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A SURVEY OF MISSION OPPORTUNITIES TO TRANS-NEPTUNIAN OBJECTS - PART 7: UTILIZATION OF A DELTA-VEGA MANEUVER

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Trans-Neptunian Objects have gained interest in lieu of the success of the New Horizons mission. This paper seeks to further the design possibilities for such missions by offering sixteen trajectories to TNO's by incorporating a Delta-VEGA maneuver, which allows for increased payload mass. These trajectories were simulated using Spaceflight Solution's Mission Analysis Environment software, which allowed for constraining of mission parameters for optimization. The trajectories were made to have a C3 below $40\frac{km^2}{s^2}$, minimized transit time, and minimized ΔV. Results are visualized in Figures 3-6 as well as Table 1, which contain all relevant descriptive parameters.

Nomenclature

C3	=	Characteristic energy
ΔV	=	Change in velocity
m_o	=	Initial mass of vehicle
m_f	=	Mass of vehicle post-flight
I_{sp}	=	Specific impulse
g_o	=	gravitational acceleration

Introduction

Launched in 2006, the New Horizons mission to Pluto and Kuiper Belt object 2014 MU_{69} has been, as of this paper's writing, the only spacecraft launched with the intent of exploring a trans-Neptunian object (TNO). The results of the successful January 1, 2019 flyby of the TNO have sparked a myriad of studies such as that by S. A. Stern et al., which highlight the unique orbital and geological characteristics of the body, as well as postulate the origins of such objects.[13] The insight provided by these results, combined with the ever-increasing catalog of TNO's

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spanning the Kuiper Belt region, are likely to inspire interest in additional missions to such objects. As such, the creation of mission profiles utilizing a myriad of trajectory strategies in the coming decades is warranted, and research into trajectory design possibilities for TNO's has been previously outlined by our research group in Mcgranaghan,[1] Gleaves,[2] Kreitzman,[3] Baskaran,[4] Johnson,[5] and Peralta[6] under the mentorship of J. E. Lyne.

As a derivative of these previous works, this research proposes a suite of flyby mission profiles which include the implementation of a Delta-V Earth Gravity Assist (ΔVEGA) maneuver to sixteen TNO's. The objects were selected due to either their unique physical characteristics or proximity to our Solar System in the coming decades. While the ΔVEGA was first suggested by Stancati et al. as a means of lowering characteristic energy requirements for trips to the outer planets,[13] little has been written regarding their application to missions to Kuiper Belt objects. As such, this maneuver was integrated into our trajectory creation strategy with the intent of: decreasing required characteristic energy (C3), decreasing overall mission ΔV requirements, and increasing available spacecraft mass. While coming at the expense of increased transit time over previous approaches investigated, the ΔVEGA trajectories offer future mission planners a diverse design space in which various spacecraft/launch vehicle combinations could be employed due to the greater possible spacecraft mass at their disposal. As was the case in previous papers produced by this group, the large heliocentric distances of the TNO's selected would render photovoltaic cells impractical, and a radioisotope thermo-electric generator (RTG) would be used as the power source for such missions.

The primary scientific goals of any of the candidate missions proposed in this piece are, at minimum, similar to that of the New Horizons Mission: 1) characterization of the global geology and morphology of the target planet, 2) mapping its surface composition and temperature, and 3) evaluation of any possible atmosphere. Therefore, a baseline set of instrumentation of such spacecraft would include a visible and infrared imager/spectrometer, an ultraviolet imaging spectrometer, a telescopic camera, an energetic plasma spectrometer and a solar wind and plasma spectrometer. This being said, the additional mass afforded by the implementation of a ΔVEGA allows for additional mission goals if desired, and could incorporate (as was done in this paper) the inclusion of multi-target missions the Ice Giants of our Solar System or the use of one or more impact probes at primary or secondary objects of interest.

