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OPTIMIZATION OF LOW FUEL AND TIME-CRITICAL INTERPLANETARY TRANSFERS USING SPACE ELEVATOR APEX ANCHOR RELEASE: MARS, JUPITER AND SATURN.

James Torla*, Matthew Peet**

*Arizona State University, Tempe, Az, USA, james.torla@asu.edu
**Arizona State University, Tempe, Az, USA, mpeet@asu.edu

Abstract

We examine the potential impact of a Space Elevator Apex Anchor for permanent human habitation of Mars and the Moons of Jupiter and Saturn. Apex anchor release trajectories refer to the low-cost interplanetary insertions corresponding to the initial velocity vector achieved at the apex of any higher-than-geosynch space elevator. The velocities of these apex anchors in most cases are beyond earth escape velocities and under certain conditions can yield interplanetary transfers with minimal Delta-v requirements. In this work, we have used iterative methods based on a variation of Lambert's Problem to determine the minimal Delta-v direct transfer from an Apex anchor to Mars under a variety of initial conditions and time-of-flight constraints. Permanent human habitation of distant planets requires both cost-effective methods of transportation of a massive amount of materiel and the ability to reduce the time-of-flight for human passengers and safety-critical supplies. Our results demonstrate that the use of an Apex anchor release can address both needs by dramatically reducing the time-of-flight for a fixed Delta-v budget, or, conversely, dramatically reducing the Delta-v budget (and hence costs) when time-of-flight constraints are relaxed.

1.0 Introduction:

Now more than ever to find the future of humanity, one must look to the stars. Each year the community of spacefaring nations grows as more and more nations achieve new milestones in spaceflight and exploration. In this year alone two nations -Nepal and Sri Lanka[1]- have launched their first satellites, both India and Israel[2] have successfully orbited the moon, and China's Chang'e 4 has made the first ever soft landing on the far side of the moon[3]. As the astronautical industry grows and maturities, National spaceflight programs and the astronomical community as a whole are moving onto the next phase of technological development. Corporations and countries alike now strive to permanently open space to humanity as a whole by reducing the financial and technological barriers that would limit the breadth of space exploration.

This change of focus towards the development of reliable, cheap, and reusable space infrastructure has fueled the growth of private companies like Space X and Blue Origin, which has in turn has supported the market for smaller operations such as CubeSat missions. However, it is unclear if the development of new rocket technologies will ever lower the cost of interplanetary spaceflight enough to truly open the market to the reach of small operators. The reality is that for humanity to go into space, there are tremendously high logistical requirements, simply to move mission support equipment or people.

During his interview on CBS on July 21, 2019 Elon Musk estimated that the construction of a self-sustaining mars colony would require the delivery of a "million tons"[4] of material to the planet. This goal is ambitious, and appears infeasible using the current generation of heavy-lift rockets.

[1] Press Trust of India
[2] O'Callaghan, Jonathan
[3] Jones, Andrew
[4] Kluger, Jeffrey

For example. if SpaceX were to attempt to deliver that necessary infrastructure using Space X's upcoming Starship (also called the BFR) –which has a Mars payload capacity of ~100 tons and requires orbital refueling by "three to five"[5] tanker BFR's– it would take at minimum 30,000 launches. In the history of space exploration, there have only been approximately 6,000 rocket launches[6] total. It would take five times as many successful interplanetary launches as there have been orbital launches ever in order to build this self-sustaining Mars colony. However, although rockets are a well-established orbital launch technology, they are not the only option.

