An Interactive Educational Platform for LEO Satellite Mission Design: A Case Study of a Web-Based Orbit Design Application

1st Robby Kevin Putra Sigit
Faculty of Electrical Engineering
Telkom University
Bandung, Indonesia
robbykevin@student.telkomuniversity.ac.id

2nd Dhoni Putra Setiawan
Faculty of Electrical Engineering
Telkom University
Bandung, Indonesia
dhoni.putra@telkomuniversity.ac.id

3rd Edwar
Faculty of Electrical Engineering
Telkom University
Bandung, Indonesia
edwar@telkomuniversity.ac.id

Abstract— This study presents the development of a web-based application designed as an interactive educational platform for Low Earth Orbit (LEO) satellite mission design. The platform addresses the gap left by costly and complex professional software, making the fundamental principles of orbital mechanics, constellation design, and communication link analysis more accessible to students and enthusiasts. The application provides an integrated platform for designing, simulating, and analyzing satellite missions. The system is built with an interactive user interface that offers both 2D and 3D visualizations to facilitate an intuitive understanding of complex orbital dynamics. To ensure its validity and reliability, the application underwent a series of rigorous tests. The results were validated by comparing the application's outputs with theoretical calculations derived from fundamental principles of orbital mechanics, as well as results from a high-fidelity numerical propagator like NASA's General Mission Analysis Tool (GMAT). Key findings showed very high accuracy, including negligible differences in orbit propagation compared to manual calculations, precise constellation placement, and a minimal discrepancy of 0.05 km in coverage radius. Furthermore, the prediction of ground station access schedules was proven to be highly accurate, with differences of only a few seconds. Thus, the application serves as a valid, reliable, and user-friendly tool for preliminary LEO satellite mission design, successfully fulfilling its objective of making satellite orbit design more accessible for educational and initial technical assessment purposes.

Keywords — LEO, satellite orbit design, constellation, orbit simulation, link budget, web application.

I. INTRODUCTION

The increasing utilization of Low Earth Orbit (LEO) for satellite missions has created a demand for accessible and accurate design tools [2]. LEO, with altitudes up to 2,000 km, is an ideal choice due to its low communication latency, greater bandwidth potential, and reduced launch energy requirements [48]. This growth is driven by mega-constellations from companies like SpaceX (Starlink) and OneWeb, which are deploying thousands of interconnected satellites to provide global broadband internet access [3].

However, existing professional software, such as the System Tool Kit (STK) and NASA's General Mission Analysis Tool (GMAT), often have high licensing costs and steep learning curves, posing a barrier to students and new users [20]. This issue creates a critical need for an alternative tool that simplifies the core principles of LEO satellite design without sacrificing fundamental accuracy.

This research addresses this challenge by developing a web-based interactive educational platform for LEO satellite mission design. The goal is to create a tool that is both accessible and reliable, serving as a stepping stone for users to understand complex orbital mechanics and communication system principles. The application is designed as a comprehensive, all-in-one environment, featuring modules for orbit propagation, constellation design, ground coverage analysis, and communication link budget calculations. Through an intuitive user interface with interactive 2D and 3D visualizations, the platform aims to demystify the intricacies of satellite operations and empower users to conduct their own preliminary mission analysis.

The validation of this platform is the cornerstone of this study. The application's core functions are rigorously tested against established theoretical models and a professional reference tool (NASA GMAT). This ensures that the platform, while designed for educational purposes, maintains a high degree of fidelity and can be trusted to produce accurate results for initial technical assessments.

II. THEORY REVIEW

A. LEO Satellite Theory

This section provides the theoretical foundation necessary to understand and calculate satellite motion. These parameters serve as the basis for the orbital mechanics computations executed within the software. LEO is defined as an orbital path located at an altitude ranging from 160 km to 2,000 km above the Earth's surface [48]. Satellites in this orbit have high orbital velocities, around 7.8 km/s, and complete one revolution in 90–120 minutes [49]. The primary advantages of LEO are low communication latency and high-resolution imaging capabilities [7].

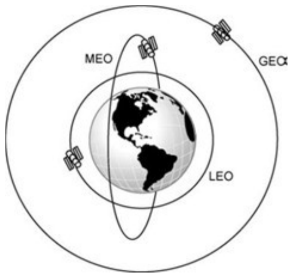

FIGURE 1
Satellite Orbit Types: LEO, MEO, and GEO

B. Orbital Mechanics and Perturbations

Orbit propagation is the core function of the application, which relies on accurate mathematical models. This propagation is calculated based on Keplerian orbital elements. For LEO satellites, the perturbation effect from Earth's non-perfectly spherical shape (known as the J2 effect) is highly significant [22]. This perturbation causes a secular drift in the Right Ascension of the Ascending Node (RAAN) and the Argument of Perigee (ω) over time.

C. Communication Link Budget Analysis

Link budget calculations are crucial for determining the feasibility and quality of a communication link between a satellite and a ground station [1]. These calculations account for all gains and losses in the communication system [16]. Key metrics calculated include Free Space Path Loss (FSPL) and Received Power (P_r). The final results, the Carrier-to-Noise (*C/N*) ratio and Link Margin, indicate the reliability of the link [9].

