Aerocapture Solutions for Flagship-class Uranus Orbiter and Probe

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The 2022 Planetary Science Decadal Survey released by the National Academies of Science have identified a mission to Uranus as the top flagship-class priority. The baseline mission, Uranus Orbiter and Probe (UOP), is based on a launch date in the early 2030s, uses a fully-propulsive orbit insertion maneuver at Uranus that requires 60-70% of total mass for propellant, and reaches the planet after 13 years of interplanetary cruise. With a launch date in mid or late 2030ś more realistic schedule and budget-wise for the next NASA flagship-class mission, the appeal of an aerocapture-enabled Uranus mission increases. Aerocapture is an orbit insertion maneuver that uses the atmosphere to decelerate to a capture orbit. A two-year study has shown a feasible aerocapture design based on heritage technologies borrowed from the entry, descent, and landing community can put the Uranus Orbiter and Probe payload into the desired science orbit.

I. Introduction

The exploration of the Ice Giant planets has become a higher priority of the planetary science community. Recent planetary mission assessments, such as the 2022 Planetary Science Decadal Survey released by the National Academies of Science[1], have focused on the need for a flagship-class mission to the Ice Giant planets, particularly Uranus. The Uranus Orbit and Probe (UOP) mission proposal [2] was used by the National Academies of Science as the baseline while making its recommendation as the top flagship-class mission for NASA in the 2020-2030s. This mission which was based on a launch date of 2031 or 2032, uses a fully-propulsive orbit insertion maneuver at Uranus (requiring 60-70% of total mass for propellant), and reaches the planet after 13 years of interplanetary cruise before the 2049 equinox, a goal of the science community. A pre-2033 launch date is required to conduct a necessary Jupiter fly-by as the giant planet will not be in the proper alignment for a later launch date. However, as the budget constraints of the NASA budget have pushed back the start date of a Uranus mission, a launch date of a flagship mission before 2033 becomes infeasible.

Aerocapture, an orbit insertion maneuver that uses the atmosphere to decelerate, can reduce the propellant load needed for a captured orbit. Additionally, the aerocapture maneuver can decelerate safely while approaching the planet at higher arrival velocities, thus allowing a mission to use a highly energetic trajectory and reduce the cruise time by

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several years. An aerocapture-enabled solution has launch opportunities in the mid 2030's, including as late as 2038 to reach Uranus by 2049. To accomplish an Uranus mission before the desired 2049 equinox, an aerocapture-enabled orbiter and probe mission opens the trade space. In 2022-2024, the NASA Space Technology Mission Directorate, via its Early Career Initiative (ECI), funded a study look at the design of an aerocapture mission to the Ice Giants. This paper discusses the feasibility of an aerocapture option for a Flagship-class mission to Uranus based on the results of that study.

II. Background

A. Uranus Orbiter and Probe

The current baseline for an Uranus mission is the UOP design that is discussed in Ref. [2]. The mission includes a 13-year interplanetary cruise with a Jupiter fly-by. The baseline launch date is 2031 with a backup opportunity for 2032. The mission is designed to be achievable with a Falcon Heavy Expendable or a Vulcan Centaur. One of the innovations in mission design for UOP is that the orbiter would go into Uranus orbit with the probe still attached, and would deploy the probe 13-60 days after orbit insertion. This is different from other past missions [3–5], which separate the probe during hyperbolic approach to the planet. Going into orbit with the probe attached leads to a ΔV added cost, but allows the scientists and mission planners more informed control over where to perform the probe release.

Although UOP has a long cruise phase with a Jupiter fly-by to reduce the approach velocity at Uranus, the Uranus Orbit Insertion (UOI) maneuver requires approximately 1000 m/s of ΔV. This means the single UOI maneuver requires over 1800 kg of fuel, which accounted for 22% of the launch mass of 8345 kg. Other propulsive maneuvers combined with UOI burn accounted for 60% of the launch mass.

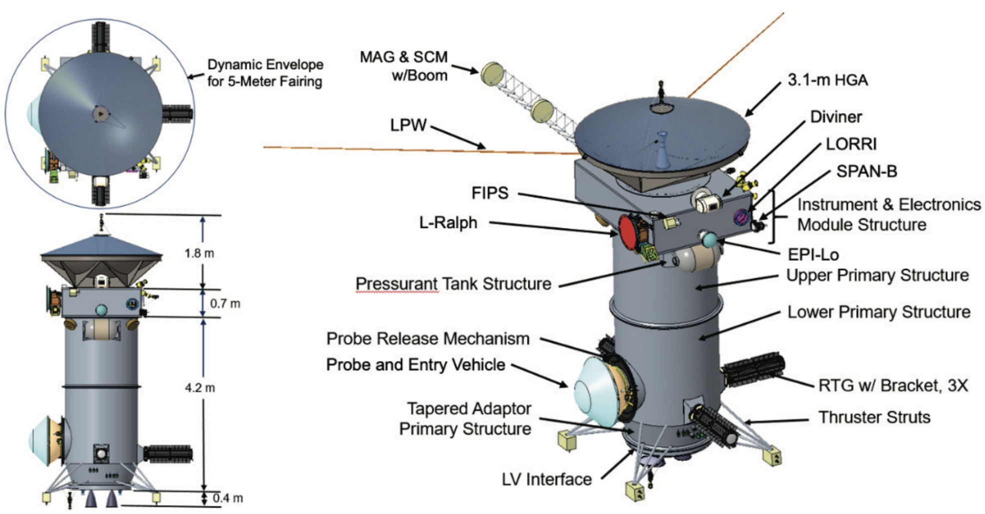
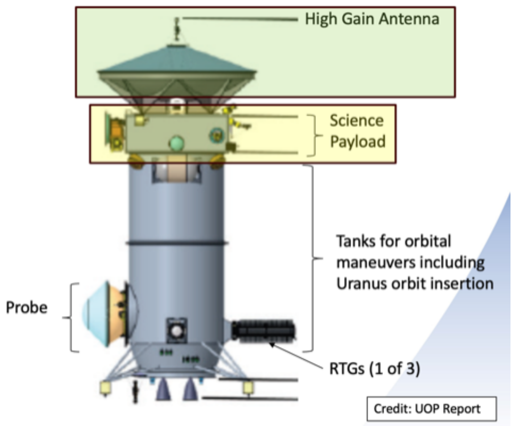


Fig. 1 Spacecraft for the Uranus Orbiter and Probe Mission (from Ref. [2]).

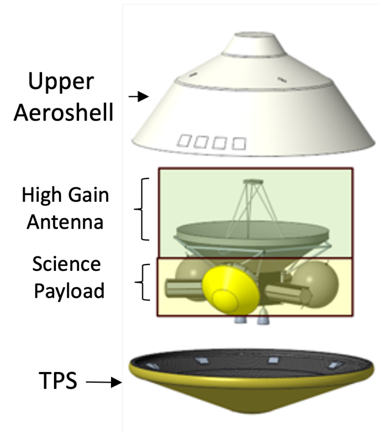
Figure 1 shows the spacecraft for the UOP concept. The vertical cylindrical structure (which is 4.2 m in height) is the pressurized tank structures for the vehicle. The large aspect ratio of the vehicle is dominated by the tanks needing to hold propellant for large propulsive burns such as the UOI. However, after the initial UOI, these pressurized tanks will be largely empty for the lifespan of the UOP mission. The scientific instruments of the actual orbiter are contained in the rectangular box below the high-gain antenna (HGA). The other crucial components include the probe and the three Radioisotope Thermoelectric Generators (RTGs) that are used to power the spacecraft so far away from the Sun.