Space Elevators are a strong contender to provide the low cost launch options necessary for the continuing growth of space flight. By their very nature as permanent structures, Space Elevators would facilitate the reliable, efficient, and inexpensive movement of materials into earth orbit at any time. While these facts will be enough to justify the development – or even the construction – of Space Elevators, the design of Space Elevator has another element that makes it uniquely ideal for large-scale interplanetary travel. Space elevators have a base fixed at the equator and as such the rotation rate of the earth at 360 degrees per day. Thus the apex of a space elevator of length 100,000km will have a velocity of 7.76 km/s. Therefore, the velocity of any object released from the Apex Anchor of the Elevator in the ECI frame would already be well beyond escape velocity. Furthermore, as shown in this paper, there are time when the excess velocity allows for transit to Mars using free release – with no additional Delta V requirements. Thus the excess velocity would obviate the need to use Hohmann transfers and would permit the release of spacecraft at times throughout the synodic period. However, the space elevator also has disadvantages. Specifically, because the space elevator is attached at the equator, it rotates in the equatorial plane and not the ecliptic plane. Thus either Mars at arrival must also lie in the equatorial plane or there must be a plane change of up to 22 degrees at departure. This issue significantly complicates the analysis of benefits of the space elevator. To date, however, this question is not well understood, as there has been no quantitative study of the Delta v savings and launch windows enabled by the development of space elevators.

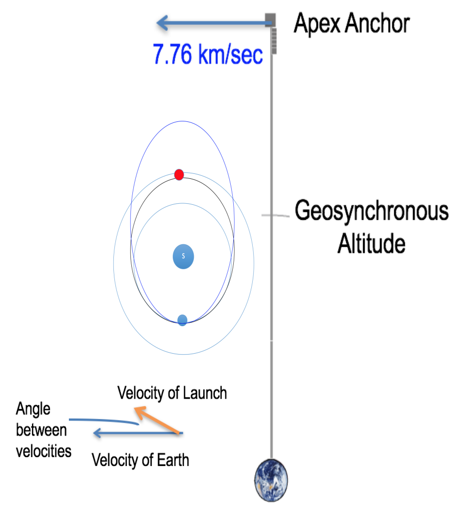

Figure 1: 100,000km Space Elevator Launch Geometries[7]

The purpose of this paper, then, is to assume a space elevator of length 100,000 km and quantify the Delta v requirements for Mars transfer and orbital insertion as a function of desired launch date. First, we explore the question of transfer to Mars using free release. That is, the only Delta v is an orbital plane change and this plane depends on the position of Mars at arrival. This analysis does not include the Delta v needed for orbital capture at Mars on arrival and simply calculates the release time (which occurs once a day) when a free release trajectory will intersect with Mars. Second, we explore the minimum Delta v trajectory including Delta v for both launch and orbital insertion at Mars as a function of date. This approach calculates searches over a set of flight times, calculating the minimum Delta v required for Lambert transfer over all possible release times for a given day. These results demonstrate that space elevators significantly reduce the total Delta v required for Mars transfer and insertion over any conceivable earth-based rocket launch scenario.

2.0 Methods:

For the construction of the code there are three key things that needs to be determined so that the search parameters of the problem are fully understood. The length of the space elevator itself is of critical

[5] Richardson, Derek. "Elon Musk Shows off Interplanetary Transport System."
[6] Harrison, Todd. "Space Environment: Total Launches by Country."
[7] Torla, James, Optimization of Low Fuel and Time-Critical Interplanetary Transfers…
[8] Fitzgerald, M, R. Penny, P. Swan, C. Swan, Space Elevator Architectures and Roadmaps

importance to the expiration of the subject since it is the length of the space elevator that provides the velocities necessary for interplanetary travel. For the study, we selected the 100,000 km[8] Space Elevator described by the International Space Elevator Consortium in the Space Elevator Architecture and Roadmaps. This Space Elevator Will produce a velocity of approximately 7.75 km/s in the Earth's equatorial plane[8]. This heliocentric velocity vector is determined by the velocity of the Earth in the heliocentric frame combined with the velocity vector of the apex in the ECI coordinate systems which is solely a function of release time. The velocity vector of the earth is determined by launch date. This launch date influences the relative location of the planets during their synodic period and is the main determinant for the time of flight and the delta V required for interplanetary travel. For Earth and Mars, for example, the synodic period is approximately 26 months during which the two plants get as close as 54.6 million[9] km. There is of course, some variation in the minimum distance between planets since no planet has a perfectly circular orbit. However, the effects of the eccentricity were discounted. That is, each planet was considered to have a circular orbit with no variation in interplanetary distance between synodic periods. Without any requirement to pick particularly years due to orbital eccentricities, we selected the synodic period beginning with 1 January 2035 and ending with 28 February 2037; around when the first Space elevator as proposed by the ISEC might begin operations.

