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Orbital Lifetime Estimation of Rocket Bodies in Eccentric Low Earth, Low Inclination Orbits

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Abstract: The dense population of Low Earth Orbit (LEO) due to frequent launches necessitates precise knowledge of the orbital lifetime of rocket bodies in this region. This study focuses on estimating the orbital lifetime of rocket bodies in eccentric, low-inclination LEO. Using the open-source software General Mission Analysis Tool (GMAT), the orbital lifetimes of rocket bodies with masses of 1000 kg, 1200 kg, and 1400 kg were calculated for altitudes ranging from 250 km to 500 km and inclinations of 0˚, 10˚, and 20˚. The orbital lifetimes of the defunct rocket bodies ranged from 3 to 832 days. GMAT-derived orbital lifetimes were compared with those obtained using Systems Tool Kit (STK). A subsequent 2D interpolation code was developed to interpolate the lifetime for a user-provided configuration of mass and orbital altitude. The Python code interpolated the orbital lifetimes for the given configurations with a maximum error of 5% compared to the GMAT-simulated lifetime values. This approach provides essential data for assessing post-mission disposal plans for rocket bodies and ensuring alignment with the Inter-Agency Space Debris Coordination Committee (IADC) 25-year guideline. Key findings reveal that the orbital lifetime of a rocket body increases with inclination. Additionally, it was observed that the orbital lifetime increases with mass due to slower orbital decay.

Table of Contents

1. Introduction

The growing frequency of satellite launches and space missions has led to an increasing number of objects in Low Earth Orbit (LEO), including inactive satellites, rocket bodies, and other fragments. These objects, commonly referred to as space debris, pose significant risks to operational assets in space, as collisions between active satellites and debris can result in catastrophic consequences, creating thousands of additional debris fragments that exacerbate the problem (Anz-Meador, 2023; Liou, 2006). With the current emphasis on sustainable space operations, understanding and predicting the orbital decay of these objects has become critical to mitigating the risks they pose. LEO, extending up to 2,000 km in altitude, is particularly vulnerable to space debris accumulation due to its high population density and relatively short orbital lifetimes for objects influenced by atmospheric drag. Spent rocket bodies left in LEO after satellite deployment are a major concern, as they continue to orbit until they decay and re-enter the atmosphere. Accurate lifetime predictions for these objects are essential to assess compliance with international debris mitigation guidelines, such as the 25-year rule recommended by the Inter-Agency Space Debris Coordination Committee (IADC), which aims to reduce the long-term presence of defunct objects in LEO (Inter-Agency Space Debris Coordination Committee (IADC), 2021). Existing methodologies for orbital lifetime estimation often rely on computationally expensive numerical simulations or oversimplified models that fail to account for dynamic atmospheric conditions. These limitations hinder large-scale studies and make it challenging to understand the effects of critical parameters such as eccentricity, inclination, and mass on orbital decay. There is a need for practical and accurate tools to predict the orbital lifetime of rocket bodies across varying conditions to support compliance with debris mitigation standards.

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This study addresses these challenges by:

- Modelling and simulating the orbital decay of rocket bodies in eccentric, low-inclination LEO using the General Mission Analysis Tool (GMAT).
- Developing a Python-based interpolation model for estimating orbital lifetimes at user-defined altitudes and inclinations.
- Examining the influence of key parameters (mass, altitude, and inclination) on orbital lifetime, offering insights for post-mission disposal planning.
- Validating the proposed model against high-fidelity simulation results and assessing its applicability for debris mitigation planning.

2. Literature Review

The orbital lifetime of space objects, particularly in Low Earth Orbit (LEO), has been a topic of extensive study due to its implications for both satellite mission planning and space debris mitigation. Research by Petersen (1956) provided profound insights into the orbital decay process, particularly highlighting the dominant role of atmospheric drag. Petersen's approach focused on decay rates at lower altitudes, where atmospheric density is higher and atmospheric drag exerts a greater influence on orbital decay. Billik (1962) advanced the study of lifetime estimation for objects in eccentric orbits. Billik's findings underscored the need to account for eccentricity when estimating lifetimes, as decay is asymmetrically affected by perigee altitude, which can alter the orbit's overall shape and eccentricity over time.

The complexity of orbital decay modeling became more apparent in the work of Lafontaine and Garg (1982), who highlighted several sources of uncertainty in orbital lifetime predictions, such as fluctuations in atmospheric density caused by variations in solar activity and geomagnetic storms. These factors can significantly alter drag effects and, consequently, the rate of orbital decay. Their research also detailed other non-gravitational perturbations, such as solar radiation pressure and the Earth's non-uniform gravitational field, that influence orbital trajectories in LEO.

Later studies, such as those by Woodburn (2005), further emphasized the challenges associated with orbital lifetime prediction, especially when atmospheric density models lack real-time data integration. Woodburn's work discussed uncertainties associated with drag coefficient estimations, which are often simplified to average values in models despite variability in surface area and orientation relative to atmospheric particle flow. These variations can impact decay rates, particularly in eccentric orbits where atmospheric interactions vary throughout the orbit. Atmospheric drag depends on several uncertain elements, such as the atmospheric density profile, solar activity, atmospheric conditions, the area-to-mass ratio, and the object's attitude (Dolado-Perez, 2014). These parameters are known with limited accuracy. Atmospheric drag strongly depends on specific perturbation-related parameters, such as CDCD and AA.

