Digital Twin Development for Space Propulsion: Modeling Optimal Earth Escape Trajectories for the WREN Spacecraft

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Background

Currently, sustained human exploration is limited by traditional chemical propulsion (CP) and nuclear thermal propulsion (NTP) methods. The methods have multiple limitations, while new solutions provide better alternatives.

- A normal trajectory will take 6-7 months for one-way interplanetary transfer.
- A lengthy flight duration will leave crew members exposed to Galactic Cosmic Radiation (GCR). Current methods of transportation surpass NASA's risk threshold of 3%.
- A solution using high-powered Nuclear Electric Propulsion (NEP) creates a higher specific impulse (Isp) that leads to easier and more flexible missions.
- The Wave Rotor Enhanced Nuclear (WREN) spacecraft is a concept created by NASA Innovative Advanced Concepts (NIAC) program. The WREN spacecraft uses NEP to increase power and efficiency.
- NASA Glenn Research Center has done extensive research on transits, risks, and materials. However, time constraints prevented NASA Glenn from completing a quantification of the WREN spacecraft's departure from Low Earth Orbit (LEO).

Introduction

The objective of this research project is to find the optimal Earth-escape trajectory for the WREN spacecraft. More specifically, "How can we quantify the departure performance of the WREN spacecraft from Earth and understand the optimal steering history for the WREN spacecraft to escape LEO?"

- The main challenge is that low-thrust methods will require multiple revolution spirals around Earth. These spirals are sensitive and possess narrow radii of convergence, which causes errors in other mathematical models.
- The objective is to develop a Digital Twin trajectory solver using a 2-dimensional spherical coordinate system based on ordinary differential equations (ODEs).
- 4th-order Runge-Kutta numerical integration and two-step continuation methods to find the energy required for the WREN spacecraft to escape the Earth's atmosphere.
- A successful model should reduce the transit time from Mars from 120 days to 45 days, improving the safety of the crew by a drastic margin.

Methods

STEM & Technical Methods

- System State Dynamics – Ordinary Differential equations are used to track radial distance, radial velocity, angular position, mass loss, & tangential velocity.
- Numerical Integration – 4th-order Runge-Kutta schemes are used to solve equations & prepare for the temporal evolution of the functions.
- Costate Estimator – Polynomial interpolation is used to estimate the mathematical markers used to find the optimal path of the spacecraft, also known as costate values.
- Computer Programming – C++ & Mojo programming languages were used. VS Code is an open-source code editor used as an Integrated Development Environment. A Looking Glass Go will be used as the digital twin model. NVIDIA Omniverse will be used to edit the digital twin model.

Data Analysis & Management & Research Communication

- Data from the WREN Spacecraft is applied in the solver to determine & generate different thrust commands and steering histories.
- Multiple research papers and studies on the following (but not limited to) topics were reviewed & used for inspiration: Optimal Earth Escape Trajectory [3], Generalized Logarithmic Spirals [5], High-Power Electric Propulsion [1].