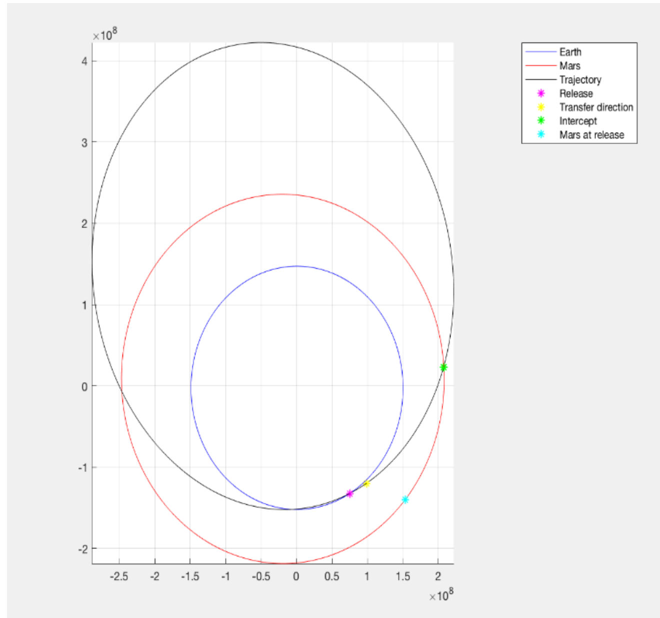

Figure 1: Free Release Flight path, July 2035

The launch time was a search parameter within the algorithm and is parameterized my LST at the root of the elevator. While it is true that the space elevator can deliver objects to orbit at any time, the precise timing for the release of the spacecraft from the space elevator matters a great deal since it only takes four minutes for the Earth and the Space Elevator to move by 1 degree. To keep things simple, a release time was discretized into 4 minute intervals. If additional precision is required, these intervals can be decreased.

Two algorithms were proposed, both implemented in Matlab. The first algorithm searches for free-release trajectories. That is, trajectories with no Delta v required other than transition to the ecliptic plane and orbital injection upon arrival at Mars. The second code utilizes Lambert's Problem to find the absolute Delta V required as a function of TOF and release time. The algorithm searches for the minimum Delta v over all release times for a given day and over all times-of-flight up to 365 days.

2.1 Implementation of the Free Release Algorithm:

The first script begins by setting a couple constants and operating parameters like the time period or the simulation for the length of the elevator. One key operating parameter is that of Phase Change 'PC' or No Phase Change 'NPC'. This variable is used to moderate whether a burn is made to account for the plane change from the Equatorial plane to the Ecliptic. When NPC is selected the code will only return the flight paths where the spacecraft intercepts Mars solely due to the initial release velocity.

[9] Prussing, John E. and Conway, Bruce A., Orbital Mechanics, Second Edition, December 2012
[10] Torla, James, Optimization of Low Fuel and Time-Critical Interplanetary Transfers using Space Elevator Apex Anchor Release: Mars, Jupiter and Saturn

The first computation done is to find the planetary elements of both Earth and Mars at the given launch date and time using J2000. From there, the velocity of the spacecraft can be calculated from the Earth's initial orbital elements, the time of release and the length of the elevator. The position and velocity vectors in the heliocentric frame are then converted to heliocentric orbital elements.

