(Preprint) AAS 19-811

A UNIFIED FRAMEWORK FOR AEROCAPTURE SYSTEMS ANALYSIS

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A unified framework for aerocapture systems analysis studies is presented, taking into account the interconnected nature of interplanetary trajectory design and vehicle design. One of the limitations of previous aerocapture systems studies is their focus on a single interplanetary trajectory for detailed subsystem level analysis. The proposed framework and aerocapture feasibility charts enable a mission designer to perform rapid trajectory and vehicle design trade-offs, and is illustrated with its application to a Neptune mission. The approach can be applied to other atmosphere-bearing Solar System destinations. The framework can be be implemented in an aerocapture software suite to enable rapid mission design studies.

INTRODUCTION

Aerocapture is a maneuver in which a spacecraft uses aerodynamic drag force from a single pass through a planetary atmosphere to perform orbit insertion. Aerocapture is a promising alternative to propulsive insertion at atmosphere bearing destinations as it can save significant propellant mass, and can enable some missions not feasible otherwise.[1] The 2013–2022 Planetary Science Decadal survey recommends NASA make systems investments in aerocapture to enable efficient orbit insertion especially for outer planet missions.[2] The Decadal Survey underscores the enormous advantages offered by aerocapture for Neptune orbiter, but also emphasizes programmatic and technical risk, and the added complexity for aerocapture. The Ice Giants Pre-Decadal Mission Study assessed the potential benefits offered by aerocapture, and the technology developments required to implement aerocapture at the ice giants.[3] A unified framework for aerocapture systems analysis considering technical, cost, and risk aspects is developed in the present paper and illustrated with its application to a Neptune aerocapture mission.

AEROCAPTURE SYSTEMS ANALYSIS

Aerocapture mission concept definition involves several diverse and interconnected component systems as shown in Fig. 1. The science definition team outlines the broad scientific questions that the mission seeks to answer and the specific investigations required to be carried out by a spacecraft.

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A mission architecture and preliminary spacecraft configuration is defined for preliminary mission design. A suite of scientific instruments is selected to realize the science investigations within the technical and cost constraints, and acceptable risks of the proposed mission. The investment and time required for risk mitigation activities must be accounted for in the aerocapture mission definition. Finally, the anticipated science return from the is compared against the original science requirements. The science return should be commensurate with the mission cost including any required technology development and the study will identify pathways and descoping options for cost and risk reduction.

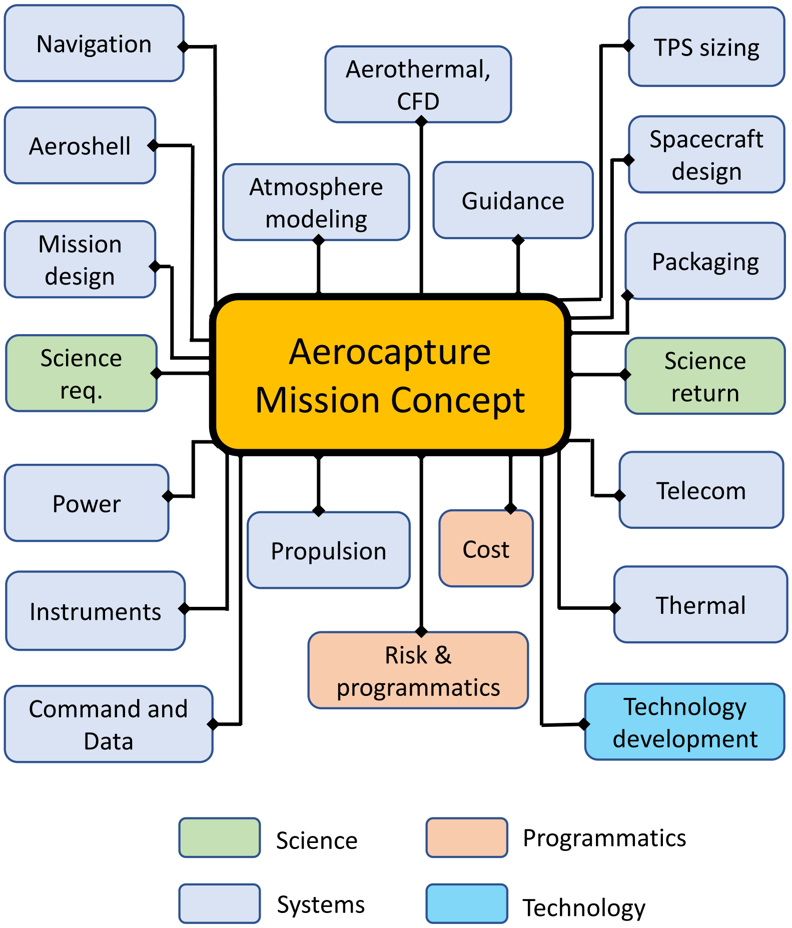

Figure 1. Component systems of an aerocapture mission concept. The interdependencies and trade-offs required between various systems to realize a feasible mission architecture warrant a unified framework for aerocapture systems analysis.