Literature Review

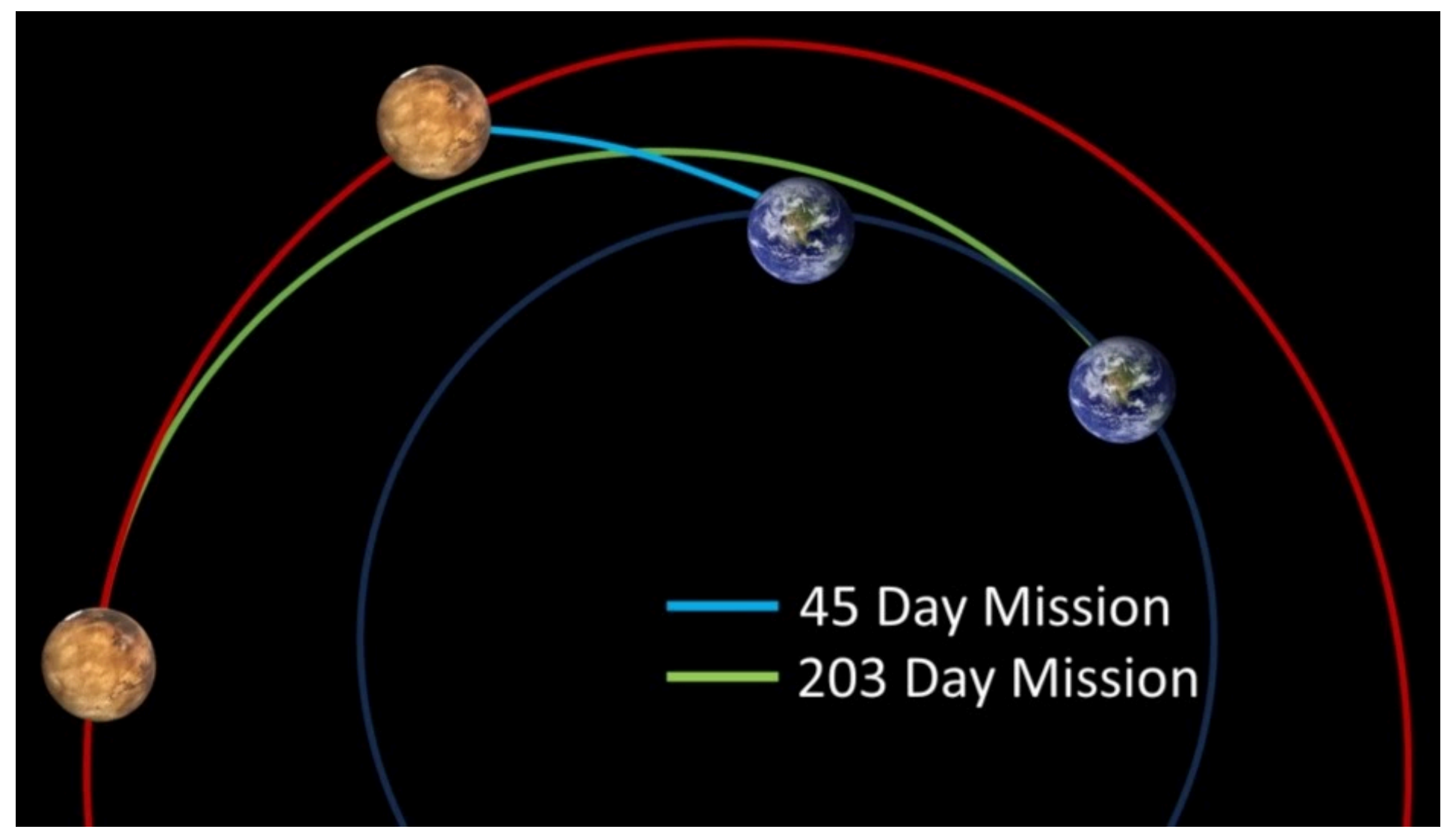

Figure 1. The Oberth Effect, followed by a demonstration of a flight directly to Mars from the Earth. High-thrust Nuclear Thermal Propulsion maximizes kinetic energy to escape Earth's gravity.