B. Aerocapture Concept

The simple objective of the aerocapture concept is to take a mature design of an Uranus orbiter and probe and put an aeroshell over the system. This concept can be envisioned in Fig. 2, where the science payload and other necessary components of the UOP mission are identified, and then put within an aeroshell. One can see that the actual science payload from the UOP concept does not take as much volume, and other necessary components like the RTGs, HGA, and the probe could conceivably fit within the aeroshell. In fact, the need for less propellant in an aerocapture concept versus the UOP design leads to large volumetric savings as the large propellant tanks in the UOP design can be discarded. Ref. [6] contains more details about mechanical and volumetric design of the aerocapture concept, but Fig. 2 shows the crux of the motivation of this concept.



(a) UOP Concept (adapted from Ref. [2])



(b) Aerocapture Concept

Fig. 2 Comparison of UOP and aerocapture concepts with the science payload and other necessary components.

The concept of operations for the aerocapture concept at Uranus is seen in Fig. 3. An aerocapture vehicle - aeroshell and a cruise stage - approach the target body and conduct Optical Navigation (OpNAV) operations a few weeks before atmospheric interface. The OpNAV campaign is based on using features of the planet and the surrounding moons to determine the spacecraft position with respect to the planetary body. Details of the OpNAV campaign are covered in Ref. [7]. Approximately 10 minutes before atmospheric interface, the cruise stage is separated and the aeroshell approaches the planet. Atmospheric interface occurs at 4000 km altitude (the rationale is described in Ref. [8]). Active aerocapture guidance, navigation, and control (GNC) shapes the trajectory within the atmosphere to dissipate enough energy to achieve the final target orbit. Following atmospheric exit, the aeroshell is jettisoned, the details of which are discussed in Sec. V.E, and a small clean-up maneuver might be executed as discussed in Ref. [7]. Finally, at the first apoapsis after atmospheric exit, a periapsis raise maneuver is conducted to increase orbit's periapsis above the atmospheric interface. The probe deployment will be close to this apoapsis. An error-correction maneuver may be conducted at the next periapsis to modify the apoapsis to maintain the target orbit. In the design of the aerocapture system, another potential burn shortly after the atmospheric exit might be needed to improve the capture success rates for some outlier cases. This maneuver is discussed in Ref. [7].

C. Aerocapture Demonstration Relevance Assessment Team Report

In 2022, the NASA Science Mission Directory assembled subject matter experts to look at the need for aerocapture technology for science mission needs and the relevance of an aerocapture demonstration mission. The aptly named Aerocapture Demonstration Relevance Assessment Team (ADRAT) produced a report in 2023 [9]. Figure 4 notes some of the risks the report identified for aerocapture missions, especially missions to the Ice Giants, and prioritized them in terms of low, medium, or high risk. The three top risks were associated with potentially high atmospheric uncertainties at the target planets, implementation costs of aerocapture if uncertainties in general are too high, and if the aerothermodynamic environment of the target body is poorly understood. The ADRAT report also had recommendations for an aerocapture demonstration mission to be traceable to the outer planets mission applications. These recommendations are discussed briefly in Sec. VI.

The work of the ECI study team, whose work is summarized in this paper, started after the completion of the ADRAT group's report. Thus, the risks identified by the ADRAT report are answered by the work of this group. For example, Ref. [10] discusses the atmospheric modeling uncertainty and robustness of the aerocapture design to large variations in the atmospheric properties. Sec. IV.A also identifies how more recent work than even the ADRAT

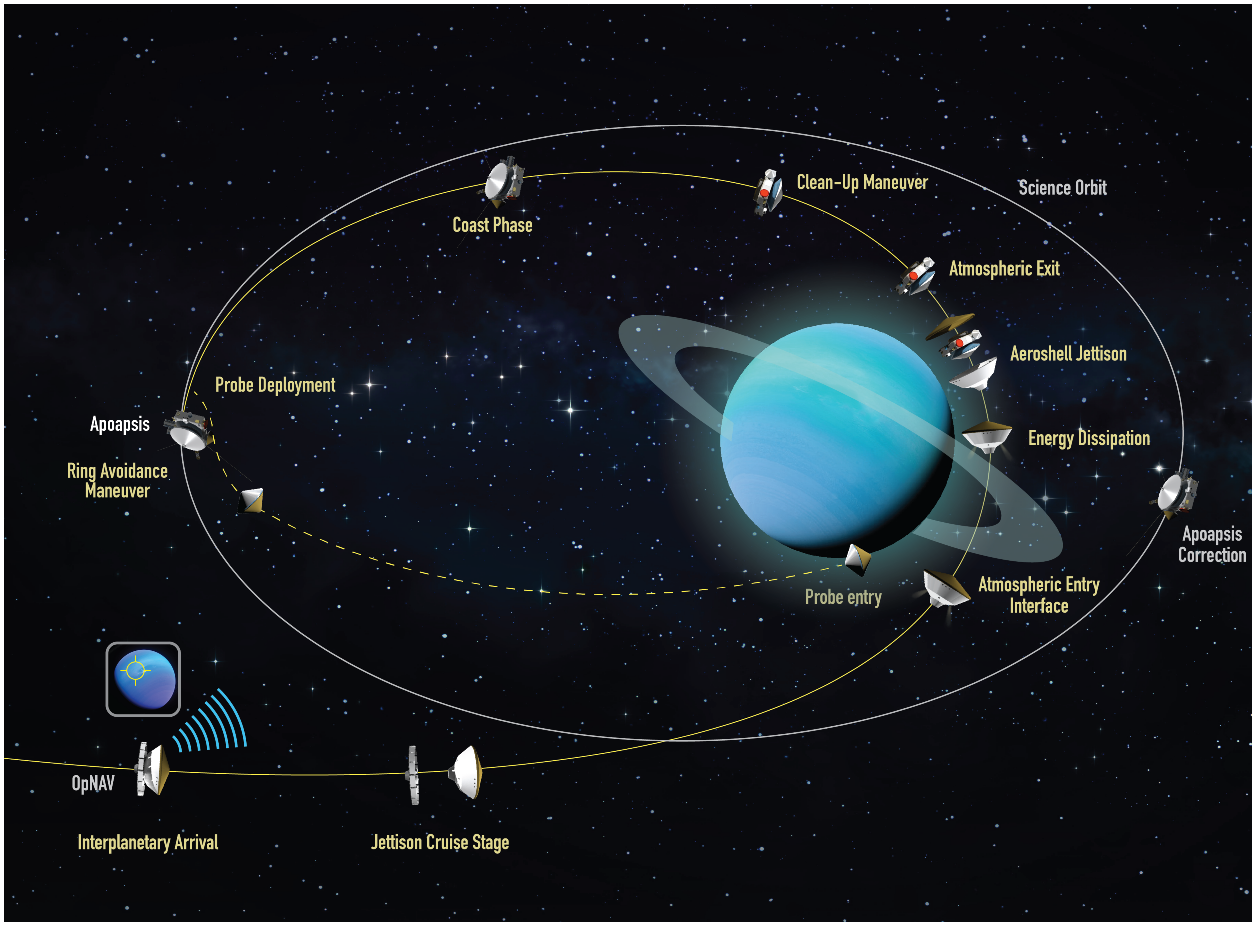


Fig. 3 Concept of operations for an aerocapture concept for Uranus.

report has attempted to improve the atmospheric uncertainty characterization, especially for Uranus. Refs. [11–13] characterize the aerothermodynamic and aerodynamic environment of the Uranus missions, especially in the presence of large uncertainties. The engineering choices made for aerodynamic and thermal protection system (TPS) solutions made for the aerocapture mission are robust enough to meet large uncertainties while still preserving margin. Finally, Ref. [6] shows that in general the design choices for the aerocapture concept have leaned heavily on flight-proven, heritage technologies that have lower development risks associated with them. The "low innovation" technologies that characterize the aerocapture concept described in this paper can drive down the risks for implementing aerocapture for a future Ice Giants mission by relying on high Technology Readiness Level (TRL) systems. These assumptions are discussed further in Sec. III.