Scientific Background

TNOs are typically found in the Kuiper Belt and the more distant Oort Cloud. Kuiper Belt Objects include Pluto, as well as a series of other larger bodies such as Haumea, Gonggong, Makemake, and Quaour. Trans-Neptunian objects are important objects of study as they contain a variety of unique materials that can give a better understanding of the formation of the Solar System. Organic materials as well as water ice can be found on the surface of these bodies, and having the opportunity to study the effects of deep-space conditions on organic compounds is a point of interest. Additionally, many of these bodies have interesting orbits, with some reaching a semi-major axis of 500 AU, as evidenced by Sedna. Table 1 below shows the physical and orbital characteristics of select TNOs that were examined in this survey.

An example of interesting characteristics in TNOs is evidenced by Lempo and Huamea, which are trinary systems. Trinary systems are rare occurrences among known TNOs, with a total of three TNOs known to have more than two components: Haumea and Lempo as well as Pluto. Additionally, studies into Haumea have shown that it is a rapidly rotating object that has resulted in it having an oblong shape. Beyond these objects, Quaour is another interesting body since it has a higher density than the other bodies examined in this survey. Sedna has an extremely elliptical orbit that is also extremely large, with a semi-major axis of 495 AU. Overall, the bodies explored in this paper have a variety of interesting characteristics that warrants further study, as it would provide valuable scientific information about the formation of our solar system and the interactions within it.

Table 1. TNO Trajectory- Related Parameters.

Body	Diameter (km)	Semi-Major Axis (AU)	Eccentricity	Inclination (deg)	Geometric Albedo (%)	Mass (10^{20} kg)	Density (g/cm^3)
Gonggong	1252±43	67.5	0.5	30.6	13±1	17.5	1.75±.07
Haumea	2100x1680x1074	43.2	0.19	28.2	80.4±9.5	40.1	2.6
Huya	458.0±9.2	39.7	0.28	15.5	8.3±0.4	-	>1.43
Ixion	1065±165	39.6	0.24	19.6	14.1±1.1	-	-
Lempo	393.1±26.8	39.5	0.23	8.42	7.9±1.3	.128±.001	.542±.317
Makemake	1502x1430	45.56	0.158	29	77.0±2.0	30.1	1.7±.3
Orcus	~1500	39.4	0.22	20.6	23.1±1.8	6.35±.02	1.53±.15
Quaoar	1200±200	43.5	0.03	8	12.7±1.0	13-15	2.18±.43
Salacia	901±45	42.2	0.11	23.9	4.4±0.4	4.92±.07	1.50±.12
Sedna	~1500	495	0.85	11.9	41±39	-	-
Varuna	900±140	43	0.05	17.2	12.7±4.2	-	.992±.086
2002 AW197	890±120	47.4	0.13	24.4	11.2±1.2	-	-
2002 MS4	934±47	42	0.14	17.7	5.1±3.6	-	-

Trajectory Analysis

Trajectory Software and Visualization

Heliocentric trajectories to the various target bodies were designed using Space Flight Solutions' Mission Analysis Environment (MAnE) tool.[A] This software implements a routine known as the Heliocentric Interplanetary High-thrust Trajectory Optimization Program (HIHTOP), which seeks to identify missions between two or more solar system bodies that are optimum with respect to some predetermined criterion, subject to the satisfaction of specified constraints and end conditions.[A] Additionally, the trajectory visualization tool built into MAnE allowed for better initial parameter estimation of Earth departure and planetary flyby dates, allowing for mission profiles to converge to acceptable criteria in a more timely fashion.

Initial Trajectory Design Using ΔVEGA

The starting point for the trajectory design process was referencing previous missions to the outer Solar System and Kuiper Belt, including Voyager 1 and 2, Pioneer, Galileo, Cassini and New Horizons.[16-19] These references revealed the success of utilizing multi-planet swingby architectures similar to that of the Cassini and Voyager missions, as well as designs incorporating single planetary flybys at either Jupiter or Saturn. Unlike the previous work of McGranaghan et al., which eliminated Venus-Venus-Jupiter Gravity Assist (VVJGA) multi-planet swingbys due to undesirable performance characteristics, it was hypothesized that incorporating a Jupiter Gravity Assist (JGA) in addition to the ΔVEGA maneuver would minimize the required ΔV of the spacecraft.[1] The result would be an Earth-Earth-Jupiter (EEJ) trajectory, that would allow for secondary (EEJx) and primary (EEJxy) targets to be reached. This potential mission structure was first tested on trajectories to Sedna, and once successful was subsequently applied to the remaining TNO's of interest.