The Delta V necessary to account for the plane change from Equatorial to the Ecliptic was then calculated using the law of sines with an angle change determined by angle between the heliocentric velocity vector and the orbital plane. The magnitude of the velocity vector is not changed during this operation Once the transfer orbit has components solely in the Ecliptic plane, the orbit is propagated using the polar equation out to the Martian orbital radius. The code then checks whether the craft is within Mars' sphere of influence at that point in time. When it is, the flightpath is a successful intercept, the Delta V due to intercept velocity at Mars is calculated using the Oberth effect. This process is repeated for each possible release time on each day within the given search parameters.

2.2 Implementation of Lambert's Method Algorithm:

The Lambert's initial setup is similar to the Free-release script. For each possible release time, we calculate the initial heliocentric velocities and use these velocities to determine the minimum elliptic Time of Flight for the Lambert's problem. Recall that Lambert's problem is: given two position vectors and a TOF, to determine the corresponding initial and final velocity vectors. Our algorithm implements the solution of Lambert's problem using the method and a Matlab code (with minor modifications) developed by Richard Battin. This yields, for a given position of Earth, and TOF, the velocities at both Earth and Mars that are required to intercept Mars for the given TOF.

The search for the optimal Time of Flight is discretized using 1/10 of a day from the minimum elliptic TOF to an arbitrary maximum of 365 days. The proposed position vector of Mars at intercept for each TOF is calculated using standard orbit propagation. For each release time and TOF, the solution to Lambert's problem now yields an initial and final velocity vector. The first Delta V for the flight is now calculated by finding the difference between the initial velocity and the velocity of the apex anchor. The second Delta v is found by finding the difference between the velocity at arrival and the velocity of Mars. This relative velocity is then propagated in the Martian sphere of influence to a periapse equal to the martial radius and the Delta v required for transition to highly elliptic (e=1) orbit is calculated. The initial and final Delta v's are summed and the minimum Delta v for each proposed launch date is calculated.

3.0 Results

A standard mission to Mars during the Hohmann transfer window in 2035, as described in NASA's Interplanetary Mission Design Handbook (Appendix A), requires a Delta V of approximately 12 km/s to arrive at Mars within 200 days. During the same time period, with a No Phase Change free-release trajectory (Figure. 3), a Space Elevator can allow a spacecraft to rendezvous with Mars in 170 days with a minimum delta V of 3.7 km/s. The Space Elevator can also deliver a craft to Mars within 76 days with 10 km/s of Delta V during the same time period that's highlighted in Figure. 6.

