Uranus Flagship-class Orbiter and Probe Using Aerocapture

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The 2022 Planetary Science Decadal Survey released by the National Academies of Science identified the exploration of the Ice Giants, particularly Uranus, as the primary next Flagship mission. The Uranus Orbit and Probe mission proposal was used by the National Academies of Science as the baseline while making its recommendation. This mission which was based on a launch date of 2031 or 2032, used a fully-propulsive orbit insertion maneuver at Uranus (requiring 60-70% of total mass for propellant), and reached the planet after 13 years of interplanetary cruise before the 2050 equinox, a goal of the science community. 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 reducing the cruise time by several years. Finally, launch opportunities in the mid 2030's combined with the orbital alignment of Jupiter indicate that a Jupiter fly-by on the way to Uranus is not realistic. For fully-propulsive missions, such as the baseline Uranus Orbiter and Probe mission, not performing a Jupiter fly-by leads to a longer cruise time, larger propellant loads, and reaching Uranus past the 2050 equinox, all of which can be mitigated by an aerocapture maneuver. This paper will discuss the feasibility of an aerocapture option for a Flagship-class mission to Uranus.

I. Introduction

Exploration of the Ice Giants, especially Uranus, via orbiter and atmospheric probes, is required to answer pressing science questions that have been raised in the latest National Academies of Sciences Planetary Decadal Survey [1]. Since the Ice Giants are the furthest planets from Earth, traditional, fully-propulsive orbit insertion techniques have transit times bordering 13-15 years [2, 3] and require a large amount of propellant (wet mass percentages of around 60-70%) for the orbit insertion maneuver, leaving less mass for the scientific payload and a planetary probe [2, 3].

Aerocapture uses aerodynamic forces generated by flight within a planetary atmosphere to decelerate and achieve orbit insertion. Aerocapture has been considered for several past missions but it has not yet been demonstrated. However, recent developments in thermal protection systems (TPS), guidance and control, and interplanetary navigation capabilities show the potential for using rigid, heritage entry vehicle configurations already flown at other planetary bodies for aerocapture at Ice Giants. Aerocapture has been shown to be capable of robustly delivering spacecraft to Ice Giant orbits, while substantially increasing on-orbit payload mass (more than 40%) [4], increase scientific return,

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or reduce mission costs. Additionally, the aerocapture maneuver has been shown to reduce the interplanetary transit time by 2-5 years (15-30%) relative to fully-propulsive orbit insertion [4]. Recent work has shown that a flagship-class mission can be conducted in a shorter time than fully-propulsive missions if using aerocapture [5].

In 2022, the NASA Space Technology Mission Directorate (STMD) funded a two-year project to consider the design of an aerocapture vehicle for a Flagship-class Uranus Orbiter and Probe. This project analyzed the mission design, navigation, aerocapture maneuver, and system design implications of an aerocapture mission to Uranus, focusing on the comparison with the design with the Uranus Orbiter and Probe (UOP) design used by the Decadal Survey during its consideration.

This paper will consider the merits of including aerocapture as the orbit-insertion technique for a Uranus mission. Specifically, the implications of aerocapture orbit insertion for in-situ atmospheric probes will be discussed. The Uranus Orbiter and Probe concept mission study [3] is considered as the potential payload. Results from the recent NASA STMD-funded activity that is designing an aerocapture mission for a Uranus orbiter will be presented.

II. Motivation

A. What is Aerocapture?

Aerocapture is an atmospheric maneuver that uses the drag generated during an atmospheric pass to decelerate a vehicle in order to capture a spacecraft into an elliptical orbit from an interplanetary trajectory. As shown in Fig. 1, a spacecraft starts the process during an arrival at the planet from interplanetary trajectory. After jettisoning the cruise stage, an aerocapture vehicle consists of an aeroshell protecting the payload, which usually includes of an orbiter. Upon reaching the planet's atmospheric interface, the aerodynamic forces begin to build and enough energy is dissipated for the spacecraft to be in a captured orbit. After exit from the atmosphere, the aeroshell is jettisoned and the orbiter is exposed. The captured spacecraft still has to do two additional maneuvers, first at the apoapsis to raise the periapsis and then again at the subsequent periapsis to clean-up any apoapsis error. The total process takes one period of the captured orbit.

