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MODERN AEROCAPTURE GUIDANCE TO ENABLE REDUCED-LIFT VEHICLES AT NEPTUNE

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Aerocapture is covered extensively in the literature as means of achieving orbital insertion with dramatic mass-saving results compared to fully-propulsive systems. One of the primary obstacles facing aerocapture is the inherent uncertainty associated with passing through a planet's upper atmosphere. In-flight dispersions due to delivery errors, environment variables, and aerodynamic performance impose a large flight envelope. System studies for aerocapture often select high lift-to-drag ratios to compensate for these uncertainties. However, modern predictor-corrector guidance strategies have shown promise in recent years to provide robust control schemes in-situ. These algorithms do not rely on a pre-calculated reference trajectory and instead employ a numerical optimizer to continuously solve nonlinear equations of motion each guidance cycle. Numerical predictor-corrector strategies may provide considerable accuracy over heritage guidance schemes. The goal of this study is reproduce a landmark study of Neptune aerocapture and apply modern guidance to illustrate relative performance improvements and cost-saving potential. Capture constraints based on the theoretical corridor width are considered. Results indicate that heritage vehicles with moderate lift-to-drag ratios, lower than previous studies have indicated, may prove viable for aerocapture at Neptune.

INTRODUCTION

Background

Aerocapture is a maneuver in which a vehicle passes through the upper atmosphere of a planet to generate aerodynamic drag. Upon exiting the atmospheric phase of flight, the vehicle has reduced its orbital energy and captured into an elliptical orbit. A corrective burn to raise the periapsis altitude is performed (dictated by the aerocapture altitude), followed by other small adjustments to apoapsis altitude or out-of-plane motion as needed. Numerous studies have identified aerocapture as a viable means of achieving orbit about a body with appreciable atmosphere.[1,2] Compared to fully-propulsive orbital insertion, the strategy is estimated to decrease overall vehicle mass by 40 to 80% based on the destination.[3] However, aerocapture requires active guidance during the atmospheric pass and often requires large control margin that cannot be provided by typical entry vehicles with low lift-to-drag ratios. Moreover, aerocapture is subject to large uncertainties due to atmospheric variability and winds, vehicle aerodynamics, and control performance among others. One of the most significant obstacles in aerocapture is the need for a vehicle to correct for unknowns in-situ. Trajectories that under-shoot or over-shoot the target orbit will rapidly deplete the limited

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propellant mass reserved for final orbit adjustments. In worst-case scenarios, dispersed trajectories could potentially perform atmospheric entry and never achieve orbit, resulting in mission failure.

The presence of large trajectory dispersions imposes severe design constraints on aerocapture missions, especially at the outer planets which are subject to appreciable atmospheric interface delivery errors. There also exists a systematic perceived risk due to the lack of any flight-proven aerocapture mission to date. As a result, system concepts for these missions are often over-designed with excess control margin (generally defined by the vehicle's L/D) to maintain feasibility. Reducing the L/D requirement is key to enabling Neptune exploration. High-heritage blunt body entry vehicle designs that produce low to moderate L/D are considerably more appealing from both a cost and feasibility outlook.

In recent years, numerical predictor-corrector algorithms have gained traction for real-time trajectory control. These strategies are robust to large dispersions and need not adhere to a pre-computed reference trajectory. A guidance system robust to in-flight dispersions is critical for aerocapture success, especially with the numerous sources of variability inherent to missions at the outer planets. Continuing advances in spaceborne computing using commercial off-the-shelf components (COTS) will enable this new generation of computationally-intensive guidance strategies.[4] Previous studies show promising results for precision aerocapture at Mars using FNPAG.[5] The goal of this study is to implement numerical predictor-corrector guidance at Neptune and reevaluate current limitations on L/D constraints.

