PARAMETERIZATION OF NUCLEAR ELECTRIC PROPULSION TRAJECTORIES FOR OUTER SOLAR SYSTEM SCIENCE MISSIONS METHODOLOGY

Sean Greenhalge,* Annabella Shaffer,† and Adam Boylston‡

This manuscript addresses the methodology used to create a database of low-thrust missions to outer planets. This database utilizes previous work modeling NEP systems to determine the maximum delivered mass to outer planets based on a range of mission parameters, such as time of flight, launch vehicle, and power system mass. Trajectories were selected which best utilized NEP benefits. Additionally, a discussion on the database outputs for missions to Saturn is included, such as time of flight based on trajectory type and maximum payload, given a specific launch vehicle. The purpose of this work was to create a basis for future mission design, and a tool to investigate general trends across mission options.

INTRODUCTION

AMA supports the Space Nuclear Propulsion program's goal to revolutionize space travel with nuclear propulsion systems through modeling and simulation work. Nuclear Electric Propulsion (NEP) is an exciting technology which utilizes a nuclear system to power electric thrusters. NEP can be utilized in scenarios where solar electric propulsion cannot, such as deep space or in planetary shadow. There is a desire from the science community to understand missions to the outer solar system which NEP enables due to its high performance even in these environments.

This manuscript describes the methodology used to perform parametric analysis of potential NEP missions, which was then used to create a database of science missions to the outer planets of the Solar System: Jupiter, Saturn, Uranus, and Neptune. The parametric analysis was conducted using a combination of:

- Copernicus[1], a NASA developed spacecraft trajectory design tool. Initial reference decks are manually converged directly in Copernicus.
- CAPYBARA (Copernicus Analysis & Processing for Yielding Batch Astrodynamics Results & Assessments), an in-house Python wrapper which runs the sweeps by modifying Copernicus decks, converging the new models in Copernicus, and creating a database of solved normalized trajectories. CAPYBARA varies parameters of interest as defined by the user: time of flight (TOF), I_{sp}, launch vehicle (LV) C_3, and spacecraft specific mass (α_{sc}).

* Mechanical Engineer, Advanced Projects, Analytical Mechanics Associates, Inc., Denver, CO, 80021, U.S.A.
† Aerospace Engineer, Advanced Projects, Analytical Mechanics Associates, Inc., Denver, CO, 80021, U.S.A.
‡‡ Aerospace Engineer, Advanced Projects, Analytical Mechanics Associates, Inc., Denver, CO, 80021, U.S.A.

- OCELOT (Object-oriented CONOPS Evaluation and Logistics Operations Toolkit), an in-house Python wrapper to post-process the CAPYBARA outputs; OCELOT utilizes user-defined subsystem sizing and launch vehicle (LV) selection to scale the normalized data.

The resulting database was post-processed to determine the maximum usable mass delivered to the destination planet by an optimal power system based on various LVs and potential NEP power system specific mass (α_{ps}). The analysis resulted in the development of a SQL database of missions; query-able by planet, maximum payload delivered, minimum required power, TOF, α_{sc}, I_{sp}, and LV. This paper additionally reviews tradeoffs that may drive optimal NEP power for a maximized payload and inform specific mission point design cases. The methodology follows an example science mission to Saturn, but the process is the same for any planet in the database.

The propellant needed for a specific ΔV mission used by electric propulsion systems is much lighter than typical chemical propellants due to the high I_{sp}. This allows a NEP system to potentially deliver a much larger usable mass compared to chemical systems. The payload delivered to the planet will be referred to as “usable mass”. Usable mass can be used however the team developing a given mission sees fit; it may be used as additional propellant and tankage for planetary operations, science instruments, or other mission critical systems such as high-power communications arrays. The Copernicus decks were built to maximize usable mass at the destination for a given mission.

NEP systems also offer unique science accommodations beyond enabling a larger payload. A NEP system can utilize the nuclear reactor to provide high power to science or communications systems, therefore enabling technological development of higher-power science instruments with a higher communication throughput.

TRAJECTORY SELECTION

NEP has many benefits when compared to chemical propulsion for a mission to the outer planets, the first being that NEP allows for greater launch window flexibility. Missions utilizing chemical propulsion often rely on planetary gravity assists (sometimes several) to achieve their desired ΔV and mission timeline. This limits the launch years that are available for traditional chemical propulsion missions to get to outer planets. NEP enables launching essentially any year by making use of direct or Earth-flyby-only trajectories. NEP enables these flexible trajectories by utilizing high I_{sp} thrusters to achieve a large ΔV budget with a much lower propellant mass cost than a comparable chemical burn. This database includes the following types of trajectories:

1. ES – A direct burn-coast-burn trajectory from Earth to Saturn.
2. E(1y)ES – A trajectory with a resonant Earth gravity assist 1 year after launch.
3. E(2y)ES – A trajectory with a resonant Earth gravity assist 2 years after launch. The 2-year resonant EGA trajectory consistently outperformed the 1-year resonant EGA trajectory in terms of mass delivered to destination so the 1-year resonant EGA trajectory was not included for all planets or in final analysis. The EGA trajectories have three NEP burns, the first to realign with the Earth for the EGA and then a burn-coast-burn sequence for the interplanetary segment.

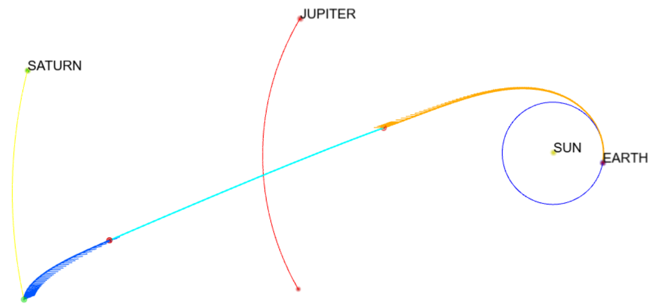

Figure 1. Example of ES Minimum Power Trajectory (C_3 = 0 km^2/s^2, TOF = 730 days, I_{sp} = 4000 s).

Figure 2. Example of E(2y)ES Minimum Power Trajectories (Left: C_3 = 0 km^2/s^2, TOF = 1278 days, I_{sp} = 4000 s. Right: C_3 = 48 km^2/s^2, TOF = 3470 days, I_{sp} = 4000 s).

Figures 1 and 2 show the ES and E(2y)ES trajectories respectively. The EGA decks, especially ones optimizing for minimum power, solve such that there is minimal or no coast before the EGA. Thus, the trajectory is limited by the power required to make that flyby happen rather than in the interplanetary section.

The goal of this database is to provide a general idea of which missions would be possible in a representative departure year, and the approximate ΔV that would be needed to complete them. While it is possible that missions utilizing flybys of other planets would result in an increased payload size, this study only looked at direct or Earth-flyby-only missions to best make use of the advantages of the NEP system.

While NEP is advantageous over chemical propulsion when a long duration low-thrust burn is feasible, for maneuvers such as orbit insertion a high-thrust chemical system is better. The missions in this database use a NEP-Chemical spacecraft where the chemical system is used to perform the impulsive orbit insertion burn and the NEP system is used to perform the long interplanetary burns.