III. Study Ground Rules and Assumptions

The genesis of this project was from a white paper [14] looking at aerocapture for Ice Giant missions that was published as part of the inputs to the Decadal Survey. The objectives for the aerocapture study have been influenced by notable studies and reports such as the Decadal Survey [1], the UOP mission design [2], and the ADRAT report [9]. Additionally, as mentioned in Sec. II, there was a strong emphasis for the study to focus on flight-proven, high-heritage concepts borrowed from the entry, descent, and landing (EDL) community. The study strove for "low innovation" solutions, meaning relying on existing technologies that were already proven in other applications, as opposed to solutions that might offer higher levels of performance but would have more risk in integration.

With emphasis on low innovation solutions, the project had a set of ground rules. Although each technical area (e.g. aerosciences, trajectory) had their own assumptions, the study-level ground rules and assumptions were the following:

- Uranus is the reference target Ice Giant body.

	Risk Statement	Type	Level of Risk
1	If the atmospheric density profile uncertainty is too large, then trajectory or flight-path calculations based on the blunt-body heritage would be in error.	Development	High
2	If the aerocapture implementation heat shield TPS performance and sizing requires more mass than studies assumed, then the dry mass will exceed the allocation.	Development	Low
3	If the aerocapture implementation requires more mass for ancillary systems (e.g., g-load mitigation, separation mechanisms, packaging, heat dissipation), then the dry mass will exceed the allocation.	Development	Medium
4	If the aerocapture uncertainties are too high, then the cost ($, mass) of implementation with sufficient capability will be too high.	Development	High
5	If the aerothermodynamics of the target body are not well understood/modeled, then heat shield performance will be compromised.	Mission	High
6	If the aerothermodynamics of the target body are not well understood/modeled, then the control actuators may not have sufficient control authority to maintain the flight path angle and the lift vector orientation.	Mission	Medium
7	If the entry heating (integrated heat flux and soak-back) cannot be accommodated, then components may overheat resulting in failures.	Mission	Medium
8	If autonomous optical navigation cannot correctly correlate the atmosphere altitude to the planet barycenter, then the density will not be as expected and may exceed the ability of the spacecraft to compensate.	Mission	Low

Fig. 4 Risks identified by the ADRAT report for aerocapture missions (from Ref. [9]).

- The science payload for the aerocapture system is the UOP orbiter payload. The study did not optimize the science payload for the orbiter.
- The probe for the UOP mission is the baseline probe that is accommodated with the aeroshell. However, additional probes and other probe designs are also explored to potentially increase the science return.
- The baseline launch vehicle is the Falcon Heavy expendable concept, although other launch vehicles are also explored and are discussed in Refs. [7, 15].
- The design of the heatshield is limited to maximum diameters between 4.5 and 5 m so that existing launch vehicle fairings would cover the design. The baseline design is 4.5 m to be accommodated within the Falcon Heavy diameter [16].
- The chosen aeroshell geometry is a 70 deg. sphere-cone with a biconic backshell, similar to the Mars Science Laboratory (MSL) and Mars 2020 designs successfully used at Mars.
- The control system for the aerocapture maneuver is bank angle modulation, which was successfully used by MSL and Mars 2020 on Mars and by Apollo and Orion at Earth. The lift-to-drag ratio (L/D) was selected as 0.25 to be similar to Mars 2020.
- The TPS material chosen is Conformal Phenolic Impregnated Carbon Ablator (C-PICA), as explained in Ref. [17]. At the time of choice, the C-PICA material did not have flight heritage, but since then it has been flown successfully by the Varda capsule that landed in Feb. 2024.
- The baseline solution for navigation is ground-in-the-loop with an OpNAV campaign a few weeks before atmospheric interface. Other variations are also studied and discussed in Refs. [7, 10].
- The guidance algorithm chosen for the aerocapture maneuver is the Fully Numerical-Predictor Aerocapture Guidance (FNPAG) [18]. The guidance algorithm is used for both software-in-the-loop and processor-in-the-loop testing during the study.
- The project uses the AIAA mass design guidelines for pre-phase A project [19].

A few notes on some of the assumptions listed above. Even though the tools, modeling and simulation setup, and fidelity of the analysis used in the study derived from best practices for interplanetary and EDL missions, the project stayed grounded to being a pre-Phase A type of study. Although the maturity of the analysis in some cases reached a Phase B level of effort, the mass and volumetric margins maintained by the project remained at the pre-Phase A level. The project developed a Maximum Possible Value (MPV) that was used for design of various subsystems, while a Current Best Estimate (CBE) and Maximum Expected Value (MEV) were maintained and updated. Positive margins based on the MPV were maintained and discussed at length in Refs. [6, 20].

This study also refrained from optimizing the science payload to increase vehicle performance or improve the design. The science payload from UOP was assumed to be the science payload for the aerocapture design, and the project maintained the volumetric and mass requirements suggested in the UOP report [2]. Potential science optimization, especially for instrumentation placement could lead to improved margins for the aerocapture vehicle, but that was deemed outside the scope of the aerocapture design focus in this study. Similar rules were followed for the probe design as well, and the project used the UOP probe design or other small probe designs [21] in the literature for Uranus as the payload instead of using the team's expertise to redesign that vehicle.

Finally, partly based on a recommendation from the ADRAT report [9] and interest from other community members, there has been a renewed look at an aerocapture demonstration mission at Earth [22] or other planetary bodies. This study focused solely on an aerocapture concepts for a flagship-class mission to Uranus and aerocapture demonstration mission design was treated as out of scope. Sec. VI discusses some potential items an aerocapture demonstration mission could pursue to show traceability to an Uranus mission concept.

IV. Differences from Previous Designs

Aerocapture technology has been suggested for various missions to planetary bodies for the past 40-50 years. Ref. [23] provided a brief literature review for these concepts for the Ice Giants while Ref. [24] provides a historical look at these concepts across many planetary destinations. Currently, the seminal work for aerocapture concepts for the Ice Giants is a NASA study summarized in Ref. [25] that designed a mid L/D vehicle for aerocapture at Neptune. The designed aeroshell (see Fig. 5) is very different from the low L/D blunt body design of this project (see Fig. 2(b)) which are primarily used for EDL missions at Earth and Mars.