Recent approaches in orbital lifetime estimation have leveraged computational tools like NASA’s General Mission Analysis Tool (GMAT) and Systems Tool Kit (STK) for high-fidelity simulations. Park et al. (2018) demonstrated the effectiveness of these tools in predicting orbital decay under various atmospheric and solar activity conditions. By incorporating numerical integration methods, such as the Runge-Kutta 4 integrator, these studies achieved accurate lifetime predictions while balancing computational efficiency. Park et al. also validated their predictions by comparing results with multiple atmospheric models, showing that model selection significantly influences lifetime estimations.

The present study builds upon these prior contributions by using GMAT for orbital lifetime simulations in LEO. Additionally, it introduces a 2D interpolation model for estimating lifetimes, leveraging findings from prior studies on the importance of atmospheric drag and density model precision for accurate lifetime predictions.

3. Methodology Proposed

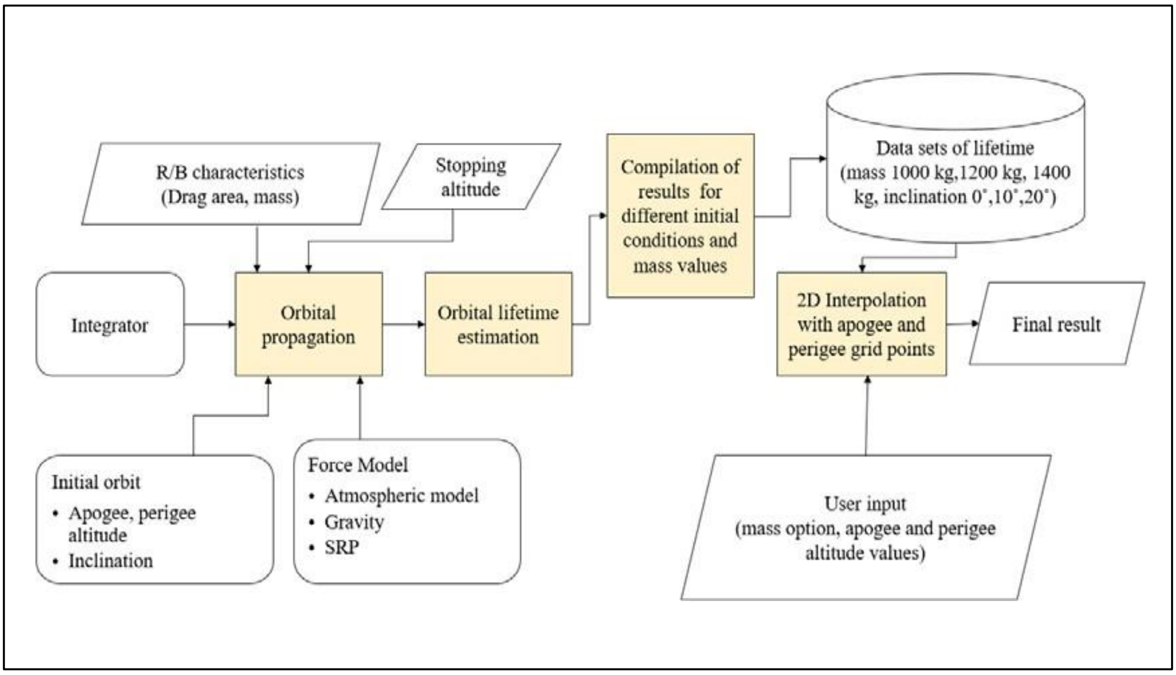


Figure-1 Methodology proposed

Figure 1 provides a visual aid of the methodology proposed for this study. This study employed GMAT to simulate the orbital lifetime of rocket bodies and a Python interpolation model for lifetime prediction for user-interested configurations. The methodology comprises simulation setup, configuration of orbital parameters, and development of a Python-based 2D interpolation model to predict lifetimes at various orbital altitudes and inclinations.

1. Simulation Setup

GMAT was chosen as the primary software for this study as it facilitates robust simulation capabilities and supports complex force models. The Systems Tool Kit (STK) – a high-fidelity tool, was used for validation, allowing comparison with GMAT results to ensure accuracy.

A. Rocket Body Specifications:

A rocket body akin to India’s PSLV was used in this study. The rocket body was assumed to be perfectly cylindrical with the following dimensions:

Table-1 Rocket Body Specifications

Length (m)	l		**4**
Diameter (m)	d		**3**
Length/Diameter ratio	(l/d)		**1.333**

For a non-spherical object, the area exposed to the atmosphere in the direction of the velocity varies due to changes in the attitude of the body. Hence, there arises a need to calculate the average cross-sectional area. The formula for the calculation of the average cross-sectional area, based on the length-to-diameter ratio of the object, is given below (De Lafontaine & Garg, 1982).

Table-2 Formula for average cross-sectional area calculation

Shape of the object	(l/d) ratio	Averaged area
Near- spherical and spherical	$(1/2) <$ $(l/d) < 2$	$\frac{1}{4}(total\ surface\ area)$

Using the formula, the calculated drag area of the rocket body for the dimensions was 12.9590 m². To avoid convolution of the coefficient of drag, a standard value of 2.2 was considered for this study.

B. Simulation Parameters

In this study, orbital lifetimes were simulated for rocket bodies with dry masses of 1000 kg, 1200 kg, and 1400 kg. These dry mass values are close to those of defunct rocket bodies in LEO, such as PSLV. The orbital altitude was varied by selecting apogee and perigee values ranging from 250 km to 500 km in increments of 25 km. Orbital inclinations of 0°, 10°, and 20° were chosen to represent low-inclination orbits. These parameters were selected to examine the effects of altitude, mass, and inclination on orbital lifetime. 3D surface plots of the results were plotted.