The interconnections and trade-offs required for a feasible concept between various systems shown in Fig. 1, as for any space mission is complex, but particularly more so and less understood for an aerocapture mission concept. There is a lack of architectural-level models of aerocapture systems for early mission concept studies in contrast to propulsive insertion where fairly accurate sizing relations are available such that trade studies can be performed relatively quickly.[3] For an aerocapture mission concept, such basic rules of thumb do not exist and high-fidelity subsystem level detailed analysis of each system is required to obtain even basic parameters such as delivered mass to orbit. As an example, the Neptune aerocapture systems study by Lockwood et al.[4] presents a single high-fidelity vehicle design and associated mass properties. The mass properties for a different set of interplanetary arrival conditions cannot be extrapolated based on the high-fidelity point design. The paper presents the basic foundation of a unified framework for aerocapture systems analysis to allow mission designers to perform trade studies and develop aerocapture mission concepts taking into the account the highly interconnected nature of the component systems.

THE NEED FOR A UNIFIED FRAMEWORK

Previous studies have often been restricted to analysis of a single high-fidelity point design with limited exploration of the underlying trade space. Multiple aerocapture studies have used a limited number of candidate interplanetary trajectories and vehicle designs to perform aerocapture systems analysis, and quantify the performance benefit compared to propulsive insertion.[1,4–7] The interplanetary trajectories are often optimized for propulsive insertion, and do not take account for the differing requirements for aerocapture. While the increased delivered mass from using aerocapture has been quantified by multiple studies, analyses with a limited set of interplanetary trajectories are not representative of the broader aerocapture design space. In addition to the mass benefit, aerocapture can allow significantly shorter time of flights for outer solar system missions compared to propulsive insertion. Previous studies have not evaluated the shorter time of flight trajectories as they would normally be considered having an arrival V_∞ too high for propulsive insertion. Such high V_∞ trajectories become feasible if aerocapture is used, and greatly widens the interplanetary trajectory options for outer planet missions where achieving feasible time of flight is of utmost importance. The present study demonstrates the coupling between interplanetary arrival conditions, vehicle selection and aerocapture performance and address this coupling in a unified framework.

Another limitation of previous studies is the choice of the aerocapture vehicle, which is primarily determined by its hypersonic trim lift-to-drag ratio L/D. To compensate for the large uncertainties at Uranus and Neptune the aerocapture vehicle must have sufficiently large L/D. All interplanetary entry missions flown to date have used ballistic or low-L/D vehicles ($L/D \leq 0.4$) and are considered high heritage entry systems. Studies investigating aerocapture at Neptune have used a mid-L/D vehicle (L/D of 0.6–0.8), assuming such a vehicle would be available. Development of a new entry vehicle incurs significant cost and risk, and the non-availability of a mid-L/D vehicle poses a serious hindrance to aerocapture at the ice giant planets. Missions to the ice giant planets stand to gain the most out of aerocapture, but are also the most challenging due to requirement of high performance vehicles and very high entry speeds. An approach to determine the required vehicle L/D considering the broader interplanetary trajectory space and vehicle control authority requirements is desirable. In addition to the previously mentioned issues for aerocapture systems, constraints arising from launch vehicle performance, deceleration loads, aerodynamic heating, thermal protection system and structural mass must be considered in preliminary mission design.

Aerocapture systems analysis studies in the past involved multiple NASA centers. For example, the Jet Propulsion Laboratory provides support in interplanetary trajectory and mission design,[8] NASA Ames and NASA Langley support entry systems, vehicle design, and flight performance analysis.[9] The proposed method as shown in Fig. 2 is not intended to replace high fidelity studies that can be performed by likely more resourceful NASA led systems analysis studies, but provide a unified conceptual framework to analyze the interdependencies among various aerocapture systems. Future studies can employ the framework to aid in the selection of a point design for high fidelity analysis and eventually realize a feasible aerocapture mission. Note that previous aerocapture

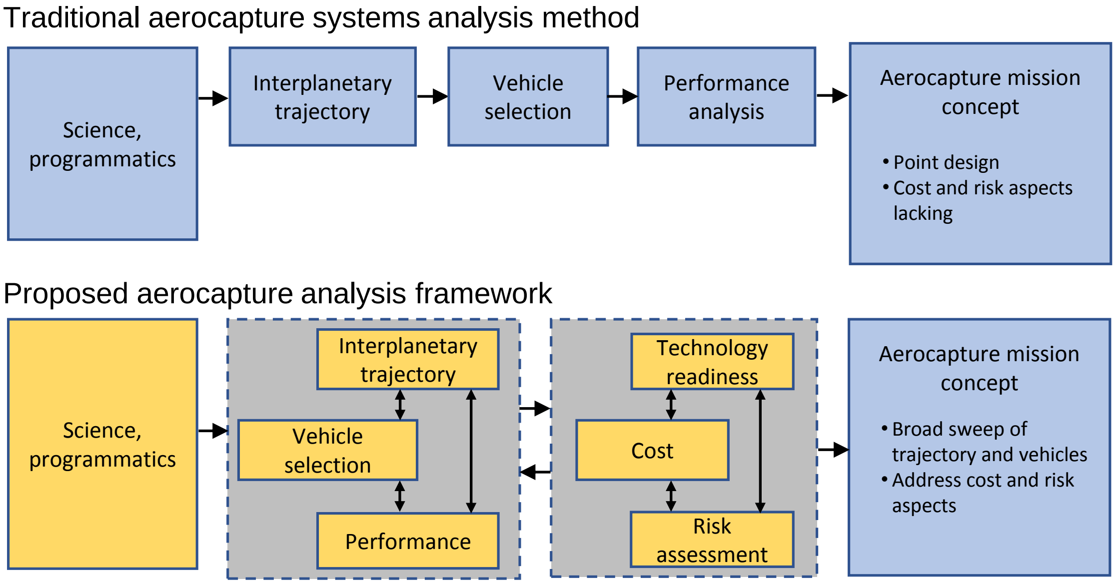

Figure 2. Comparison of traditional method and proposed integrated aerocapture systems analysis framework. Traditionally a single interplanetary trajectory is baselined, along with a single vehicle design during the early phase of the mission concept study. The disadvantage of this method is that the analysis and conclusions are only valid for the selected point design. The proposed framework enables a mission designer to perform rapid trade studies between a broad set of interplanetary trajectories and vehicle designs during any phase of the study, and thus remove the need to use a single trajectory and vehicle design for the entire study.