Once the general trajectory architecture was decided upon, attention could then be brought towards determining specific constraints on mission profiles. While certain constraints and/or end conditions varied on a profile-by-profile basis, some universal criteria were established in order to develop initial results:

1) The intended launch date of any proposed mission must be at least eight years after the writing of this paper, and before 2060. The lower bound constraint was made in reference to the New Horizons mission, which took approximately eight years to manifest into a launch-ready spacecraft.

2) The characteristic energy of any proposed mission must remain below $40 \frac{km^2}{s^2}$. This constraint was made after referring to the market-available launch vehicles present on the NASA Launch Vehicle Tool, in conjunction with the desire to increase the available spacecraft mass from the 476 kg New Horizons vehicle.[18,B]

3) The geocentric declination of the asymptote (DLA) of any proposed mission must remain within $\pm 28.5°$. This decision is grounded in the fact that these are the reasonable DLA bounds for a mission sent to orbit from the Kennedy Space Center in Cape Canaveral.

4) The Earth passage distance of any proposed mission cannot be less than 1.05 Earth radii during the ΔVEGA maneuver. This constraint was made in reference to the spacecraft Messenger, which travelled at the aforementioned Earth passage distance.

5) The Jupiter passage distance of any proposed mission cannot be less than 2.2 Jovian radii during the Jupiter swingby. This constraint was made in reference to the radiation shielding research conducted by J. G. Stewart, who concluded that this distance, travelled by Pioneer 10 and 11, could be achieved given proper spacecraft shielding.[12]

6) Proposed TNO missions must have a transit time (time of flight) of less than thirty years. While arbitrary, the intuition behind placing this limit was one of concern for high turnover of staff monitoring the project over time, and out of courtesy to allow those who started the project to see it through to completion.

With these fundamental criteria established, initial trajectories for each TNO were created and analyzed for other constraining criteria that could be established to provide improvement to individual mission profiles.

Trajectory Optimization Techniques

After a quality target has been established, the optimization process begins to reduce C3, ΔV, and transit time while keeping healthy passage distances and DLA values. Multiple techniques are used to do this. The first and most trivial is the movement of the dates of arrival and departure at each leg of the trajectory. Oftentimes, the best mission design consists of a space burn that is on the opposite side of its trajectory relative to Earth. This allows for the best use of ΔV to change the overall trajectory. This can be seen in the 2002 MS4 trajectory in figure 1. Secondly, the position of Jupiter is very important to the burns required to send the spacecraft to the correct location. The most common position for Jupiter is when it is in almost the same angular position as the optimized space burn. However, experimenting within a year of this location leads to the most optimized trajectory because the location of the TNO matters to this optimization process as well. It is specifically important that the TNO is in the correct inclination relative to Jupiter so that the required swingby does not need to be too close to Jupiter to change its path. It is also sometimes helpful to try a trajectory when Jupiter makes a full revolution around the Sun. This could put the TNO in a much more favorable position.

The other major technique used to improve trajectories is the addition of hard constraints on some of the departure ΔVs, flight times and arrival and departure excess speeds. Using this technique, a target ΔV could be set for the space burn and powered swingby burn. Flight times were important to constrain because MAnE would try to optimize to the minimum ΔV, which happened to also be when the time of flight was the longest. Although you might be able to get to a target TNO with little to no ΔV, the transit times as high as 40 years are not reasonable in this application. Constraining the arrival excess speed was also a way to drive down the flight time. This constraint usually drives up the ΔV required at Earth, whereas the flight time constraint might change the point and time of the TNO flyby. The departure excess speed constraint was specifically used to dictate the C3 of the trajectory. Constraining this to a low value and then seeing the effects on the other parameters was important to finding the correct combination of parameters.

All in all, the key to optimizing these trajectories was the use of trial and error with all of these techniques. As local minimums were found, it was important to investigate parameters around the ones optimized to to see if there are lower minimums in the design space. This is especially important if the solution space converges to an unusable solution due to high ΔV, C3 or transit times. Using a combination of these techniques allows for further exploration of the solution space in this case to find a usable alternative. A visualization of the trajectory resulting from the application of this optimization scheme can be seen in Figure 1 below.