Copernicus Deck Constraints

The Copernicus decks are simplified by departing from Earth's center and arriving at the destination planets' center. Other than during segments including EGAs, planetary gravity is not included in the force model. A high-fidelity mission analysis would need to include departure and arrival orbits. The NEP interplanetary segment was constrained by the Earth departure velocity and a set arrival velocity at the destination planet. The Earth departure velocity corresponds to launch vehicle capability and is defined by the characteristic energy (C_3), which was parameterized in the CAPYBARA sweep. Therefore, these trajectories are possible by any LV or kick-stage that can achieve the C_3. For each trajectory the full sweeps were performed at a single arrival velocity constraint. The TOF was also constrained to a constant and parameterized in the CAPYBARA sweep. This approach does not determine the exact optimal TOF but rather captures the trends across the trade space; it is unlikely that an optimal trajectory would be at exactly 12-year TOF, for example.

Table 1. Arrival Velocity and Orbit Insertion ΔV Per Trajectory.

Mission	Arrival Velocity, v_∞ (km/s)	Orbit Insertion ΔV (m/s)
EJ	2	194.568
E(2y)EJ	2.5	214.372
ES	2	178.779
E(2y)ES	2.5	211.961
EU	3	277.434
E(2y)EU	3.5	210.323
EN	3	257.627
E(2y)EN	3	257.627

The chemical orbit insertion burn was not modeled in Copernicus. Instead, the ΔV required is calculated in OCELOT based on the trajectory's arrival velocity to the destination planet. Table 1 includes the arrival velocity used for each trajectory and the calculated ΔV required for insertion into a 120-day period orbit. This chemical burn is then included in the sizing of the spacecraft, reducing the final usable mass delivered.

The Copernicus decks are mass normalized; the mass at arrival is set to be 1000 kg immediately before the chemical orbital insertion burn and the initial mass is left free to be optimized by Copernicus' internal algorithms. Each trajectory is valid for the thrust-to-weight ratio at which it converged, which is directly proportional to the power-to-mass ratio. These results are considered "unscaled", meaning they are not scaled up to a real vehicle size yet. The post-processor, OCELOT, which scales and sizes spacecraft subsystems is described in more detail in a later section. For scaling in this analysis, α_{sc} is defined as the arrival mass of the spacecraft in kg per kW_e of jet power. This is not to be confused with α_{ps}, defined as the mass of the NEP power system in kg per kW_e of power delivered to the thruster PPUs (Power Processing Unit). This is not necessarily the typical industry definition of α_{sc}, however, AMA set up the model in this way after testing the differences between locking the initial versus final masses in the Copernicus deck. Locking the final mass at 1000 kg was more consistent with the desired trajectory types since locking the initial mass resulted in 100% duty cycle trajectories.

Launch Year Flexibility Analysis

To understand the impact of launch date, Copernicus decks were created for launch years of 2026 to 2044 and the resulting ΔV was recorded. The decks assumed a 400 kg/kW$_e$ α_{sc} NEP spacecraft with 4000 s I_{sp} thrusters, launching with a C_3 of 50 km^2/s^2. For a valid ΔV comparison between the outer planets, TOF was fixed at the TOF for a Hohmann transfer to each planet. Only direct trajectories were used for this analysis to demonstrate maximum launch year flexibility.

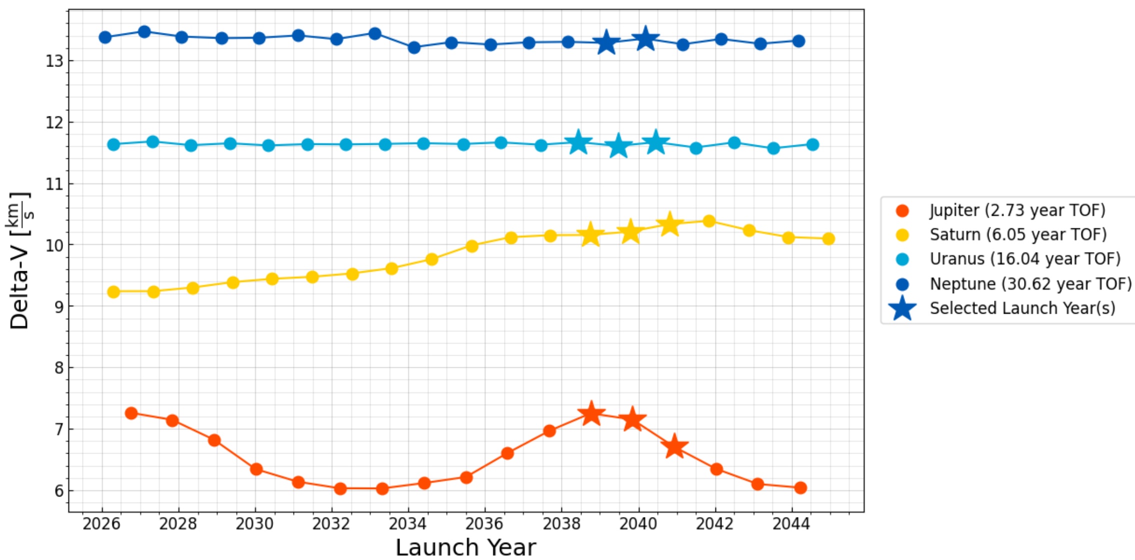

Figure 3. Launch Year Analysis for the Outer Planets with a 4000 s I_{sp}, 400 kg/kW$_e$ α_{sc} and a C_3 of 50 km^2/s^2 at Hohmann Transfer TOFs.

The difference in ΔV across launch years is shown in Figure 3 for each outer planet. The approximately 12-year Earth-Jupiter resonance is most apparent, where the maximum ΔV trajectories require 1.2 km/s more than the minimum cases. A similar trend is partially visible for Saturn, which has an approximately 30-year resonance with Earth. For both Jupiter and Saturn, the selected launch years represent the higher end of possible required ΔVs. This was intentional to show missions that could launch in any year, demonstrating launch year flexibility. The same ΔV trends seen in Jupiter and Saturn are not clearly visible for Uranus and Neptune due to their orbital resonances being far longer than the time scale shown (84 and 165 years respectively). NEP flight readiness was also a factor in launch year selection.

Table 2. Converged Launch Year Range Per Trajectory.

Mission	Optimized Launch Year Range
EJ	2039 – 2040
E(2y)EJ	2038 – 2040
ES	2038 – 2040
E(2y)ES	2038 – 2039
EU	2039 – 2040
E(2y)EU	2038
EN	2040
E(2y)EN	2039

The selected launch years were used as an initial condition in the reference decks. However, the launch dates were allowed to optimize within two years above and below that launch date. Table 2 summarizes the ranges of launch years that each mission converged to.