studies involved assembling a multidisciplinary team which within the limited time and resources available can only explore parts of the entire aerocapture trade space. The proposed framework can result in a database of interplanetary trajectories, and aerocapture performance for a wide range of entry vehicles which can be queried for rapid trade space analysis.

METHODOLOGY

The present work proposes a integrated framework to analyze an end-to-end aerocapture mission concept. The interconnected role of interplanetary trajectory and aerocapture vehicle design has not been fully explored in the literature. The present work uses a single chart to concisely capture the interdependencies among launch vehicle performance, interplanetary trajectory trades, arrival conditions, and vehicle performance. The proposed method allows the mission designer to perform a rapid and comprehensive analysis of the underlying trade space and maximize the performance benefit from using aerocapture for a planetary science mission. The objective of the unified framework is to enable trade studies using a large database of interplanetary trajectories and wide range of vehicle L/D to be performed quickly during an aerocapture mission concept study.

The first step in the proposed framework is the creation of a database of interplanetary transfer trajectories representing a wide range of launch and arrival conditions. Figure 3 shows the arrival V_∞, time of flight and launch C_3 for a comprehensive set of interplanetary trajectories from Earth to Neptune. Traditionally, interplanetary trajectories to Neptune have been constrained to a maxi-

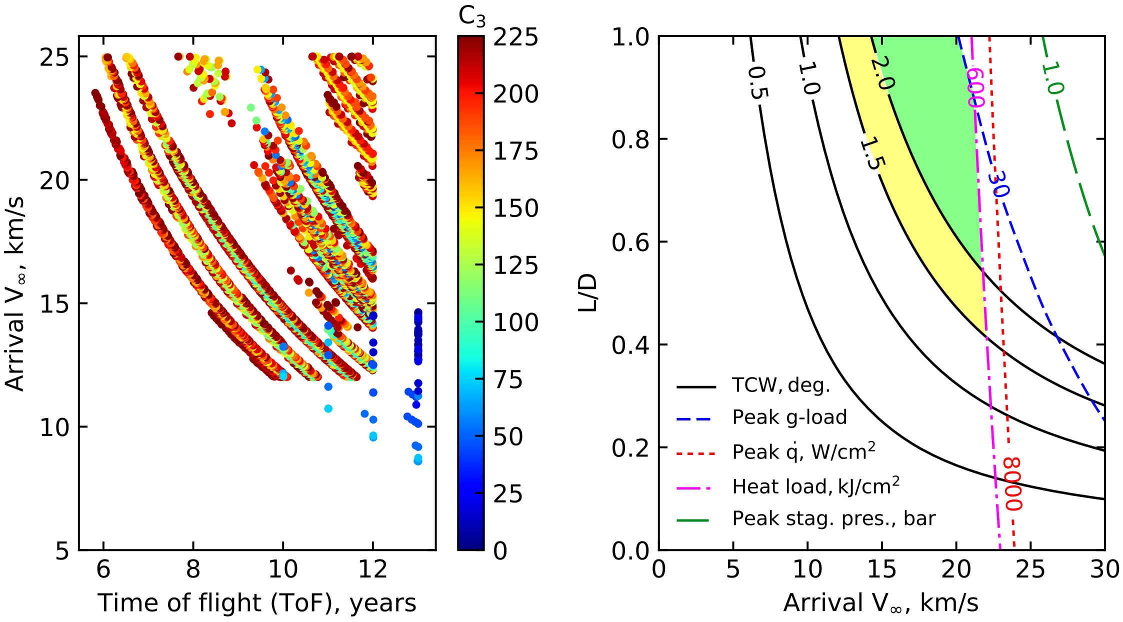

Figure 3. (Left) Arrival V_∞ vs Time of flight for interplanetary trajectories to Neptune. (Right) Aerocapture feasibility chart showing constraints from Theoretical Corridor Width (TCW), peak g-load, peak heat rate, total heat load, and peak stagnation pressure as a function of vehicle L/D and arrival V_∞. The green shaded region indicates the feasible set of L/D and V_∞ for 2.0 degree TCW requirement and other constraint values. If the uncertainties could be reduced such that 1.5 degree TCW is sufficient, the yellow region becomes feasible in addition to the green region. A higher arrival V_∞ trajectory allows a shorter time of flight, and also lowers the vehicle L/D requirement. Results are for vehicle ballistic coefficient β = 200 kg/m^2, target capture orbit period = 20 day, vehicle nose radius = 1 m.

mum V_∞ of approximately 12 km/s as higher approach speeds result in prohibitively low payload mass fraction using propulsive insertion. The interplanetary data set used in the present study includes both low arrival V_∞, long time of flight trajectories and high arrival V_∞, short time of flight trajectories. Propulsive insertion and aerocapture require two different classes of interplanetary trajectories—propulsive insertion requires arrival V_∞ to be minimized, while aerocapture requires a high arrival V_∞ to maximize vehicle control authority during the atmospheric flight phase.