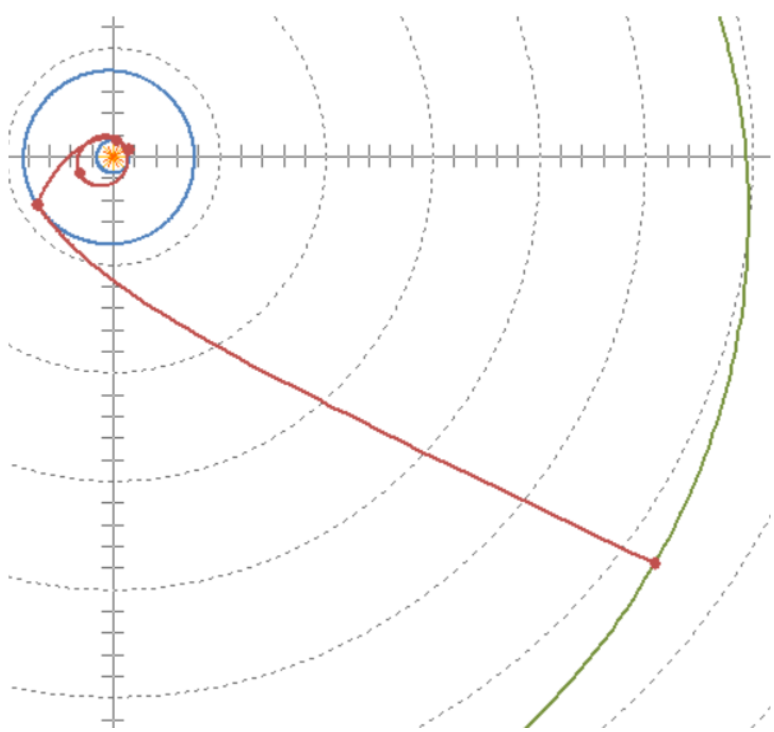

Figure 1. Optimized mission to 2002 MS4

TRAJECTORY RESULTS

Launch Vehicle Selection

Prior to calculation of critical mission parameters such mass on target for TNO's, it was decided that the Atlas V 551 would be the simulated launch vehicle of choice. This decision was derived from the fact that this version of the Atlas V possesses the greatest mass-to-orbit capabilities (aside from an Expendable Falcon Heavy, whose capabilities are superfluous given our findings), as well as it being a standard of comparison to previous work done within our group.[2] Referring once again to NASA Launch Vehicle Tool, the capable payload mass as a function of C3 can be described as seen in Figure 2 below:

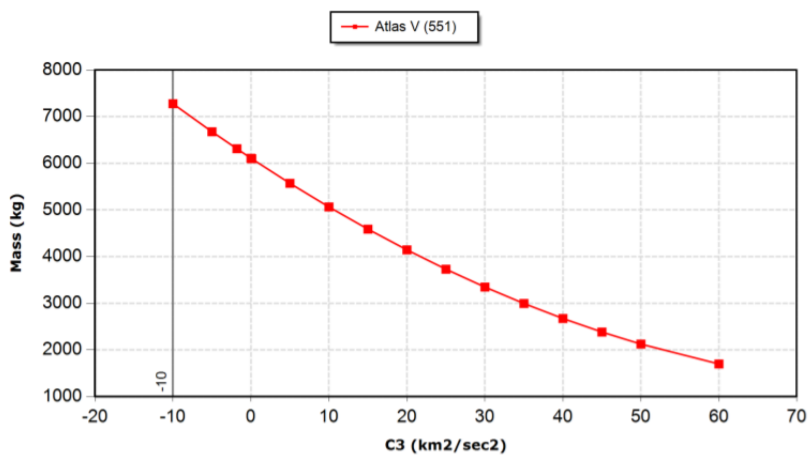

Figure 2. Mass vs. C3 Plot for the Atlas-V (551) Rocket.