C.A.P.Y.B.A.R.A. – COPERNICUS ANALYSIS & PROCESSING FOR YIELDING BATCH ASTRODYNAMICS RESULTS & ASSESSMENTS

CAPYBARA is an in-house Python wrapper used for parameterizing and iterating Copernicus decks. CAPYBARA takes reference decks developed in Copernicus, as well as an input file that defines which parameters will be changed, and outputs every possible combination of trajectories across the given inputs. For each mission, initial reference decks are created and converged in Copernicus. Before beginning a sweep, the user can specify whether CAPYBARA should run "increasing" or "decreasing" over the trade space, which sets the direction that the parameterized decks will attempt to converge. CAPYBARA will then start at either the lowest or highest end of the trade space using the initial manually converged reference deck(s) as well as any newly converged decks as references as it moves through the trade space. For this reason, it is often best to manually converge cases on one end of the sweep to seed the first set of trajectories with a reference that is similar in C_3 and TOF.

Minimum Power Sweep

Initial low-thrust reference decks minimize spacecraft power. CAPYBARA then sweeps across the mission parameters, varying launch vehicle C_3, TOF, and I_{sp}. The final mass is fixed at 1000 kg, and the initial mass and exact launch date are left free for Copernicus to optimize. Minimizing power in Copernicus solves for the trajectory with the maximum spacecraft α_{sc} for each set of parameter inputs. This approach solves for the maximum total mass at the destination for a given power. However, the maximum total mass does not necessarily mean the maximum usable mass. The raw Copernicus data must be post-processed to account for the mass of the nuclear power system, tankage mass of the EP and chemical propellant, and the other subsystems that are sized as a function of the spacecraft mass. The post-processor, OCELOT, is described in detail in a later section.

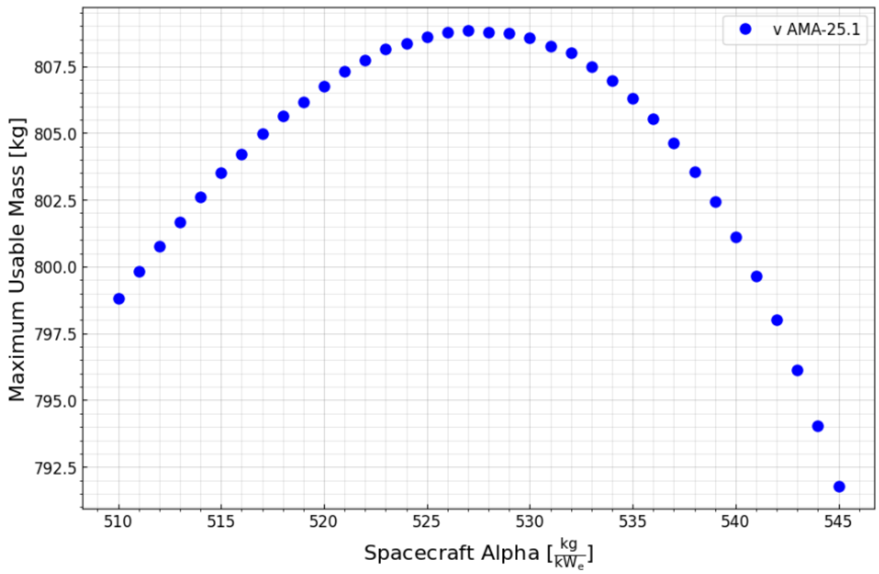

Figure 4. Maximum α_{sc} Does Not Necessarily Align with the Maximum Usable Mass.

As these are low-thrust trajectories, the lowest power that closes a mission typically will have a higher duty cycle than a mission optimized for minimum ΔV. The minimum power case results in the far-right point corresponding with maximum α_{sc}. However, the minimum ΔV case results in the maximum usable payload because it required less mass allocated to propellant. Figure 4 shows a very dense sweep for a single trajectory of α_{sc}, after being run through OCELOT. Every α_{sc} value was swept near the maximum α_{sc} for the given trajectory. It can clearly be seen that the maximum α_{sc} is not necessarily the maximum usable mass. However, for this mission, the maximum usable mass came within 2% of the maximum α_{sc} case. For some missions investigated, the highest usable mass did align with the maximum α_{sc} case.

Maximum α_{sc} Surface

The minimum-power optimization outputs the maximum α_{sc} for a given trajectory (e.g., E(2y)ES at a specific I_{sp}, C_3, TOF). The maximum α_{sc} represents the bounding case for a trajectory, meaning that if a mission with a higher α_{sc} value is attempted it will not close. Any α_{sc} higher than the value solved in the minimum power runs is attempting to deliver more mass with less power than the optimized solution and is therefore impossible. However, any α_{sc} lower than the maximum value can be run and closed. The existing minimum power sweep is used within CAPYBARA to map a three-dimensional maximum α_{sc} surface by interpolating between the converged points.

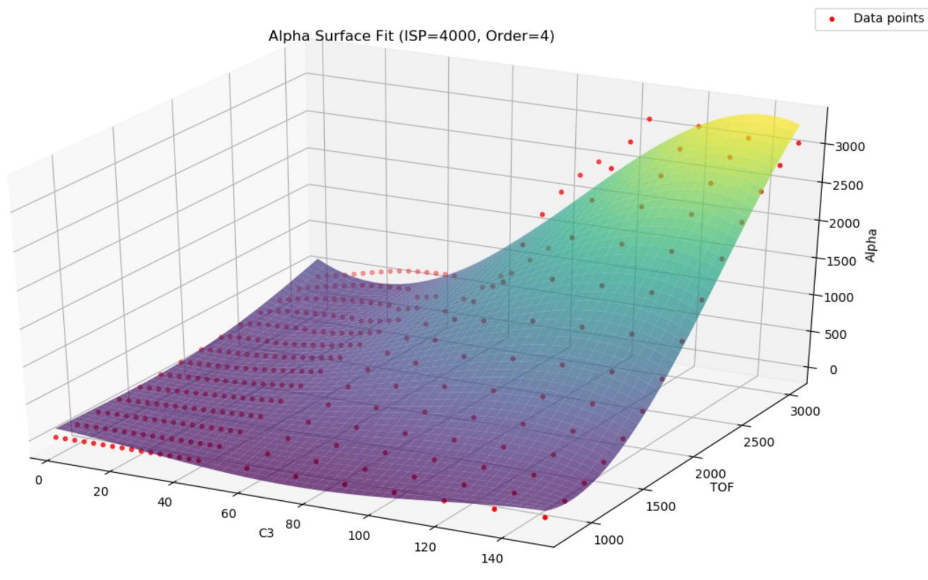

Figure 5. Sample 3D Maximum α_{sc} Surface Used in CAPYBARA.

A sample surface for the ES 4000s trajectory is shown in Figure 5. CAPYBARA utilizes the surface equation to determine what α_{sc} may close for a given input range and generates a grid of missions to run below the surface. The user inputs an α_{sc} minimum (often 50 kg/kW$_e$) and an α_{sc} step size (often 25 kg/kW$_e$). This minimizes computational time required for the minimum ΔV sweep, as only cases below the maximum closeable α_{sc} will be run.