The second step is to select the vehicle L/D such that it provides sufficient control authority to perform aerocapture and also ensure the peak g-loads, aerodynamic heating are within acceptable limits. Aerocapture relies on the judicious use of aerodynamic drag to decelerate the spacecraft and perform orbit insertion. To ensure the spacecraft exits the atmosphere with the desired set of conditions for the target capture orbit, the vehicle must enter the atmosphere within the theoretical aerocapture corridor. Entering too steep can result in unacceptably high deceleration and aerodynamic heating, while entering too shallow can result in the vehicle exiting the atmosphere without having decelerated enough. The width of the acceptable entry corridor is quantified by the Theoretical Corridor Width (TCW). TCW is a measure of the control authority offered by the aerocapture vehicle at specified arrival conditions and atmospheric conditions, and is an important parameter in aerocapture mission design. A non-zero TCW is required to allow the aerocapture vehicle to accommodate the uncertainties. The major uncertainties involved are entry-flight path angle uncertainty from approach navigation, atmospheric density uncertainties, and vehicle aerodynamics uncertainties. The uncertainties can be quantified in terms of degrees,[4] and the root-sum-squared total uncertainties defines the Required Corridor Width (RCW). To ensure the success of the aerocapture maneuver without risk of burn up or accidental escape, the available TCW should exceed the RCW with sufficient safety margin. Figure 3 shows contours of TCW as a function of vehicle L/D and arrival V_{∞}. In addition, contours of peak g-load, peak heat rate and other constraints are also shown in Fig. 3. The peak heat rate and stagnation pressure constraints arise from TPS material and testing limitations while sensitive instruments and aeroshell structure impose a constraint on the acceptable peak deceleration.

The uncertainties can be quantified and root-sum-squared to obtain a required corridor width (RCW) and is expected to be in the range of 0.5 to 2.0 degrees for aerocapture at Neptune. The design TCW should be greater than the RCW. Figure 3 shows that to achieve a required TCW a minimum L/D and minimum arrival V_{∞} are required, while the deceleration and heating constrains limit the maximum feasible V_{∞}. It is desired to minimize the L/D required as all planetary entry vehicles flown so far have L/D less than 0.4. While previous studies have assumed that a higher performance vehicle with L/D in the range of 0.6–0.8 would be available such vehicles have not been developed yet. For aerocapture at Neptune to be feasible in the near term, it is presumed low-L/D vehicles must be used to limit technology development costs. Using interplanetary trajectories with high arrival V_{∞} can lower the vehicle L/D requirement as seen in Fig. 3, and also allow a shorter time of flight. Figure 3 thus allows a mission designer to perform trade-offs between interplanetary trajectory parameters and vehicle design parameters accounting for their interdependence through the arrival V_{∞}. The methodology is applicable to all atmosphere bearing destinations in the Solar System, and provides a mission designer with a comprehensive picture of the coupled interplanetary and vehicle design trade space before selecting a single point design for higher fidelity analysis. The selected interplanetary trajectory and vehicle L/D should satisfy the following preliminary requirements: 1) The launch C_3 should be selected such that it allows a feasible time-of-flight and sufficient delivered mass at the target. 2) The selected $(L/D, V_{\infty})$ should provide sufficient control authority using preliminary estimates of the uncertainties involved. 3) The arrival V_{∞} should be high enough to minimize the L/D requirement, but not too high as to exceed the capability of TPS materials or result in an unacceptably high TPS mass fraction.

The third step is to use the selected interplanetary arrival condition (V_{∞}) and vehicle L/D to perform high fidelity Monte Carlo simulations to assess vehicle performance. The best available estimates of the uncertainties from delivery errors, atmospheric uncertainties, and aerodynamics are required to analyze the performance of the aerocapture guidance algorithm. The ability of the guidance algorithm to accommodate errors in delivery state, atmospheric mean density variations, random high frequency density perturbations, mass and aerodynamics uncertainties and other relevant uncertainties is evaluated using Monte Carlo simulations. The statistical results from Monte Carlo simulations can be used to validate that the selected $(L/D, V_{\infty})$ offers sufficient control authority and reliably perform aerocapture. It is possible that some runs result in trajectories that accidentally escape, or result in too high deceleration or heating. In such cases, it is worth fine-tuning of the entry-flight path angle, guidance scheme numerical parameters or target capture orbit to improve the performance metrics. If satisfactory performance cannot be achieved, then it may be necessary to return to steps 1 and 2 to revise the choice of interplanetary trajectory and vehicle L/D and repeat step 3 until results are satisfactory.

The fourth step involves incorporation of other systems outlined in Fig. 1 such as spacecraft design, instrument suite, power, data handling, packaging inside the aeroshell, aeroshell structure design, telecom, and thermal management. Due to limited time and resources available for the present study, the above mentioned systems will not be studied further, but is well within the capabilities of NASA concurrent engineering facilities. The study recommends that steps 1 through 3 be completed before such any subsystem level studies are initiated so that optimal reference interplanetary trajectories and vehicle L/D are readily available. The study systems engineer will carefully balance the trade-offs to be made for various systems such as instruments, power, data rates etc. to realize a technically feasible spacecraft and aeroshell design the mission design constraints. Figure 4 shows the trajectory trades and aerocapture feasibility chart for a Uranus mission.

