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Analysis and Design of an Operational Orbit for PdQSat

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Abstract

This work presents the orbital design of the CubeSat PdQSat, whose mission aims to validate the technological performance of a commercial Li-S battery and an academic-developed supercapacitor in-flight. In this context, a suitable orbit selection is essential for mission success. Thus, possible operational orbits are proposed and analyzed based on the need to meet established requirements, considering orbital decay time, data transmission capacity between mission segments, and CubeSat power budget, validated by energy generation capability via solar panels. This analysis is performed using the commercial software Systems Tool Kit® (STK), allowing the generation of data and visualizations for different scenarios to assess the impact of orbital altitude and inclination on the evaluated parameters.

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1 Introduction

The CubeSat PdQSat project was initiated in 2020 by the Aerospace Engineering program at the Federal University of Minas Gerais (UFMG) [1]. Entirely developed at UFMG, the mission aims to test two components in-flight: a commercial Lithium-Sulfur (Li-S) battery and a supercapacitor designed by UFMG's Department of Chemistry.

The Li-S battery, provided by a regional company, shows potential for aerospace use due to its high energy density and low weight. This collaboration with Minas Gerais could foster high-tech industry growth in the region, provided that local industries have shown interests in such battery. Additionally, testing an UFMG's supercapacitor in space, initially intended only for battery validation, adds scientific visibility to the project.

Given the mission's objectives, selecting an operational orbit for PdQSat is crucial to ensure adequate conditions for mission success [2]. Orbital parameters impact mission duration, power generation, and communication windows with ground stations [3]. Thus, the CubeSat's orbital design involves constraints that must be carefully assessed for their impact on mission success.

The primary objective of the present paper is to design the orbit of the CubeSat PdQSat by comparing different orbital configurations, focusing on orbital decay time, data transmission capacity, and power budget. Specific goals include identifying applicable orbits based on mission requirements, validating orbital propagation models, radiofrequency communication, and power generation via solar cells, and establishing references for using the STK software in future academic aerospace projects.

2 Methodology

The orbital design and analysis for the CubeSat PdQSat mission is conducted using STK, a platform for analyzing complex systems in aerospace, defense, and telecommunications [4]. STK was selected due to its robust orbital propagators and its capabilities in simulating onboard communication and power generation systems. This section outlines the requirements and assumptions used in PdQSat's orbital analysis and describes the procedure for scenario creation and result validation.

2.1 Mission Analysis Methodology

1. **Define Mission Requirements**:
   - *Ground Segment*: A single ground station was established at UFMG's School of Engineering.
   - *Mission Duration*: The mission duration was set to a minimum of six months.
   - *Data Transmission*: A daily data transmission of at least 1 Mb with an acceptable bit error rate was required.
   - *Energy Supply*: The energy supply relied solely on solar panels.
2. **Orbit Selection**:
   - *Orbit Type*: The study focused on Low Earth Orbit (LEO) for efficiency and feasibility.
   - *Orbit Characteristics*: Circular orbits with altitudes ranging from 400 km to 700 km and inclinations from 0° to 90° were examined.
   - *RAAN*: Right ascension of the ascending (RAAN) node was excluded in initial analyses.
3. **Simulation Setup in STK**:
   - *Ground Segment Visibility*: An unobstructed view from the ground station to the CubeSat was assumed, with a conservative minimum elevation angle to account for atmospheric and topographical obstructions.
   - *CubeSat Assumptions*: The CubeSat was modeled with no propulsion, focusing on natural orbital decay.
4. **Orbital Decay Analysis**:
   - *CubeSat Parameters*: The CubeSat was modeled as a 3U size with a 4 kg mass and a drag coefficient of 2.2.

- *Atmospheric Model*: The MSISE 1990 atmospheric model was employed for accurate drag and density simulations.
- *Reentry Condition*: Orbital decay was defined as reaching an altitude of 180 km, signaling reentry into Earth's atmosphere.

5. **Communication System Modeling**:
   - *Hardware Configuration*: Downlink and potential uplink were modeled using an ISIS UHF/VHF transceiver and antenna.
   - *Frequency and Modulation*: Downlink frequency was set at 437 MHz and uplink at 146 MHz, with BPSK and FSK modulations.
   - *Data Rate*: The bitrate was set to 9600 bps.
   - *Elevation Angle for Communication*: A minimum elevation angle of 20° was used to mitigate atmospheric absorption losses during communication.

