73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

IAC-22-D4.3.10

THE STUDY OF DIRECT, PLANETARY INSERTION ORBITS FROM SPACE ELEVATORS

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Abstract

Space elevators have the potential to launch thousands of interplanetary missions within the next 5 decades. The extensive number of opportunities to explore the solar system allows for a large range of scientific experimentation along with increased interplanetary colonization opportunities. This project has studied the possible orbits from Earth to the other planets of the solar system without the use of a midcourse correction maneuverer. There has been limited research published about these potential transfers, so they have also been tested in a high-fidelity professional-grade orbital simulator in order to be validated.

Keywords: (maximum 6 keywords)
Space elevators, mission planning, MATLAB, GMAT

Nomenclature

V_r – radial velocity
V_t – tangential velocity
r_f – orbital radius of the apex anchor
r_0 – orbital radius of the release point along the elevator
e – eccentricity from Tier 1 deployment
$\boldsymbol{R_1}$ – rotation matrix about x-axis
$\boldsymbol{R_2}$ – rotation matrix about y-axis
$\boldsymbol{R_3}$ – rotation matrix about z-axis
ω_{Earth} – Earth's angular rotation rate
μ_{Earth} – Earth's mass times the gravitational constant
$\theta_{TA,tot}$ – turning angle for Tier 2 and 3 elevator departure
θ_{TA} – turning angle for Tier 1 elevator departure
θ_{LST} – angle between vernal equinox and space elevator
V_∞ – excess velocity
η – departing hyperbola velocity decrement factor
$\boldsymbol{V_{Launch}}$ – vector of velocities upon release from elevator
$\boldsymbol{V_{GCRF}}$ – velocity vector in Geocentric Celestial Reference Frame (GCRF)
ϵ – Earth's tilt angle
θ_V – rotation about x-axis from the Perifocal Coordinate System to the Space Elevator Inertial frame
θ_R – rotation angle of apex anchor
V_p – departure velocity in Perifocal Coordinate System

Acronyms/Abbreviations

National Aeronautics and Space Administration (NASA)
NASA's General Mission Analysis Tool (GMAT)
Jet Propulsion Laboratories (JPL)
Development Ephemerides 405 (DE405)
Time of flight (TOF)
Turning Angle (TA)
Local Sidereal Time (LST)
Geocentric Celestial Reference Frame (GCRF)

1. Introduction

The space elevator has long been imagined becoming a part of humanity's future in exploring and settling the solar system. These monolithic structures will stretch from the surface of Earth to beyond the distance of geostationary orbit, about 36,000 Km in altitude, and provide its users with launch opportunities not possible with its rocket launch system counterparts. Using a space elevator, spacecraft components can be sent up the elevator and be assembled at the apex anchor before launching. With the construction of payloads moved into space, it allows for the creation of larger and heavier spacecraft than ever before. Once built, spacecraft can be transported to the top of the elevator, home to the apex anchor. Spacecraft released here will have enough energy to be able to embark on interplanetary transfer orbits across the solar system.

In the process of raising the spacecraft components up the space elevator, there are no greenhouse gas emissions. The machines built to scale the space elevator are designed to use electric motors. The required power is generated from renewable energy sources on the ground or from solar power further up the space elevator. With that in mind, spaces elevators will be humanities "green road" to space once the concept becomes fully operational.

However, this study intends to determine that space elevators can also be humanities "green road" to interplanetary space. Using a series of modifications at the apex anchor and the method of spacecraft deployment from the space elevator, it becomes possible for space elevators to generate a launch profile that requires no midcourse corrections or gravity assists to reach every planet in the solar system. As a result, extensive amounts of opportunities are created for humanity to explore the solar system and learn more about our place in the universe.

This study will analyze the interplanetary trajectories from Earth to each planet of the solar system over the next 50 years. Each orbit will be modeled from three different space elevators, each with a different modification intent on improving the overall performance of the megastructure. Once viable trajectories are determined, the corresponding orbits will be modeled in a high-fidelity, professional-grade orbital simulator to validate the transfer.

2. Material and methods

In order to reproduce the work performed in this study a sound knowledge of orbital mechanics, MATLAB, and GMAT are required. The MATLAB algorithms written for this research use equations created to model spacecraft launch profiles from space elevators [3]. Additional MATLAB algorithms were used for orbital propagation to model the progress of trajectories likely to intercept their target planet. After successful transfers were identified, one final MATLAB code took the corresponding data and created a new GMAT script to be simulated so that the MATLAB successful transfer could be validated.

3. Space Elevator Release Concepts

As previously mentioned, spacecraft launched from the apex anchor of a space elevator are provided a large increase in orbital energy due to Earth's rotation. Following Dr. Peet's nomenclature [3], this would be classified as a Tier 0 space elevator. This elevator provides a departing spacecraft with a velocity directly proportional to the radius upon release.

However, a Tier 0 elevator can be modified to increase its overall performance. The first modification is in the method of deployment. Rather than releasing from the apex anchor, spacecraft are deployed along the space elevator. At any altitude above geostationary orbit, centripetal acceleration is stronger than gravity and any object allowed to slide will begin to accelerate towards the apex anchor.

As seen in Figure 25, spacecraft deployed anywhere above geostationary orbit will not only have any increased velocity due to Earth's rotation in the tangential direction, but will also have some radial velocity, relative to the space elevator. Unfortunately, the vectors of V_t and V_r are orthogonal to each other and do not produce an ideal launch profile. If V_r could be rotated in such a way that it is in line with V_t then both the space elevator performance capabilities would be greatly improved, and the required length of the space elevator could be shortened. This can be solved by adding a 90° ramp at the apex anchor and classifies this as the Tier 2 space elevator, as seen in Figure 26. Though to use the ramp spacecraft may endure high gee loads not found during deployment from a Tier 0 or 1. In order to minimize those effects, the radius of the ramp can be increased and or spacecraft can be released from higher positions along the elevator in order to lower their velocity when entering the ramp. Although not impossible, it will be hard to change the size of the ramps once the space elevator is built. Changing the initial release position along the space elevator will be the easiest way to guarantee no violations of an imposed G-limit.