One of the most important objectives in the research community moving forward is to identify which sources of uncertainty are preventing low to moderate lift-to-drag vehicles from performing aerocapture at Neptune. Sources include navigation errors, entry interface delivery errors, atmospheric variability, vehicle performance uncertainty, and guidance errors. Due to a lack of permanent assets at the outer planets, navigation and atmospheric uncertainties are unlikely to see significant improvements within the next launch cycles. Guidance algorithms, however, are continually evolving and improving, and the strategy used in the Lockwood study is superseded by modern numerical predictor-corrector methods.[6] In addition, guidance strategies may be studied a-priori with relative ease using computational simulation methods.

The goal of this research is to reproduce the Lockwood study and implement a modern numerical predictor-corrector guidance algorithm. Performance will be compared one-to-one where possible, including L/D for successful capture, entry aerothermal and g-load constraints, as well as final orbit insertion propulsive requirements. The expected result of this work is to relax constraints on overdesigned high L/D vehicles and discuss potential risk and cost tradeoffs as a result.

Reference Mission

The baseline of comparison in this research is a mission concept from a multi-center NASA study of Neptune aerocapture by Lockwood.[7] The mission was designed for a retrograde orbit about Neptune to allow Triton fly-bys, with the option of two probes performing atmospheric entry. The launch window was February of 2017 with an approximately ten year transit time. The nominal entry interface velocity of 29 km/s and flight-path angle (FPA) of -12.818 deg were selected based on the interplanetary transfer orbit. The post-aerocapture target was a high-energy science orbit with apoapsis and periapsis altitudes of 430,000 km and 3,986 km, respectively. The baseline vehicle concept was a flat-bottom ellipsled aeroshell with a mass of 2200 kg and ballistic coefficient of 896 kg/m^2. The concept used the Hybrid Predictor-corrector Aerocapture Scheme (HYPAS) for onboard guidance. HYPAS guidance was based on piecewise analytical approximations of solutions to the reentry trajectory problem. The algorithm consisted of two phases, the first of which utilizes equilibrium guide approximation, and the second assuming constant altitude rate. Assumptions used for HYPAS required uncoupled longitudinal and lateral dynamics as well as constant or exponential atmosphere models.

The Lockwood study achieved 100% successful capture after several design cycles based on transfer orbit navigation accuracy, aeroshell configuration, and entry performance. The final vehicle configuration was an ellipsled lifting-body outer mold line (OML) capable of producing a moderately high L/D of 0.8. Table 1 summarizes performance findings from the Lockwood study using HYPAS guidance. While an L/D of 0.6 design was kept as an option, a higher lift-to-drag ratio was deemed necessary to overcome conservative assumptions on atmosphere and navigation. This conclusion, however, severely restricted design options incorporating aerocapture at Neptune. It necessitated the design and testing of a novel entry vehicle capable of performing autonomous guidance and control during capture. Compounded with the inherent uncertainty regarding aerocapture in general, this L/D requirement essentially shelved most realistic mission opportunities at Neptune based on risk and cost alone. Although the Lockwood study was based on a now-expired launch window, it still represents the current state-of-the-art for Neptune aerocapture.

	HYPAS
Performance Metric	L/D = 0.8
Apoapsis Altitude - $\pm 3\sigma$	12.85e5 km, 3.25e5 km
ΔV - 3σ high	456 m/s
Max g's	20 g's
Heat Rate - 3σ high	3.13e7 W/m^2
Heat Load - 3σ high	2.94e9 J/m^2
Percent Captured	100%

Table 1. Summary of Lockwood reference study using HYPAS guidance without angle of attack modulation.

Entry Corridor

The theoretical corridor width (TCW) is defined as the range of flight-path angles allowing for successful capture. The lower FPA bound is found by optimizing for the steepest possible entry assuming a full lift-up trajectory. Similarly, the upper FPA bound is determined by the shallowest full-lift down trajectory. TCW is strongly dependent on the vehicle L/D and entry velocity. These quantities represent available control authority to produce force in the vertical plane. TCW is weakly dependent on ballistic coefficient and thus ballistic coefficient is assumed constant across L/D.[8] The TCW is a useful first-order approximation of aerocapture performance, allowing the designer to identify sources of uncertainty as contributions to degrees of flight-path angle width. The required corridor width may be considered as the root sum squared (RSS) of these contributions. If the required width is less than the TCW to within a desired margin of error, then the aerocapture design is considered feasible.