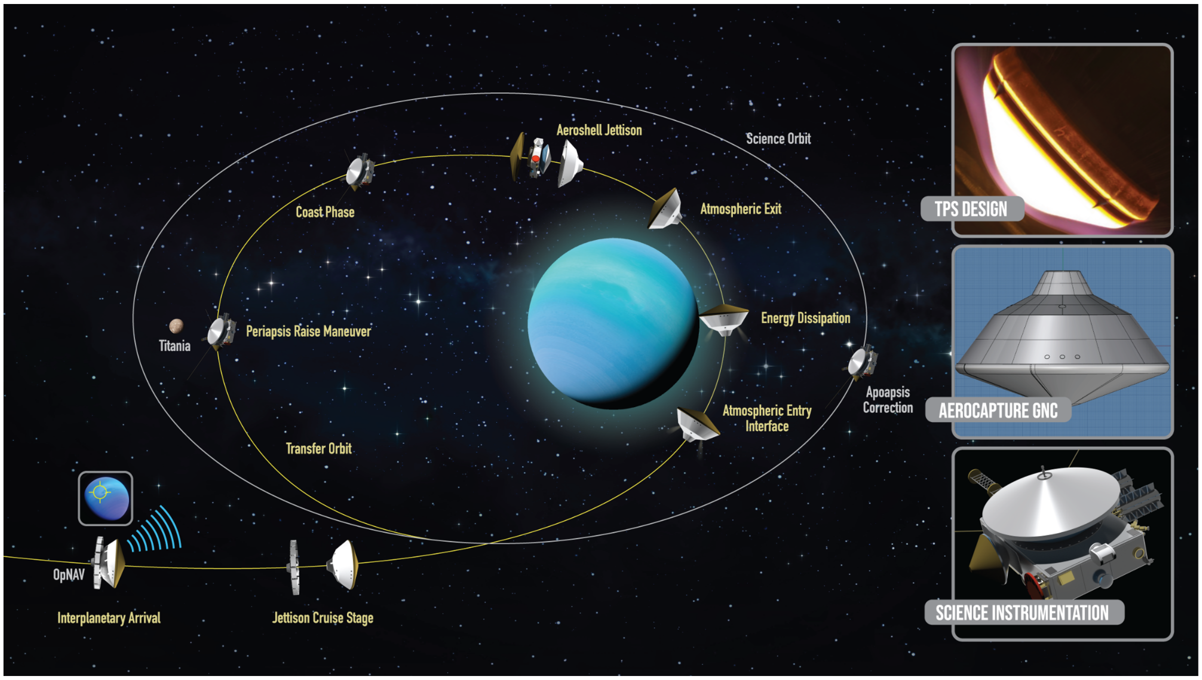
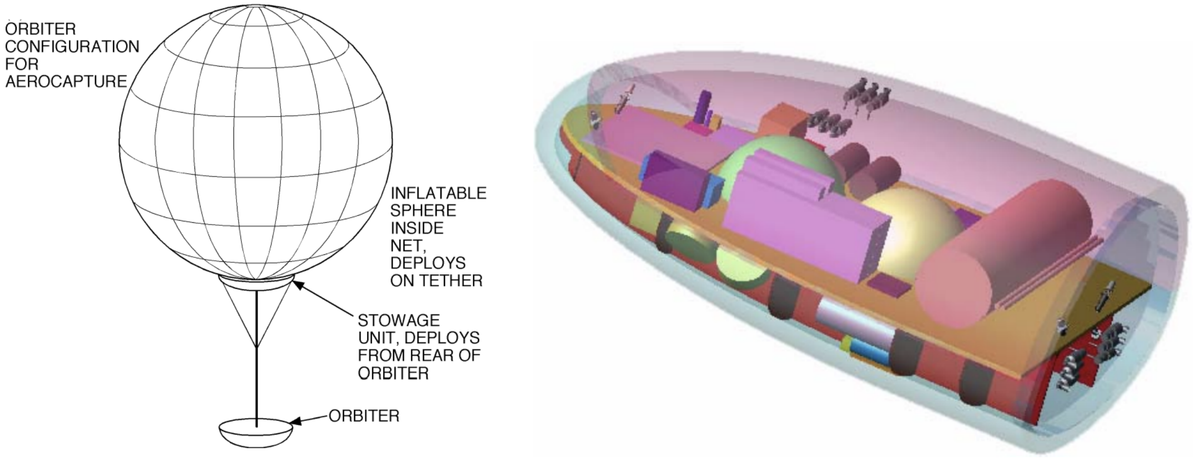


Fig. 1 Concept of operations for aerocapture. The insets of Thermal Protection System design, Guidance, Navigation, and Control (GNC) options, science instruments, and Optical Navigation (OpNAV) showcase potential components of a Uranus aerocapture mission.