Now a distinct problem with the Tier 0, 1, and 2 space elevators is that they can only launch a spacecraft into an interplanetary trajectory exactly twice a day. The ideal departures into the ecliptic plane occur around each of the solstices. If the planets are misaligned during those times of the year, then any of viable launch windows will be several years apart. So, in order to increase the number of launch windows, the elevator should be able to deploy spacecraft at any time of day. Shown in Figure 27, the Tier 3 space elevator can track the ecliptic plane regardless of its position around Earth. This in turn allows for interplanetary launches to occur each time Earth and the target planet are properly aligned.

4. Simulation Parameters

The simulation will produce a series of launch profiles from successful, interplanetary trajectories from Tier 1, 2, and 3 space elevators between the dates of January 1, 2022, and January 1, 2072. Each space elevator will be 100 Mm in length with the Tier 2 and 3 space elevators containing an apex ramp with a radius of 1 Mm. Each elevator will attempt to launch spacecraft to Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune for interplanetary travel. Every trajectory has a limited time of flight, equal to the transfer time of a Hohmann transfers rounded up to a full year. In order to determine if a mission has successfully entered the target planet's sphere of influence, the planetary position will be generated by NASA JPL's DE405. This ephemeris data set ensures that accurate, real-time solutions can be found across the search window. After a mission is found to successfully intercept its target planet's sphere of influence, its launch parameters are saved for further review and analysis later in this study.

Once the successful transfers have been saved, the corresponding launch window is modeled in GMAT for comparison. The goal is to verify that the MATLAB predictions are valid interplanetary trajectories and that the space elevator technology is a viable solution for future space travel.

5. Simulation Results

5.1 Unsuccessful Interplanetary Transfers

After completing the simulations, there was a large disparity in the amount of data collected between the gas giants and the terrestrial planets. While trajectories to the gas giants could be found in repeating transfer windows and produced in tens of thousands of successful intercepts, journeys to the terrestrial planets generated only a few dozen successful results with large periods of time between transfers. Due to the nature of the scattered data and small sample size, missions to Mercury, Venus, or Mars will not be studied in this paper.

5.2 Jupiter

As Jupiter is the only planet in this study that can be reached by all three tiers of space elevator, this provides an ample comparison among the modifications. Looking at the data in Table 1, a Tier 1 space elevator under performs by all aspects compared to the Tier 2 and 3. The Tier 2 and Tier 3 elevators have more and larger launch windows and can achieve a fly-by of Jupiter is less than one year. However, the Tier 3 shows off its greatest advantage, its rotating apex ramp. The Tier 3 can achieve a launch window at nearly every opportunity and provides plenty of launch opportunities for both high and low energy approaches, making the best of both the Tier 1 and the Tier 2.

Once the transfer data was collected, a launch window that spanned 60 days, December 24, 2052, to February 22, 2053, was discovered to contain interplanetary trajectories from all three space elevators. Figures 1, 4, and 7 are porkchop plots highlighting the relative velocities upon approach to Jupiter. Figures 2, 5, and 8 show the orbital path of the fastest daily launches of this window as simulated in MATLAB. Finally, Figures 3, 6, and 9, are the GMAT simulations of the corresponding launches.

Table 1 – Simulation statistics on the interplanetary transfers to Jupiter

	Tier 1	Tier 2	Tier 3
Number of Launch Windows in 50 years	7	12	43
Average Launch Window Length (days)	23	39	49
Minimum TOF (days)	526	230	230
Maximum TOF (days)	1095	1095	1095
Average TOF (days)	748	356	545