The Jacchia-Roberts atmospheric model was employed in GMAT to account for atmospheric drag, as this model offers adequate performance in LEO. Atmospheric drag is a major non-gravitational perturbation affecting objects in LEO. Additionally, Jacchia-Roberts accurately models the density variations influenced by solar activity.

The F10.7 cm solar flux values were imported from Celestrak in GMAT to carry out the simulations. GMAT used solar flux values for 5 years to simulate the lifetime. GMAT's Runge-Kutta 4 (RK4) numerical integrator was used as the primary propagator due to its accuracy in handling complex, variable forces in dynamic orbital environments. The RK4 integrator provides a balance between accuracy and computational efficiency, making it suitable for long-term decay predictions. The force model included gravitational and drag forces, with the Earth's JGM-2 gravity model used to account for gravitational variations, and solar radiation pressure and luni-solar gravitational effects included to enhance accuracy.

The Jacchia-Roberts atmospheric model works only up to an altitude of 100 km. Hence, the terminating altitude for the simulations was set to 100 km.

2. Development of the 2D Interpolation Model

A Python-based code was developed to process the simulation results and perform 2D interpolation. The code utilized the Pandas library for data manipulation, NumPy for numerical computations, and SciPy for interpolation. The interpolation technique employed was linear interpolation, which provided smooth and continuous estimates of orbital lifetimes for user-defined orbital altitude and inclination configurations. The GMAT-obtained lifetime values served as the database for the interpolation model. The model reads the data and performs interpolation at user-provided mass and orbital altitude configurations. Figure 2 visualizes the execution of the interpolation model.

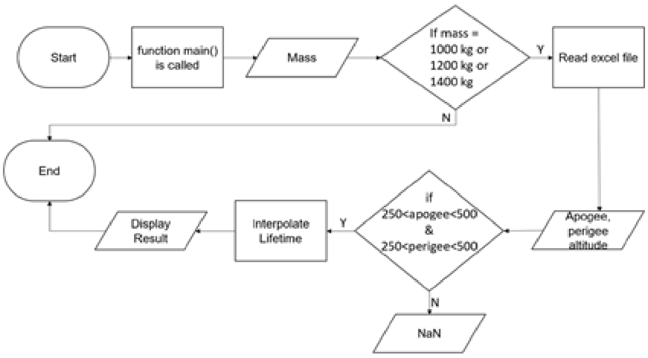


Figure-2 Flow chart explaining the execution of the interpolation code

To ensure accuracy, the interpolation model was validated by comparing predicted lifetimes to GMAT values. The model achieved a margin of error of up to 5%, demonstrating reliability across the studied parameter range.

3. Validation and Comparison

To confirm the accuracy of the GMAT simulations, results were compared with STK-derived values for similar configurations. This validation process ensured consistency and verified the efficacy of the selected force models and integration methods used in GMAT.

4. Results

The results of this study were obtained through GMAT simulations and validated using STK. These results illustrate the relationships between orbital lifetime and variables such as altitude, mass, and inclination for rocket bodies in low-inclination, eccentric low Earth orbits. In this study, 594 simulations were conducted. The results were presented as lookup tables and visualized using surface plots to identify any anomalies. A table comparing the lifetime values obtained by GMAT and STK is included in this section. Tables comparing the lifetimes obtained by the interpolation code and GMAT with percentage error are also included. Subsequently, clustered column charts of the same are provided to aid in understanding the results clearly. All the orbital lifetime values in the tables below are truncated to one decimal place.

A. GMAT Obtained Results

The orbital lifetimes obtained ranged from 3.2 days for a 1000 kg rocket body in a 250 km×250 km orbit with an inclination of 0° to 830.2 days for a 1400 kg rocket body in a 500 km×500 km orbit with an inclination of 20°. Although the study focuses on elliptic orbits, circular orbits were simulated to generate the surface plots. Figures 3, 4, and 5 present the surface plots generated from the simulated lifetime values.