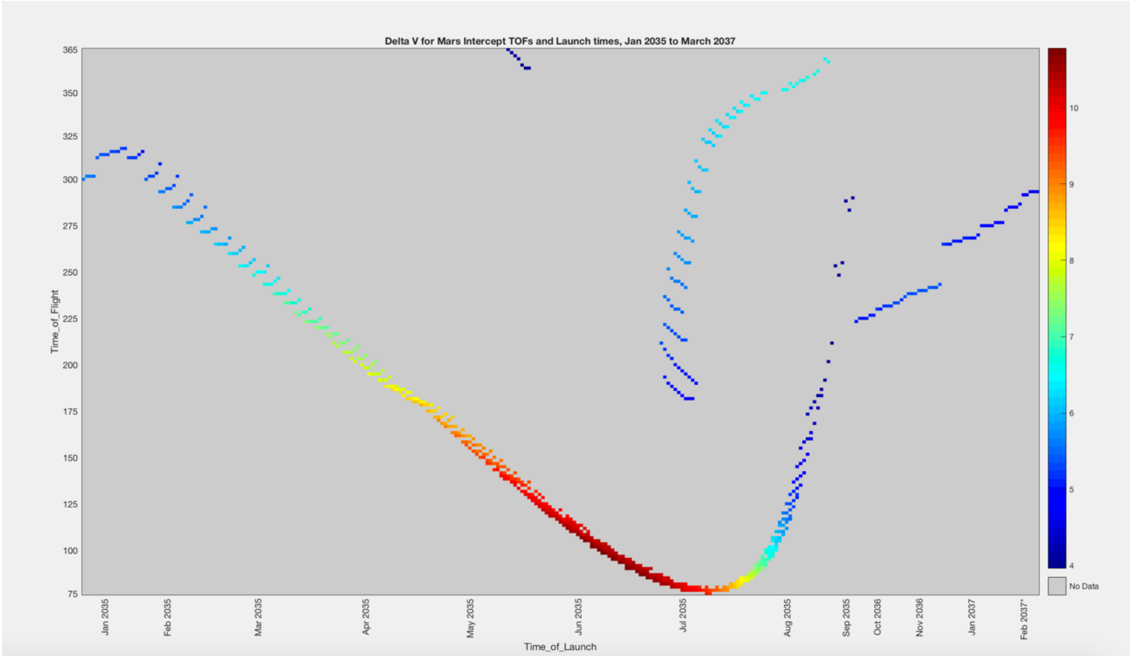

Figure 3: Delta V heat map for Free Releases, Jan 2035 to Mar 2037

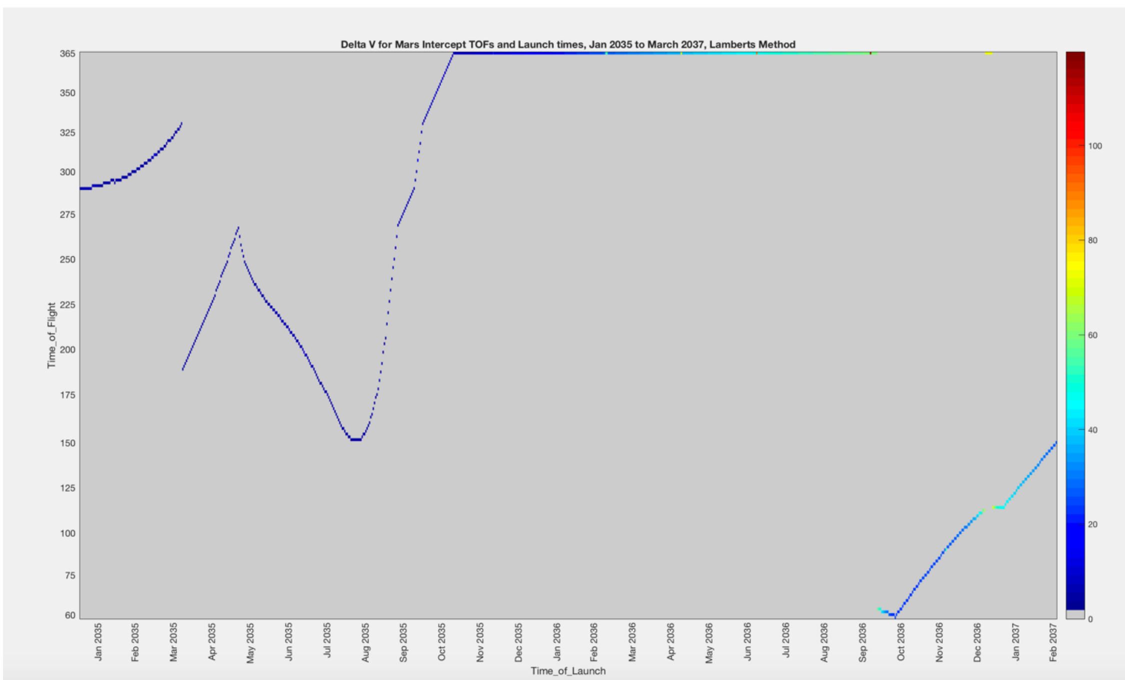

Figure 4: Delta V heat map for Lambert's script, Jan 2035 to Mar 2037

In fact, while the optimal Hohmann transfer window is limited to three or four weeks, a Space Elevator offers trajectories that are lower Delta V and quicker every week for a period of 11 months as shown in Figure 5. Between November 2034 (which is identical to Jan 2037 due to the synodic period) and October 2035, there are an abundance of intercept trajectories available each week.