Aerocapture has been a topic that has been proposed for decades. Studies since the 1960's have proposed atmospheric techniques for orbital transfers at different planetary bodies [6–8]. These studies are the foundation for aerocapture as an orbit insertion technique. Recently, Ref. [9] has tracked aerocapture research from the 1960's to the present day while capturing several seminal studies in the literature.

Looking at the Ice Giants, Neptune had some focused aerocapture studies where large inflated drag surfaces for aerocapture were investigated [10, 11]. Figure 2(a) shows the diagram of the large inflated drag surface, known as a ballute, to allow an orbiter to capture around a planet.



(a) Ballute Concept for Neptune Aerocapture [10]

(b) Mid Lift-to-drag Ratio Vehicle for Neptune Aerocapture [4]

Fig. 2 Historical vehicle concepts for aerocapture at Ice Giants.

NASA conducted systems analysis for aerocapture design reference missions in 2004 for Venus [12], Mars [13], Titan [14], and Neptune [4]. Specifically, the Neptune system analysis considered orbit insertion into a highly elliptical, retrograde orbit to enable an orbiter flyby of Triton while deploying two atmospheric probes prior to aerocapture. To achieve the control authority necessary to conduct aerocapture given the limited atmospheric knowledge and higher approach navigation uncertainty, a new, higher lift design for the entry vehicle was selected (see Fig. 2(b)). The study demonstrated the feasibility and robustness of aerocapture, but a drawback was the design and qualification of a new entry vehicle configuration. In fact, most past Neptune aerocapture designs necessitated the use of a vehicle that had not flown in any planetary setting. Although Uranus has not been studied as in-depth as Neptune by past aerocapture studies, it would potentially have a similar design as a Neptune aerocapture system.

B. Why the Ice Giants?

Uranus and Neptune, the Ice Giant planets, are frequently identified as high-priority science targets. To date, they have only been visited by Voyager 2 during its flyby in the 1980s. Most of our knowledge about the planets come from brief encounters. Understanding how the Ice Giants formed and evolved is key to unlocking the history of our solar system and comprehending the physics behind planetary formation [15].

Current planetary formation models show a low probability that Uranus and Neptune should exist, yet many of the discovered exoplanets are a similar size to the Ice Giants, as seen in Fig. 3. In addition to the planets themselves, their systems (i.e. moons, rings, and magnetosphere) provide an exceptional opportunity for new discoveries.

Due to the dearth of knowledge about Uranus and Neptune, a robust and comprehensive science payload is needed, which is fulfilled by having both orbiter and probe elements [15, 17]. In addition to remote sensing instruments on-board the orbiter, an in-situ atmospheric probe is needed to sample the atmosphere and understand its chemical composition. While past studies have released the probe on approach to decrease spacecraft mass [2] and thus the amount of propellant required, it is preferable that the probe is carried to orbit, so that the science team can utilize on-orbit observations and choose a probe target location to maximize science return.

It should also be noted, there is a preference to reach Uranus prior to the equinox in 2050, as the Northern hemisphere lighting and magnetic alignment will revert to a configuration already observed by Voyager 2 after that date [15]. The fully-propulsive proposals being considered have a launch date of 2030-2034 to reach the Uranus system before the