Minimum ΔV Sweep

The minimum ΔV sweep builds a database of missions for a variety of possible α_{sc} values in addition to the LV C_3, TOF, and I_{sp} swept in the minimum power run. Sweeping across a variety of possible α_{sc} values is desirable, as a future mission may have a variety of different α_{sc} values dependent on design choices. The intention of the database creation was to capture all possible missions and their required ΔV. There are many reasons that a mission may fly with a lower-than-maximum α_{sc}: a nuclear power system was designed at a specific power level that is suboptimal for a given mission, a massive futuristic launch-vehicle can give a massive C_3 but it requires the spacecraft to then spend the whole trip slowing down to capture, mass margin is left from the design process that is not used, a suboptimal TOF is chosen to complete a science objective by a specific timeframe, potential thruster duty cycle requirements to allow communications periods with Earth with zero thrust, etc.

New reference decks were created in Copernicus, minimizing ΔV. A new sweep of the trade space was performed, now additionally varying α_{sc} as an input with LV C_3, TOF, and I_{sp}. α_{sc} was swept from 50 kg/kW$_e$ to the maximum α_{sc} defined by the surface generated from the minimum power sweep. The α_{sc} step size was, in some cases, left sparse away from the maximum value, but α_{sc} steps as low as 20 kg/kW$_e$ near the maximum. The maximum usable mass cases are near the maximum α_{sc}, so those cases were of higher importance in trajectory generation. The results of these sweeps will be shown below. Minimizing ΔV gives the maximum usable mass for a given trajectory (α_{sc}, I_{sp}, LV C_3, TOF).

Table 3. Trade Space Swept in CAPYBARA.

Mission	LV C_3 (km^2/s^2)	TOF (years)	Alpha (kg/kW_e)	I_{sp} (s)
EJ	0 - 150	1.5 - 6	50 - 1400	4000, 6000, 8000
E(2y)EJ	15 - 48	3.5 – 8.5	50 - 1575	4000, 6000, 8000
ES	0 - 150	2 – 8.5	50 - 3275	4000, 6000, 8000
E(2y)ES	0 - 48	3.5 - 10	50 - 2200	4000, 6000, 8000
EU	0 - 150	7 - 15	50 - 2775	4000, 6000, 8000
E(2y)EU	0 - 60	9 - 15	150 - 1400	4000, 6000, 8000
EN	0 - 150	7 - 18	50 - 4250	4000, 6000, 8000
E(2y)EN	15 - 48	8 - 18	50 - 1000	4000, 6000, 8000

The complete trade space of the missions in AMA's database is described by Table 3. LV C_3 was generally swept with a step size of 3 km^2/s^2 on the lower end, and 15 km^2/s^2 on the higher end (above 50 km^2/s^2). TOF was generally swept with a step size of 0.5 years. Alpha step size is described above. I_{sp} was only run at three levels.

C_3 Breakeven Point for an EGA

EGA trajectories do not always outperform direct trajectories. For an EGA trajectory, if the C_3 is too low the spacecraft does not have enough energy and needs a large ΔV burn to align the orbit for the flyby. If the C_3 is too high, the spacecraft has too much energy and again needs additional ΔV to slow down for orbit alignment for the flyby. The point of the EGA is to gain orbital energy so the ΔV requirement should be less for the 2-year time penalty to be worth it. These C_3 breakeven points were determined by comparing the direct trajectory Earth departure ΔV with the sum of the ΔV for the first two NEP burns of the EGA trajectory across the C_3 space. The minimum C_3 to make an EGA worthwhile was the point where the summed EGA ΔVs was less than the direct departure ΔV. The maximum C_3 was the point where the summed EGA ΔVs once again were greater than the direct departure ΔV. The final trade space included one data point of leeway in each direction.

Data Checking

Copernicus is a tool designed to find local minima in trajectories as opposed to the global absolute minimum, therefore solutions are dependent upon the initial guesses input by the user. For these sweeps Copernicus uses the built-in SNOPTA numerical optimizer as the solution method. When sweeping several hundred or even thousands of cases, it is possible for a suboptimal solution to be found due to the reference case that is selected potentially giving suboptimal initial guesses. This is especially true when only a single reference deck is available, it is more likely a suboptimal solution may be found because the trajectories have a larger difference to the reference it is using for initial guesses. Each new closed trajectory is added as a possible reference deck to following trajectories and CAPYBARA attempts to use the closest possible reference case for the next trajectory it solves. However, if a large trade space is being swept, occasionally the initial guesses and available reference decks are inadequate. The results from CAPYBARA are inspected using a variety of built-in tools to identify any possible outliers.

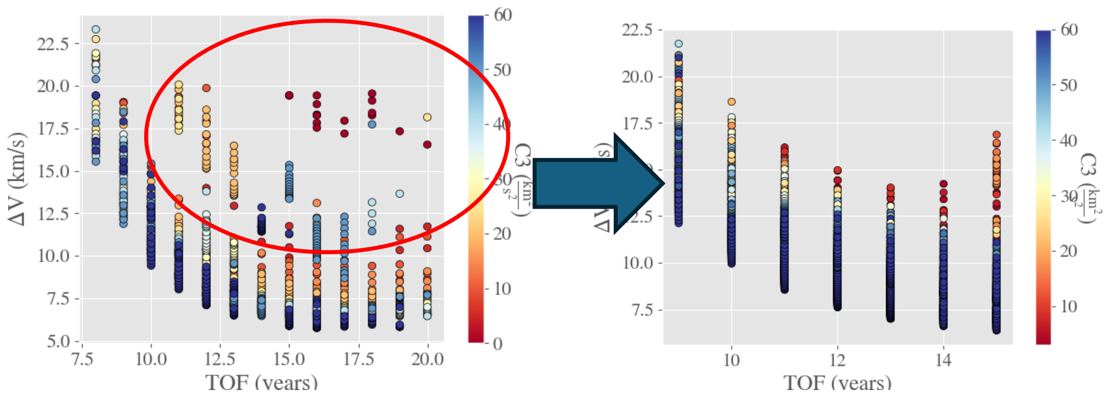

Figure 6. E(2y)EU Total ΔV vs TOF CAPYBARA Results Before and After Outlier ΔV Values are Purged and Re-swept.

The easiest way to identify outliers is by finding and purging cases with ΔVs significantly worse than other similar cases, as shown in Figure 6. Often large groups of outliers form a singular shared input. This issue is caused by a single trajectory converging to a sub-optimal result, which is then used as a reference deck for following cases with similar input variables. This is one benefit of sweeping the full trade space in chunks; it allows for finding and removing sub-optimal trajectory families prior to it propagating throughout the entire database. Additionally, as each closed case can be used as a reference to new cases, having verified there are no outliers allows more cases to be run concurrently which further speeds up computation time. CAPYBARA includes tools that allow for only attempting cases that have not yet been closed within the defined trade-space. For each sweep, if outliers are found, they are deleted, and the sweep is re-run.

One plot used to identify correlations is a pairs plot. This plots every chosen variable against every other variable; creating an easy way to parse which variables show interesting patterns when plotted against each other.