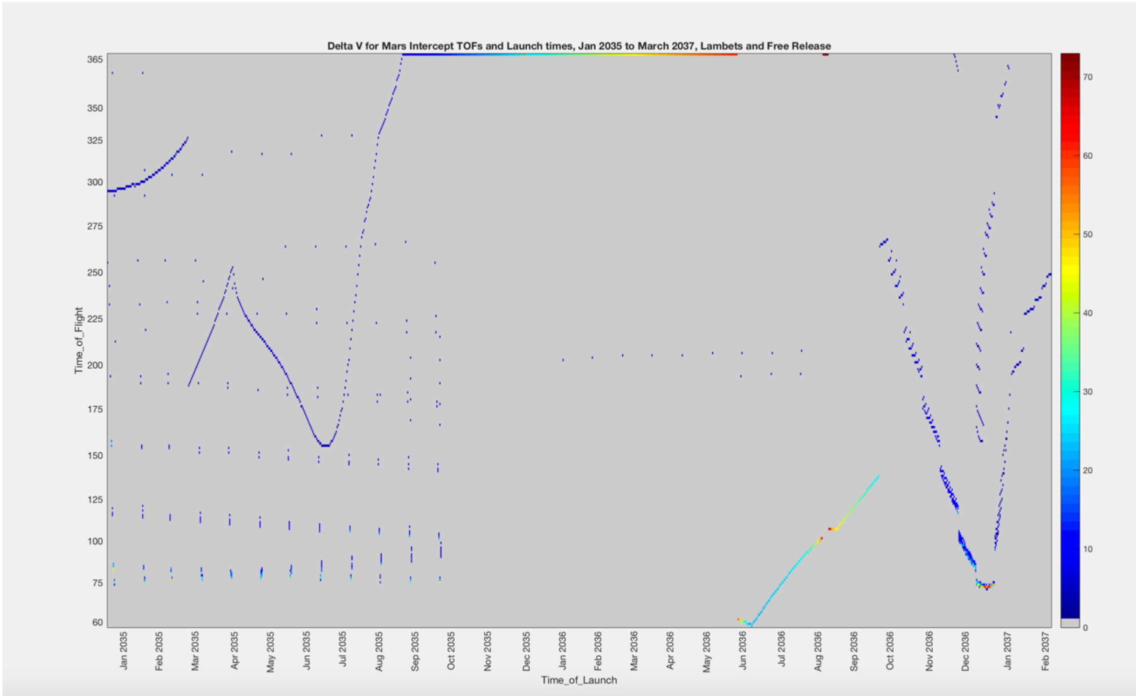

Figure 5: Delta V combined heat map for Free Releases & Lambert's Problem, Jan 2035 to Mar 2037