Due to the frequency in which this curve would be referenced, a second-order fit for initial payload mass as a function of C3 was created to represent the available data seen in Figure 2, which can be defined as:

$$m(C3) = 0.5763*(C3)^2 - 106.9*(C3) + 6033 \quad (1)$$

The curve fit in Equation (1) had an R-squared value of 0.9988, thus indicating that the calculated values involving initial spacecraft mass would reflect the truth values to a high degree.

Single Body Missions

Within this paper, the term "single body mission" refers to a mission that launched from Earth, followed an EEJ trajectory, and then concluded its mission by performing a flyby of a specific TNO. Of the sixteen mission profiles presented in this paper, fifteen of them are considered to be single body missions. It was known from the outside of this design problem that a thirty day launch window would be created around our mission profiles as a means of testing the rigidity. This simulates the real-world possibilities of launch movement forward or backward within a calendar month from inclement weather, launch vehicle technical difficulties, etc. The resulting parameters of interest from applying a launch bucket to seven of the fifteen single body mission trajectories can be seen in Figures 3-6 below.

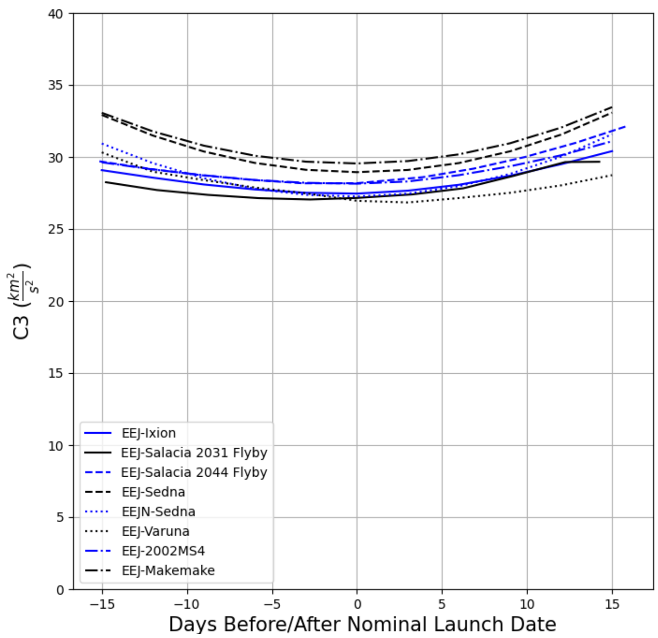

Figure 3. C3 vs. Days Before/After Nominal Launch Date for Various TNO Trajectories.

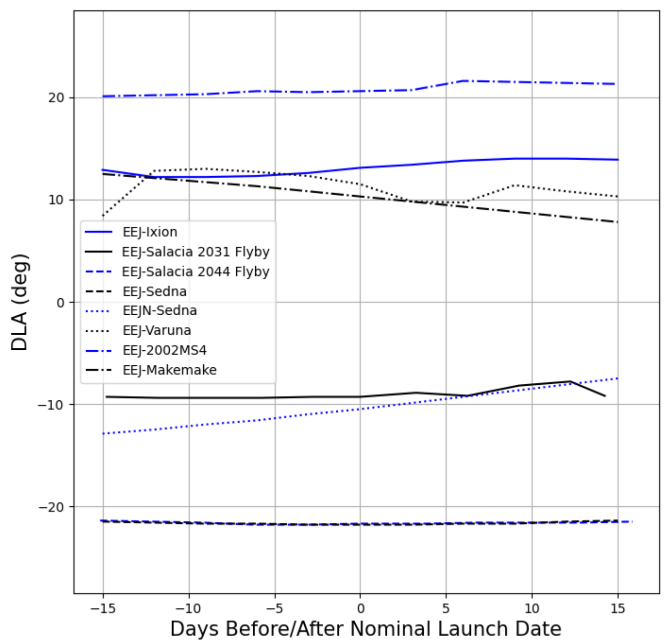

Figure 4. DLA vs. Days Before/After Nominal Launch Date for Various TNO Trajectories.