5.2.1 Tier 1 Transfers to Jupiter

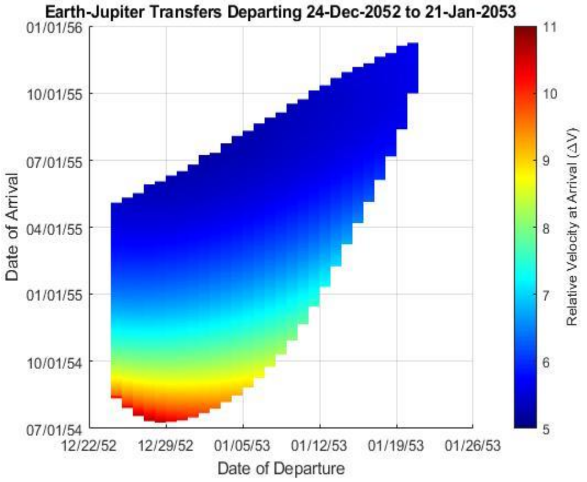

Fig. 1. Porkchop Plot of Excess Velocities at Jupiter from Tier 1 Departures

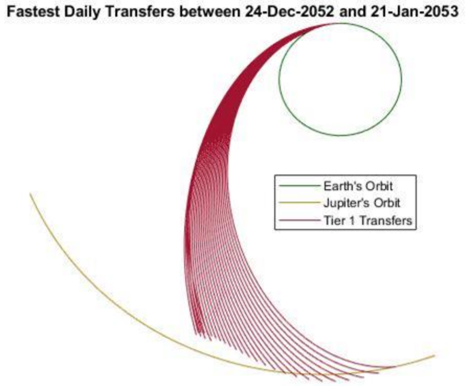

Fig. 2. MATLAB Tier 1 Interplanetary Orbit Simulation to Jupiter

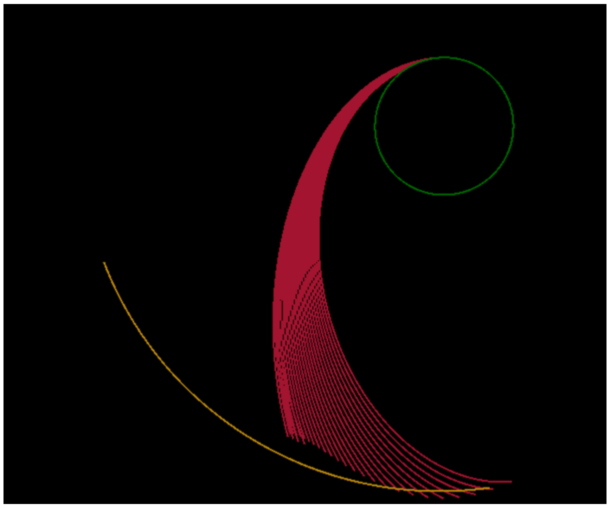

Fig. 3. GMAT Tier 1 Interplanetary Orbit Simulation to Jupiter

5.2.2 Tier 2 Transfers to Jupiter

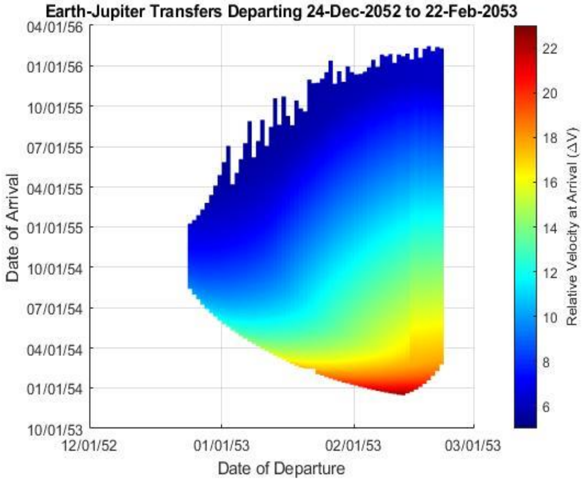

Fig. 4. Porkchop Plot of Excess Velocities at Jupiter from Tier 2 Departures

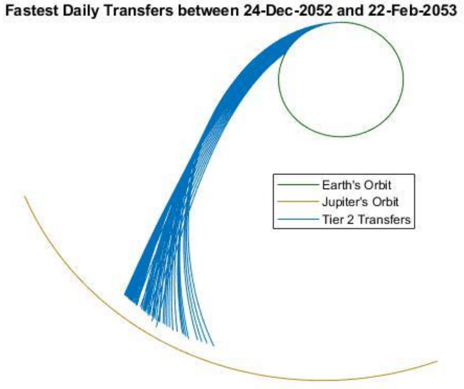

Fig. 5. MATLAB Tier 2 Interplanetary Orbit Simulation to Jupiter

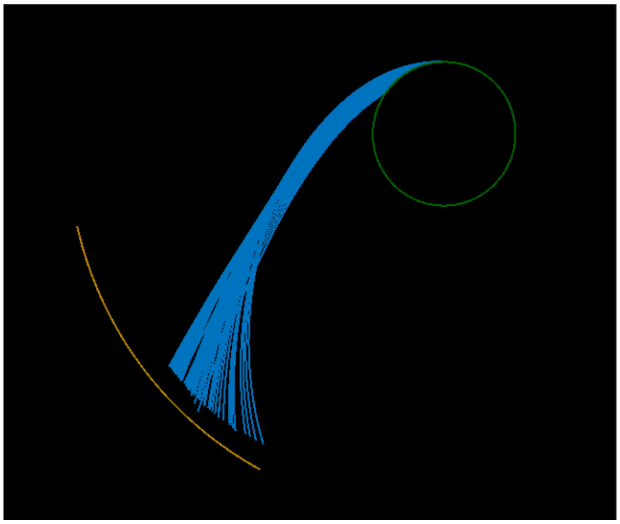

Fig. 6. GMAT Tier 2 Interplanetary Orbit Simulation to Jupiter

5.2.3 Tier 3 Transfers to Jupiter

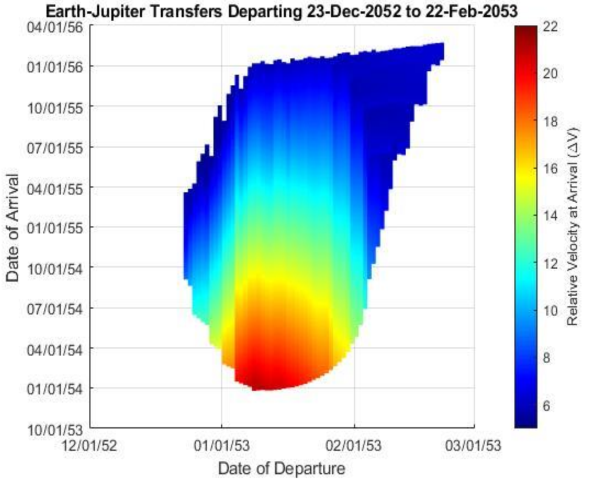

Fig. 7. Porkchop Plot of Excess Velocities at Jupiter from Tier 3 Departures

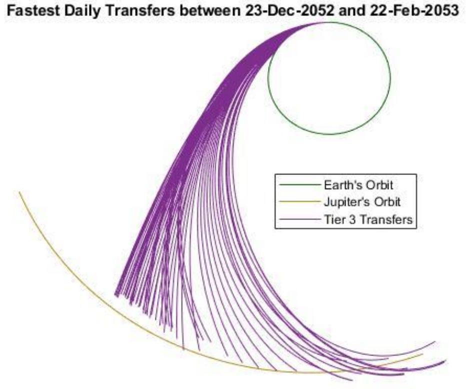

Fig. 8. MATLAB Tier 3 Interplanetary Orbit Simulation to Jupiter

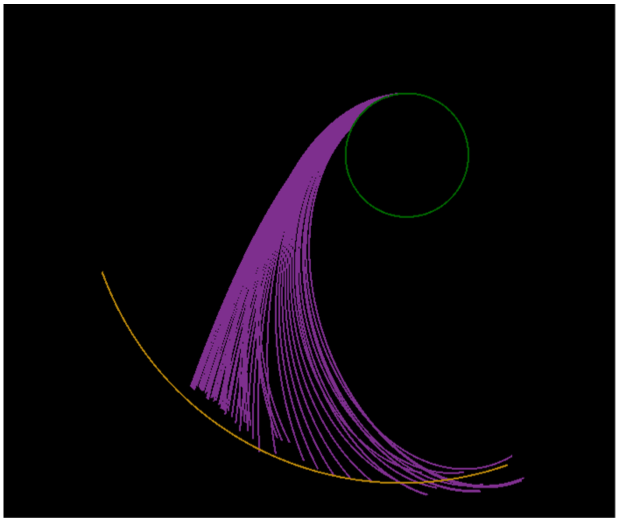

Fig. 9. GMAT Tier 3 Interplanetary Orbit Simulation to Jupiter

5.3 Saturn

Although the Tier 3 elevator provides much more launch opportunities to Saturn, the results from the Tier 2 data suggests that, on average, its launch windows were longer. This is because some of the 40, Tier 3 launch windows were only 