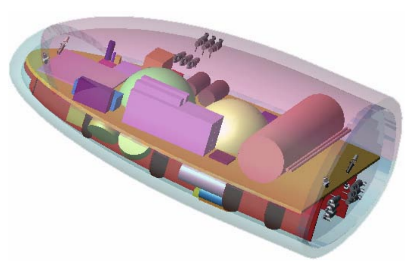
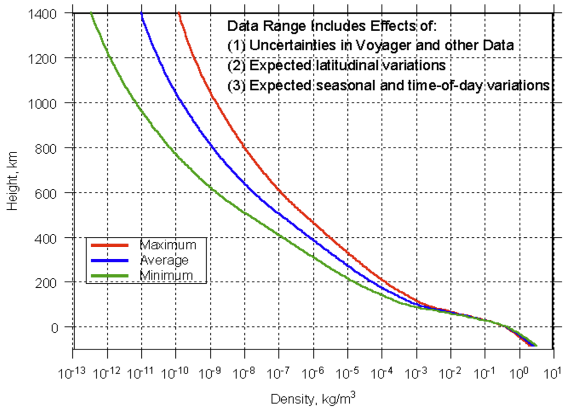


Fig. 5 Mid lift-to-drag ratio aerocapture vehicle from past Neptune studies (from Ref. [25]).

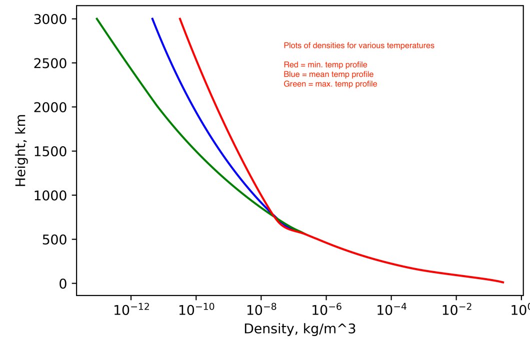
The concept from Ref. [25] has many differences from the design discussed in this paper. Primarily, by using a lower L/D vehicle, the current design has lower control authority. However, despite that, analysis for the current design has shown similar or even better performance [8]. The rationale for the performance differences are shown in Sec. IV.B, with atmospheric model being a difference as discussed in Sec. IV.A. Finally, presenting the first iteration of the current design that was discussed in Ref. [23] to mission proposers and planners for the outer planets led to a few design questions. These questions are addressed in Sec. IV.C.

A. Atmospheric Model Uncertainty

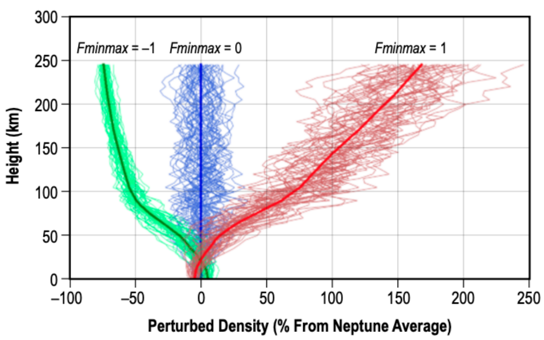
One of the main areas of difference between the 2006 Neptune aerocapture study [25] and the current study is in the atmospheric model. The atmospheric profiles used for the 2006 study were Neptune Global Reference Atmosphere Model (Neptune GRAM) [26], while the current study used an early version of the atmospheric model in the 2024 Uranus GRAM [27]. The density profiles, both mean and perturbed, for the Neptune study and the current Uranus study are shown in Fig. 6.



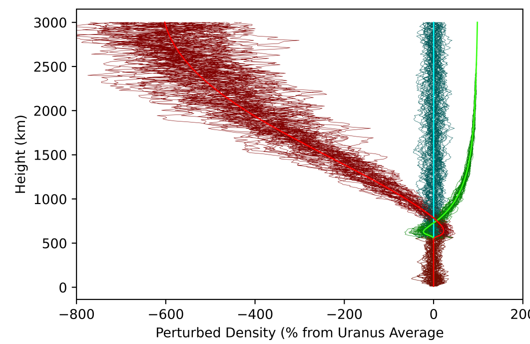
(a) Neptune GRAM density (from Ref. [26])



(b) Uranus atmosphere density for the current study



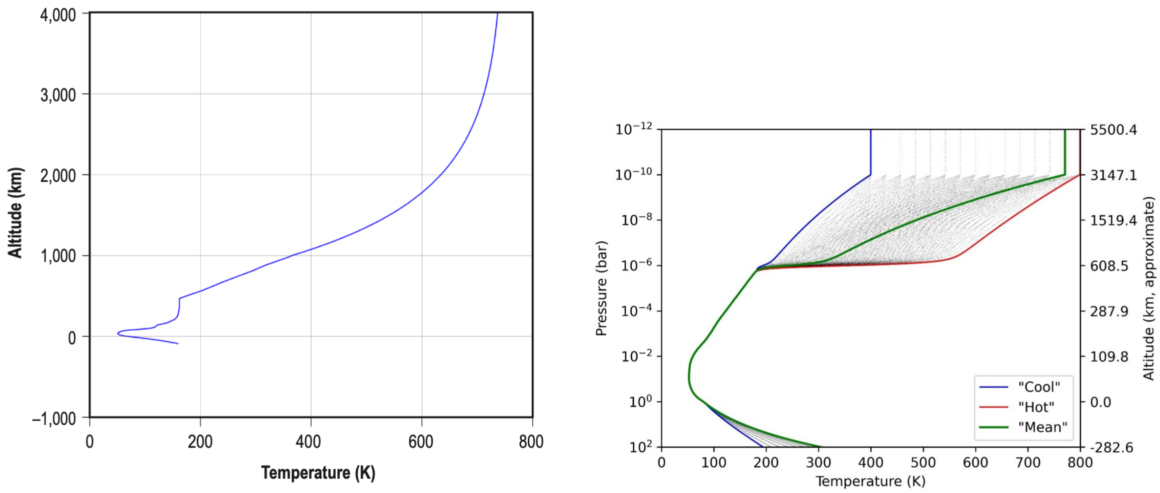
(c) Neptune GRAM deviations (from Ref. [28])



(d) Uranus atmosphere deviations for the current study

Fig. 6 Density comparisons between the 2006 aerocapture study and the current aerocapture concept.

Besides the atmospheres being compared in Fig. 6 being from two different planets, the question that has been raised when the first iteration of the current study was published [23] was if the atmospheric model used for the current study was less conservative than the model used for the 2006 study. Comparing the mean density profiles and the perturbations, one can see similar level of uncertainties in the common altitude band between the two models. Additionally, the aerocapture trajectories for this study [10] are simulated to be in the atmosphere from 4000 km through 500 km altitude, with the maximum deceleration occurring in the 1000 km to 500 km region. The atmospheric density deviations in this region of the new Uranus study are of the same order of magnitude if not slightly larger than the old Neptune study. The conservatism in the current study is further highlighted by the families of temperature in Fig. 7, which shows that the Neptune GRAM temperature had very little dispersion, but the current Uranus model [27] used in the study has a large amount of dispersion captured, especially at the higher altitude thermosphere region.



(a) Neptune GRAM Temperature (from Ref. [26])

(b) Uranus GRAM Temperature (from Ref. [27])

Fig. 7 Temperature comparisons between the 2006 aerocapture study and the current aerocapture concept.