In order to assess the TCW at Neptune, a trade is performed across L/D and entry velocity using the simulation environment described below. A navigation study of the Neptune transfer orbit conservatively estimates the 3-σ entry interface flight-path angle uncertainty at ± 0.51 degrees, or a TCW of 1.02 deg.[9] A more recent pre-decadal survey of the Ice Giants found a larger TCW of 1.5 deg.[10] However, the goal of this research is to reproduce the Lockwood study as closely as possible to allow for direct comparison of relative performance benefits. Therefore, a TCW of 1.02 deg is used as a lower-bound constraint, below which the required corridor is greater than the available corridor and therefore infeasible. While the TCW is a useful tool for quick mission assessment, a more in-depth Monte Carlo analysis dispersing the full state delivery covariance is typically needed to fully understand the problem.

APPROACH

Simulation Environment

The primary flight simulation tool in this study is the Program to Optimize Simulated Trajectories II (POST2). POST2 is a high-fidelity event-driven numerical simulation tool that models both atmospheric flight and orbital dynamics. The vehicle is modeled as a 3-DOF point mass with constant mass properties and aerodynamic coefficients. Bank angle dynamics are approximated as a second-order pseudo actuator with maximum bank rate and bank acceleration of 20 deg/s and 5 deg/s^2, respectively, to simulate a realistic bank angle control. Atmosphere is modeled using a Global Reference Atmospheric Model (GRAM). Neptune GRAM provides atmospheric quantities that vary with latitude and time, as well as dispersed models for Monte Carlo analysis.

Guidance

This study takes advantage of an aerocapture guidance scheme called Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG).[11] FNPAG is based on optimal control theory to minimize the post-aerocapture apoapsis error or ΔV. The algorithm utilizes a bank-to-steer control method. The vehicle flies lift-up until an optimal switching time is found, after which the vehicle enters a predictive lift steering phase. For each guidance cycle, the method applies a planning strategy where the remaining trajectory is simulated and a corrector scheme computes the necessary bank angle to achieve targeting conditions. Cross range control is achieved in FNPAG using predictive lateral logic. The lateral logic is based on a fixed number of bank reversals triggered by the error ratio of cross range errors produced by opposite (in bank angle sign) terminal states.[12] Since the goal for aerocapture is precise orbit insertion, the lateral logic in FNPAG operates on the final orbit inclination errors. For this study, a maximum of two bank reversals is deemed adequate for robust cross range control.

Due to its numerical implementation, FNPAG is able to incorporate high fidelity vehicle, environment, and dynamics models compared to previous-generation algorithms. The internal logic of FNPAG includes coupled nonlinear equations of motion, as well as Neptune GRAM atmospheric density models. Aerodynamic coefficients are assumed fixed for this study, but future implementations of this software may also include Mach and angle of attack dependency, or even more complex aerodynamic models. FNPAG is integrated into POST2 using a custom flight software interface and tested for a range of L/D at nominal entry conditions. Figures 2 and 3 show the bank angle history and targeting performance of FNPAG. Almost no tuning parameters are required for the different cases, making the algorithm convenient for comparing performance across L/D.

Performance Metrics

In order to assess the relative benefits of utilizing numerical predictor-corrector guidance, aerocapture performance metrics are defined. One of the most practical quantities to consider is the exo-atmospheric ΔV, which dictates the necessary propellant mass to attain the target orbit. Orbit burns are accounted for in POST2 as instantaneous ΔV maneuvers. The series of burns is shown in Figure 1. The first ΔV_1 burn is used to raise the periapsis altitude, on the order 80-100 m/s. This burn is generally unavoidable in aerocapture as it prevents the vehicle from reentering the upper atmosphere after the first pass. A second ΔV_2 burn is performed to correct for errors in final apoapsis altitude. A third corrective burn may be performed to correct out-of-plane motion due to errors in orbit inclination and ascending node. A third burn is not accounted for in the study, since cross range control is accounted for in the lateral logic of FNPAG. Inclination and orbit phasing are generally secondary to semimajor axis targeting in terms of mission success criteria. Other performance metrics such as aerothermal and inertial loads are also considered. However, these are upper or lower-bound constraints and typically secondary to the primary ΔV measures.