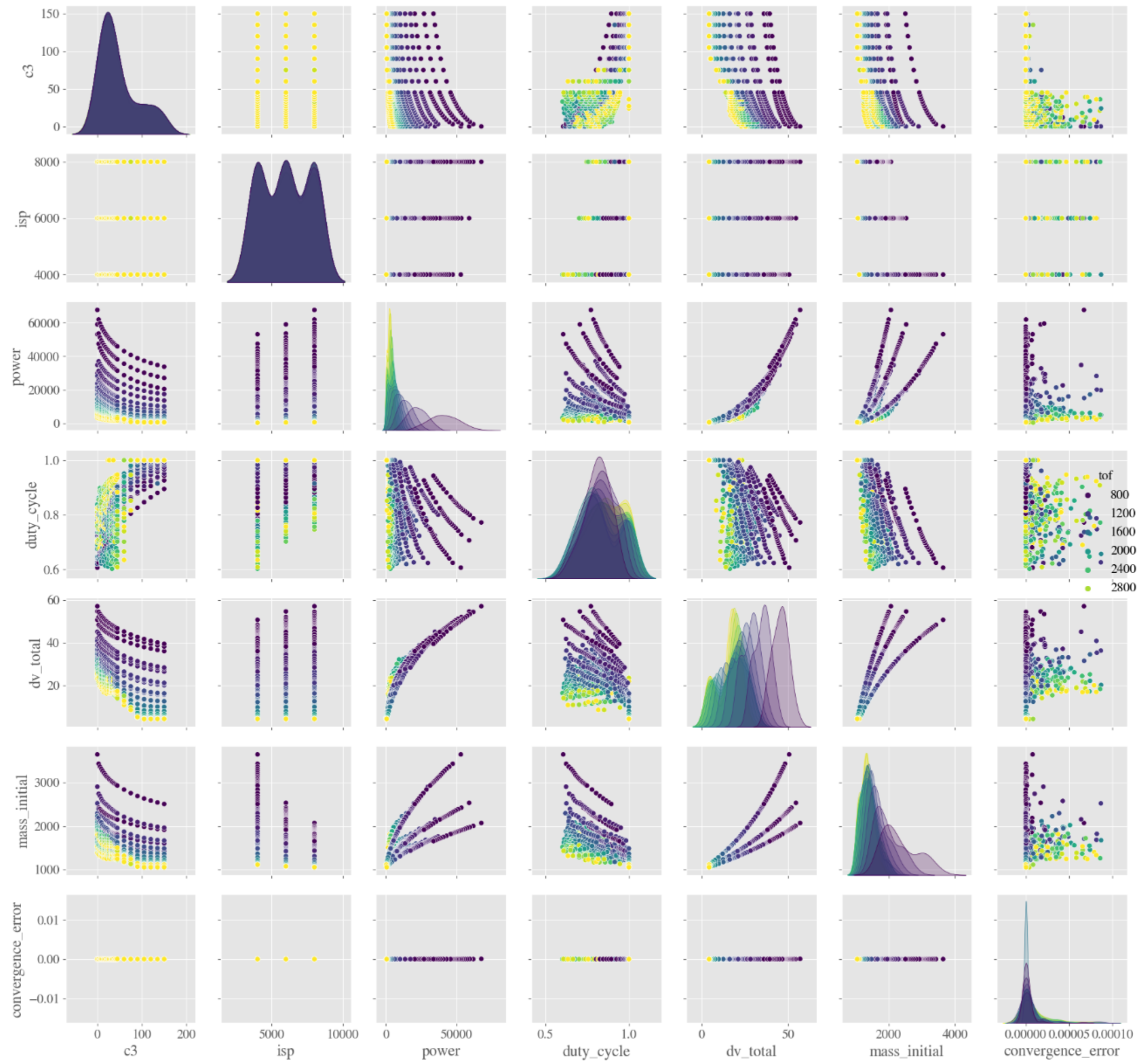

Figure 7. Pairs Plot Comparing Raw CAPYBARA Outputs for ES Mission.

Figure 7 shows the entire trade space for the ES mission in a large pairs plot. The pairs plot generates three-dimensional plots with the third dimension being represented by the color of the point. The variable used to sort by color can also be changed, such as sorting by C_3 or I_{sp}. The pairs plot and other similar breakdowns of the data are also key in quickly identifying and eliminating outliers.

There remain some limitations to the sweep outputs. Due to the nature of Copernicus, and the methods used as described, there remains possibilities for undetected outliers within the data. Many NEP trajectories require spiraling out around the sun for long TOF cases, maybe even multiple times. As CAPYBARA approaches the point where different amounts of spirals are needed, Copernicus will favor the same trajectory family until the difference is too great. This may result in a ΔV difference for some missions shown in the database, where the converged trajectory has a slightly higher ΔV.

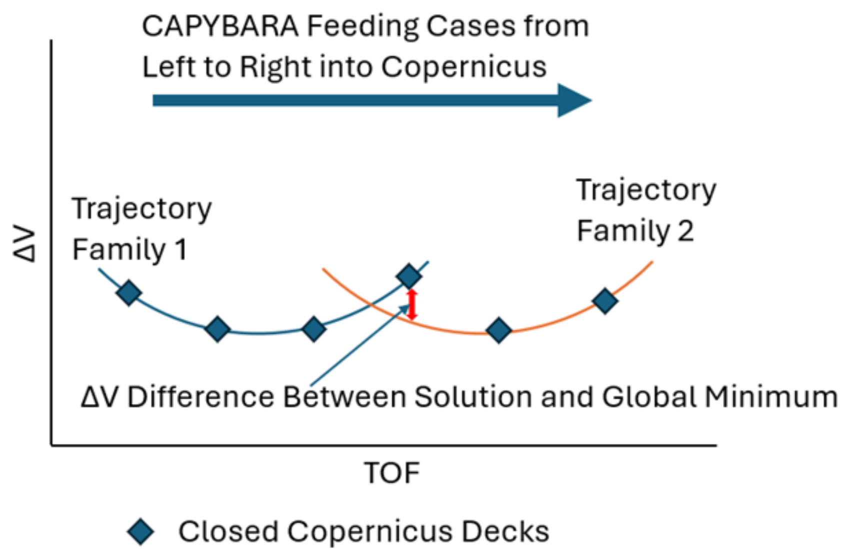

Figure 8. Notional Example of CAPYBARA Methodology Resulting in Slightly Overestimated ΔV in Some Cases.

Figure 8 shows this in a notional example and highlights the importance of running the sweep with both the "increasing" and "decreasing" settings. AMA has taken steps to mitigate this as much as possible, but without manually checking every solution it is always possible that more cases exist. All cases that are converged in the database are valid trajectories, and detailed mission design would reveal the possible ΔV differences for a given case.

O.C.E.L.O.T. – OBJECT-ORIENTED CONOPS EVALUATION AND LOGISTICS OPERATIONS TOOLKIT

Outputs from CAPYBARA must be post-processed to give useful payload data for a given power system mass curve and vehicle subsystems sizing model. This post-processing is done using OCELOT, an in-house python mission tool. OCELOT has many capabilities, but for these large databases of normalized trajectories it follows this process:

1. The user defines the mission variables: margins for the Reaction Control System (RCS) and NEP propellant ullage, which NEP α_{ps} curve to utilize, and launch vehicle selection.

2. For each trajectory in the database, OCELOT finds the maximum launchable mass for the selected LV to the trajectory's launch C_3, based on the LV C_3 curve.