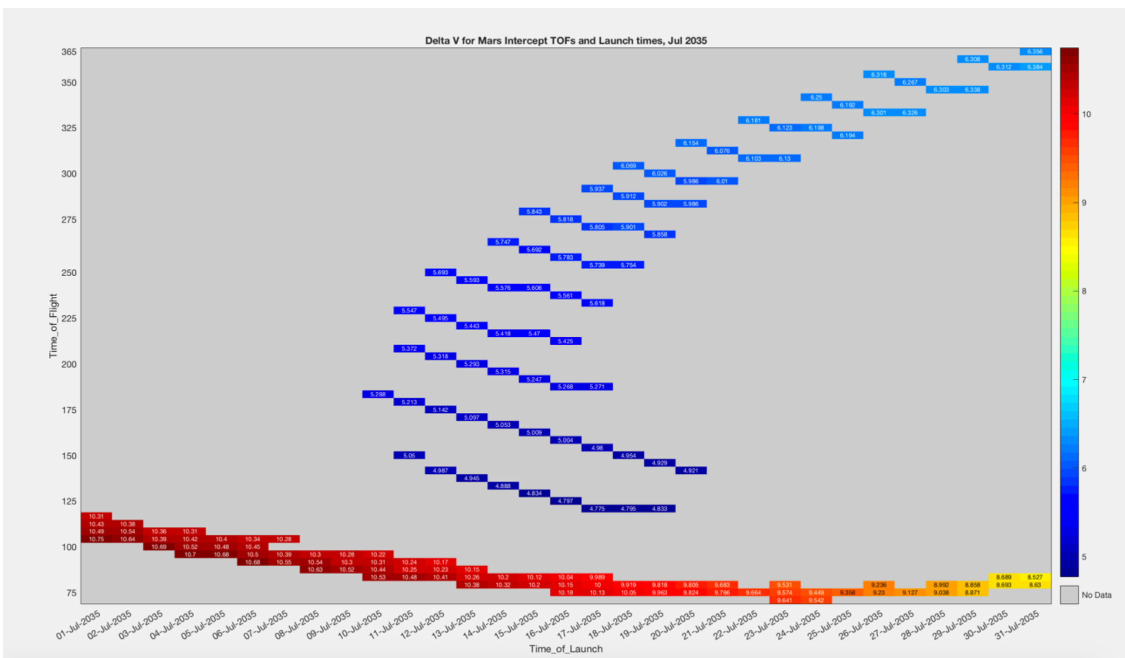

Figure 6: Delta V heat map for Free Releases, July 2035

The combination of the Lambert's Method and the free release method demonstrate the wide range of possible interplanetary flight paths to Mars provided by the Space Elevator. However, the Space Elevator launch window does have limitations. Due to the dynamic nature of the orbital mechanics of interplanetary flight, there is a large amount of variance in both the of flight and in the Delta Vs found throughout the Earth/Mars synodic period. For example, in the free release heat map (Figure 3) there are large periods of time where it is simply not possible for the spacecraft intercept Mars without any burn other than the plane change. Because of this, there are no free release intercepts at all during the first half of 2036. In a similar manner, there are large periods of time – especially during first six months of 2036 – where there are no low Delta V intercepts. As shown by the Lambert heat map (Figure 4), there are no launches during that 6-month window that require less than 20 km/s of Delta V. Despite this, the space elevator offers a plethora of launch times with reasonable Time of Flights and Delta Vs far beyond the capacity of contemporary rockets.

4.0 Conclusion

Throughout the cycle, the space elevator presents a large number of launch. During the optimal launch window, a Space Elevator provides time of flights comparable to or less than the standard Hohmann Transfer windows at Delta V budgets as low as 1/4th of the Hohmann Delta V budget. It also provides time of flights up to 1/3 as long as a Hohmann Transfer for comparable Delta V budgets. As a result, a Space Elevator of the proposed length would significantly decrease the cost of interplanetary exploration and colonization.

However, perhaps the main benefit of the Space Elevator is in the broad range of possible flight times. As mentioned before, the construction of a Space Elevator would increase the optimal Earth/Mars transfer window from 4 weeks to 11 months. This alone would significantly alter the astronautics industry since a few week project delay would no longer postpone the launch of a spacecraft for a full 25 months. Projects could just use a later launch slot that would require a minor increase in fuel costs rather than the large fuel requirements imposed at the boundaries of the Hohmann Transfer Window.

Furthermore, the Space Elevator launch times contain a great deal of flexibility within each time period. Figure 6 shows the Free Release Delta V heat map for July of 2035, which is the month with the most intercepts with Mars. During this month there are a great number of different launch types available every day from the Space Elevator. On July 16th, for example, there are 3 separate low time of flight launch times and 6 separate low Delta V launch times. Different clients with different time windows and budgets could purchase the launch time that best fits their needs with the greater flexibility offered by the Space Elevator.