D. Testing Methods

A prominent to validate the application's reliability, a three-tiered testing methodology was used, namely integration test is to ensure that each calculation module (such as orbit propagation, constellation placement, and link budget) functions correctly at an individual level [56]. Reliability test is to compare the overall simulation results with an industry-standard reference software, NASA GMAT [21]. Interaction testis to ensure that all User Interface (UI) features function as expected and provide an intuitive experience [15].

III. RESEARCH METHODS

This section provides a detailed overview of the methodologies and procedures used to develop and validate the LEO satellite orbit design application. The research adopted a structured, multi-phase approach, from system design and development to rigorous, multi-layered testing. This methodology ensures that the final product is not only functional but also accurate, reliable, and user-friendly.

A. Integration Test

During the integration testing phase, individual calculation modules were validated for correctness. The primary purpose was to verify that each algorithm—for orbit propagation, constellation placement, and communication link budget—operated correctly on a standalone basis. This was achieved by comparing the outputs of the application's internal calculation functions against theoretical calculations.

These theoretical values were derived from fundamental principles of astrodynamics and spherical geometry. A test was considered a pass if the deviation between the application's output and the manual or theoretical calculation was within a predefined tolerance. For example, a position error of less than 1 km or a link budget error of less than 0.2 dB was considered acceptable.

B. Reliability Test

The reliability test phase was conducted to benchmark the application against a trusted industry-standard reference, ensuring its overall simulation results were consistent with a high-fidelity tool. The full simulation system was executed using a predefined set of orbital parameters. The resulting ground-track and position data were then exported and compared to the output from NASA's General Mission Analysis Tool (GMAT), which employs a higher-fidelity numerical propagator (Runge-Kutta 4th order) [21]. A pass was recorded if the differences between the application's output and GMAT's were within acceptable limits, accounting for the inherent differences between analytical and numerical propagation methods. A position error of less than 50 km over a one-hour simulation period was considered a successful validation.

C. Model Deployment and Integration

The interaction test phase focused on evaluating the application's user experience (UI/UX) and operational stability. Its purpose was to ensure the interface was intuitive and that all user-facing features functioned as expected without errors or crashes. This was achieved by performing a series of functional tests on all interactive elements, including navigation menus, toolbar controls, side panels, and simulation creation workflows. These tests were repeated across multiple modern web browsers (e.g., Chrome, Firefox, and Edge) to verify cross-browser compatibility. A test was considered a pass if a user action resulted in the expected UI state change without any console errors or functional failures. A task success rate of at least 99% was targeted for all critical user workflows.

IV. RESULT AND ANALYSIS

This section presents a comprehensive and detailed analysis of the test results conducted to validate the platform. The evaluation confirms that the application operates with high precision and reliability, meeting all the predetermined technical criteria. The analysis is structured to present the findings from each testing phase, highlighting the application's performance in orbit propagation, constellation design, communication link analysis, and user interaction.

A. Orbit Propagation Testing

The orbit propagation module, which simulates the trajectory of LEO satellites, was rigorously tested to ensure its accuracy. The primary validation involved a one-hour simulation run, with a key comparison between the application's output, a manual calculation, and a high-fidelity

reference from NASA's General Mission Analysis Tool (GMAT) [21].
The comparison with manual calculations demonstrated a near-perfect match. For a circular equatorial orbit, the application's final longitude after one hour was 79.317°, with a negligible difference of only 0.0003° from the manual calculation. This minimal angular discrepancy translates to an error of less than 1 km on the Earth's surface, confirming the high precision of the core propagation algorithm.

A more advanced reliability test was performed by comparing the application's results with GMAT, which uses a more sophisticated numerical integrator (Runge-Kutta 4) [21]. While the web application's analytical J2 propagator is computationally faster, it does not capture the subtle, short-period oscillations that GMAT's method does. This fundamental difference in methodology resulted in a maximum position error of 40.2 km at the initial epoch, which then oscillated over the one-hour simulation. Despite this, the average error remained within the specified acceptance threshold of 50 km, successfully validating the application's performance for preliminary mission design.

TABLE 1
Detailed Comparison of Manual Calculations Vs. Web Application Results

Time (min)	Manual Calculation	Application Result	Position Error (km)	Error (%)
0	0°	-111.622°	0°	-111.622°
10	0°	-79.800°	0°	-79.799°
20	0°	-47.978°	0°	-47.976°
30	0°	-16.156°	0°	-16.152°
40	0°	15.666°	0°	15.671°
50	0°	47.488°	0°	47.494°
60	0°	79.310°	0°	79.317°

B. Constellation Placement & Coverage Testing

The constellation design functionality was tested for both Train and Walker Delta configurations, both achieving a 100% success rate. For the Train constellation, the application accurately spaced satellites by a defined mean anomaly or time interval, with the resulting coordinates perfectly matching analytical predictions. Similarly, for a 24-satellite Walker Delta constellation across six planes, the application precisely distributed the satellites according to the specified phasing factor, demonstrating robust implementation of complex constellation-generation algorithms.