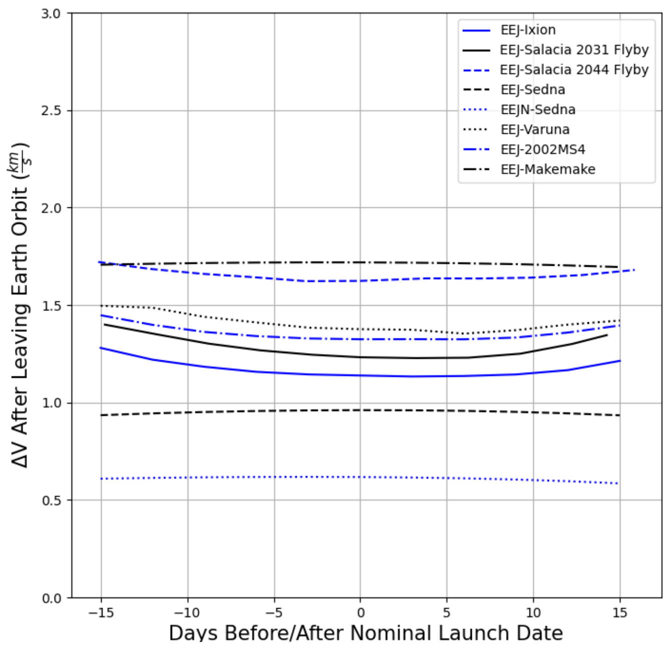

Figure 5. ΔV vs. Days Before/After Nominal Launch Date for Various TNO Trajectories.

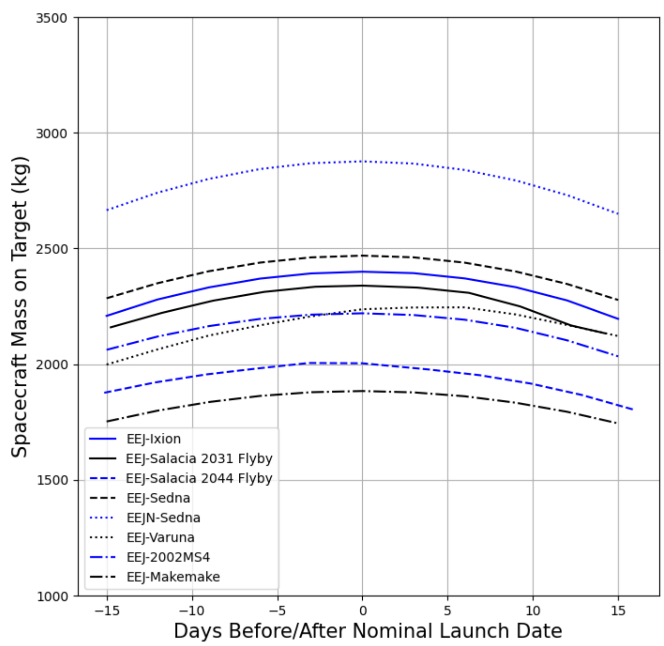

Figure 6. Spacecraft Mass on Target vs. Days Before/After Nominal Launch Date for Various TNO Trajectories.

At the time of this abstract writing, the remaining profiles require further analysis, but initial results have proven promising enough to include them in the total count of missions this paper seeks to discuss. One can see that the above trajectories satisfy the desired mission criteria of C3 and DLA. The observed arrival V_∞ at each TNO are consistent with the observed arrival excess speed of 13.78 $\frac{km}{s}$ achieved during the New Horizons flyby[15]. As for the simulated ΔV values, it should be noted that the values presented do not include the initial velocity to leave Earth's orbit (generally an additional 4.5$\frac{km}{s}$), as it was assumed this would be handled by the heavy lift vehicle. This being said, these values are still well below that of the 8.92$\frac{km}{s}$ observed during New Horizons, and is a product of the fact that HIHTOP optimized around minimizing this parameter.