2-5 days in length before Earth and Saturn would be out of position. Although ample time to deploy a spacecraft into a direct, planetary insertion orbit, a longer launch window could provide extra time for support crews to repair or modify the vehicle before launch should there be any issue. Additionally, the overall launch performance of the Tier 2 and Tier 3 are comparable. While both elevators have near equal minimum and maximum TOFs their average TOF is only about 100 days apart, approximately a 4% of the maximum flight time. Referring to Table 1, the average TOFs for the Tier 2 and 3 elevators are closer to 200 days apart, constituting 17% of the max TOF of 1095 days. If the demand for transfer to Saturn were low, the Tier 2 may find itself more valuable than the Tier 3.

Much like how Figures 1-9 displayed data from the interplanetary transfers to Jupiter, Figures 10-15 highlight the data compiled from the transfers to Saturn. The launch window being simulated in the following figures is 58 days, spanning from July 8, 2058, to September 4, 2058.

Table 2 – Simulation statistics on the interplanetary transfers to Saturn

	Tier 1	Tier 2	Tier 3
Number of Launch Windows in 50 years	N/A	10	40
Average Launch Window Length (days)	N/A	36	27
Minimum TOF (days)	N/A	593	593
Maximum TOF (days)	N/A	2546	2555
Average TOF (days)	N/A	1055	1168