6. **Power Generation Modeling**:
   - *Solar Panel Modeling*: A 3D solar panel model was imported from SolidWorks into STK for realistic power calculations.
   - *Orientation Configuration*: The solar panel orientation was aligned with the CubeSat's tangential orbital velocity to maximize power generation throughout the orbit.

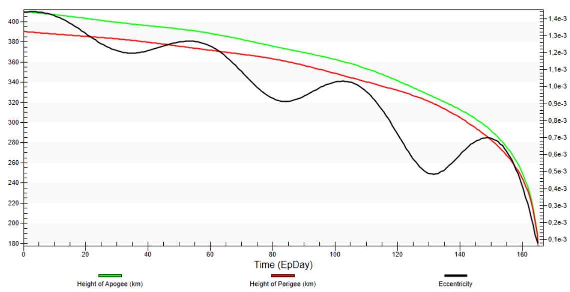
3 Results and Analysis

3.1 Orbital Decay Analysis

The decay analysis of the CubeSat PdQSat was conducted using J4 and HPOP propagators until reaching an altitude of 180 km. As expected, simulations using HPOP model showed a shorter duration until decay compared to J4, for it takes into account the atmospheric drag. Results indicate that at altitudes of 500 km or higher, the orbital decay time exceeds one year. Considering that the minimum duration of the mission is six months, all orbits above 400 km are suitable. For 400 km orbits, decay times were 160 days for 0° inclination (worst case) and 201 days for 70° (best case). All inclinations starting from 40° (185 days) fulfill the minimum mission duration requirement.

The analysis showed that increasing orbital inclination extended the CubeSat's lifetime due to gravitational gradients inducing slight eccentricity, which prolongs orbit duration. Such effect is shown in Figure 1. Solar radiation pressure was negligible, consistent with findings from other nanosatellite studies [5].

Figure 1: Orbital decay for a = 400 km and i = 50° via HPOP

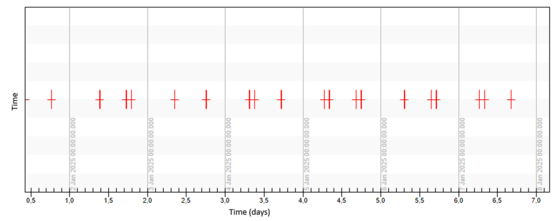


3.2 Communication Analysis

3.2.1 Data Budget Summary

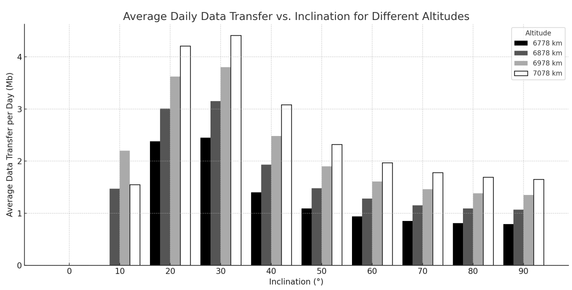
Simulated orbital configurations over 180 days reveal all communication windows between Ground and Flight Segments, with average duration per window illustrated in Figure 2.

Figure 2: Example of communication intervals between segments. a = 400 km, i = 50°



Initially, a 20° minimum elevation angle limited the daily data transfer to below the 1 Mb requirement. Adjusting to a 10° elevation angle allowed for increased access time and average data transfer rates, as seen in Figure 3. Based on these new parameters, a minimum daily transfer rate of 1 Mb is achievable in orbits above 500 km with non-equatorial inclinations.

Figure 3: Average Daily Data Transfer vs. Inclination for Different Altitudes



3.2.2 Link Budget Summary

The link budget analysis was conducted across a range of conditions, from optimal (400 km altitude with 90° elevation) to worst-case scenarios (700 km altitude with 10° elevation). Constants and variable parameter ranges for downlink are detailed below.

- Constant Parameters:
  - Frequency: 0.437 GHz
  - Transmitted Power: 0.5 W, or -3.01 dBW
  - Transmission Gain: 0 dBi
  - Polarization Loss (L_p): 3 dB
  - Implementation Loss (L_i): 3.5 dB
  - Reception Gain: 15.5 dB
  - System Temperature (T_s): 700 K
  - Bit Rate: 9600 bps
  - Figure of Merit: -12.95 dBK
  - Operational Margin: 3 dB
- Variable Parameters (best case/ worst case):
  - Elevation Angle (El): 90° (400 km) to 10°(700 km)
  - Distance Between Segments: 400 km to 2155.2 km
  - Path Loss (L_s): 137.30 dB to 151.93 dB
  - Atmospheric Loss (L_a): 0 dB to 1.1 dB
  - Received Power: -127.81 dBW (1.65E-13 W) to -143.53 dBW (4.42E-15 W)