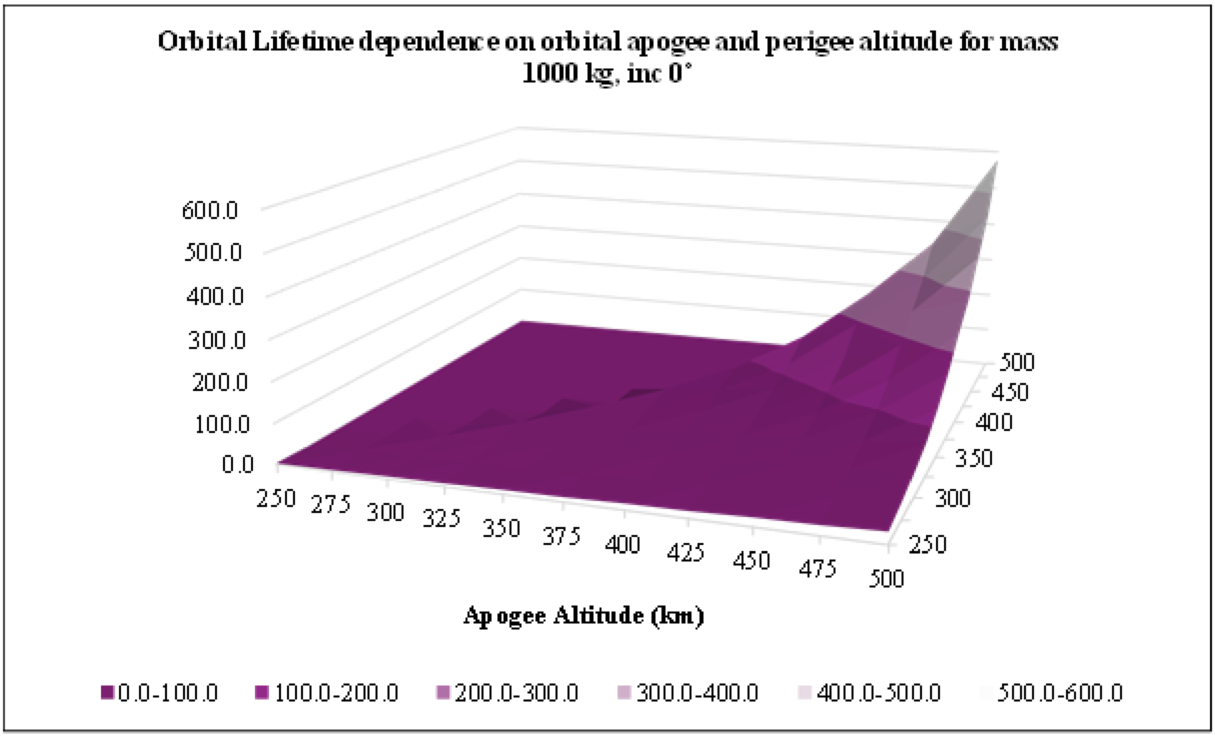


Figure-3 Orbital Lifetime dependence on orbital apogee and perigee altitude for mass 1000 kg & inclination 0°

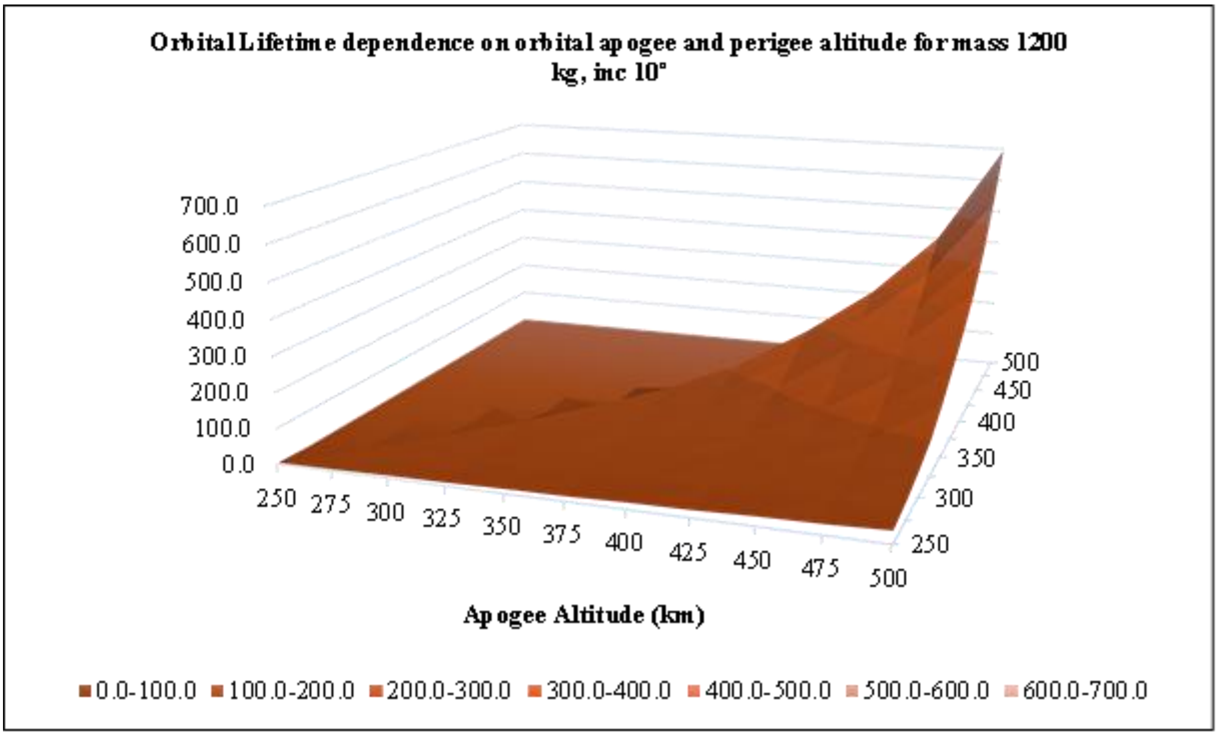


Figure-4 Orbital Lifetime dependence on orbital apogee and perigee altitude for mass 1200 kg & inclination 10°