5.3.1 Tier 2 Transfers to Saturn

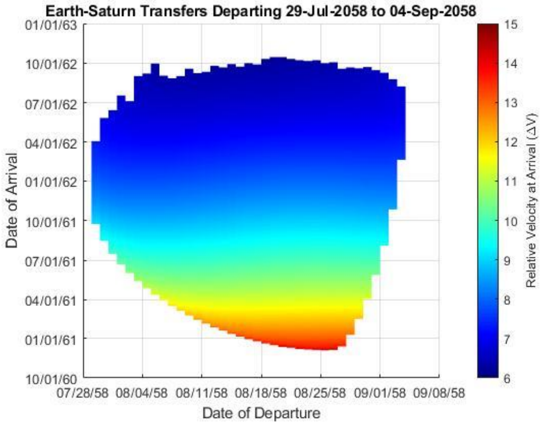

Fig. 10. Porkchop Plot of Excess Velocities at Saturn from Tier 2 Departures

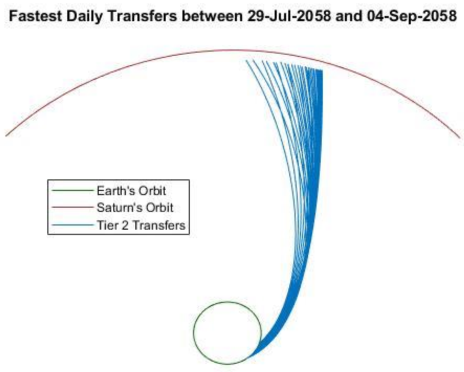

Fig. 11. MATLAB Tier 2 Interplanetary Orbit Simulation to Saturn

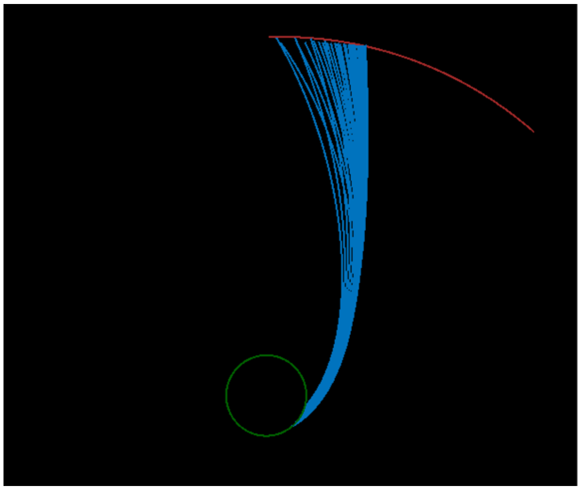

Fig. 12. GMAT Tier 2 Interplanetary Orbit Simulation to Saturn

5.3.2 Tier 3 Transfers to Saturn

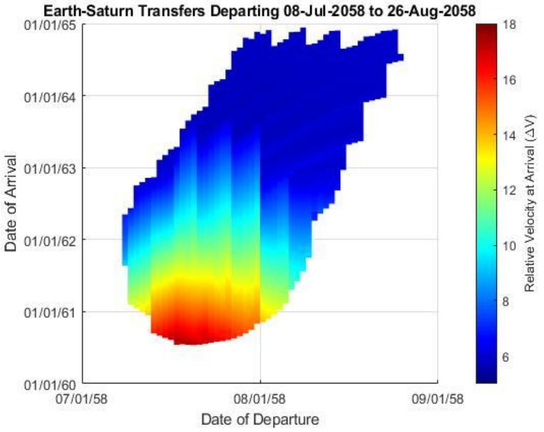

Fig. 13. Porkchop Plot of Excess Velocities at Saturn from Tier 3 Departures

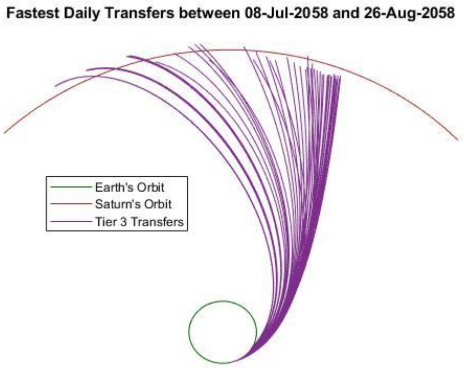

Fig. 14. MATLAB Tier 3 Interplanetary Orbit Simulation to Saturn

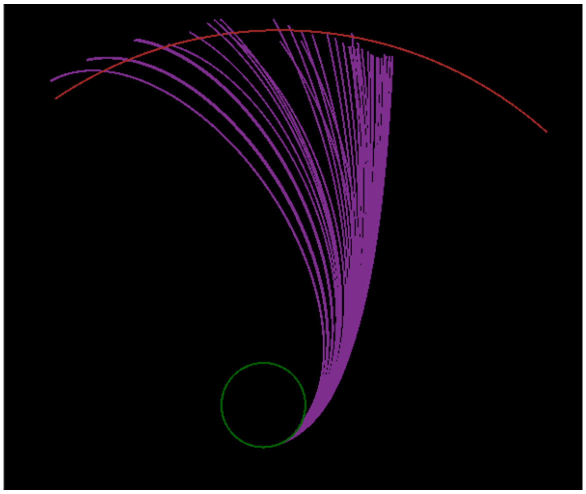

Fig. 15. GMAT Tier 3 Interplanetary Orbit Simulation to Saturn

5.4 Uranus

Much like the information data found with the transfers to Saturn, the Tier 2 launch windows to Uranus are less frequent but longer. However, the Tier 3 can launch into much lower energy trajectories compared to the Tier 2 and can again demonstrate it performance capabilities over the Tier 2. The following figures show the data for a transfer window that lasts 45 days from July 6, 2023, to August 20, 2023.

Table 3 – Simulation statistics on the interplanetary transfers to Uranus

	Tier 1	Tier 2	Tier 3
Number of Launch Windows in 50 years	N/A	3	33
Average Launch Window Length (days)	N/A	39	21
Minimum TOF (days)	N/A	1624	1624
Maximum TOF (days)	N/A	4999	6204
Average TOF (days)	N/A	2531	3551