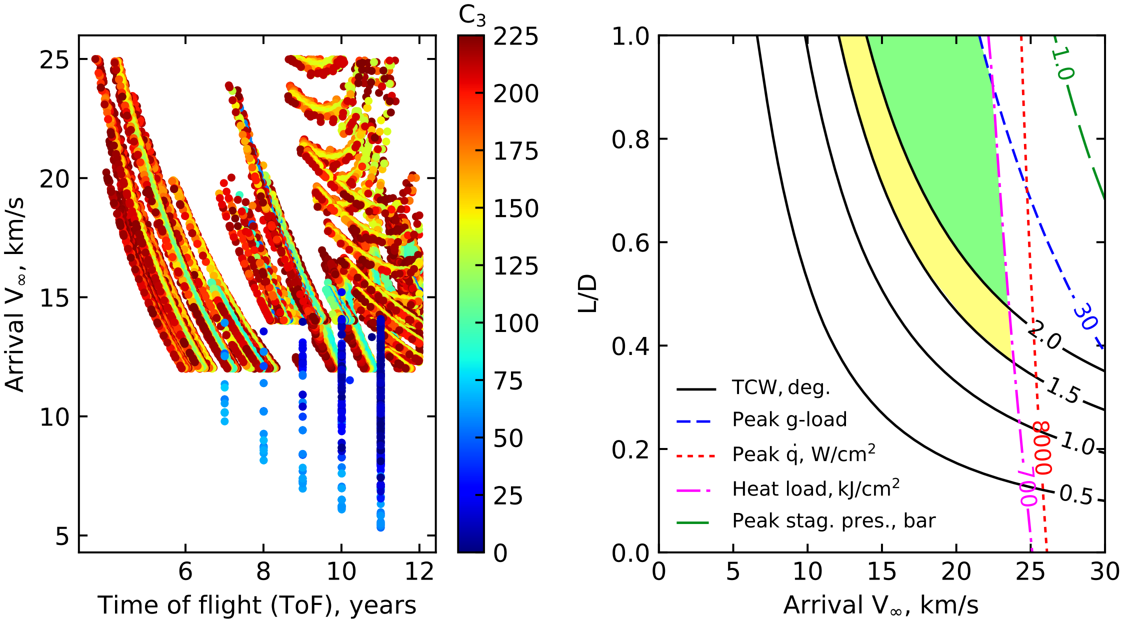

Figure 4. (Left) Interplanetary trajectory trade space for missions to Uranus. (Right) Aerocapture feasibility chart for Uranus.

The fourth step also involves risk assessment, cost estimation, and identification of technology developments to be made to realize the concept as the spacecraft components are being defined. A major limitation of the previous aerocapture systems studies and area of concern expressed in the Decadal survey is the cost and risk implications of using aerocapture for a highly visible space mission.[2] While cost estimation and risk assessment is not possible at the level of the present paper, more resourceful studies using NASA design facilities can perform such assessments. As with any major space mission, staying within the budgetary constraints and plans for mitigating outstanding risks is critical to the realization and flight implementation of any aerocapture mission concept. The availability of suitable TPS materials, investments required for further TPS development and flight qualification tests, aeroshell development etc. are factors which are of significant concern from a cost and risk perspectives and must be satisfactorily addressed in future studies. It may be necessary to return to and repeat any of the previous steps to realize a technically and fiscally credible, low-risk aerocapture mission concept.

RESULTS FOR A NEPTUNE AEROCAPTURE MISSION

The proposed methodology is applied to Flagship class Neptune-Triton exploration mission. The ice giants Uranus and Neptune represent a distinct class of planets, quite different from the gas giants Jupiter and Saturn. While the gas giants have been studied in exquisite detail by the Galileo, Juno, and Cassini-Huygens, the ice giants remain the last class of planets to not have had a dedicated orbiter mission. The Planetary Science Decadal Survey identified a Uranus orbiter with Probe (UOP) as the third highest priority for Flagship class missions in the 2013–2022 decade. The survey notes that both the ice giants are equally compelling scientifically, but Uranus's smaller heliocentric distance, associated shorter flight time, and programmatic considerations favored Uranus over Neptune. Aerocapture is a strongly enhancing to enabling technology for a Neptune mission, and there is current interest in the short time-of-flight trajectories to Neptune using aerocapture.[10] Neptune is also one of the most challenging destinations to perform aerocapture, due to the large uncertainties involved, risk of accidental escape, and harsh aerothermal environment. Neptune is chosen as the destination for the present study as the benefits from aerocapture are most significant, but also presents significant risk. The results can be extended to Uranus using the data presented in Fig. 4.