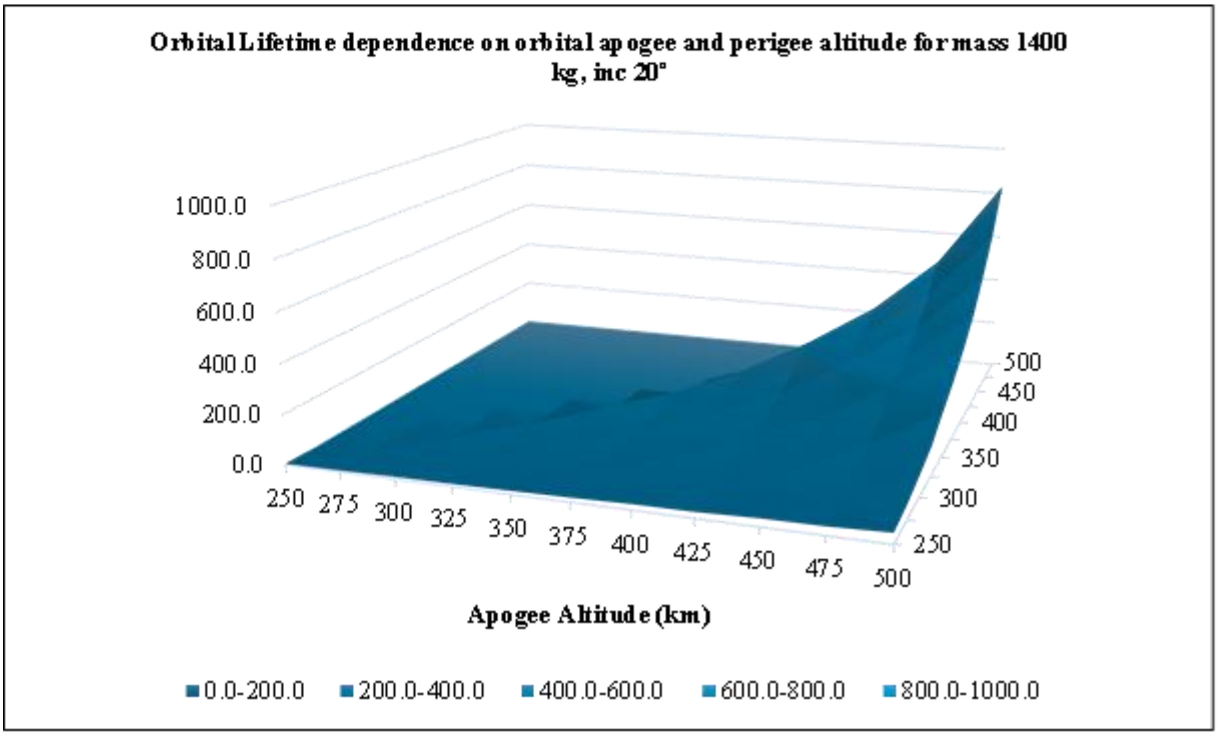
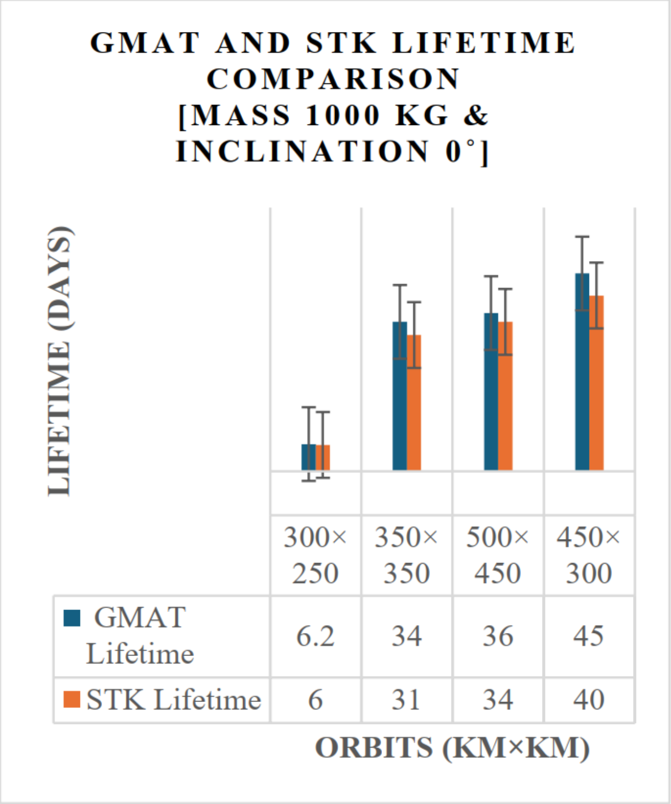


Figure-5 Orbital Lifetime dependence on orbital apogee and perigee altitude for mass 1400 kg & inclination 20°

B. GMAT and STK Lifetime Comparison

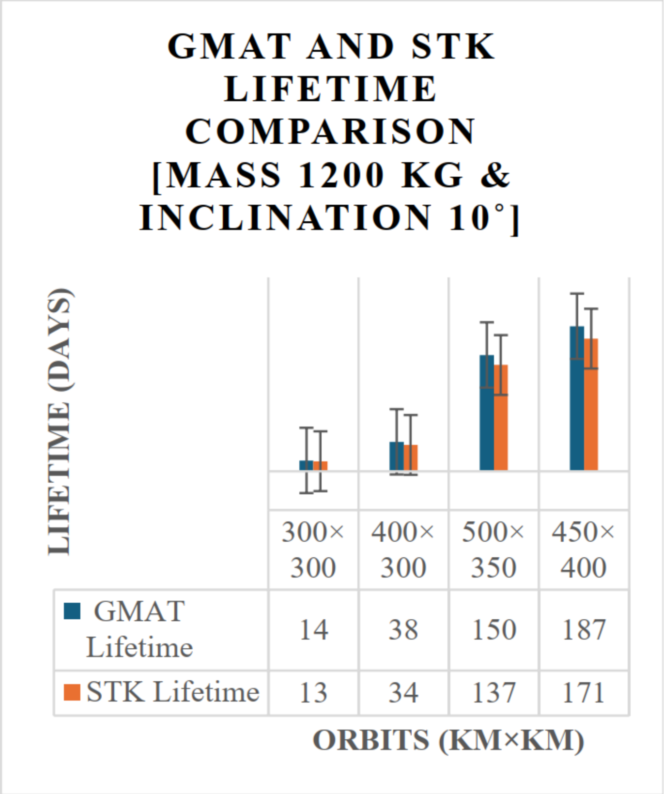
The GMAT-obtained lifetime values were validated against those from STK, a widely used software by renowned space agencies globally. For smaller orbits, the lifetimes obtained from both GMAT and STK demonstrated close alignment with negligible deviations. However, as the orbit size increased, a discernible disparity emerged between the lifetime results obtained from the two software tools.