B. Comparison with the Older Neptune Aerocapture Study

Despite more conservative atmospheric modeling, the results from the current study (Refs. [8, 10]) show good performance with a low L/D vehicle that has a lower controllability compared to the mid L/D vehicle that the old Neptune study (Ref. [25]) had to use. One might wonder why did the old study need a new vehicle, like a mid L/D, while the current study can use a heritage, low L/D design. The reason for the differences are due to three factors: different delivery errors assumed; larger aerodynamic uncertainties for the less studied mid L/D concept; and designing controllability over the full range of atmospheric variation.

The Neptune study had atmospheric interface delivery errors in the entry flight path angle of ±0.5 deg at 3 standard deviations (3σ) [29], while the current study's baseline flight path angle uncertainties are ±0.15 deg (3σ) [7, 15]. Both studies are modeling ground-in-the-loop with OpNAV campaigns in which instead of on-board processing, the camera and ranging data are sent back to Earth for analysis and then the commands are sent back the spacecraft, adding two-way light time delay to data and command. However, the camera used in the Neptune study was based on the Mars Reconnaissance Narrow Angle Camera [25], while the camera used in the current study uses the Long Range Reconnaissance Imager (LORRI) camera already part of the payload of the proposed UOP orbiter [2]. LORRI camera is already flight-proven on the New Horizons spacecraft and has 10x better angular resolution, leading to vast improvement in flight path angle uncertainties. The improved delivery errors increase the margin for controllability significantly with aerocapture.

The Neptune study's dependence on a novel mid L/D shape (see Fig. 5) led to large aerodynamic uncertainties, since the shape was new and there were less experimental or flight data to substantiate the computational data. The uncertainties were between 15-25% for force and moment coefficients [29]. Comparatively, the current aerocapture concept that uses a 70 deg. sphere-cone, with strong heritage and flight data from Mars missions, has aerodynamic uncertainties between 3-5% for the aerodynamic coefficients [13, 30]. Even after accounting for the aerodynamic modeling differences in the atmospheres between the largely CO_2 Mars and the largely H_2/He Uranus, the lower aerodynamics uncertainties of the low L/D concept leads to increased controllability margin with aerocapture.

Finally, the older Neptune study [29] dispersed the atmospheric profiles for the simulation between the maximum and minimum estimates of Neptune's atmosphere (see Fig. 6(c) and fminmin and fminmax as the minimum and maximum variables). This tantamount to dispersing the atmosphere for any season at the planet. Later versions of the Neptune study [25] reduced the variation slightly, but the atmosphere dispersion were still of the order of magnitude where the aerocapture vehicle and trajectory was designed to fly through either a summer day or winter night. Atmospheric uncertainties at Uranus, like Neptune, are large, but assuming a flagship-class mission will not have knowledge that the arrival location will be in summer or winter is hard to fathom. Thus, for this study, the density deviations for various sensitivities were confined to only each family of density dispersion from Fig. 6(d). The variation in density was still large (densities varied by 100-200% in the colder density family). However, the trajectory simulations did not disperse the atmosphere to a level where the vehicle was flying through summer profiles and winter profiles at the same time. A sensitivity study conducted during the study showed that if atmospheric properties were varied to the large extent of the Neptune study, there would be a 10% reduction in capture success rate and higher controllability would be required; however, this study assumed a baseline confined to each family of density dispersion. Additionally, with the advent of new spacecraft like James Webb Space Telescope, potential for atmospheric measurements from stellar occultation of the Ice Giants [31], and other resources expected to be devoted to Uranus if it is chosen for a flagship-class project, it is expected that characterizing density dispersion for a specific arrival season the planet is a realistic assumption.

C. Questions Raised about the Previous Iteration of the Current Design

When the previous iteration of the current Uranus study [23] was published, a few questions were raised about some design elements. Specifically, there was concern about internal heating within the aeroshell and inability to conduct science during the cruise phase due to the orbiter being enclosed.

The UOP design has three next-generation Radioisotope Thermoelectric Generators (RTG) [2] for power. In the aerocapture design, these RTGs are enclosed within an aeroshell and thus the issues arising from the heating from the RTGs need to be addressed. Past and currently-planned EDL missions with aeroshells (e.g. MSL, Mars 2020, and Dragonfly) will carry one RTG within the aeroshell, but the heat from three next-generation RTGs would be larger [2]. Thermal analysis was added to the scope of the study; these results are published in Ref. [6]. A few scenarios stoking heating concerns were investigated, such as during commissioning of the RTGs shortly after launch, heating near close heliocentric distance such as during a Venus fly-by, or during the 20-30 minutes of flight after cruise stage separation and during the atmospheric pass of aerocapture. Thermal mitigation strategies for these scenarios are explained in Ref. [6], including having radiators on the cruise stage and heat rejection through the aeroshell, but this is still an active area of study that requires further investigation following the conclusion of this current work.

An open backshell has been proposed as a solution for RTG heating, which would also enable more opportunities for science observations during the cruise to Uranus. The team studied the idea, but the aerosciences discipline felt there was a non-negligible chance of flow interaction in the wake with the payload, especially the HGA. The current study did not possess sufficient resources to properly characterize the risks associated with the flow impingement and this exercise was left for future studies. Moreover, due to this study's strong emphasis on low-innovation, high-heritage design philosophy, sticking to the MSL and Mars 2020 backshell concept was selected to be the best strategy. The radiator design described in Ref. [6] resolved the heating concerns, while Sec. V describes some options, like a clamshell open design for the backshell during cruise and window accommodations in the backshell, to enable science observations during cruise.

V. Aerocapture Design Updates

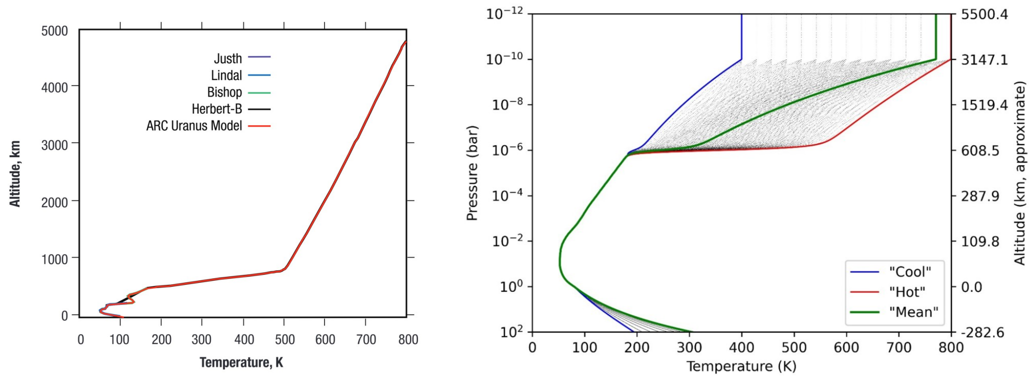
The initial design for the Uranus aerocapture concept for an UOP-like payload was presented in Ref. [23]. That concept showed a feasible design with margins consistent with a pre-Phase A study. This paper summarizes the updates to that initial design and adds maturity in modeling and simulation and refinement of a few areas of the concept of operations. References are also provided for the papers that have the modeling and simulation details.

