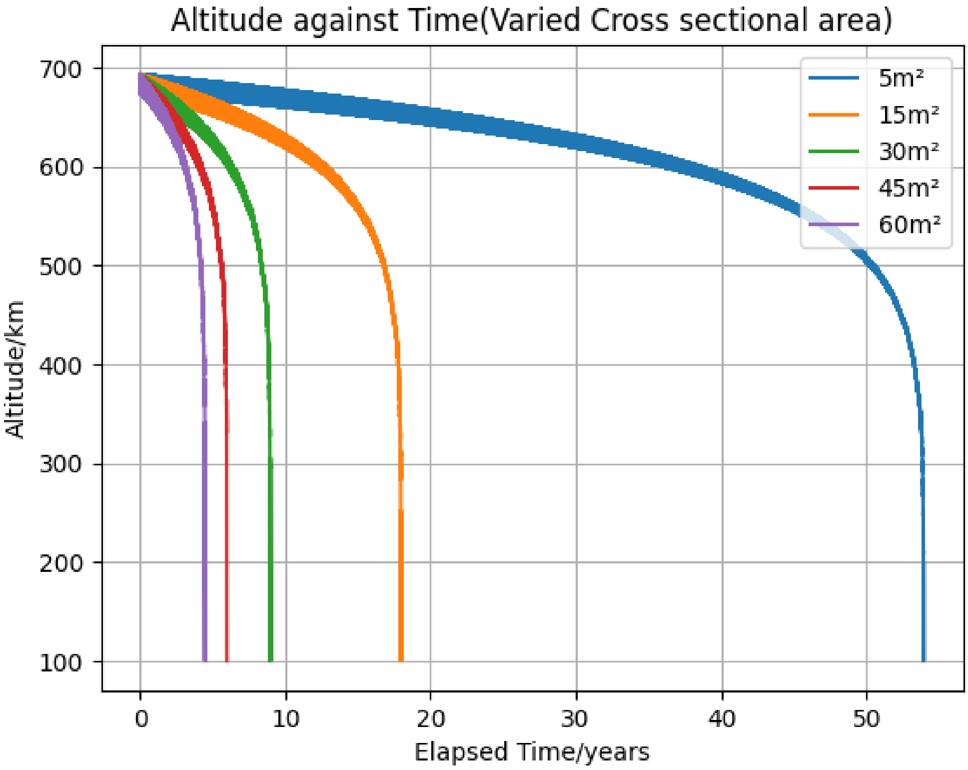

Figure 7. Altitude against time for cross-sectional area

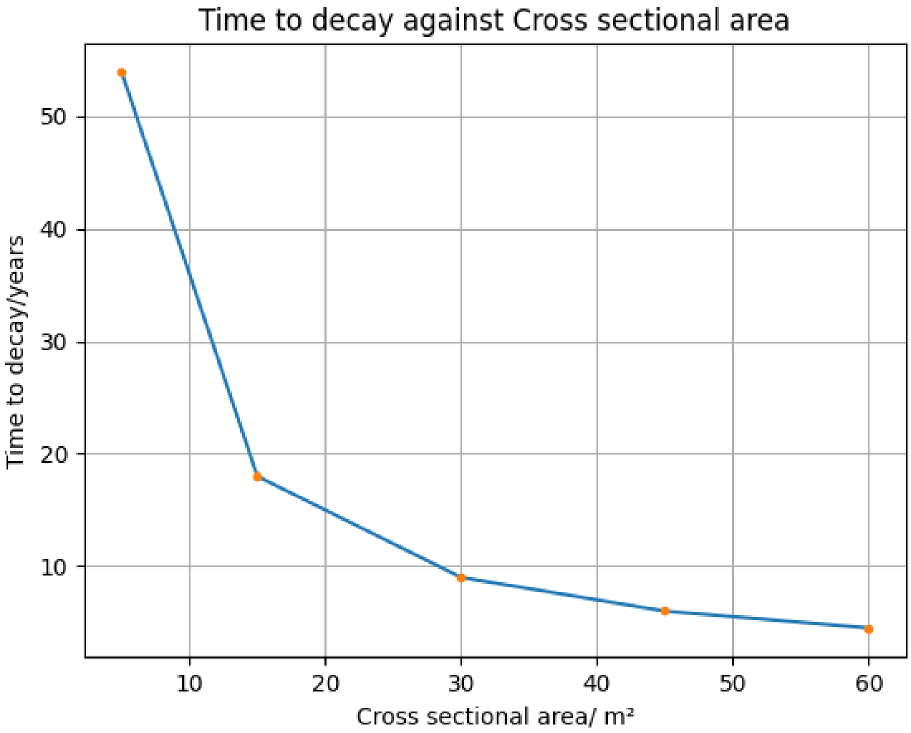

Figure 8. Time to decay to 100km against cross sectional area

**Table 3:** Time to decay to 100km against cross-sectional area

| **Area/m$^2$** | **Time/years** |
|---|---|
| 5 | 53.913 |
| 15 | 17.969 |
| 30 | 8.9841 |
| 45 | 5.9896 |
| 60 | 4.4911 |