In comparing the range of L/D cases, it is helpful to consider final orbital energy at atmospheric exit. Orbit energy represents the robustness and targeting capabilities of the guidance scheme and sets margins for failure. Orbits with energy greater than or equal to zero are considered overshoot failures, where the final orbit is parabolic or hyperbolic and thus not captured. In contrast, any exit condition with orbital energy less than that of a circular orbit at the same radius are considered undershoot failures, instead performing direct entry.

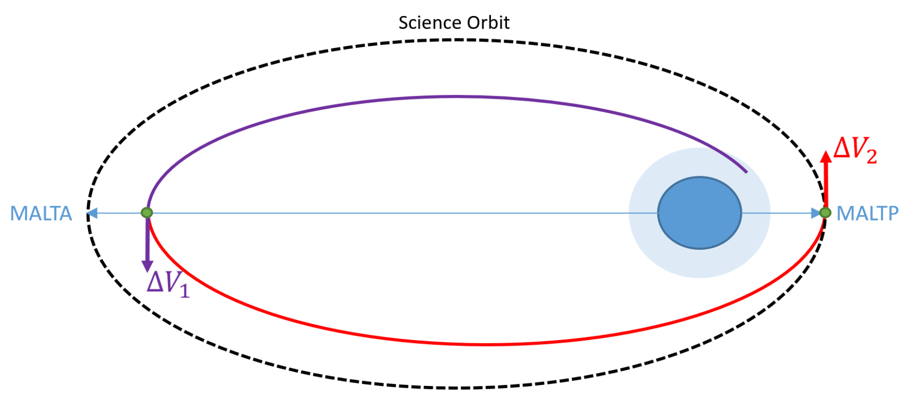

Figure 1. Overview of periapsis raise (ΔV_1) and apoapsis correction (ΔV_2). Not to scale.

RESULTS

Entry Corridor

A TCW trade is performed across inertial entry velocity and L/D to examine capture constraints at Neptune. See Figure 4. The results are indicative of those presented in the original Lockwood study and serve as a means of validating simulation and environment models. The trade shows several useful ideas. The TCW increases with both L/D and entry velocity, and for the reference case entry velocity of 29 km/s, there exists over a 0.4 margin in L/D available due to an overdesign of the vehicle to compensate for atmospheric and environment uncertainties. The original study by Lockwood assumed HYPAS guidance could capture 95% of all dispersed trajectories. However,

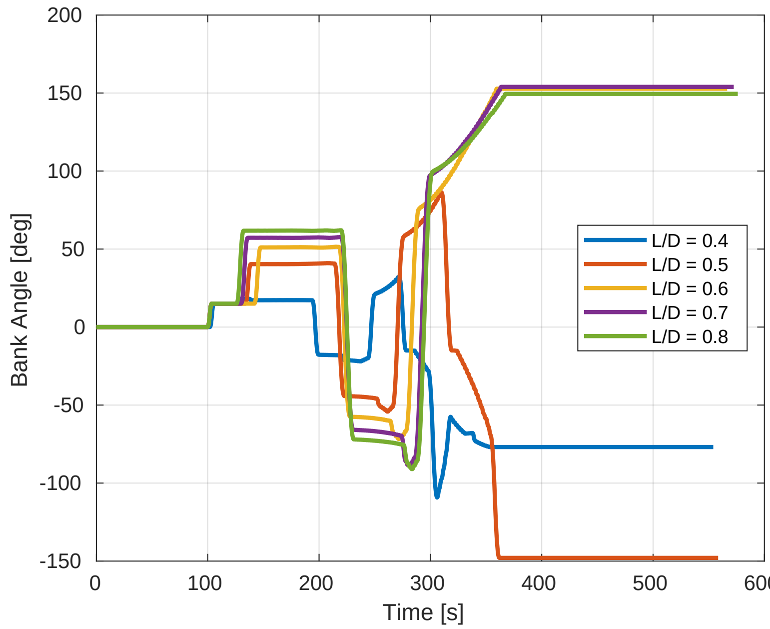

Figure 2. FNPAG bank angle command history across L/D for nominal entry interface conditions.