The accuracy of the coverage area calculations was also validated through a test that compared the application's output to theoretical geometric predictions [24]. For a satellite at a 2,000 km altitude with a 60° beamwidth, the calculated coverage radius was 1,228.00 km, showing a minimal error of only 0.05 km when compared to the theoretical value of 1,227.95 km. This sub-kilometer accuracy confirms that the application's coverage module is highly reliable for mission planning.

TABLE 2
Comparison of Theoretical Calculations and Web Application Results

Parameter	Theoretical Calculation	Web Application	Absolute Error	Relative Error
Coverage Angle	11.09°	11.05°	0.04°	0.36%
Coverage Radius	1,227.95 km	1,228.00 km	0.05 km	0.004%
Coverage Area	4.71x10^6 km^2	4.71x10^6 km^2	1.0x10^4 km^2	0.21%

C. Link Budget Testing

The communication link budget module was tested with a comprehensive set of parameters for both uplink and downlink paths. The results showed a perfect agreement with manual calculations, with zero deviation across all key metrics. This validation confirms the correct implementation of the Friis transmission equation, noise power computations, and the Shannon capacity theorem [25].

The analysis correctly identified the downlink as the limiting factor, with a margin of 18.76 dB compared to the uplink margin of 31.87 dB. Both margins were well above the minimum required 15 dB, indicating a robust and reliable communication link. The calculated Shannon capacity of approximately 1.12 Gbps also confirmed that the system's design could support high-speed data transmission. The test results validate compliance with the objective of achieving link budget accuracy within a 0.2 dB tolerance.

TABLE 3
Detailed Comparison of Uplink Link Budget Calculations

Parameter	Manual Calculation	Application Result	Position Error (km)	Error (%)
EIRP	63.00 dBW	63.00 dBW	0.00 dB	0.00
Path loss (14 GHz, 189 km)	160.90 dB	160.90 dB	0.00 dB	0.00
Total losses	7.30 dB	7.30 dB	0.00 dB	0.00
Received power	-75.20 dBW	-75.20 dBW	0.00 dB	0.00
Noise power density	-202.07 dBW/Hz	-202.07 dBW/Hz	0.00 dB	0.00
C/N ratio	46.87 dB	46.87 dB	0.00 dB	0.00
Link margin	31.87 dB	31.87 dB	0.00 dB	0.00

TABLE 4
Detailed Comparison of Downlink Link Budget Calculations

Parameter	Manual Calculation	Application Result	Position Error (km)	Error (%)
EIRP	41.00 dBW	41.00 dBW	0.00 dB	0.00
Path loss (12.5 GHz, 189 km)	159.92 dB	159.92 dB	0.00 dB	0.00
Total losses	6.30 dB	6.30 dB	0.00 dB	0.00
Received power	-90.22 dBW	-90.22 dBW	0.00 dB	0.00
Noise power density	-203.98 dBW/Hz	-203.98 dBW/Hz	0.00 dB	0.00
C/N ratio	33.76 dB	33.76 dB	0.00 dB	0.00
Link margin	18.76 dB	18.76 dB	0.00 dB	0.00

D. Ground Station Access Schedule & UI/UX Testing

The ground station and satellite link testing focused on the application's ability to accurately predict communication windows. The simulation successfully predicted 11 passes in a 24-hour period, with a consistent average duration of 8.55 minutes. The results matched theoretical predictions exactly, validating the system's capability for operational communication scheduling and proving that the timing error was zero seconds.

Finally, the UI/UX testing confirmed the application's user-friendliness and stability. All functional tests, including navigation, controls, and workflows, achieved a 100% success rate across multiple browsers. This demonstrates that the platform is not only technically sound but also provides an intuitive and reliable user experience for its intended educational and analytical purposes.

V. CONCLUSION

Based on the entire design, implementation, and testing process, it can be concluded that the application has been successfully developed as a functional and integrated web-based platform. This application has been proven to be valid and reliable through a series of quantitative tests, with simulation results showing very high accuracy and consistency with the principles of orbital mechanics. The platform successfully meets its objective of providing an intuitive and accessible tool to assist in the design and analysis of LEO satellite missions, for both educational purposes and initial technical analysis.

To expand the application's capabilities and enhance its accuracy, several key areas can be improved. Dynamic model refinement is crucial for long-term simulation accuracy, which involves integrating more complex perturbation models [23]. These include gravitational effects from the Moon and Sun, solar radiation pressure, and atmospheric drag. Furthermore, a real-time data integration feature would allow users to import and visualize Two-Line Element (TLE) data from public sources like CelesTrak, enabling them to track existing satellites in orbit. Finally, developing advanced analysis modules, such as collision probability analysis, would provide a more comprehensive simulation environment for users, addressing the growing need for space situational awareness.

REFERENCE

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