3. The initial mass, final mass, and power from the CAPYBARA outputs are scaled up. The scale factor is calculated by Eq. (1) which sets the initial mass to equal the maximum launchable mass as found in the previous step.

$$SF = {}^{M_{LVmax}}/_{M_{initial}} \tag{1}$$

ΔVs for a given trajectory remain constant if the thrust-to-weight ratio (T/W) is constant, so scaling up the normalized decks is viable as long as the T/W is maintained. This is done by scaling the mass and the power from each trajectory by the same scalar value.

4. Sub-system masses are applied. For many subsystems physics-based modeling is used to determine an appropriate mass. α_{ps} values for the power subsystem are applied based on the new scaled up power. The mass values are summed to give the dry mass of the spacecraft.

5. The ΔV values from the CAPYBARA outputs are used to calculate propellent and tankage sizes, which are added to the dry mass.

6. Structures mass is calculated as a percentage of the other dry masses.

7. Dry mass margin is applied.

8. The calculated dry mass plus propellent masses subtract from the scaled up initial mass to give the maximum usable mass at the destination.

Many assumptions are carried through this process, but the key assumptions are the α_{ps} values, as well as the masses of each subsystem. The mass at destination is described as "Usable Mass" as opposed to just the payload to avoid confusion. Usable mass can be additional tankage and propellent for increased maneuverability at the destination, or it can be a traditional science payload. OCELOT outputs usable mass unassigned to any use. It is up to a mission design team to identify the best uses for that mass for specific mission goals. An additional input, a thruster efficiency curve, is used in calculating the spacecraft power as needed to deliver the thruster jet power at a given I_{sp}. As mentioned above, CAPYBARA was swept at multiple I_{sp} values. These values are effectively set points for specific thrusters, which dictates the thruster mass.

Table 4. Margin Applied to Sweep During Post-Processing.

Margin Description	Value
EP mass Margin	4 %
EP Unusable Residual Propellant	1 %
EP Thruster Performance Margin	5 %
EP Thruster Efficiency	~75 % curve dependent on thruster
PPU Efficiency	~95 % curve dependent on thruster
RCS Mass Margin	75 m/s ΔV propellant mass calculated at destination
RCS Ullage	3 %
Dry Mass Margin	43 % [2]

Margin is applied to the sweep in multiple ways as described above in Table 4.

Power System Alpha α_{ps} Curve

The α_{ps} value is a function of power, with higher powers having better α_{ps} values due to reactor and power conversion technology scaling up well with power.

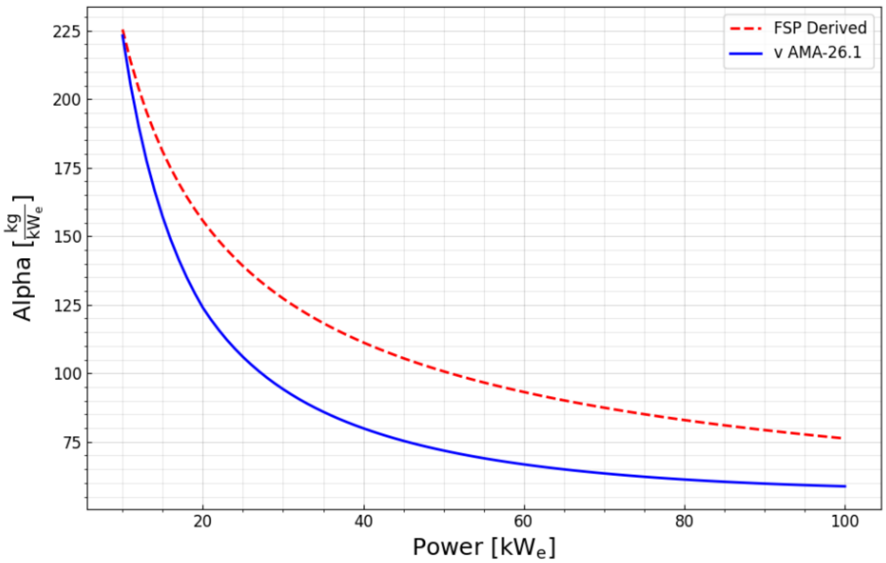

Figure 9. Two Estimates for α_{ps} as a Function of Electrical Power, More and Less Conservative Technology Estimates.

Figure 9 demonstrates example power system curves that were used in this analysis. The FSP Derived line represents what is possible in the near term with minimal technological development. The v AMA-26.1 line represents longer term technology potential after investment. Updates to the v AMA-26.1 curve include: 50 K hotter temperature at power conversion inlet, higher Brayton cycle peak pressure, higher temperature radiator inlet, higher efficiency turbomachinery assumption, better heat spreading in the radiator, a lighter mass recuperator, and a heat transport fluid of NaK instead of water.

All plots presented in this report assume the v AMA-26.1 alpha curve, however post-processing was done using both curves. FSP Derived results are also included in the final database.

Thruster Curves

For this analysis, NEXT-C thrusters at 4000 s and HiPEP thrusters at 6000 s and 8000 s were investigated.[3, 4] Initial results with the FSP derived curve showed that the NEXT-C thrusters narrowly outperformed the HiPEP thrusters, despite the lower efficiency. This is a direct result of the α_{ps} curve. Higher efficiency HiPEP thrusters require more power to get a similar thrust. The increase in power past a certain point for the FSP derived case resulted in a sub-optimal trade-off of mass, and therefore less mass delivered to the destination. However, the scaled reference case that is now being used in analysis has better performance at higher powers. The best performing thruster therefore is dependent on the power of the system being used, as well as the other mission parameters, such as TOF.

LV Curves

A range of launch vehicles are modeled in OCELOT, from Falcon 9 to a fully fueled Starship. The LV curve is maximum launchable payload mass as a function of LV C_3 which is used by OCELOT to determine the scaling factor for each mission case per LV.