A. Atmospheric Modeling

The previous version of the study used the Uranus GRAM released in 2021 for analysis. An example of the temperature profile from that model is shown in Fig. 8. Although the data included in the 2021 model of the atmosphere came from several analyses, the dispersion for the temperature was small; the updated 2024 model, shown earlier but duplicated in Fig. 8, shows larger variations in potential temperature in the thermosphere and deeper atmosphere. Ref. [27] discusses the modeling assumptions involved in the newer temperature profile and its more conservative dispersion model. The aerocapture study used the newer atmospheric analysis in the updated trajectory modeling and simulation results that are presented in Refs. [10, 32–34].

B. Aerosciences Improvements

For the previous iteration of the study, the aerodynamic and aerothermodynamic results are discussed in Refs. [30, 36]. Some of the highlights included a larger range of rarefied solutions that were needed due to the different mean free path of H_2-He atmosphere at Uranus compared to Earth and Mars equivalent cases, as well as the observation that radiative heating was very low for the range of cases for aerocapture entry at Uranus.



(a) Uranus Temperature from GRAM 2021 (from Ref. [35])

(b) Uranus Temperature from GRAM 2024 (from Ref. [27])

Fig. 8 Temperature comparisons between the 2006 aerocapture study and the current aerocapture concept.

The updated analysis included three-dimensional characterization of the heating, and sensitivities to roughness augmentation, turbulence, and other flow characteristics. Ref. [11] discusses the latest aeroheating analyses for the baseline aerocapture concept as well as looks at several high energy (high hyperbolic excess velocity or V_∞) aerocapture trajectories that might be feasible based on mission design and navigation (MDNAV) scenarios for launch to Uranus in the next two decades. The goal of the high-energy trajectories was to find feasible designs that will stress the radiative heating environments and bound when radiative heating might be a concern. Some of the heating scenarios for the high energy cases are summarized in Sec. V.F. The aeroheating environment was also characterized as heating indicators at selected body points over the outer mold line of the aerocapture vehicle. These indicators are based on the form of the Sutton-Graves indicator [37] with calibration of the model parameters to fit time histories of the actual aeroheating environment for a given body point. These indicators were used by the TPS team to size the heatshield material [12].

Ref. [13] describes the aerodynamic database was also augmented with further Computational Fluid Dynamics (CFD) solutions in hypersonic, continuum flow for Uranus' H_2-He atmosphere. The aerodatabase constructed for the aerocapture scenario was of similar form and fidelity used for EDL missions at other planetary destinations and covered rarefied flow through hypersonic flow at a range of sidelip angle and angles. Additionally, the uncertainties of the aerodynamic coefficients were quantified to bound the potential dispersion, allowing trajectory simulations to capture the variations in aerodynamic performance.

The updated TPS design is described in Ref. [12]. The forebody TPS material is still C-PICA, but the TPS thickness has been updated based on the three-dimensional aeroheating environment characterized in Ref. [11] and firming up of some concept of operations details like the heatshield separation timing that discussed in Sec. V.E. Several aftbody TPS material choices were also considered, including heritage materials like Acusil II and SLA-561, or new upcoming low density TPS materials. The backshell must also allow for radio frequency transparency that is need for telecommunications during the aerocapture maneuver. One concerted effort was to characterize any cliff of C-PICA performance. This data is discussed in Sec. V.F. Finally, to accommodate science instruments and other observations during cruise, the TPS team also looked at creating thermal windows for near infrared, ultraviolet, and visible length frequency instruments in the backshell.

C. Trajectory and GNC Sensitivities

The trajectory and GNC design presented in Ref. [23] for the previous iteration of the aerocapture concept relied on a Falcon Heavy expendable launch vehicle and heritage entry guidance concepts, like bank angle control, to control the trajectory within the Uranus atmosphere to achieve the target orbit. The results from the previous iteration [8, 38] showed substantial margin with the low L/D solution and the atmospheric profiles being considered at that time.

An emphasis in the trajectory design and GNC tuning for the current year was to stress the baseline concept while also improving the performance of outlier cases in the baseline concept of operations. In terms of stressing the baseline, the MDNAV solutions considered high-energy cases, especially those with next-generation launch vehicles, like Starship, in the mix. The search space in terms of launch years was extended from the mid 2030's all the way in to the 2040's; the resulting MDNAV trajectories were high-energy and had short time-of-flight. Ref. [7] discusses these trajectories and Sec. V.F presents a few of these results.

As far as improving outlier performance, for the baseline cases, there have been some very low percentage (< 1%) of cases that have a large apoapsis error and require large velocity corrections (ΔV) to achieve the desired orbit. The team approached the project to fix these cases in two ways. The bank angle formulation and FNPAG tuning parameters were slightly revised to make the guidance more robust in these almost hyperbolic trajectories. Ref. [33] discusses some of these modifications, and the results can be seen in Ref. [10] as well. Additionally, the post-aerocapture concept of operations was refined to consider an additional ΔV within one hour of atmospheric exit based on navigational errors of the vehicle. Ref. [7] discusses this concept of operations and its effect in more detail, but this modification can help save the small percentage of cases that previously requireing large ΔV.

On the side of GNC sensitivities, although bank angle modulation had been chosen as the baseline guidance and control method, alternative formulations were also explored, such as direct force control [33], where angle of attack and sideslip angle are independently controlled, as well as hybrid angle of attack and bank angle strategies [34]. Additionally, the bank angle formulation of FNPAG was also implemented on a processor with performance representative of that expected on a flagship-class flight computer. The processor-in-the-loop testing showed, for the aerocapture scenarios being investigated, the bank angle guidance was able to produce satisfactory performance on flight computers expected on a UOP-like mission. Further work needs to be done to test the robustness of these scenarios.

Finally, many past aerocapture simulations, including the results from the previous iteration of this study, assumed perfect navigation errors for the aerocapture phase of flight. In reality, knowledge errors from sensors on-board will be a significant source of perturbation in trajectory performance. The guidance and controller will not have perfect knowledge of the trajectory states of the vehicle. Ref. [32] discusses the development of a six degree-of-freedom (6DOF) simulation along with a navigation error simulation in which inertial measurement unit (IMU) data are simulated and the errors are propagated using a navigation filter. The results of this 6DOF navigation simulation provide further stress cases for the robustness of aerocapture performance.

D. Mechanical Design

The mechanical design of the aerocapture concept has been improved to capture some less defined elements in the previous design iteration [23]. One of the key focus areas were the development of secondary systems that are still crucial to the success of the mission. These include the design of the cruise stage, backshell concepts to accommodate science operations during cruise, and accommodation for multiple probes. The design of the thermal management system was discussed earlier in Sec. IV.C and is elaborated in Ref. [6].

The cruise stage mass was allocated in the overall master equipment list (MEL) in the previous design iteration. However, the definition of the cruise stage was more defined in the current design cycle, with designs for attachment to the aeroshell, accommodations for the thermal radiators, and allocations for cruise stage instrumentation made more explicit. The design was based on the MSL cruise stage. Ref. [6] elaborates on the design and structural analysis conducted for the cruise stage design.

The baseline design concept consists of a single fixed backshell attached to the forebody through cruise and the aerocapture maneuver. But as discussed in Sec. IV.C, both to be a potential solution to RTG heating and to enable science observations during cruise, alternate backshell concepts were explored. Due to potential issues with flow impingement during the aerocapture maneuver if no backshell was present, an assumption for the backshell design exploration was that the the payload will be covered during the atmospheric phase of flight. However, the team explored designs such as a clamshell backshell, used by the Genesis capsule, and the Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer (OSIRIS-REx) hinged backshell [6] as possible avenues to expose the payload during cruise. Most likely, if either of these backshell concepts became baseline, the cruise stage described above will have to redesigned.