This variance is likely due to differences in orbit propagation methods and optimization approaches. GMAT employs numerical integration, while STK uses a full orbit propagation method. Additionally, STK is optimized to produce higher-fidelity results compared to GMAT. The lifetime values obtained from both software were truncated to one decimal place. A total of 32 orbital lifetime values were compared, and a clustered column chart of 12 values is presented here. These clustered bar charts clearly represent the disparities in lifetime values calculated by GMAT and STK across different orbit sizes. These visual aids enhance the clarity of the study's findings and facilitate a comprehensive interpretation of the comparative analysis. Figures 6, 7, and 8 depict the comparative analysis of GMAT and STK lifetime values. The horizontal axes represent the different orbit sizes in increasing order of their orbital lifetime, while the vertical axes represent the orbital lifetime in days.



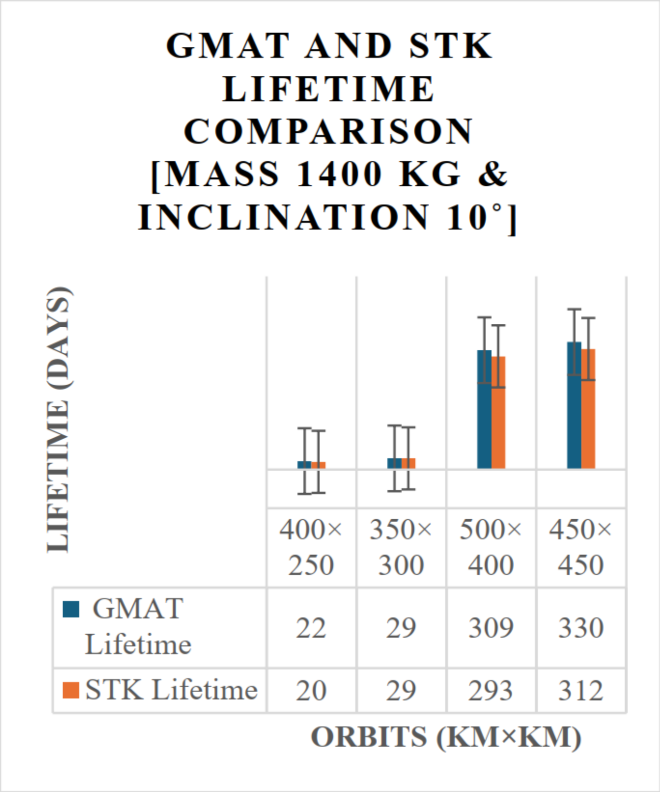
	300×250	350×350	500×450	450×300
■ GMAT Lifetime	6.2	34	36	45
■ STK Lifetime	6	31	34	40

Figure-6 GMAT and STK Lifetime Comparison for Mass 1000 kg and Inclination 0˚



	300×300	400×300	500×350	450×400
■ GMAT Lifetime	14	38	150	187
■ STK Lifetime	13	34	137	171

Figure-7 GMAT and STK Lifetime Comparison for mass 1200 kg and inclination 10˚

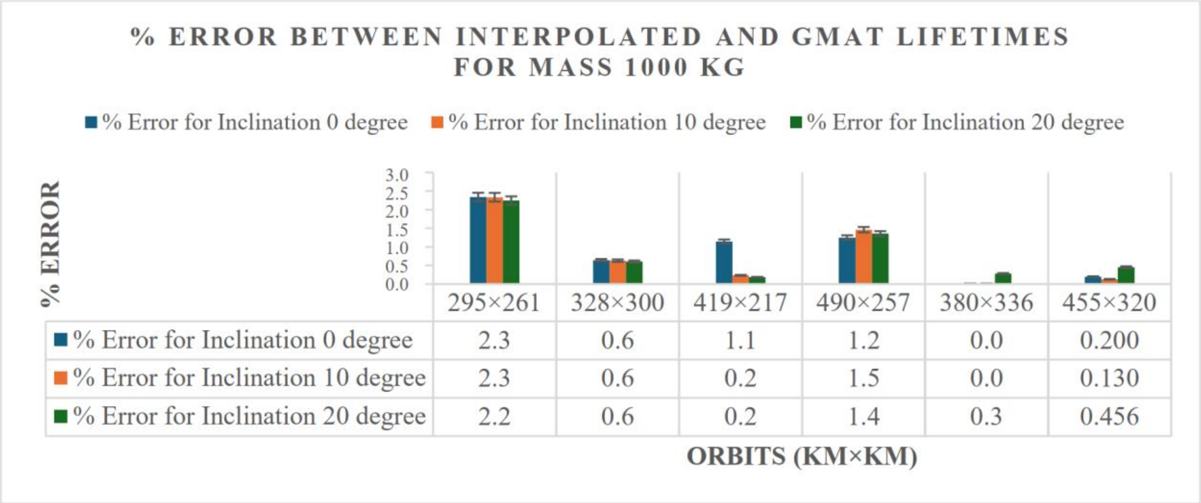


	400×250	350×300	500×400	450×450
■ GMAT Lifetime	22	29	309	330
■ STK Lifetime	20	29	293	312