5.4.1 Tier 2 Transfers to Uranus

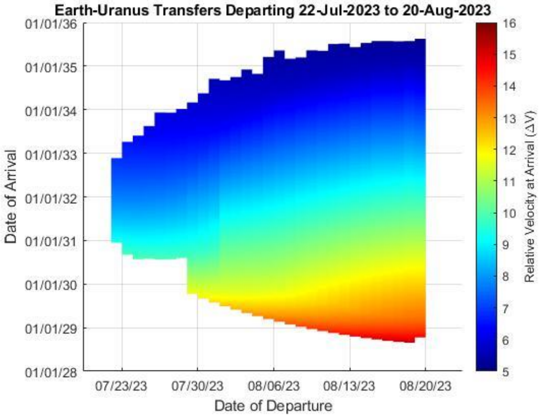

Fig. 16. Porkchop Plot of Excess Velocities at Uranus from Tier 2 Departures

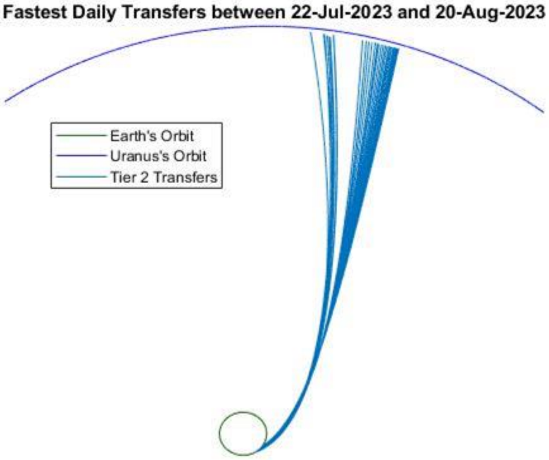

Fig. 17. MATLAB Tier 2 Interplanetary Orbit Simulation to Uranus

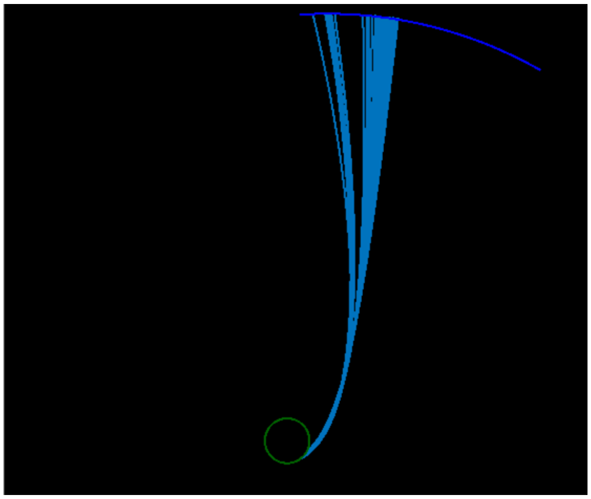

Fig. 18. GMAT Tier 2 Interplanetary Orbit Simulation to Uranus

5.4.2 Tier 3 Transfers to Uranus

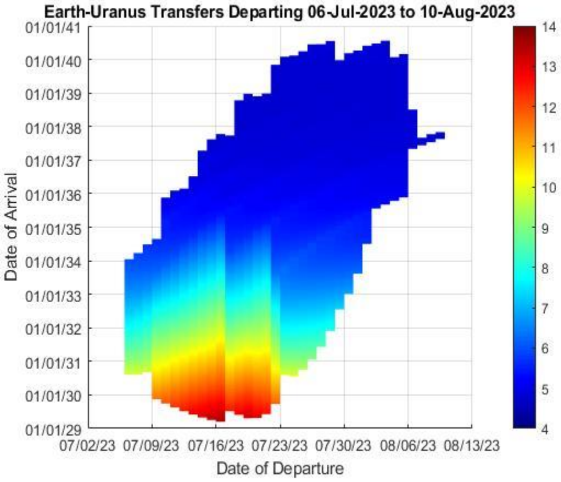

Fig. 19. Porkchop Plot of Excess Velocities at Uranus from Tier 3 Departures

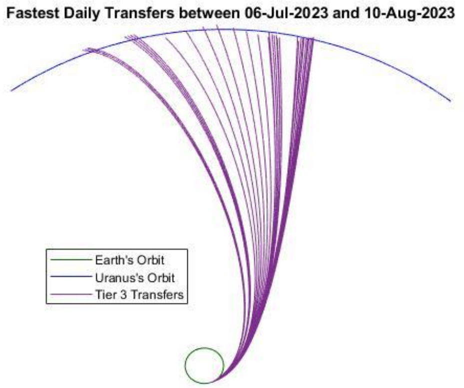

Fig. 20. MATLAB Tier 3 Interplanetary Orbit Simulation to Uranus

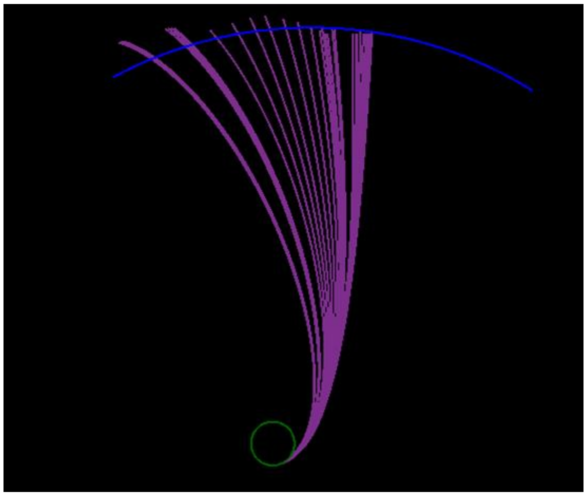

Fig. 21. GMAT Tier 3 Interplanetary Orbit Simulation to Uranus

5.5 Neptune

The 100 Mm long Tier 3 space elevator is reaching its maximum performance in order to launch spacecraft to Neptune. In the previous figures comparing the MATLAB simulation to the GMAT one, the visuals have demonstrated that the results are likely viable transfers. Yet looking at Figure 23 and Figure 24 seems to show otherwise. Despite the orbital paths looking identical, the orbits in Figure 24 are not reaching Neptune likely because of the differences in propagation techniques performed in each software. At the vast distance Neptune is away from the Sun, the MATLAB script's 2-body propagation may not be valid. However, a longer space elevator may be able prove itself more capable in reaching Neptune. The following figures, 22-24, show the data of a launch window lasting 17 days from April 18, 2022, to May 5, 2022.

Table 4 – Simulation statistics on the interplanetary transfers to Neptune

	Tier 1	Tier 2	Tier 3
Number of Launch Windows in 50 years	N/A	N/A	6
Average Launch Window Length (days)	N/A	N/A	13
Minimum TOF (days)	N/A	N/A	7129
Maximum TOF (days)	N/A	N/A	10944
Average TOF (days)	N/A	N/A	8700