The UOP probe was the baseline design as the probe payload for the current aerocapture concept. However, since an Uranus flagship-mission would be a generational mission to the Ice Giant, there is interest in the science community to have multiple probes available to take in-situ measurements of the planet in different places. Although the aerocapture concept can be space constrained due to the payload having to be packaged with the aeroshell, Ref. [6] explored alternative designs to accommodate multiple probes. Additionally, the Small Next-Generation Atmospheric Probe (SNAP) probes [21], which are smaller than the UOP probe but designed with multi-probe infrastructure in mind, were also incorporated in the various design concepts to increase the number of science payloads while still meeting mass and volume margin for the overall aerocapture concept.

E. Heatshield Separation

A specific emphasis area was defining the concept of operations of heatshield separation. The heashield protects the orbiter and probe payload during the hypersonic heating in the atmosphere, but soon after atmospheric exit, the soak back of the heating from the TPS to the inner structure is a thermal problem. The heatshield should be separated as soon as possible and past sensitivities by the TPS team [17] have shown a significant increase in required TPS thickness (and system mass) for every five minutes the TPS stays on.

Based on mechanical system design of the explosive bolts that will separate the forebody and backshell using NASA Standard Initiators (NSI) (discussed in Ref. [6]), the aerosciences analysis of the heat flux value where it is safe to discard the heatshield (see Fig. 9), and the trajectory design of how long it will take to rotate the vehicle to point the forebody backwards, a concept of operations of the heatshield separation was designed in Fig. 10.

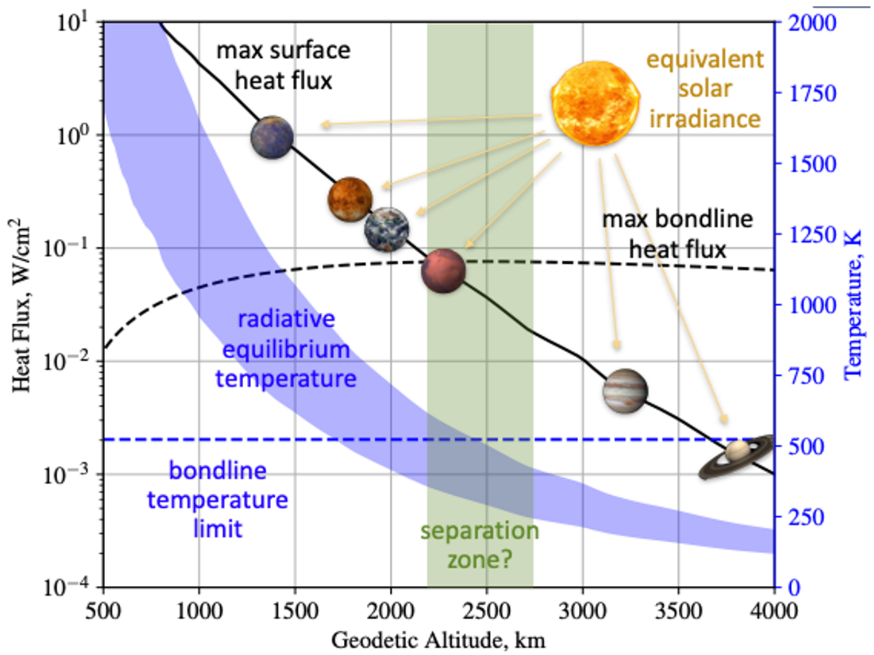


Fig. 9 Heat flux for aerocapture exit and heatshield separation based on other surrogates.

From Fig. 9, a total bondline heat flux value of the order 0.01 W/cm^2 is asymptotically reached in the 2250-2750 km altitude region on the atmospheric exit side. An interesting visualization of the bondline heat flux is that it is the order of magnitude of equivalent solar irradiance at Mars, i.e. the solar irradiance that will be felt at the surface of the planet. The radiative equilibrium temperature also is below the bondline temperature limit in the same time frame. Thus, that zone of altitude seemed as an acceptable area to jettison the heatshield and expose the payload without any high risk of damage.

In Fig. 10, the concept of operations was developed to add a further time margin of 156 s to the point where the 0.01 W/cm^2 heat flux is reached, and then start the maneuver to rotate the vehicle 180 deg. to make the forebody point backwards. Upon reaching the forebody backwards orientation, the forebody is ejected with 5 s of margin for the NSI to fire and the two mechanisms to separate. After the forebody separation, the vehicle undergoes another rotation to reorient the backshell aftward before doing a final separation to release the orbiter. This concept of operation can potentially be simplified if some of the separation events are combined or the heatshields are separated perpendicular to the direction of travel, but for this study the current concept of operations could be easily fit in the timeline.

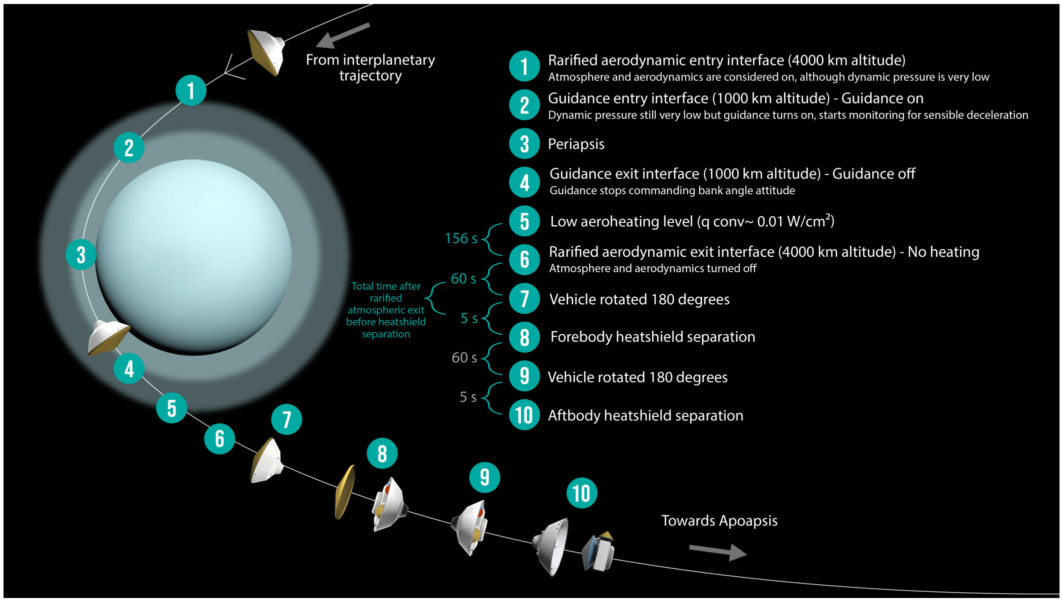


Fig. 10 Concept of operations for the heatshield release.

F. Overall Design Space at a Glance

The high-energy aeroheating sensitivity study, the discussion of limitations in the C-PICA TPS material for the Uranus aerocapture design, and the look at alternative fast-transit MDNAV solutions are all visualized in an overall design space summary in Fig. 11.