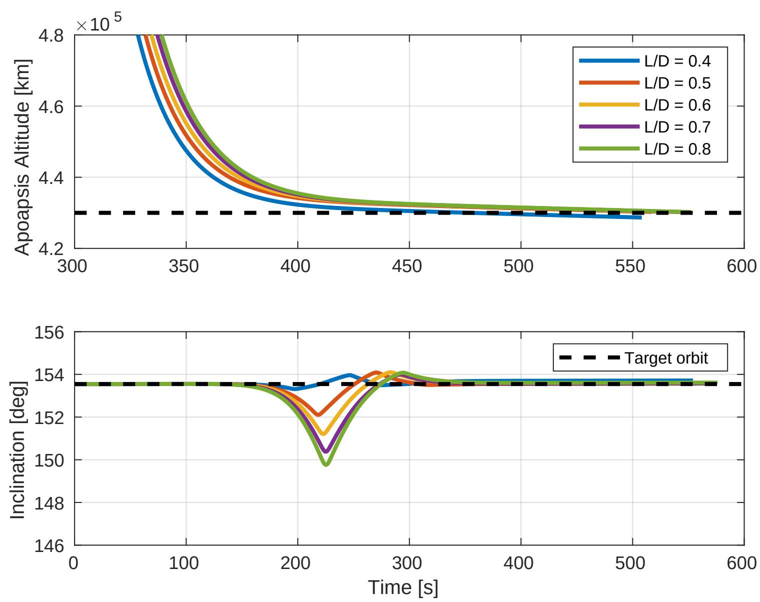

Figure 3. FNPAG longitudinal and lateral targeting performance across L/D. Cross range targeting is achieved using inclination errors with a maximum of two discrete periodic bank reversals.

FNPAG incorporates more accurate dynamics and atmosphere models allowing for reduced L/D margins. The TCW trade indicates an L/D of 0.4 is feasible at Neptune with other uncertainties accounted for. In practice, navigation errors and atmospheric uncertainties at the outer planets are conservatively estimated and unlikely to decrease significantly in the next launch cycles.

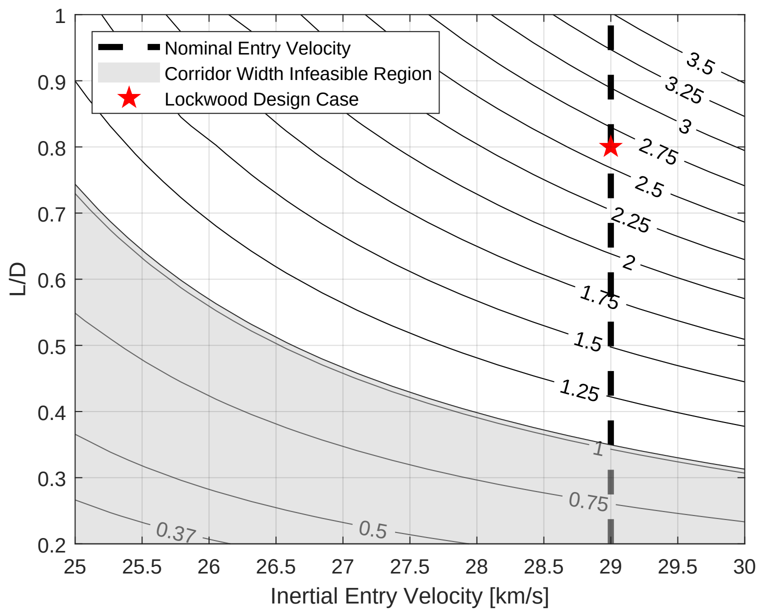

Figure 4. Theoretical corridor width (deg) available at Neptune as a function of entry velocity and L/D.