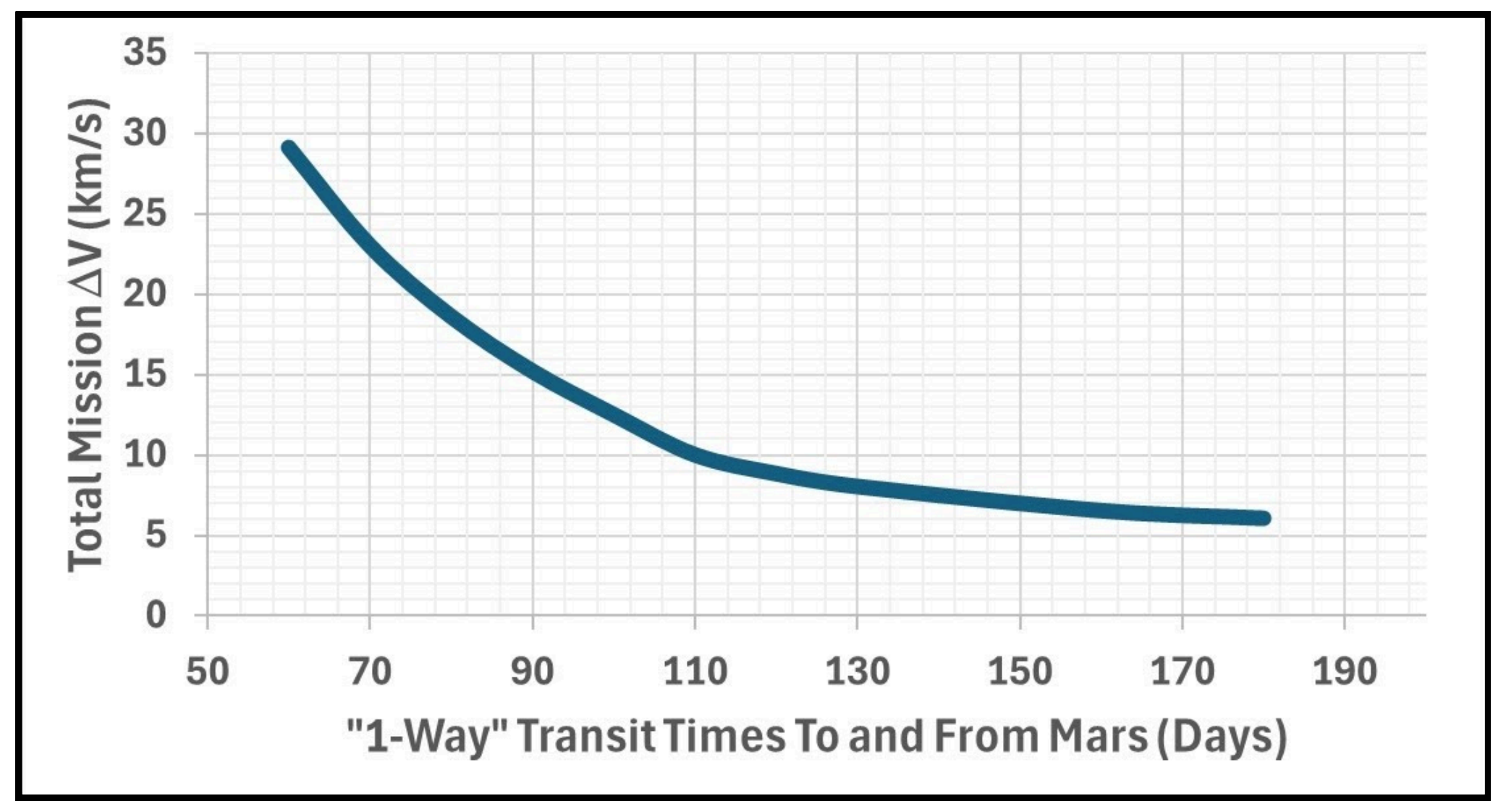

Figure 2. A chart depicting the historical transfer time to and from Mars. It highlights the 180-day transit time and serves as a model for advanced systems like the WREN spacecraft to enhance.