The baseline 2036 launch date trajectory cases are shown as Monte Carlo simulation results on the bottom left-hand side of the figure. These cases correspond to an approximately 11 km/s V_∞ MDNAV case and can be accomplished by Falcon Heavy (FH) and a time-of-flight (ToF) of 12.8 years. Curiously, there is also a 2042 Starship-enabled trajectory with a ToF of 6 years that is in the same aeroheating environment. As the energy (V_∞) of the MDNAV scenarios increase, one can see that the heat flux and load correspondingly increase. For most feasible MDNAV scenarios, the current tested C-PICA heat flux capabilities bound the performance, and further testing of C-PICA can extend this range [12]. Additionally, C-PICA is at a high demonstrated, manufacturing capability with the successful flight test of the Varda space capsule in Feb. 2024. That said, for manufacturing C-PICA at the size of 4.5 m diameter, some further development in gap fillers will be needed [12]. However, for most feasible MDNAV scenarios in the next two decades that reach Uranus by the 2049 equinox, the aerocapture designs with C-PICA and the aeroheating conditions considered in this study do not show any large barriers.

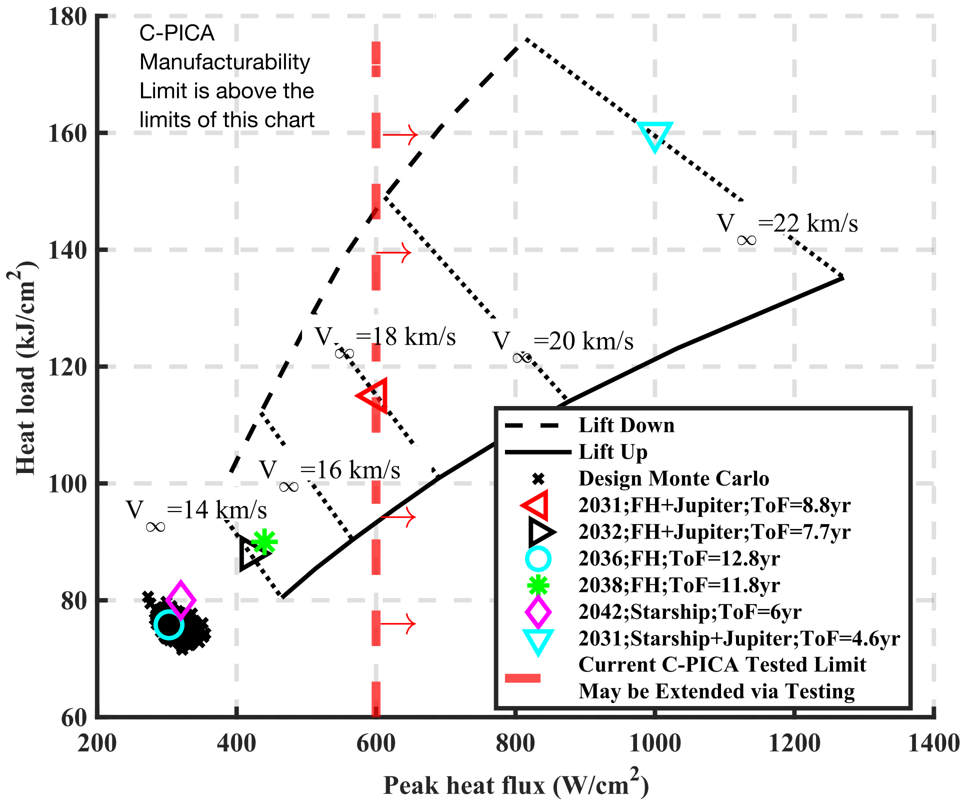


Fig. 11 Comparison of various Uranus aerocapture opportunities and heating environments. The time of flight (ToF) for each opportunity is included.

VI. Forward Work

The aerocapture design presented in this study shows there is a feasible path to using high-heritage designs from the EDL community for an aerocapture mission to Uranus, with an UOP-style orbiter and probe as the payload. There are still some areas of further development, such as update of the thermal system needed to manage heat from the three RTGs, as well as considering a no-backshell option where flow impingement and its effect are investigated. This study provides some initial solutions in those cases, but if the aerocapture concept moves forward from the pre-Phase A state, those two design choices should be further refined.

The aerocapture project also did not optimize the science payload, assuming the UOP orbiter and probe as the payload. However, there has been recent work to potentially redefine the science payload from what was chosen in Ref. [2] and pair the design with next-generation launch vehicles, such as Starship. Combining the aerocapture concept with an updated payload and newer launch vehicle could yield benefits such as shorter time of flight and a later launch date, both boons in the NASA development schedule. These trajectory trades should occur in the future with aerocapture as a trade space option.

Finally, the ADRAT Report [9] and other recent studies have identified a need for an aerocapture demonstration mission to reduce risks associated with using aerocapture at Uranus and other planetary destinations. One of the ground rules of this study was to avoid designing the aerocapture demonstration mission, since the project's focus was Uranus. However, an aerocapture demonstration mission that can demonstrate hypersonic guidance to achieve a target orbit, demonstrate autonomous operations such as the periapsis raise maneuver and aeroshell separation, and collect instrumentation data to improve aerodynamic and TPS modeling can be beneficial for a future aerocapture mission to Uranus.

VII. Conclusions

The 2022 Planetary Science Decadal Survey identified Uranus as a top flagship-class mission destination and identified the Uranus Orbiter and Probe mission as a baseline design. However, due to the mission's reliance on early 2030 launch dates, which are now untenable, and a need for a large orbit insertion burn that accounts for 60-70% of the launch mass, alternative orbit insertion mechanisms could be lucrative. This study presented an aerocapture-based concept that delivers the Uranus Orbiter and Probe's science payload to Uranus. A feasible design was presented leveraging largely high heritage technologies. The paper identified improvements in the aerocapture design from the first iteration presented in Ref. [23] and explained differences between the current study and previous aerocapture studies from the early 2000's. Ultimately, the baseline design from the current aerocapture study shows robust performance, even after atmospheric uncertainties have been refined, and heating environments that are within the capabilities of proven thermal protection systems. Aerocapture is shown to be a feasible alternative to fully-propulsive orbit insertion and should be considered for future Uranus mission designs.

Acknowledgments

The work presented in this paper is funded by the Early Career Initiative project sponsored by the NASA Space Technology Mission Directorate. The work was also supported by external partners at Draper Laboratories, Intuitive Machines, and Booz Allen Hamilton (BAH). The authors acknowledge the work from Thomas Palazzo, Lylia Benhancine, and Louis Breger from Draper Laboratories, for supporting the GNC and Optical Navigation independent verification and validation work. Additionally, Wyatt Johnson, Brent Mathews, Shaun Stewart, James Blakeslee, and Lucas Ward from Intuitive Machines provided valuable insight into how the predictor-corrector guidance algorithm will perform on flight-like hardware. Finally, Kasey Phillips, Jinfeng Ni, and Christopher Munk from BAH provided invaluable support with Agile project management and probabilistic risk assessment resources. The authors also acknowledge the project mentors at NASA Langley Research Center, Ames Research Center, Jet Propulsion Laboratory, and Johnson Space Center. Additionally, the authors thank Ron Neale for developing some of the graphics used in this paper and the reviewers of this paper at NASA Langley.

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