Monte Carlo Study

An 8,000 run Monte Carlo study is conducted to test the efficacy of FNPAG in the POST2 simulation environment under dispersed initial conditions, atmospheric quantities, and vehicle parameters. Parameters are dispersed identically to the original Lockwood study, including initial state covariance, Neptune GRAM "Fminmax" and "Rpscale" inputs, vehicle mass properties, and aerodynamic coefficients. A nominal L/D of 0.8 is run with FNPAG guidance to establish a baseline of comparison. Results are shown in Figure 5. The algorithm performs reliably and captures 99.96% of all cases utilizing bank angle control only. The 3σ post-capture orbit insertion propulsive ΔV is reduced by nearly half compared to the refence mission. Aerothermal performance and g-loading are both on par with reference values. A small percentage of failed runs are present due to edge cases where the initial state covariance produces entry FPAs outside the TCW. The results indicate that (1) the simulation environment and modeling are comparable to the reference study and (2) the inclusion of modern numerical predictor-corrector guidance greatly decreases variability in propulsive ΔV performance. FNPAG show promise for numerical predictor-corrector guidance algorithms to improve aerocapture options in the presence of large uncertainties.

With a baseline established, Monte Carlo simulations with lowered lift-to-drag ratios of 0.6 and 0.4 are considered. The L/D of 0.6 cases perform on par with the reference L/D of 0.8. However, it is immediately evident that the L/D of 0.4 cases are subject to significant undershooting, resulting in a large number of trajectories well below the target apoapsis radius, or in other cases performing

Variable	Nominal	3σ or min/max	Distribution
Entry B-plane Elements	–	From Covariance	Correlated
Lift Coefficient	1.124	$\pm$ 0.1717	Normal
Drag Coefficient	1.405	$\pm$ 0.1193	Normal
Weight	2200 kg	$\pm$ 10%	Normal
Atmo Perturbation Seed	1	1:9999	Uniform
Atmo Fbias	0	-0.56:0.56	Uniform

Table 2. Dispersed parameters for Monte Carlo simulations in POST2.

direct entry resulting in failure. However, the initial state and covariance reported in Lockwood reference paper were designed for a high-lift vehicle. Since the reduced L/D cases have limited control authority, a shallower nominal entry flight-path angle of -12.5 deg may be utilized to compensate. From an orbital mechanics perspective, small changes to the initial flight-path angle are essentially "free," and may be adjusted based on the interplanetary orbit phasing. Energy-based quantities, such as inertial velocity and radius at entry, are more difficult to manipulate and require large ΔV burns.

Monte Carlo runs with L/D of 0.4 are repeated for the shallower nominal entry flight-path angle. Figure 6 shows the Monte Carlo results for the L/D of 0.4 cases with reduced entry flight-path angle. The results are promising and show similar performance metrics to the higher lift-to-drag ratio cases. Due to a shallower entry flight-path angle, the vehicle experiences lower peak heating and higher integrated heat load. G-loads are also reduced marginally. The distribution of exit state orbital energy for the three L/D cases is shown in Figure 7. All three L/D options are approximately normally centered about the target orbital energy. The L/D of 0.6 cases appear skewed with a longer tail in the undershoot direction, offering an explanation as to why the L/D of 0.4 cases required a shallower entry flight-path angle.

Table 3 summarizes several performance metrics for FNPAG in the three L/D cases. The most apparent tradeoff between the three L/D cases is the number of failures, particularly with the L/D of 0.4 cases at 1.43%. The majority are undershoot failures where the vehicle flies completely lift-up but lacks the necessary control authority to recover. The L/D of 0.4 cases appear to have a lower 3σ ΔV compared to the higher L/D cases. This behavior is due to the fact that failures with reduced L/D would have been recoverable with the higher L/D options, and thus included in final the ΔV statistics. These edge cases can achieve capture with excess L/D margin, but a larger ΔV penalty is necessary in order to achieve precise orbit.