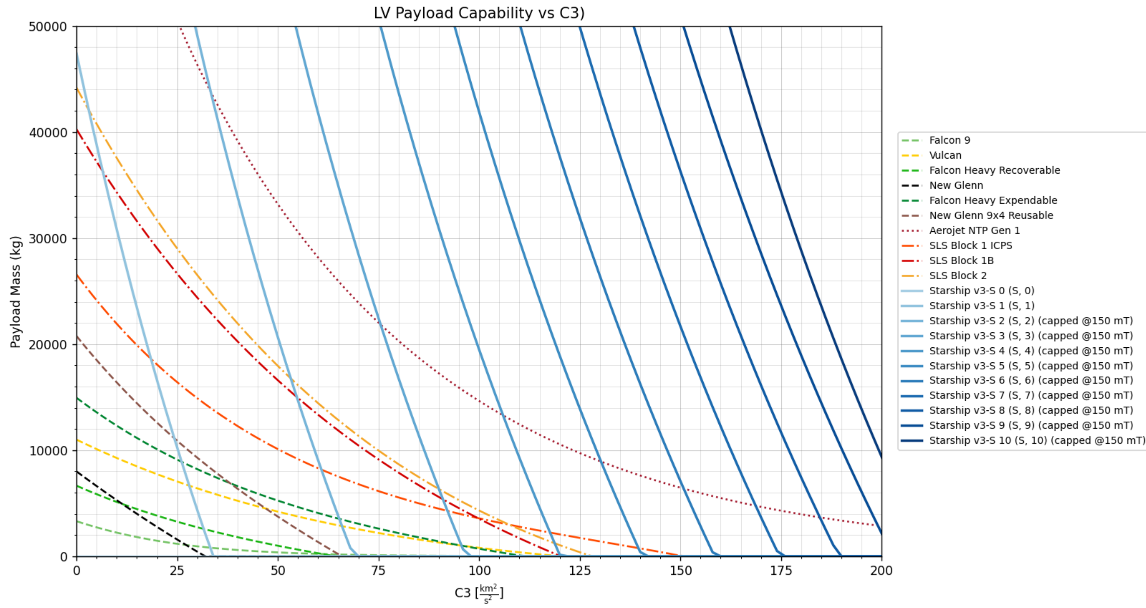

Figure 10. LV Payload Capability vs C_3.

With the exception of Starship, all of the LVs are modeled using a simple double exponential function with their coefficients stored in a dictionary. Starship is modeled through a Python function as a function of the number of refuels. Payloads for Starship were capped at 150 mT based on the claimed performance of Starship v3 delivering 150 mT to LEO.[5] An Aerojet NTP upper stage curve was also added, assuming launch on a Starship[6]. Figure 10 shows the LV curves plotted against each other, illustrating how powerful Starship v3 is compared even to SLS.

TRADESPACE DISCUSSION

Sweeping over large trade spaces results in a substantial number of unique trajectories, with the exact number dependent on the parameter space. OCELOT includes plotting functionality to look at a variety of different trade space trends. Looking at the trends across the trade space informs mission and spacecraft design, this database is intended to be used as a starting point for higher fidelity mission design.

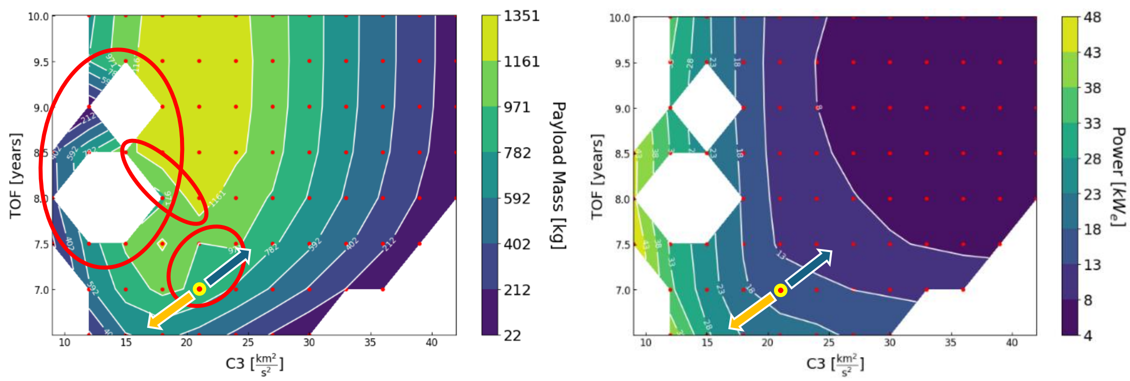

Figure 11. Maximum Payload and Corresponding Optimal Power for E(2y)ES Trajectory Launched on Falcon Heavy Expendable Using v AMA-26.1 NEP and 4000 s NEXT-C Thrusters.

It can be more helpful to visualize the trends across the trade space by plotting against both independent variables (C_3 and TOF). Contour plots like the one shown in Figure 11 are used to do this, with color bars representing the dependent variables like max payload or optimal power. Each red dot on the contour plots represents a converged trajectory for a given vehicle MEL, I_{sp}, launch vehicle, and launch year. The resulting maximum payload (usable mass at destination) for each trajectory is shown with the color bar on the left plot. The corresponding powers to deliver those maximum payloads are shown in the accompanying plot on the right. The power is labelled as "optimal" because it is the power that delivers the highest usable mass at that C_3-TOF pair for the assumed spacecraft and trajectory type. An important note is that for each trajectory, lower payloads are possible at lower powers; the thrust to weight ratio must be maintained.

The white regions on the contour plots represent regions where cases did not converge. The red circles on the maximum payload highlight the aliasing from Copernicus not solving on the global minimum solution. A lower power system takes longer to deliver the same payload as shown by the blue arrow in Figure 10. Despite the lower-mass NEP system, the additional ΔV needed to complete a less-efficient trajectory results in either less payload or longer trip time. A higher power system devotes more dry mass to NEP. As shown by the yellow arrow in Figure 10, despite the ΔV of higher power NEP system, either the payload goes down or the trip time goes up.

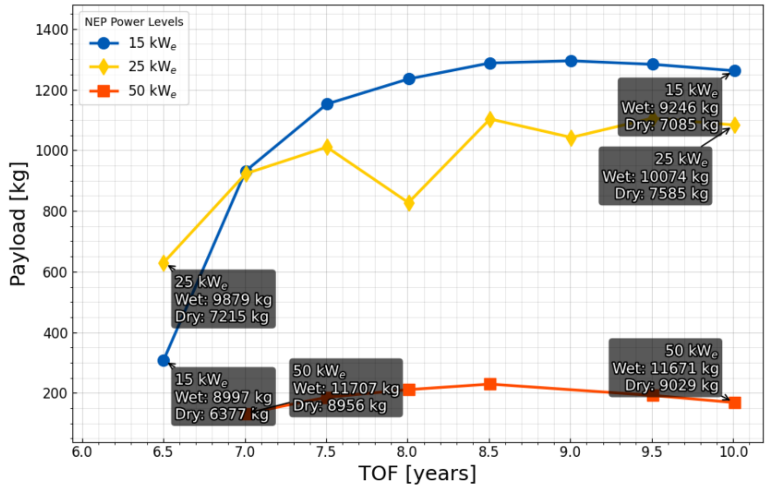

Figure 12. Maximum Payload at 3 Power Levels for a E(2y)ES Trajectory Launched on Falcon Heavy Expendable Using v AMA-26.1 NEP and 4000 s NEXT-C Thrusters.

OCELOT can be configured to produce many different types of line plots. Line plots are helpful for isolating the trends from the contour plots for a more defined mission. In the case of Figure 12, three power levels are isolated to compare trip time with delivered payload. This plot has the additional capability of showing the wet and dry vehicle masses at a select few points. Note that the longer TOF, lower ΔV, missions require less propellant and therefore deliver larger payloads. For these cases the payload, or "usable mass", makes up a larger portion of the dry mass than for shorter TOF cases. Comparing dry mass across power levels reveals the large impact of power on dry mass due to higher power NEP systems being higher mass. Once again aliasing from the initial sweep is visible, particularly with the 25 kW$_e$ case. Despite aliasing, this plot captures the crossover point of optimal power for flight time. Above a TOF of 7 years, the lower power NEP system becomes more optimal than the mid-range power NEP system.