Ground Rules and Assumptions

The mission design begins with the following set of ground rules, assumptions, and programmatic requirements. Meeting the science objectives at Neptune requires a 1500 kg dry mass spacecraft delivered to a retrograde orbit (with respect to Neptune) which permits regular Triton flybys. In addition, a 300 kg atmospheric entry probe is required to be carried and preferably released after the spacecraft goes performs aerocapture. Assuming a propellant load of 700 kg, the total mass required to be delivered to orbit is 2500 kg. To allow for at least two years of primary science, a 12 year maximum allowable time of flight constraint which due to radioisotope power source decay. SLS Block-1B is assumed to the highest performance launch vehicle available. The launch should occur within the next decadal period of 2023-2032. Technology development cost constraints are assumed to require that a low-L/D ($L/D \leq 0.4$) aeroshell is used, preferably with $L/D \leq 0.24$ so as to leverage MSL heritage. Heatshield for Extreme Environment Entry Technology (HEEET) is the Thermal Protection System (TPS) material used and can sustain a maximum heat rate of 8000 W/cm^2[11] at an assumed 1 atm stagnation pressure. It is assumed a Theoretical Corridor Width (TCW) of at least 1.25 degrees is required to accommodate navigation and atmospheric uncertainties.

Mission Design

The mission design begins with the down selection from the wide range of interplanetary trajectories shown in Fig. 2 (left) based on the allowable time of flight and launch C_3 (for sufficient delivered mass at Neptune). For the feasible set of interplanetary trajectories based on their arrival V_∞ the minimum required vehicle L/D can be computed from Fig. 2 (right). The chart also demarcates constraints arising from deceleration loads, heating rate, and total heat load. The total heat load can be used to estimate the approximate TPS mass fraction, and improve the estimate of the delivered mass to orbit. An interplanetary trajectory that satisfies all the top level constraints maximizes a merit function based on delivered mass and time of flight is optimal for the aerocapture mission concept, and is a candidate for higher fidelity study. Preliminary results indicate that an Earth-Jupiter-Neptune trajectory launching in 2031 with a flight time of 7.87 years and C_3 = 111 km^2/s^2 is a promising candidate. The launch SLS-Block 1B launch capability at this C_3 is approximately 6000 kg, the aerocapture entry vehicle mass is expected to be about 5000 kg after jettisoning the cruise stage, antennae etc. Assuming an entry vehicle useful payload mass fraction of 50%, this allows 2500 kg to be delivered to orbit. The useful payload mass fraction estimate is preliminary and will be refined in the later phases. From Fig. 3 (right) the high arrival V_∞ = 20 km/s along with the 1.25 degree TCW requirement allows a vehicle with L/D = 0.4 to provide sufficient control authority for aerocapture. Note that the 1.25 degree TCW is preliminary at this stage, and is based on projected improvements in the uncertainties over estimates by Lockwood et al.[4] The expected heating rates are within the capability of HEEET TPS, and the peak deceleration and heat load is within reasonable limit. If any of these constraints could not be satisfied, it will be required to revise the interplanetary trajectory selection such that the arrival V_∞ can be adjusted accordingly. Figure 3 thus allows a mission designer to go back and forth between interplanetary trajectory trade and vehicle selection trade accounting for their interconnectedness through the arrival V_∞.

Vehicle Performance Analysis

The next step is to perform Monte Carlo simulations to assess aerocapture vehicle performance. Using Monte Carlo simulations to ensure satisfactory performance of the guidance scheme is particularly important for Uranus and Neptune due to the narrow aerocapture corridor and high risk of accidental escape, but less so for other destinations such as Venus or Titan which have relatively larger corridor widths. The narrow entry corridor drives the need for accurate estimation of the EFPA uncertainties from delivery errors, atmospheric, and aerodynamics uncertainties at this stage. While heritage low-L/D vehicles have been shown to provide sufficient control authority at other destinations, previous studies have used a mid-L/D vehicle at Uranus and Neptune. The lack of a proven flight-heritage mid-L/D planetary entry vehicle has been a major hurdle for Neptune aerocapture due to the significant developmental efforts required to realize such an entry system. L/D of 0.4 is a nominal upper limit for heritage entry systems such as Apollo, and using such blunt-body aeroshells is beneficial if they can be shown to provide sufficient control authority. Techniques to lower the L/D requirement from mid-L/D vehicles to low-L/D vehicles include reduction of delivery errors from improved optical navigation, reduced atmospheric uncertainties, and improved guidance schemes. High fidelity aerocapture performance analysis using the selected interplanetary trajectory and heritage blunt body aeroshell (L/D = 0.4) is presented in a companion paper abstract submitted to this conference[*].

Note that nominal trajectories with flight times less than 13 years are difficult to achieve with propulsive insertion,[3] and hence aerocapture allows a 5 year reduction in flight time to Neptune. Preliminary results indicate the high arrival V_∞ of 20 km/s enables the use of a heritage blunt body aeroshell with L/D = 0.4, and is within the capability of existing TPS materials. Further study is on-going to investigate if the L/D requirement can be reduced to 0.24 to enable use of an MSL-derived aeroshell for Neptune aerocapture. The statistical performance metrics from Monte Carlo simulations (such as percentage of cases captured successfully, apoapsis dispersion etc.) shown in Fig. 5 must be assessed and compared to the preliminary estimates used earlier. If the vehicle performance is satisfactory (in a statistical sense i.e. the probability of mission critical failure such as accidental escape is sufficiently low) the mission concept can proceed to the next step of more detailed system analysis. If not, it is necessary to identify the cause of the failures and adjust the interplanetary trajectory, vehicle design, and guidance scheme to ensure acceptable performance.

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[*] Athul Pradeepkumar Girija et al. "Aerocapture Performance Analysis for a Neptune Mission Using a Heritage Blunt-Body Aeroshell", AAS 19-815, 2019 AAS/AIAA Astrodynamics Specialist Conference, Portland, ME.