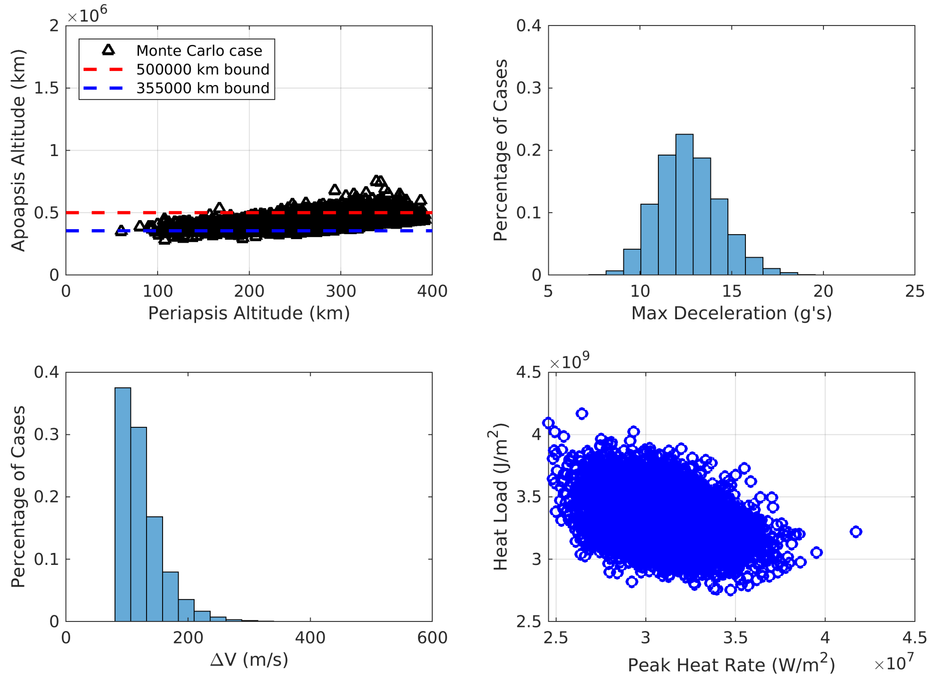

Figure 5. Monte Carlo results for Neptune aerocapture using FNPAG (L/D of 0.8).

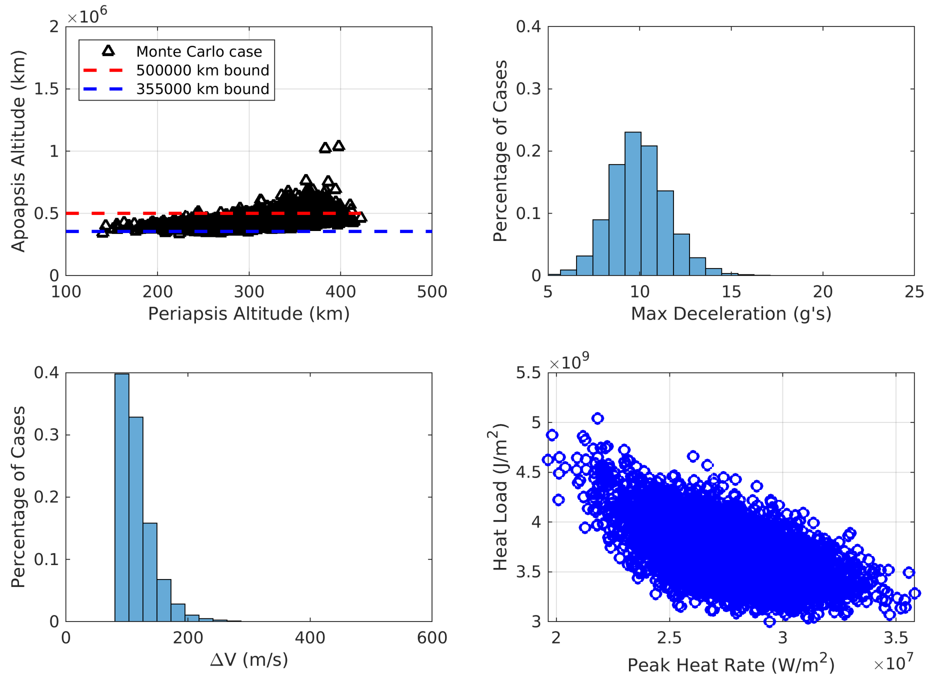

Figure 6. Monte Carlo results for Neptune aerocapture using FNPAG (L/D of 0.4, reduced entry flight-path angle of -12.5 deg).