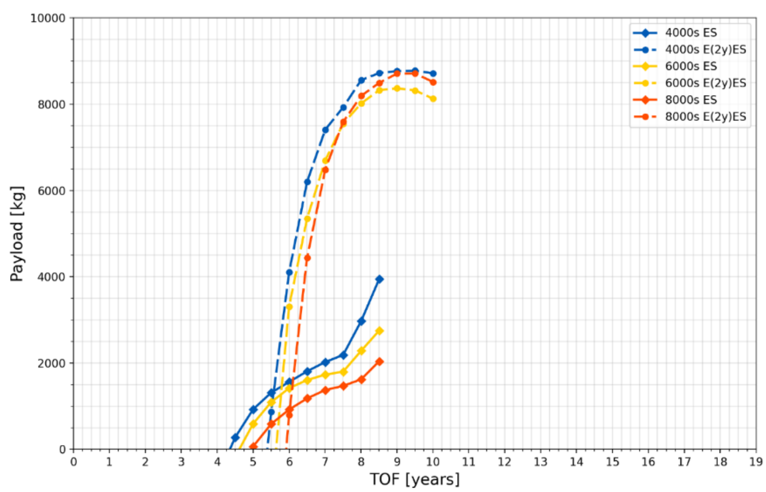

Figure 13. I$_{sp}$ Comparison of Saturn Missions Launched on SLS Block 1B.

Figure 13 compares the direct and EGA trajectories across I_{sp}. The 4000 s NEXT-C thrusters are the optimal I_{sp} for both trajectory types among the thrusters investigated. Additionally, this plot clearly highlights the benefit of a gravity assist when a slightly longer mission duration is acceptable. For missions longer than 6 years the E(2y)ES trajectory delivers significantly more payload to Saturn than the direct ES trajectory, regardless of I_{sp}.

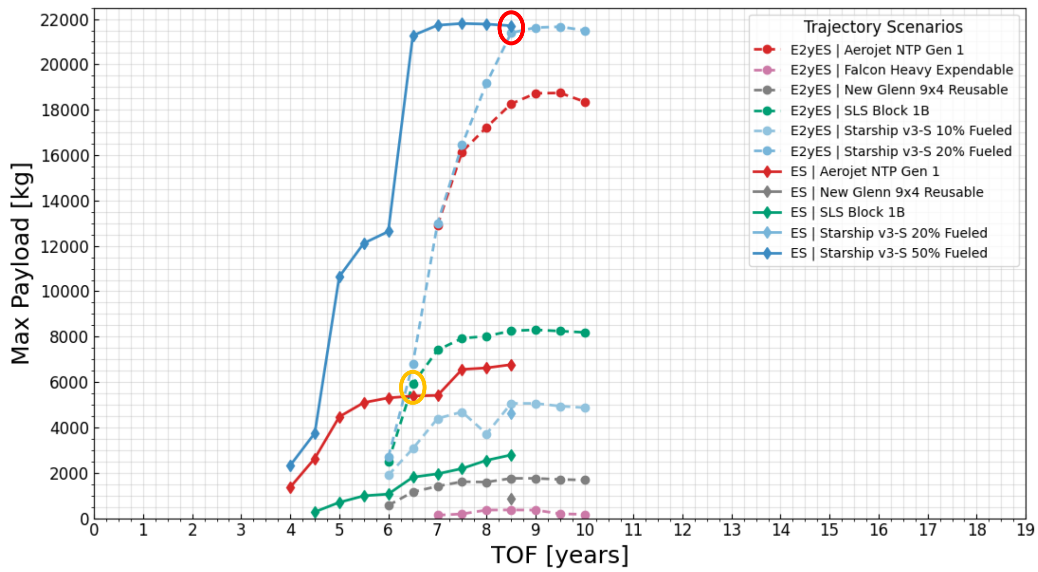

Figure 14. Comparison of Launch Vehicle Selection and Trajectory Scenarios for Saturn Mission.

Figure 14 similarly compares ES and E(2y)ES trajectories, this time launched on different launch vehicles. Trends remain consistent across launch vehicles with longer TOF missions delivering more usable mass and EGA trajectories delivering more usable mass than a comparable direct trajectory. Figure 16 clearly shows the energy gained from the EGA. The yellow circle highlights a direct trajectory launched with the powerful Aerojet NTP upper stage (launched on Starship) compared to an EGA trajectory launched on SLS Block 1B. For the same 6.5-year TOF, the mission using the less powerful SLS delivers more payload to Saturn due to the energy gained with the EGA. Similarly, an EGA enables less Starship refuels needed to deliver a similar payload as highlighted by the red circle. An E(2y)ES mission using a 20% fueled Starship can deliver nearly the same payload as an ES mission using a 50% fueled Starship.

FORWARD WORK

AMA is working to publish these results as a query-able SQL database. The goal is to provide other mission analysts with the trends across the thousands of trajectories in this trade space to inform future NEP missions. The database is organized such that it can be updated with new sets of trajectories such as a 0 v_∞ arrival with a NEP spiral into orbit at the destination planet, or post-processed to update results with new α_{ps} performance or launch vehicles as space technology develops.

ACKNOWLEDGMENTS

This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) program. Analytical Mechanics Associates, Inc. was funded for this effort under NASA Contract No. 80LARC23DA003.

Special thanks to Matthew Duchek for his review of this work.

NOTATION

α_{ps}	power system specific mass
α_{sc}	total spacecraft specific mass
ΔV	change in velocity
C_3	characteristic energy
I_{sp}	specific impulse
kW_e	kilowatts electric
LV	launch vehicle
TOF	time of flight
SF	scale factor (used in OCELOT)
$M_{initial}$	initial mass (from CABYBARA output)
M_{LVmax}	maximum launchable mass (from LV C_3 curve)

REFERENCES

[1] J. Williams, *Copernicus Version 5.2.0,* NASA Johnson Space Center, 2022.

[2] ANSI/AIAA S-120A-2015 (2019), American National Standards Institute (ANSI) and American Institute of Aeronautics and Astronautics (AIAA), *Mass Properties Control for Space Systems,* AIAA, 2015.

[3] R. Shastry, G. Soulas, M. Aulisio and G. Schmidt, "Current Status of NASA's NEXT-C Ion Propulsion System Development Project," in International Astronautical Congress, Adelaide, 2017.

[4] J. E. Foster, T. Haag, M. Patterson, G. J. Williams Jr., J. S. Sovey, C. Carpenter, H. Kamhawi, S. Malone and F. Elliot, "The High Power Electirc Propulsion (HiPEP) Ion Thruster," AIAA/NASA, Fort Lauderdale, 2004.

[5] G. D. Krebs, "Starship (Super Heavy Starship, BFR, Big Falcon Rocket)," Gunter's Space Page, [Online]. Available: https://space.skyrocket.de/doc_lau/super-heavy-starship.htm#citation. [Accessed 17 June 2026].

[6] T. Rueter, R. Meyers, P. Christensen, L. Dudzinski and K. Polzin, "Accelerating Space Science with Nuclear Technology: The Tempe Workshop," Institute for Space Science and Development, 2023.