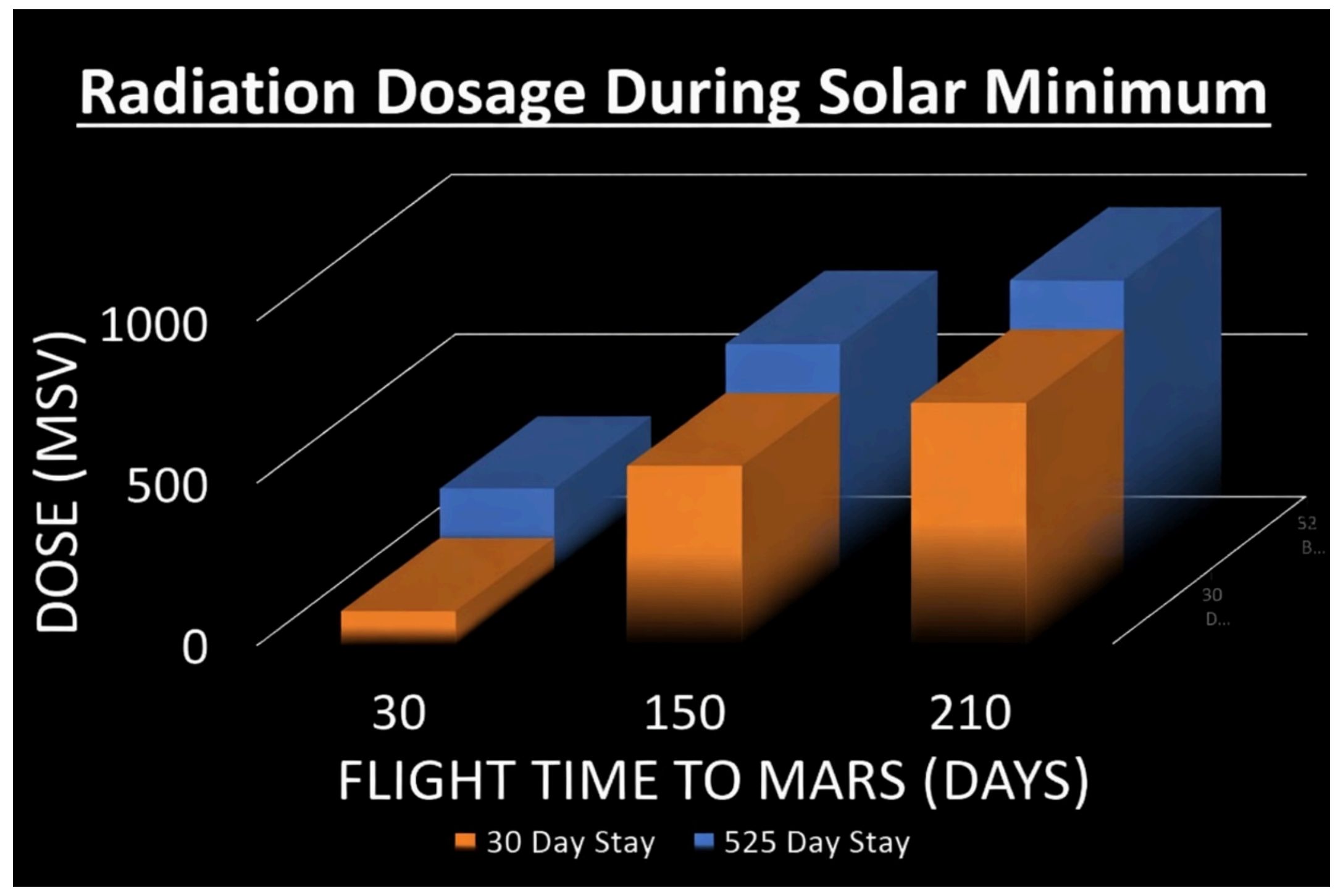

Figure 3. Chart of radiation dosage during minimum exposure to solar power and galactic cosmic rays. It is a healthy and safe justification for the creation of the WREN spacecraft.