Figure-8 GMAT and STK Lifetime Comparison for mass 1400 kg and inclination 10˚

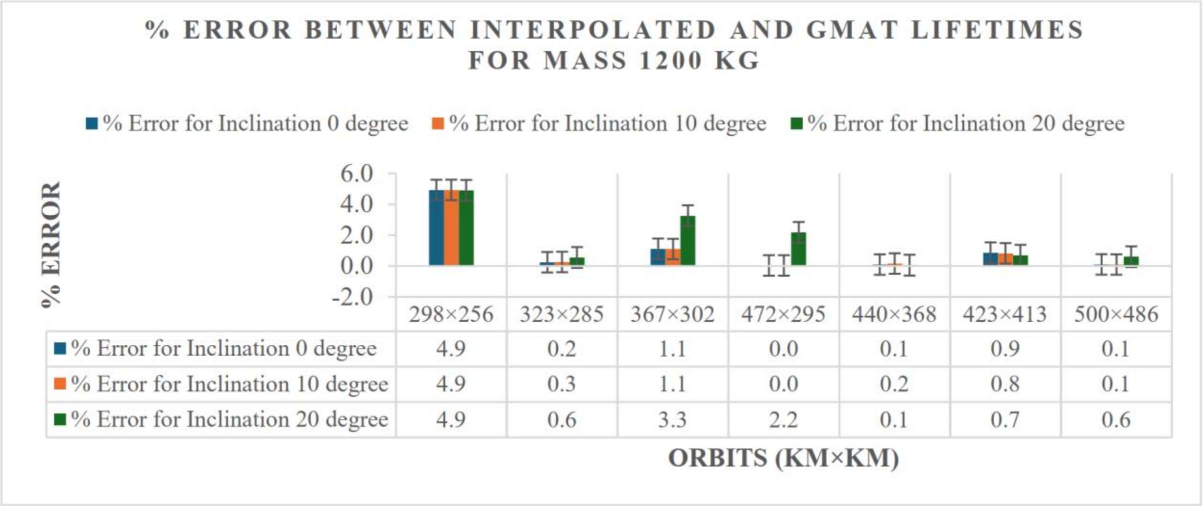
C. GMAT and Interpolated Lifetime Comparison

The lifetimes predicted by the interpolation code were compared with those obtained from GMAT, and the percentage error was calculated. The interpolation code successfully predicted orbital lifetimes with an error margin within 5%. This demonstrates the reliability of the interpolation model for lifetime prediction across various configurations. The comparison, including the percentage error of lifetime values obtained from the interpolation code and GMAT, was visualized for 18 randomly selected orbits. The percentage errors in orbital lifetimes were calculated using the GMAT-obtained values as the reference. Figures 9, 10, and 11 provide visual aids depicting the percentage errors. The horizontal axes represent the selected orbits, while the vertical axes indicate the percentage error. These visuals effectively highlight the accuracy and performance of the interpolation code.



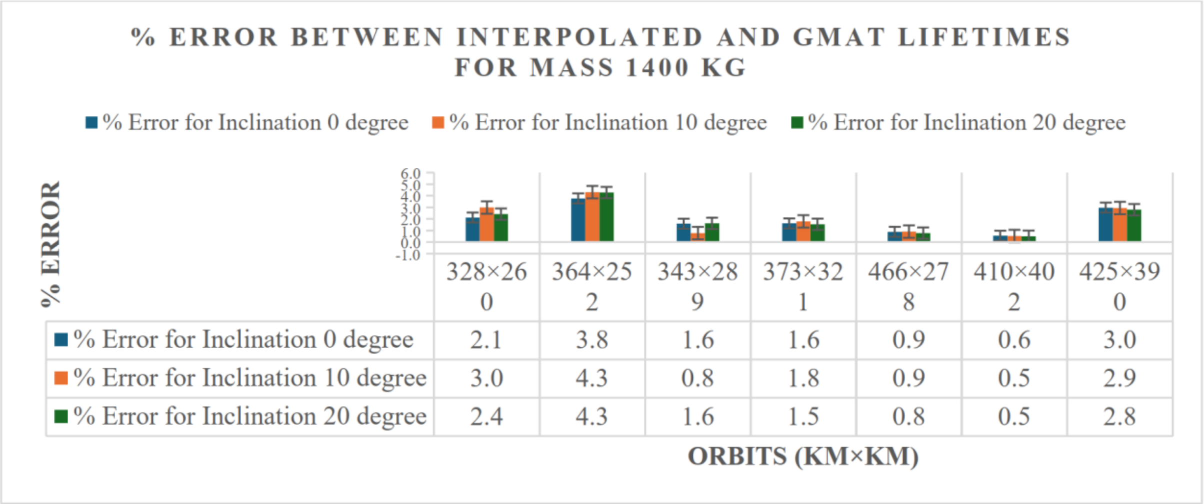
	295×261	328×300	419×217	490×257	380×336	455×320
■ % Error for Inclination 0 degree	2.3	0.6	1.1	1.2	0.0	0.200
■ % Error for Inclination 10 degree	2.3	0.6	0.2	1.5	0.0	0.130
■ % Error for Inclination 20 degree	2.2	0.6	0.2	1.4	0.3	0.456