This leaves discussing the calculations involved with determining the possible mass on target for a given TNO trajectory, which started with tabulating the maximum possible initial spacecraft mass by utilizing the C3 data available in Table 1 and the second-order fit described in Equation (1). Following this calculation, the fundamental rocket equation shown in Equation (2) was used to calculate final spacecraft mass, or possible mass on target to the TNO.

$$m_f = m_o e^{-\frac{\Delta V}{I_{sp} g_o}} \tag{2}$$

Where m_o denotes the initial spacecraft mass, m_f denotes the final space mass, ΔV denotes the net change in velocity experienced by the spacecraft, I_{sp} denotes the specific impulse of the main spacecraft engine, and g_o denotes the gravitational constant of the Earth. Given current industry standards, the specific impulse of the spacecraft's main engine was conservatively simulated at 300s, and could be modified if desired. The primary takeaway from the implementation of a ΔVEGA maneuver is in the fact that nearly all optimized TNO trajectories could carry approximately four times the mass of that required on for the New Horizons mission (476 kg), opening new possibilities to the kinds of experimentation and instrumentation that could be incorporated.

With the launch window proving to have an inconsequential impact on the performance characteristics of interest, the correlating trajectory parameters from the "best-case" launch date for each of the seven TNO trajectories can be seen in Table 1 below.

Table 2. TNO Mission and Trajectory- Related Parameters.

Target	Mission	Launch Date	DLA (deg)	C3 (km^2/s^2)	ΔV (km/s)	Time of Flight (years)	E_r (Earth Radii)	R_f (Jovian Radii)	Arrival V_∞ (km/s)	Mass on Target (kg)
2002 MS4	EEJ2002	10/18/2037	20.6	28.15	1.32	16.7	1.05	2.70	14.98	2220
Ixion	EEJI	11/17/2038	13.1	27.46	1.14	14.8	1.10	10.79	11.80	2399
Makemake	EEJM	7/19/2034	10.3	29.55	1.72	18.0	1.05	3.21	16.02	1883
Salacia	EEJSa	1/15/2029	-9.3	27.16	1.23	18.4	1.05	6.26	13.0	2339
	EEJSa	2/27/2042	-21.7	28.18	1.62	18.2	1.10	10.49	13.3	2005
Sedna	EEJSe	2/24/2042	-21.8	28.94	0.96	25.5	1.05	2.63	15.97	2469
	EEJNSe	1/17/2041	-10.5	27.25	0.62	29.2	1.05	2.20	14.88	2876
Varuna	EEJV	7/13/2032	11.5	26.96	1.38	22.5	1.20	7.87	9.42	2245

Of equal importance to launch bucket analysis is the study of how the desired performance characteristics vary as a function of the transit time, as one could have a mission profile that favorably trades off a decrease in ΔV for an increase in time of flight. An example of implementing this technique to the best-case Ixion trajectory can be seen in Figure 7 below:

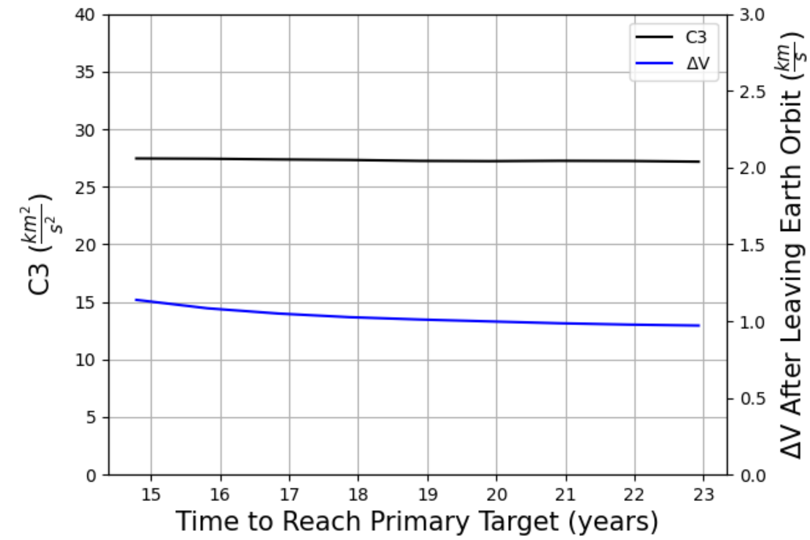

Figure 7. C3 and ΔV vs. Transit Time for Ixion Best-Case Mission Profile

While there is no evident trade-off present between the two parameters for this trajectory set, the merits of the transit time procedure warrant its application to the remaining simulated missions, and will be done as the results of this study are finalized in the coming months. A final area of interest is describing the relationship between Earth and Jovian passage distance with increasing transit time. These parameters follow the known trend of varying as the duration of the trajectory is modified, and specifically will increase with time if not constrained.