- E_b/N_0 (Energy per Bit to Noise Power Density): 29.01 dB to 13.28 dB
- Operational E_b/N_0: 26.01 dB to 10.28 dB

Constants and variable parameter ranges for uplink are:

- Constant Parameters:
  - Frequency: 0.146 GHz
  - Transmitted Power: 10 W, or 10 dBW
  - Transmission Gain: 15.5 dBi
  - Polarization Loss (L_p): 3.0 dB
  - Reception Gain: 0 dB
  - System Temperature (T_s): 700 K
  - Bit Rate: 9600 bps
  - Figure of Merit: -12.95 dBK
  - Operational Margin: 3 dB
- Variable Parameters (best case / worst case):
  - Elevation Angle (El): 90° (400 km) to 10° (700 km)
  - Distance Between Segments: 400 km to 2155.2 km
  - Path Loss (L_s): 127.77 dB to 141.41 dB
  - Atmospheric Loss (L_a): 0 dB to 1.1 dB
  - Received Power: -120.78 dBW (8.36E-13 W) to -136.51 dBW (2.24E-14 W)
  - E_b/N_0 (Energy per Bit to Noise Power Density): 55.05 dB to 39.32 dB
  - Operational E_b/N_0: 52.05 dB to 36.32 dB

In both scenarios, the link budget calculations confirm that the system meets the bit error rate (BER) requirement of 10^{-6} for BPSK modulation, even under the worst-case conditions. The difference in E_b/N_0 between the best and worst cases primarily results from variations in distance and transmission power, with downlink performance slightly impacted by the lower transmitted power. Key differences between downlink and uplink scenarios arise from transmission power and receiver noise temperature, with the lower transmission power in downlink resulting in a slightly reduced E_b/N_0.

3.3 Power Budget Analysis

In the power budget analysis, we assess the energy generation and consumption requirements for CubeSat operation, with a particular focus on eclipse periods, which are more pronounced in lower orbits, such as the 400 km altitude considered in this study. Extended eclipse periods challenge battery discharge limits, making this analysis critical.

To identify the worst-case operational scenario, power generated by the CubeSat's solar panels at altitudes of 400 km and 700 km was examined. The power profiles over these orbits, shown in Figures 4 and 5, confirm that the variation in generated power across altitudes is relatively minimal. Therefore, focusing on the 400 km orbit (where eclipse duration is longest) provides a conservative basis for validating the mission's power budget.

Figure 4: Generated power - 400km altitude

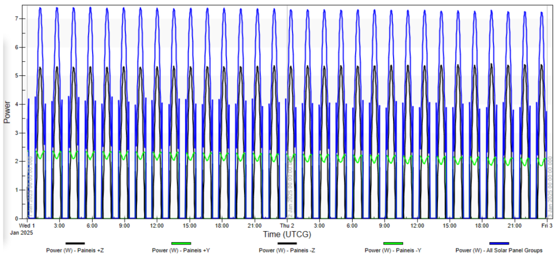
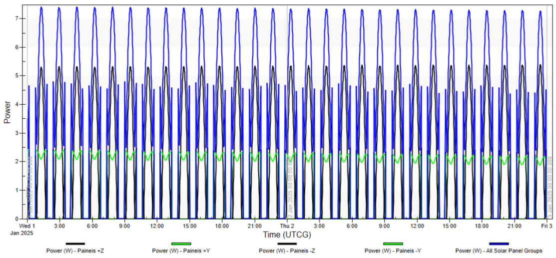
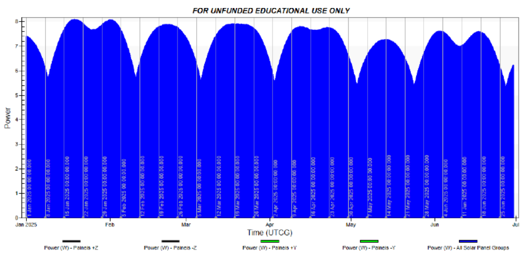


Figure 5: Generated power - 700km altitude



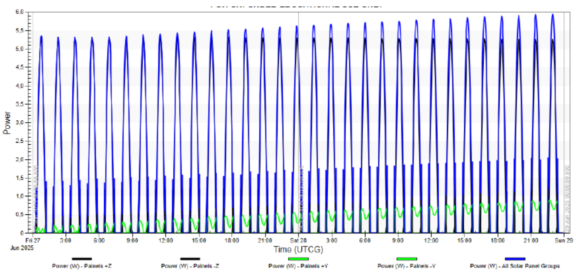
Simulated power profiles for the 400 km orbit, as shown in Figure 6, reveal typical variations in maximum and minimum power generation over six months.