Figure-9 % Error between Interpolated and GMAT lifetimes for mass 1000 kg



	298×256	323×285	367×302	472×295	440×368	423×413	500×486
% Error for Inclination 0 degree	4.9	0.2	1.1	0.0	0.1	0.9	0.1
% Error for Inclination 10 degree	4.9	0.3	1.1	0.0	0.2	0.8	0.1
% Error for Inclination 20 degree	4.9	0.6	3.3	2.2	0.1	0.7	0.6

Figure-10 % Error between Interpolated and GMAT lifetimes for mass 1200 kg



	328×260	364×252	343×289	373×321	466×278	410×402	425×390
% Error for Inclination 0 degree	2.1	3.8	1.6	1.6	0.9	0.6	3.0
% Error for Inclination 10 degree	3.0	4.3	0.8	1.8	0.9	0.5	2.9
% Error for Inclination 20 degree	2.4	4.3	1.6	1.5	0.8	0.5	2.8

Figure-11% Error between Interpolated and GMAT lifetimes for mass 1400 kg

Following were the observations from the study:

- Inclination and Mass Impact: The study demonstrated that orbital lifetime increases with higher orbital inclinations. Additionally, the mass of the rocket body significantly influences orbital decay; heavier rocket bodies experience slower decay, leading to extended orbital lifetimes.
- STK and GMAT Disparities: The observed differences in lifetime values between STK and GMAT can be attributed to the type of orbit propagator employed by each software. Furthermore, STK's optimization for higher fidelity results contributes to the variance.
- Interpolation Accuracy: The interpolation code reliably predicted orbital lifetime values, achieving an error margin of less than 5%.

5. Conclusion

This study established a reliable method for estimating the orbital lifetime of rocket bodies in eccentric, low-inclination low Earth orbits (LEO). By leveraging the General Mission Analysis Tool (GMAT) and a Python-based 2D interpolation model, it successfully predicted lifetimes across various altitudes, masses, and inclinations with an error margin under 5%. The findings indicated that orbital lifetime increases with altitude, mass, and inclination due to reduced atmospheric drag-induced decay. This methodology aligns with the Inter-Agency Space Debris Coordination Committee’s (IADC) 25-year deorbit guideline and offers a practical tool for mission planning and post-mission disposal of rocket bodies.

The interpolation model developed in this study enables efficient lifetime predictions for custom altitude configurations without requiring full simulation runs, making it valuable for preliminary assessments. However, its applicability is currently constrained to the studied range of parameters (250–500 km altitude). Future studies could expand the model to cover broader altitude ranges and incorporate advanced atmospheric density models that account for real-time solar and geomagnetic fluctuations. Additionally, integrating solar flux data and examining the effects of higher eccentricity orbits could enhance the model's accuracy and versatility across diverse mission scenarios. Overall, the methodologies and results of this study contribute to ongoing efforts in space debris mitigation, promoting safer and more sustainable use of LEO. By refining lifetime prediction techniques and adhering to international guidelines, future research can further optimize orbital decay estimates and advance responsible post-mission strategies for rocket bodies and other space objects.

6. References

[1] Anz-Meador, P., & Carman, C. (2023). History of on-orbit satellite fragmentations (NASA Technical Paper No. TP-20220019160). NASA.

[2] Billik, B. (1962). Survey of current literature on satellite lifetimes. ARS Journal, 32(11), 1641–1650. **https://doi.org/10.2514/8.6304.**

[3] Celestrak. (n.d.). Space data for the last 5 years. Retrieved 2024, from **https://celestrak.org/SpaceData/SW-Last5Years.txt**

[4] De Lafontaine, J., & Garg, S. C. (1982). A review of satellite lifetime and orbit decay prediction. Proceedings of the Indian Academy of Sciences - Section C: Engineering Sciences, 5, 197–258. **https://doi.org/10.1007/BF02839302.**

[5] Dolado-Perez, J., & Pardini, C. (2014). OPERA: A tool for lifetime prediction based on orbit determination from TLE data. Proceedings of the 24th International Symposium on Space Flight Dynamics.

[6] Inter-Agency Space Debris Coordination Committee (IADC). (2021, June 10). IADC Space Debris Mitigation Guidelines. Retrieved from **https://www.iadc-online.org**

[7] Liou, J.-C., & Johnson, N. L. (2006). Risks in space from orbiting debris. Science, 311(5759), 340–341. **https://doi.org/10.1126/science.1121337.**

[8] Mukherjee, B., & Bhatia, A. (2021). Post mission disposal of Cartosat-2: Compliance with IADC guidelines. 8th European Conference on Space Debris, 135.

[9] Park, S.-H., & Hwang, D.-S. (2018). Orbit, orbital lifetime, and reentry survivability estimation for orbiting objects. Advances in Space Research, 62(11), 3012–3032. **https://doi.org/10.1016/j.asr.2018.08.010.**

[10] Petersen, N. (1956). Lifetimes of satellites in near-circular and elliptic orbits. Journal of Jet Propulsion, 26(5), 341–351. **https://doi.org/10.2514/8.7003.**

[11] Woodburn, J., & Coppola, V. (2005). A numerical study of orbit lifetime. Proceedings of the AAS/AIAA Astrodynamics Specialists Conference, 2005–297.

7. Conflict of Interest

The author declares no competing conflict of interest.

8. Funding

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