5.5.1 Tier 3 Transfers to Neptune

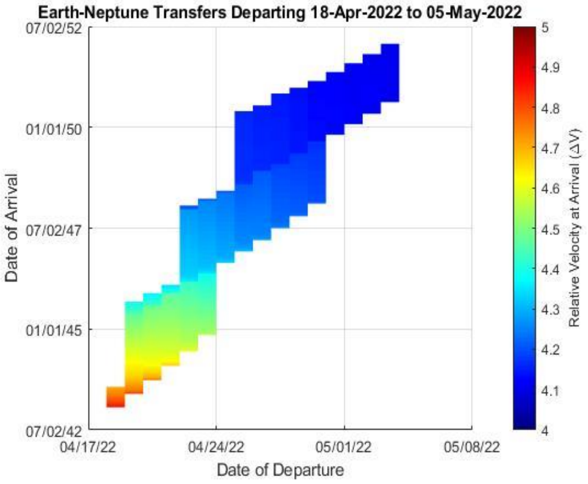

Fig. 22. Porkchop Plot of Excess Velocities at Neptune from Tier 3 Departures

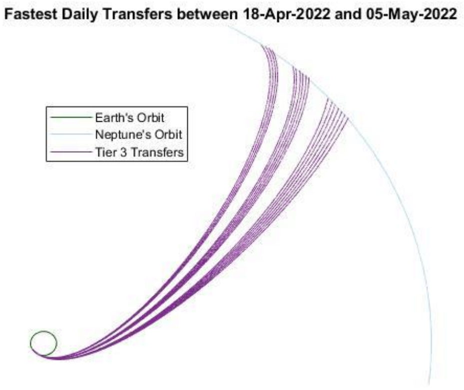

Fig. 23. MATLAB Tier 3 Interplanetary Orbit Simulation to Neptune

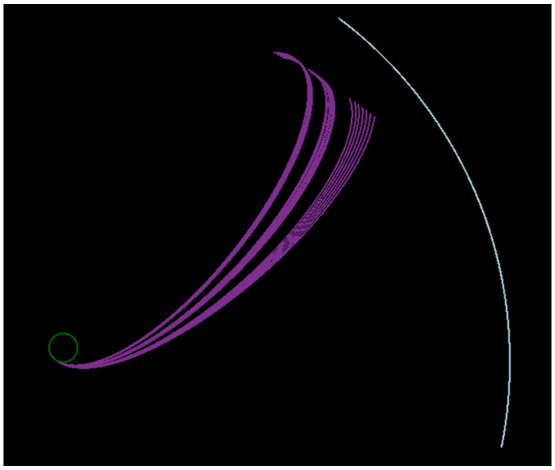

Fig. 24. GMAT Tier 3 Interplanetary Orbit Simulation to Neptune

6. Conclusions

Upon further review, the space elevator has the right to be called the "green road" to interplanetary space. There are an extensive number of opportunities over the next 50 years to explore and study the solar system from space elevators. Most of these chances are made possible by the Tier 3 space elevator, followed by the Tier 2 and then the Tier 1. When comparing the orbital trends, the Tier 1 elevator produced lower energy orbits and tended to have longer TOFs, meaning many launch opportunities were unavailable as Earth and the target planet were out of alignment. The Tier 2, on the other hand, frequently produced orbits with high orbital energy which in turn lowered its average TOF. The faster trajectories allowed for the Tier 2 to access more launch windows than the Tier 1 as well as averaged longer launch windows. By comparison, the Tier 3 was the average result of the Tier 1 and 2. The Tier 3 was able to achieve the low energy, long TOF orbits from the Tier 1 while also being able to launch into high energy, lower TOF trajectories. Also due to the rotating apex ramp the Tier 3 was able to launch to the target planet whenever the two planets aligned, which is impossible to do with both the Tier 1 and Tier 2 elevators.

If one of the three modifications had to be chosen for future construction, the Tier 3 space elevator should be the most logical choice. The ability to access a launch window whenever the planets are correctly aligned, and the plethora of both high and low energy transfers is invaluable. It would entice any potential users with a wide range of options that best suits their needs. Although there could be further advancements in both space elevator theory and technology, the modifications modeled in this study will great increases the space elevator's ability to spread the reach of humanity across the solar system.

Acknowledgements

Special thanks to Dr. Matthew Peet, Dr. Peter Swan, Arizona State University, and the International Astronautical Congress. Thank you Dr. Peet for approving access to your work in order to create this study. Your support and insight into this research over the past few school years helped drive the conclusions found and discussed in this paper. Thank you to Dr. Swan for introducing the idea of what a space elevator is. Your guest lecture two years ago was an eye-opening experience to what the future of space travel could look like. Thank you to Arizona State University for providing its undergraduate students access to perform research. Your encouragement through the Fulton Undergraduate Research Initiative helped spark a passion for research and its presentation among colleagues. Thank you to the International Astronautical Congress for a place to publish and present this research for the global community.

Appendix A – Launch Profile Equations

The launch profile is array of velocities after the release from a space elevator. These equations are then rotated to be in a frame a reference around the Sun and used to propagate its respective orbits across the solar system. Each launch profile requires the 3-dimensional rotation matrices as listed below.

$$\boldsymbol{R_1}(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix}$$

$$\boldsymbol{R_2}(\theta) = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

$$\boldsymbol{R_3}(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

A.1 Tier 1 Launch Profile Equations

$$V_r = \sqrt{\frac{2\mu_{Earth}}{r_0} + \omega_{Earth}^2 (r_f^2 - r_0^2)}$$

$$V_t = \omega_{EArth} r_f$$

$$e_1 = \sqrt{\left(\frac{\omega_{Earth}^2 r_f^3}{\mu_{Earth}} - 1\right)^2 + \left(\frac{V_r \omega_{Earth} r_f^2}{\mu_{Earth}}\right)^2}$$

$$\theta_{TA,tot} = \sin^{-1}(\frac{1}{e_1})$$

$$\theta_{TA} = \theta_{TA,tot} - \cos^{-1}\left(\frac{\left(\frac{\omega_{Earth}^2 r_f^3}{\mu_{Earth}} - 1\right)}{e_1}\right)$$

$$\theta_{LST} = \tan^{-1}\left(-\frac{\omega_{Earth} r_f}{V_r}\right) - \theta_{TA} + 180° \text{ and}$$
$$\theta_{LST} = \tan^{-1}\left(-\frac{\omega_{Earth} r_f}{V_r}\right) - \theta_{TA} + 360°$$

$$V_\infty = \sqrt{\left(\omega_{Earth} r_f\right)^2 + V_r^2 - \frac{2\mu_{Earth}}{rf}}$$

$$\eta = \frac{V_\infty}{\sqrt{V_r^2 + \left(\omega_{Earth} r_f\right)^2}}$$

$$\boldsymbol{V_{Launch}} = \begin{bmatrix} V_r \\ \omega_{Earth} r_f \\ 0 \end{bmatrix} \tag{1}$$

$$\boldsymbol{V_{GCRF}} = \eta \boldsymbol{R_1}(-\epsilon) \boldsymbol{R_3}(\theta_{LST} + \theta_{TA}) \boldsymbol{V_{Launch}} \tag{2}$$

A.2 Tier 2 Launch Profile Equations

$$e = \frac{(V_r + \omega_{Earth} r_f)(\omega_{Earth} r_f + V_r) r_F}{\mu_{Earth}} - 1$$

$$\theta_{TA,tot} = \sin^{-1}(\frac{1}{e})$$

$$\theta_{LST} = 90° - \theta_{TA} \text{ and}$$
$$\theta_{LST} = 270° - \theta_{TA}$$

$$V_\infty = \sqrt{\left(\omega_{Earth} r_f + V_r\right)^2 - \frac{2\mu_{Earth}}{rf}}$$

$$\eta = \frac{V_\infty}{\sqrt{V_r^2 + \left(\omega_{Earth} r_f\right)^2}}$$

$$\boldsymbol{V_{Launch}} = \begin{bmatrix} 0 \\ \omega_{Earth} r_f \\ 0 \end{bmatrix} + \boldsymbol{R_3}(90°) \begin{bmatrix} V_r \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

$$\boldsymbol{V_{GCRF}} = \eta \boldsymbol{R_1}(-\epsilon) \boldsymbol{R_3}(\theta_{LST} + \theta_{TA}) \boldsymbol{V_{Launch}} \tag{4}$$