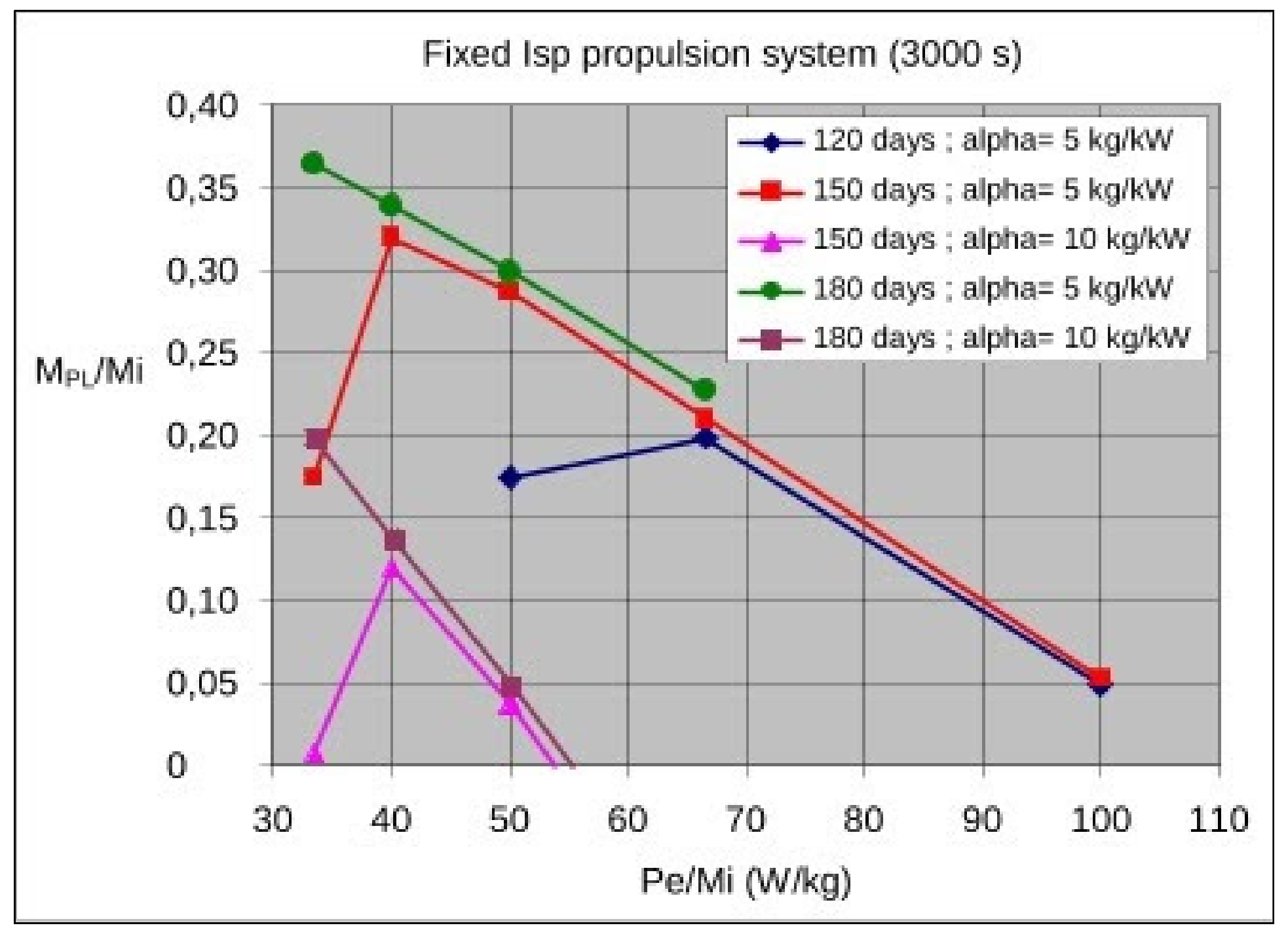

Figure 4. Fixed Isp propulsion system, displaying different paths, times, and propulsion systems. Represents the limits of constant specific impulse electric propulsion used for different aeronautical systems. Some possess lower payload mass, but require longer transfer times.