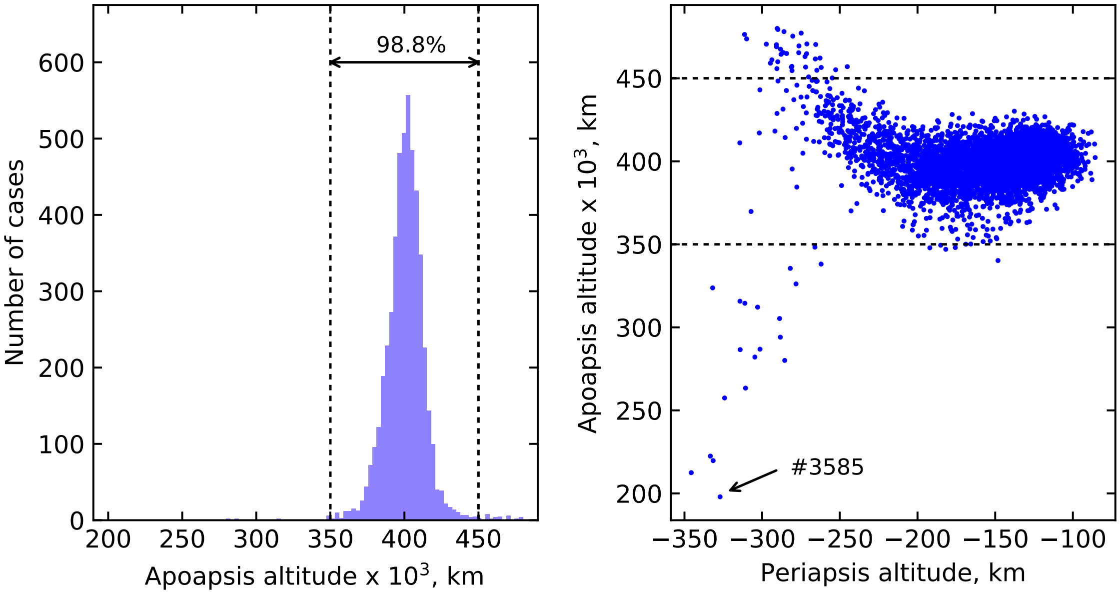

Figure 5. Representative aerocapture vehicle performance analysis results from Monte Carlo simulations for a vehicle with L/D = 0.4 entering Neptune atmosphere at 30.5 km/s. Target apoapsis alt. = 400,000 km. (Left) Histogram of apoapsis altitude achieved. 100% of the cases captured successfully in this simulation i.e. no cases resulted in atmospheric burnup or escape. (Right) Apoapsis vs. periapsis altitude at atmospheric exit. Refer to the companion paper* for more details.

Subsystem Design, Cost and Risk Assessment

The final step in the proposed framework is the incorporation of power systems, instruments, command and data handling, propulsion, aeroshell configuration and structure, thermal protection system (TPS), spacecraft design and packaging inside the aeroshell, telecom and thermal management. This step is suitable for a NASA concurrent engineering design lab such as Team X[8] for a high fidelity mission concept study. Subsystem level analysis may be required for aerothermal predictions and TPS sizing for which the expertise specialized research groups and facilities and NASA Ames Research Center can be leveraged.

A major limitation of the previous high fidelity aerocapture systems analysis studies[4–6] is that a cost and risk assessment is lacking. The lack of cost and risk assessment could be attributed to the fact that these were among the first ever detailed aerocapture systems studies and the schedule and time constraints limited the investigations that could be performed. In the proposed framework, once the system definition reaches an acceptable level, a cost estimate (based on parametric models, historical data etc.) is performed. Such an estimate is difficult to perform at the level of the present paper, and hence is not performed for a Neptune aerocapture mission. However, the study emphasizes the importance of being able to provide a reliable cost estimate for any future aerocapture mission concept study. The science return should be commensurate with the mission cost, and should allow ample margins for cost growth and options for descopes if required.

Despite acknowledging the significant performance benefit offered by aerocapture for outer planet missions, the concern of the risks associated with aerocapture is clearly visible in the literature. The Decadal survey remarks,“Further risk reduction will be required before high value and highly visible missions will be allowed to utilize aerocapture techniques." There are very few studies which has investigated quantitatively the nature and magnitude of risks associated with aerocapture. Studies over several decades have shown that the technical risks associated with aerocapture can be mitigated, for example many of the technologies a future aerocapture vehicle would use such as guided hypersonic flight has been demonstrated by Apollo and Mars Science Laboratory (MSL).[12]

The cost and schedule risks for aerocapture are substantially less understood, along with programmatic and political risks. The present study recommends that future aerocapture studies apply quantitative risk assessment techniques which NASA has matured though numerous manned and robotic missions.[13] A recent study initiated by the NASA Planetary Science Division concluded that a technology demonstration mission is not required before use of aerocapture on a mission, but remarks that ice giants require additional study.[12] Quantitative cost and risk estimate for an ice giant aerocapture mission concept is highly desired and will inform the upcoming Decadal survey studies regarding the readiness of its use for a large strategic mission.