Figure 6: Generated power - 400km altitude, i = 45° - 6 months



The orbit with a 45° inclination consistently exhibited the lowest power generation due to extended eclipse periods, marking it as the critical case. In this period, illustrated in Figure 7, the minimum energy generated per orbit was 3.58 Wh.

Figure 7: Generated power - 400km altitude, i = 45° - 6 months (critical case)



This minimum generated energy is compared to the estimated average energy consumption per orbit, which totals 3.45 Wh (2.52 Wh during illuminated phases and 0.93 Wh during eclipses). This comparison supports the adequacy of the mission's power budget for all considered orbits. Finally, based on a 30% Depth of Discharge (DoD) requirement, the minimum battery capacity needed is 5.12 Wh, which aligns with commercial off-the-shelf (COTS) battery options available for CubeSat missions.

3.4 Suitable Orbits

Based on the scenarios discussed, a family of suitable orbits has been identified for this stage of the project. The next steps will involve analyzing the effects of other engineering decisions, such as attitude control, and conducting further studies on power generation once more detailed hardware information becomes available.

The combined results are shown in Table 1, where "U" indicates unsuitable orbits, and "P" indicates promising orbits.

Table 1: Orbit Suitability Assessment

Incl (i) [°]	***Radius*** **(a) [km]**			
	6778	6878	6978	7078
0	U	U	U	U
10	U	P	P	P
20	U	P	P	P
30	U	P	P	P
40	P	P	P	P
50	P	P	P	P
60	U	P	P	P
70	U	P	P	P
80	U	P	P	P
90	U	P	P	P

4 Discussion

4.1 Orbital Decay Analysis

The orbital decay study demonstrated that orbits above 400 km support the mission's minimum six-month duration, with decay times extending beyond a year for altitudes above 500 km. For orbits at 400 km, the mission meets the duration requirement starting from inclinations of 40° . This analysis highlights how increasing orbital inclination positively impacts lifespan due to gravitational effects, allowing for longer mission durations at higher inclinations.

4.2 Communication Analysis

The data budget assessment revealed that setting the minimum elevation angle to 10° enabled sufficient daily data transfer (1 Mb or more) for orbits above 500 km. This adjustment increased the communication windows, essential for meeting data requirements. The link budget analysis confirmed that all configurations satisfy the bit error rate (BER) requirement for BPSK modulation, even under the most challenging conditions (700 km with 10° elevation). Variations in E_b/N_0 between downlink and uplink scenarios were attributed to differences in transmission power and path loss, with downlink performance slightly lower due to reduced transmission power.

4.3 Power Budget Analysis

The power budget analysis indicated that eclipse durations are longest in the 400 km orbit, posing the greatest challenge for battery discharge limits. Simulations at both 400 km and 700 km showed consistent power profiles, supporting the focus on the 400 km orbit for conservative analysis. The power generation profile over six months revealed that the 45° inclination experienced the lowest power generation due to longer eclipse periods. However, the minimum energy generation per orbit (3.58 Wh) was still above the average consumption (3.45 Wh), validating the power budget adequacy. With a 30% Depth of Discharge (DoD), the required minimum battery capacity of 5.12 Wh is achievable with COTS solutions.

4.4 Suitable Orbits

Based on these analyses, a family of suitable orbits has been identified, balancing longevity, data capacity, and power requirements. Future work will involve refining the selection based on other engineering constraints, such as attitude control, and more specific power generation studies as hardware details are finalized.

5 Conclusion

The main outcomes of this study confirm the feasibility of the PdQSat mission in terms of mission duration, communication capacity, and energy viability for various orbits between 400 and 700 km with different inclinations. This provides a degree of flexibility in choosing the launch vehicle. Additionally, the development of validation procedures for mission aspects such as orbital decay, data and link budgets, and solar panel power generation represents a significant contribution, offering a framework for verifying the mission design once components and operational conditions are finalized.

Future work based on this study includes re-evaluating mission parameters once the PdQSat design details are finalized. There is also an opportunity to use the communication analysis results to guide the ground segment antenna design, which could enhance students' learning experience and reduce mission costs. Lastly, further investigation into the impact of attitude control on drag area, effective communication, and power generation is suggested, as these factors could influence panel arrangement, effective area, and efficiency.

References

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