Findings & Visuals

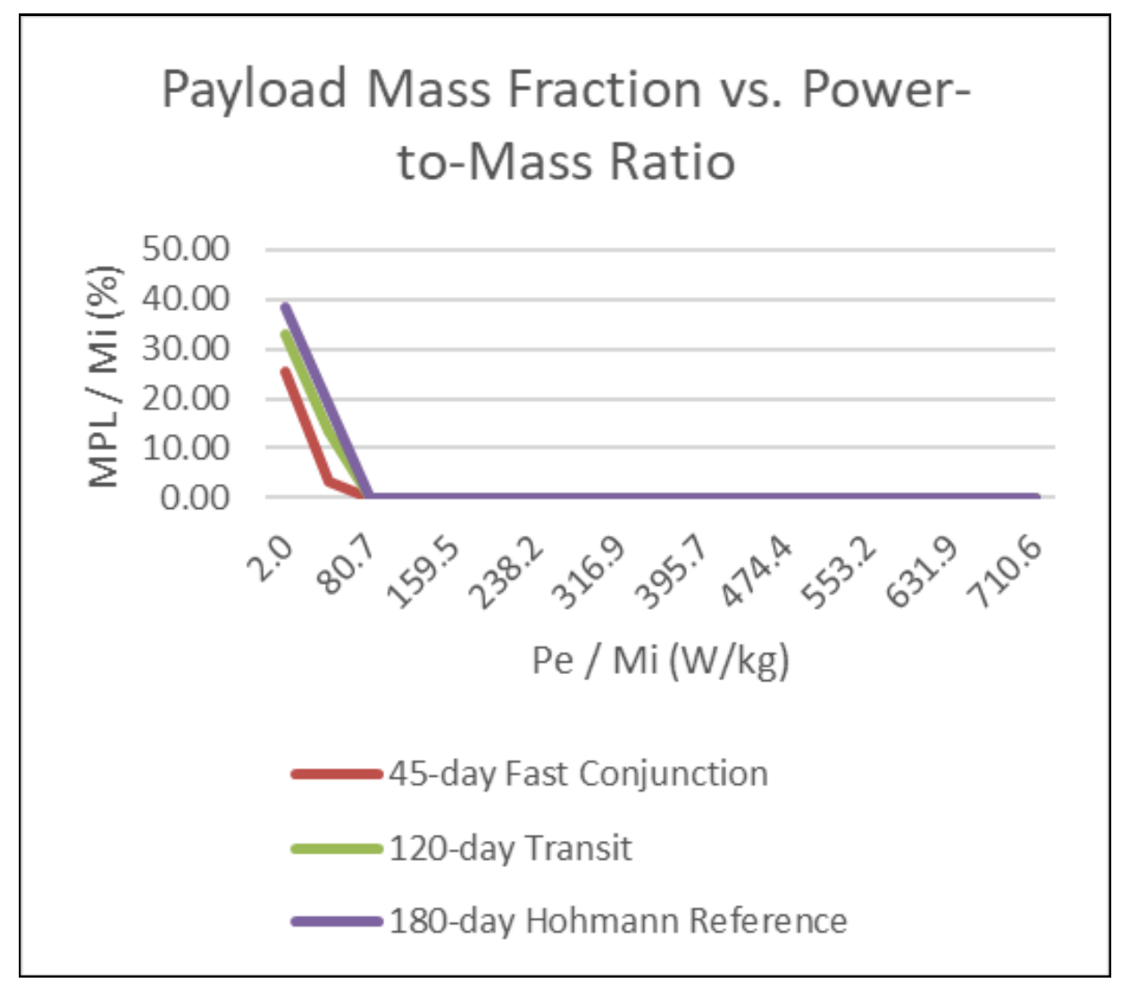

Figure 5. Chart of the relationship between Payload Mass Fraction and Power-to-Mass Ratio. A "hump" curve that reveals the optimal power to initial mass ratio needed to maximize the transfer time of a spacecraft.