AEROCAPTURE MISSION ANALYSIS TOOL

The identification of techniques that enable missions or significantly lower their cost is of interest to the planetary science community.[2] The proposed integrated framework presented can be implemented in an aerocapture mission analysis software suite for rapid mission architecture studies. One of major issues faced by the Ice Giants Pre-Decadal Mission study was the lack of software tools for analysis of aerocapture mission concepts. The tool can be used in concurrent engineering facilities to enable mission designers to perform trade studies and assess what-if scenarios for aerocapture mission concepts. The software suite can enable cost-effective, rapid aerocapture mission concept studies without having to resort to selecting a single-point design in the early study phase when the requirements and capabilities may not be well defined.

CONCLUSIONS

The present study proposes a unified framework for aerocapture mission concept studies. The importance of interconnectedness between the interplanetary trajectory and vehicle design in early mission design is presented using aerocapture feasibility charts. The methodology is applied to a Neptune aerocapture mission, and shows that fast arrival trajectories can allow the use of low-L/D ($L/D \leq 0.4$) aeroshells and also allow significantly shorter flight times (<8 years) compared to propulsive insertion architectures which take 13 years or longer. The analysis can be extended to other atmosphere-bearing outer planer destinations such as Uranus and Titan. The proposed integrated framework presented can be implemented in an aerocapture mission analysis software suite for rapid mission architecture studies.

ACKNOWLEDGMENT

The authors acknowledge Dr. Anastassios Petropoulos at the NASA Jet Propulsion Laboratory and and Dr. Nitin Arora, formerly at the NASA Jet Propulsion Lab for providing the interplanetary trajectory data used in this study. A.P.G was a participant of the 30th Plannetary Science Summer Seminar (PSSS) which contributed to the end-to-end mission life-cycle analysis methodology used in the study. A.P.G. thanks Dr. Charles Budney, Dr. Karl Mitchell and Ms. Leslie Lowes, all at the NASA Jet Propulsion Laboratory for valuable lessons during PSSS.

REFERENCES

[1] J. L. Hall, M. A. Noca, and R. W. Bailey, "Cost-Benefit Analysis of the Aerocapture Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, 2005, pp. 309–320, 10.2514/1.4118.

[2] *Vision and Voyages for Planetary Science in the Decade 2013-2022*. National Academies Press, 2012.

[3] M. D. Hofstadter, A. Simon, K. Reh, and J. Elliot, "Ice Giants Pre-Decadal Study Final Report," Tech. Rep. JPL D-100520, NASA, Pasadena, CA, 2017.

[4] M. K. Lockwood, K. T. Edquist, B. R. Starr, B. R. Hollis, G. A. Hrinda, R. W. Bailey, *et al.*, "Aerocapture Systems Analysis for a Neptune Mission," Tech. Rep. NASA/TM-2006-214300, NASA Langley Research Center, Hampton, VA, 2006.

[5] M. K. Lockwood, B. R. Starr, J. W. Paulson, D. A. Kontinos, Y. K. Chen, Laub, *et al.*, "Systems Analysis for a Venus Aerocapture Mission," Tech. Rep. NASA/TM-2006-214291, NASA Langley Research Center, Hampton, VA, 2006.

[6] M. K. Lockwood, E. M. Queen, D. W. Way, R. W. Powell, K. Edquist, B. W. Starr, *et al.*, "Aerocapture Systems Analysis for a Titan Mission," Tech. Rep. NASA/TM-2006-214273, NASA Langley Research Center, Hampton, VA, 2006.

[7] P. Agrawal, G. A. Allen, E. B. Sklyanskiy, H. H. Hwang, L. C. Huynh, K. McGuire, M. S. Marley, J. A. Garcia, J. F. Aliaga, and R. W. Moses, "Atmospheric Entry Studies for Uranus," *2014 IEEE Aerospace Conference*, Big Sky, MT, IEEE, 2014, pp. 1–19.

[8] B. Sherwood and D. McCleese, "JPL Innovation Foundry," *Acta Astronautica*, Vol. 89, 2013, pp. 236–247.

[9] D. W. Way, R. W. Powell, A. Chen, A. D. Steltzner, A. M. San Martin, P. D. Burkhart, *et al.*, "Mars Science Laboratory: Entry, Descent, and Landing System Performance," *Aerospace Conference, 2007 IEEE*, Big Sky, MT, IEEE, March 3–10, 2007, pp. 1–19, 10.1109/AERO.2007.352821.

[10] OPAG, "Outer Planets Assessment Group (OPAG): Scientific Goals for Exploration of the Outer Solar System," Tech. Rep. OPAG-Report-Draft-Sep-2018, 2018.

[11] E. Venkatapathy, D. Ellerby, P. Wercinski, and P. Gage, "Venus Entry Challenges and Solutions for Aerial Platform Deployment," *Venus Aerial Platform Workshop #2*, Pasadena, CA, December, 2017.

[12] T. R. Spilker, M. Adler, N. Arora, P. M. Beauchamp, J. A. Cutts, M. M. Munk, *et al.*, "Qualitative Assessment of Aerocapture and Applications to Future Missions," *Journal of Spacecraft and Rockets*, Nov. 2018, pp. 1–10.

[13] D. M. Gerstein, J. G. Kallimani, L. A. Mayer, L. Meshkat, J. Osburg, P. K. Davis, B. Cignarella, and C. A. Grammich, *Developing a Risk Assessment Methodology for the National Aeronautics and Space Administration*. Santa Monica, CA: RAND Corporation, 2016.