Finally, we note that there are free-release launches which do not require a plane change for intercept. In these launches the orbital plane at release intersects the ecliptic plane at Martian arrival. However, this study does not account for the benefits of these trajectories and they are left for later research.

While it is true that a Space Elevator is not a panacea that would allow transit at any time to any place for free, the design of a Space Elevator increases the options available for interplanetary travel both throughout the synodic period and throughout each day. Those mission that require speedy transit would use the 11 month transfer window, while those that have no urgency could utilize the mid-cycle slow period where Delta Vs could be brought down with time of flights beyond 365 days. The numerous, quick, and economical launch options provided by the Space Elevator would revolutionize interplanetary flight, lowering the economic impediment that bars Humanity from exploring the Heavens.

5.0 Appendices

Appendix A:

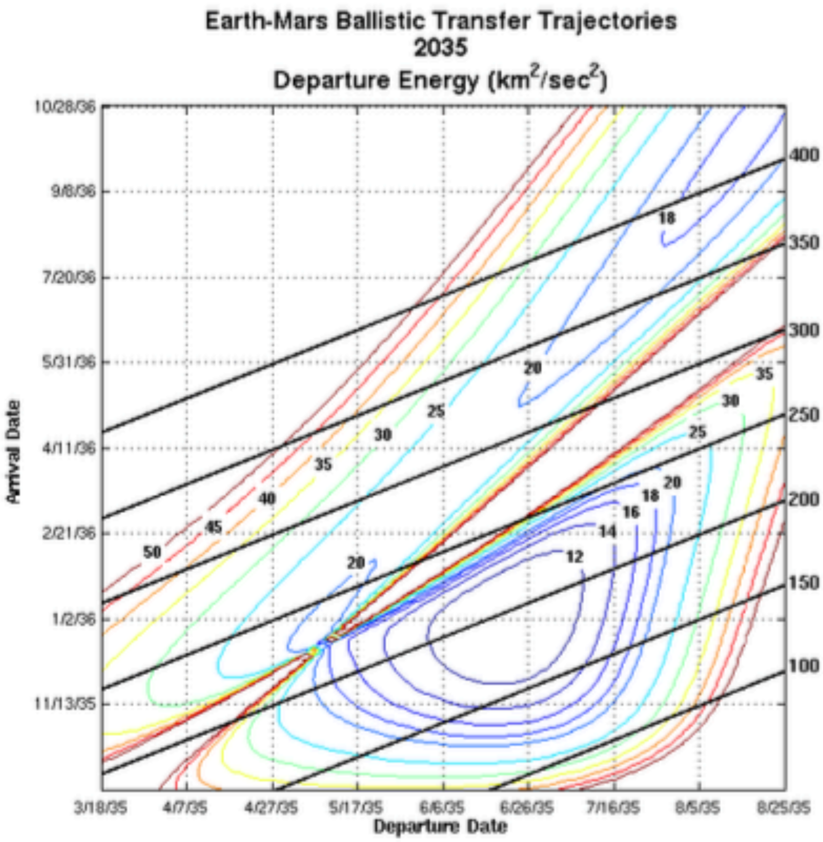

Figure 7: Earth/Mars Interplanetary Flight heat map, NASA Interplanetary Mission Design Handbook[11]

Appendix B:

Recognition: Thanks to Dr. Matthew Peet, Dr. Peter Swan, and to all the students who assisted with this project:
Mars Team Members: Mark Lyons, Runa Nakamura, Renzo Curay De La Ros, Shawn Michael Bauer, and Nathan Renard
Io Team Members: Nicholas Iannacone, Tyler Mebane, Avi Brahmbhatt, Samuel Bolar, Jose Valenzuela, Jonathan Johnson, and the team leader Ryley Miller

Appendix C:

Matlab codes and Algorithms: https://github.com/james-torla/Apex-Anchor-Release

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