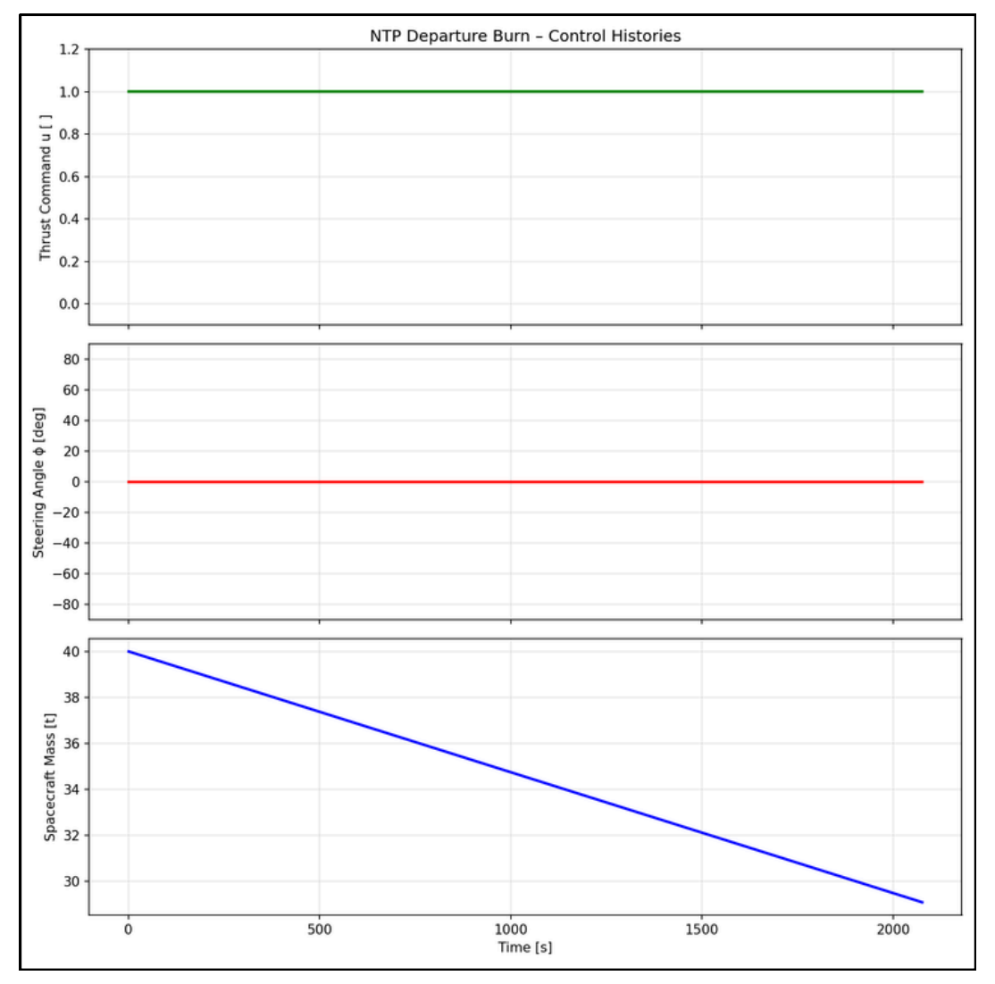

Figure 6. Three graphs of the control histories: Thrust Command, Steering Angle, and Spacecraft Mass. They demonstrate the nature of the spacecraft during departure.

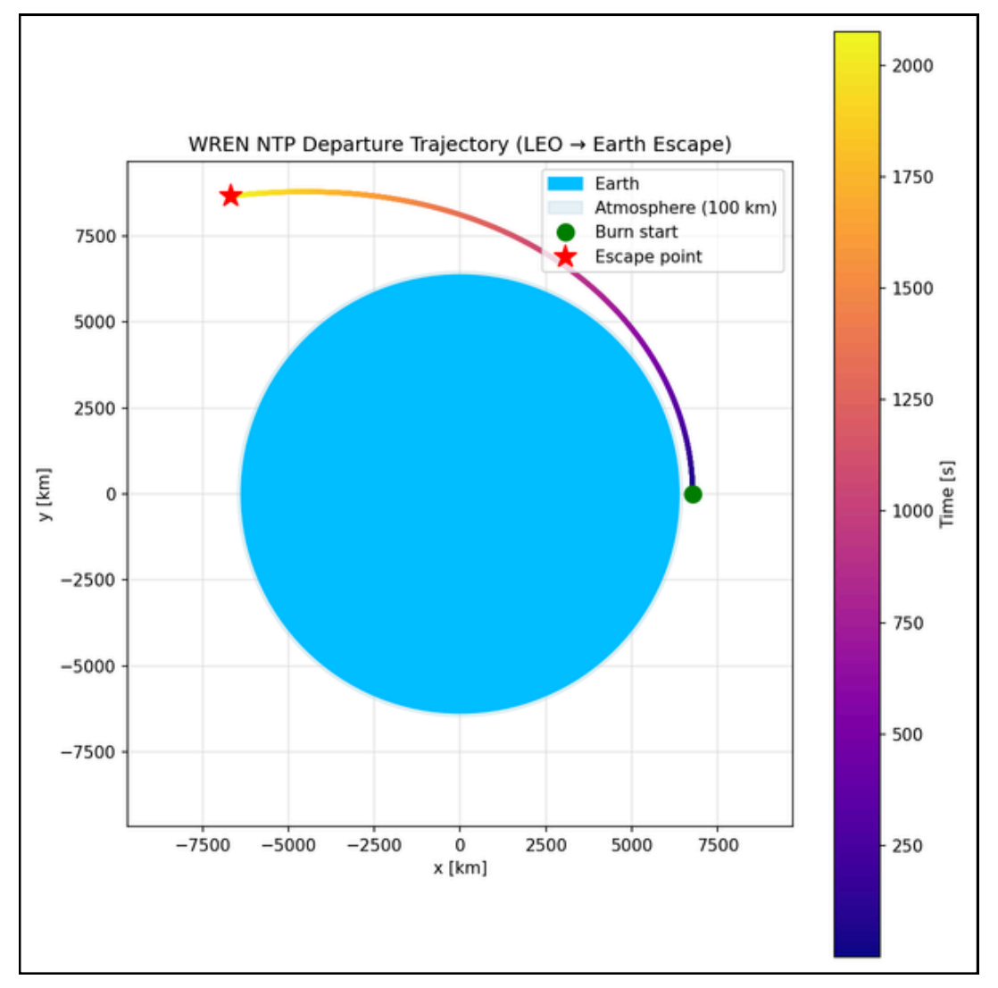

Figure 7. Another visualization of the Spacecraft's Nuclear Thermal Thrust using the Oberith Effect to decrease departure time.