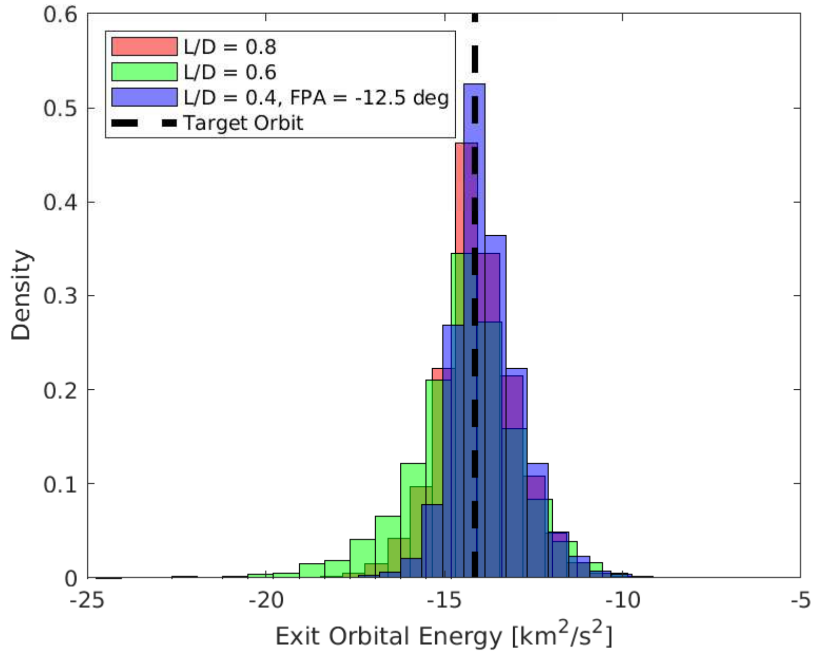

Figure 7. Monte Carlo results for exit orbital energy with L/D of 0.4 and reduced entry FPA of -12.5 deg. Failed capture cases not pictured.

	FNPAG		
Performance Metric	L/D = 0.8	L/D = 0.6	L/D = 0.4
Apoapsis Altitude - $\pm 3\sigma$	5.56e5 km, 3.23e5 km	5.44e5 km, 3.13e5 km	5.63e5 km, 3.34e5 km
ΔV - 3σ high	231 m/s	341 m/s	200 m/s
Max g's	20.5 g's	18.4 g's	17.0 g's
Heat Rate - 3σ high	3.55e7 W/m^2	3.55e7 W/m^2	3.23e7 W/m^2
Heat Load - 3σ high	3.86e9 J/m^2	3.81e9 J/m^2	4.41e9 J/m^2
Percent Captured	99.96%	99.96%	98.59%

Table 3. Monte Carlo performance metrics using FNPAG. The L/D of 0.4 case assumed a shallower nominal entry flight-path angle of -12.5 deg compared to the reference study.

CONCLUSION

This research was a preliminary investigation into performing aerocapture at Neptune with reduced lift-to-drag vehicles utilizing numerical predictor-corrector guidance. Results were validated against a baseline study by Lockwood. Sources of uncertainty were discussed, as well as the nature of failure cases for various lift-to-drag ratios. The results show promise for numerical predictor-corrector guidance to relax existing constraints on L/D for aerocapture at Neptune. Mid-range L/D vehicles, typical of the high-heritage blunt-body designs, are an attractive option to attempt aerocapture with considerably reduced risk and complexity. Missions incorporating these vehicles may greatly improve options for Neptune exploration or other bodies with appreciable atmosphere to attempt aerocapture. Future work includes increasing aerodynamic and environment model complexity in FNPAG, as well as further identifying individual sources of uncertainty to reduce the required entry flight-path angle corridor width.

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