A.3 Tier 3 Launch Profile Equations

$$\theta_V = \frac{\tan^{-1}(V_r \sin(\theta_R))}{\omega_{Earth} r_f + V_r \cos(\theta_R)}$$

$$V_p = \sqrt{(\omega_{Earth} r_f)^2 + 2\omega_{Earth} r_f V_r \cos(\theta_R) + V_r^2}$$

$$e = \frac{V_p^2 r_f}{\mu_{Earth}} - 1$$

$$\theta_{TA,tot} = \sin^{-1}\left(\frac{1}{e}\right)$$

The value of θ_R cannot be solved for directly but it must satisfy the following equation.

$$\begin{aligned} &\sin(\epsilon)\sin(\theta_{LST})\sin(\theta_{TA}) \\ &= \cos(\theta_{TA})\,(\cos(\theta_{LST})\cos(\theta_V)\sin(\epsilon) \\ &- \cos(\epsilon)\cos(\theta_V)) \end{aligned}$$

Once the value of θ_R has been determined, then the launch profile of a departure from ta Tier 3 space elevator can be constructed.

$$\boldsymbol{V_{Launch}} = \begin{bmatrix} 0 \\ \omega_{Earth} r_f \\ 0 \end{bmatrix} + \boldsymbol{R_3}(90°) \begin{bmatrix} V_r \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

$$V_\infty = \sqrt{V_p^2 - \frac{2\mu_{Earth}}{r_f}}$$

$$\boldsymbol{V_{GCRF}} = \boldsymbol{R_1}(-\epsilon) \boldsymbol{R_3}(\theta_{LST}) \boldsymbol{R_1}(\theta_V) \boldsymbol{R_3}(\theta_{TA}) \begin{bmatrix} 0 \\ V_\infty \\ 0 \end{bmatrix} \tag{6}$$

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Appendix B – Larger Images

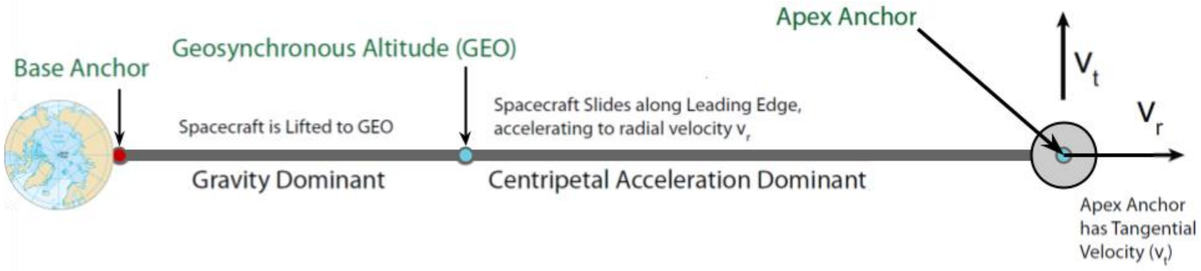

Fig. 25. Tier 1 Space Elevator Release Concept

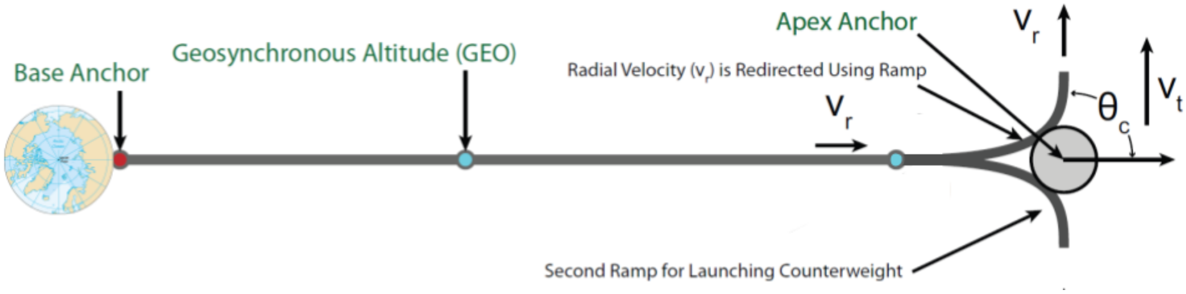

Fig. 26. Tier 2 Space Elevator Release Concept

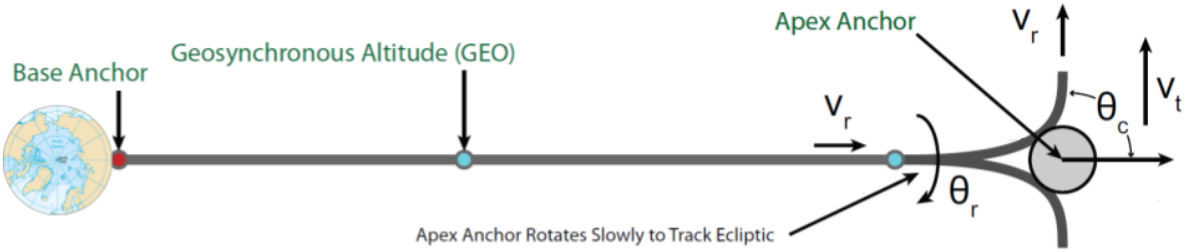

Fig. 27. Tier 3 Space Elevator Release Concept

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