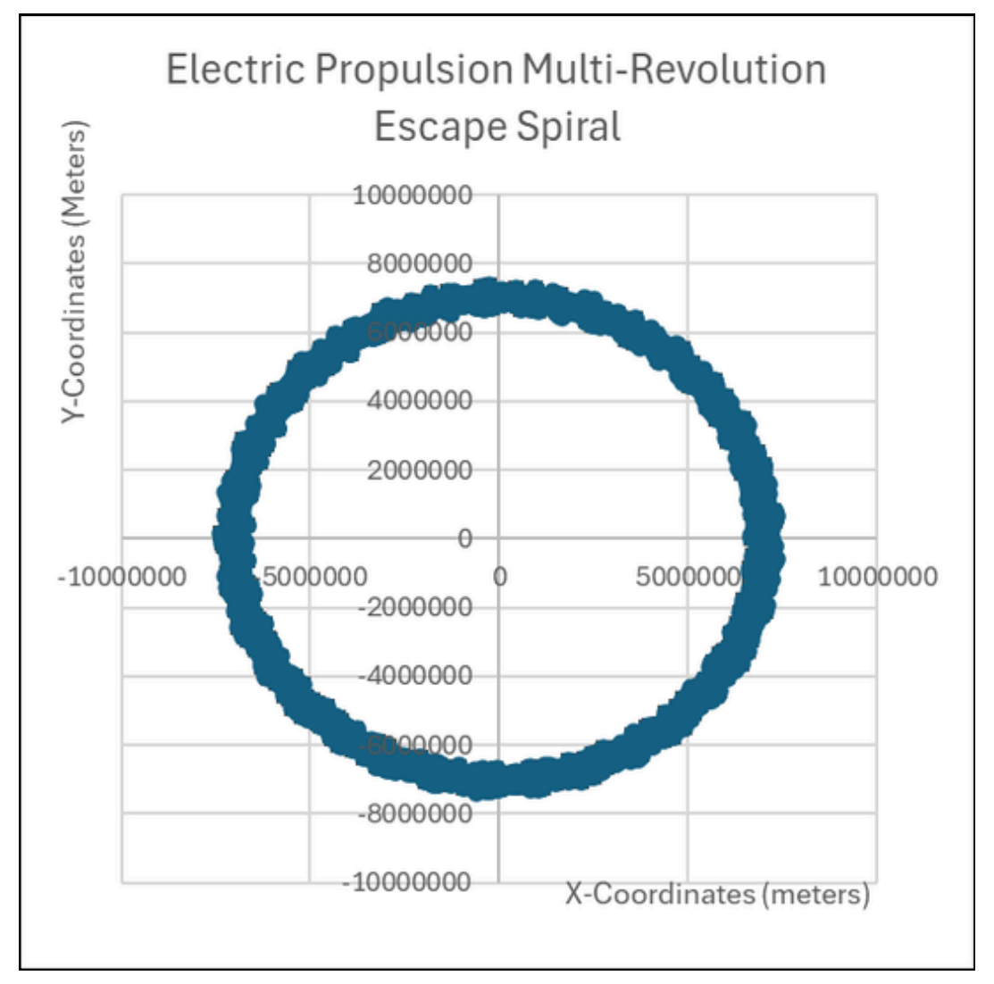

Figure 8. Chart of 100 hours' worth of positions during the geocentric phase of low-thrust systems. Displays the limits of electric propulsion systems.

Results

The results of this research project show the accuracy of the trajectory solver. They also display the performance advantages of NTP methods for deep-space missions.

- The digital twin was able to simulate the WREN spacecraft in stable orbit. The generic RK4 was able to achieve an absolute error that matched with the solution.
- The WREN spacecraft was able to achieve Earth-escape levels of energy in approximately 35 minutes. It also reached an optimal fixed steering angle and burnt mass to effectively use the Oberth Effect.
- NTP methods offer a greater specific impulse and departure time efficiency compared to other methods like NEP. This allowed the one-way transit to Mars to successfully go from 120-180 days to 45 days.
- Because the research project shows results that create a flight time of less than 120 days, the crew members are now underneath the radiation exposure threshold of 3% Risk of Exposure Induced Death (REID).

Acknowledgements

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