Multi-Body Missions

Some missions may have the opportunity for a split of probe to approach a secondary target. The selection of targets is based on total ΔV increase and time of flight to the secondary target. This idea was started late in the process of this experiment, so only one trajectory has some proposed secondary targets. For the EEJ-Salacia trajectory, a split off probe to Neptune is considered. Three different options to neptune were proposed, two of which being an orbiter mission. A probe would split off before the Jupiter flyby, and approach Jupiter in a different way. This makes it possible to approach another target without too much increase in total ΔV. An example of that mission is shown below. As V_{inf} at Neptune increases, the opportunity to orbit decreases. All or none of the below trajectories may be included in the final paper as this is just an example of what could be done for a multi body mission. Future missions may incorporate a split off before the second Earth passage so that there is a greater margin for error in the space flight. Doing this would also open up more split off options and would not require a flyby of Jupiter.

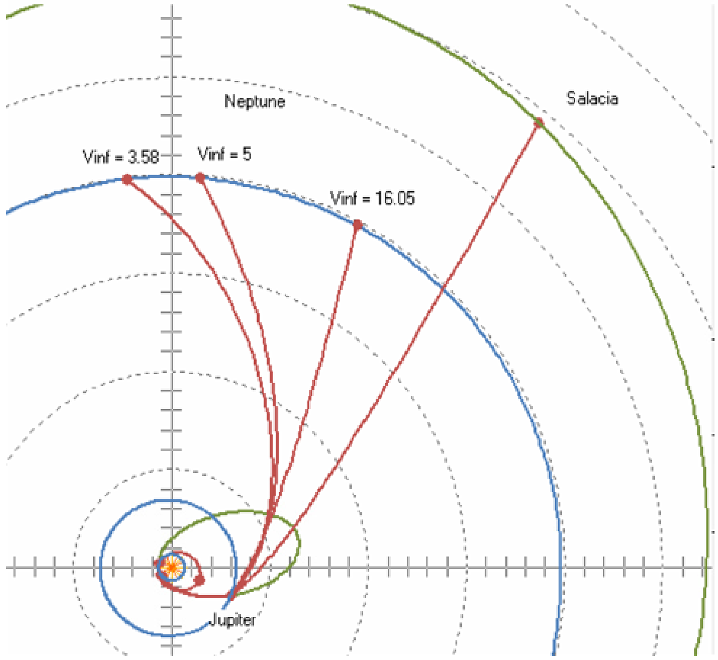

Figure 8. Multi-Body Mission to Salacia and Neptune.

Initial Conclusions

This inspection was successful at the investigation in the use of a ΔVEGA maneuver. It is shown that the trajectories in this paper have improved upon the trajectories previously researched by our group by lowering the C3 to a small enough value to largely increase the throw mass of the launch vehicle used to get out of Earth's orbit. This allows for more mass on board the spacecraft for science, a smaller launch vehicle and/or more targets out of a single trajectory. These improvements allow for an abundance of science to be conducted and the opportunity of shorter launch times at the cost of more propellant on board the spacecraft.

Continuing Work

A top priority moving forward for the research group is completing the optimization of the eight remaining TNO's of interest. This includes conducting both launch bucket and transit time analysis on these mission profiles, and discern if shifting the nominal trajectory date is necessary. Upon completion of these trajectories, more multibody missions will be pursued in an attempt to further diversify the launch opportunities presented in this piece. With the large throw masses calculated in Table 1, multiple New Horizons sized spacecrafts will be able to be sent to more than one target. Another option will be the design of missions that split off, likely prior to encountering Jupiter, that then continue independently to other planets for exploration with orbiters, landers or atmospheric probes. Finally, if time permits, an extension of the work done by J. G. Stewart regarding Jovian Radiation effects on spacecraft will be conducted and applied directly to our intended missions, in an effort to prove robustness of the trajectories created.

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