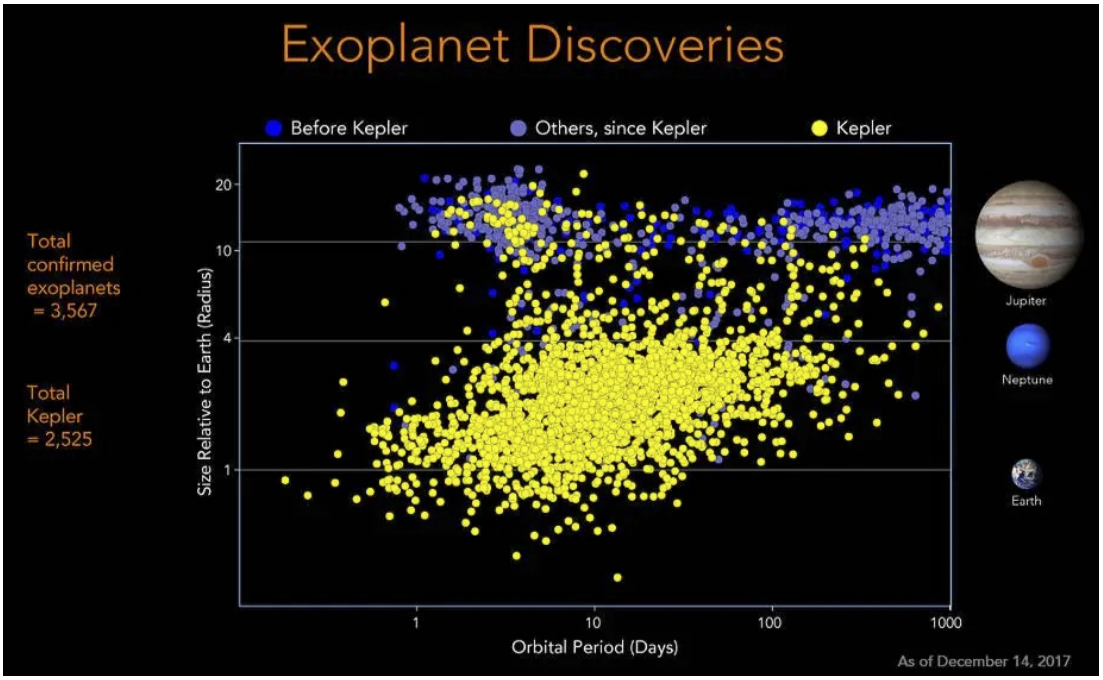


Fig. 3 Classification of exoplanets found by the Kepler telescope based on Solar System planets [16].

equinox.

Ice Giants signify an important and previously untapped source for planetary exploration. As stated by the 2022 Decadal Survey [1], only a future, dedicated mission to the Ice Giants will allow scientists to answer the many unknown questions about our least-known planets in the Solar System.

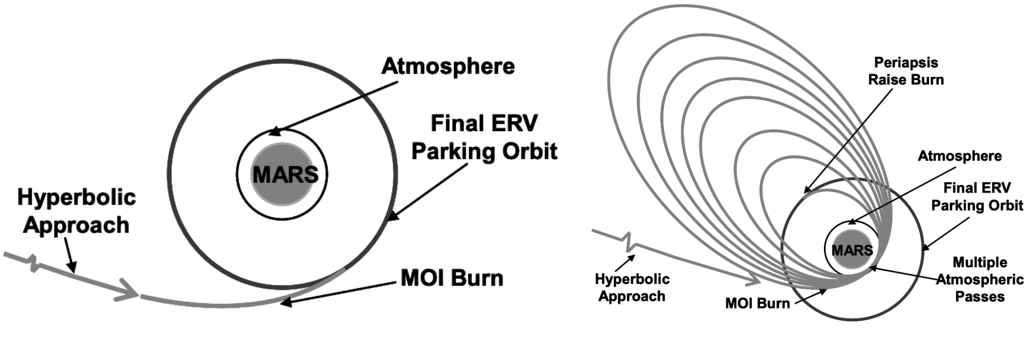
C. Gaps and Motivation for an Aerocapture Study

Historically, fully-propulsive options have been used for planetary orbiters. Such maneuvers consist of a single, but large, orbit insertion burn into an elliptical orbit from the incoming hyperbolic, interplanetary trajectory. Figure 4(a) shows the concept of operations of a full-propulsive orbit insertion. More recently, another orbit insertion method, aerobraking, has been used to achieve a target orbit. Similar to fully-propulsive maneuvers, aerobraking achieves an initial elliptical orbit after a large propulsive insertion. This first orbit is an intermediate one and is usually highly elliptic to minimize the orbit insertion burn (ΔV). The spacecraft reaches its target orbit by incrementally skimming the top of the atmosphere to produce small amount of drag, usually on the deployed solar arrays of the spacecraft, and after several passes over the course of months, the vehicle reaches its target orbit. This process for aerobraking is shown in Fig. 4(b).

Ice Giants missions are particularly challenging due to their remoteness from Earth (~20 AU for Uranus and ~30 AU for Neptune), and the large orbit insertion ΔV requirement (upwards of 1 km/s) for trajectories that reach the planets in a reasonable amount of time (<13 years). This, in turn, results in propulsion system and propellant masses that severely limit available science payload mass and scientific value of the missions. The operation constraints of monitoring several aerobraking passes of the atmosphere in addition still requiring an orbit insertion burn makes that maneuver unappealing for the Ice Giants.

If atmospheric forces reduce the propulsive needs of orbit insertion, more mass can be allocated to the science instrumentation and an atmospheric probe. Therefore, decreasing the required propellant mass of Ice Giant mission designs can greatly enhance the science value for Uranus and Neptune missions. Studies have shown that for the same launch vehicle, aerocapture can deliver more mass to orbit than a fully-propulsive orbit insertion design [4, 19].

Additionally, aerocapture maneuver can attain a large ΔV during the atmospheric segment of flight [20, 21], allowing the interplanetary trajectory to be faster than traditional designs and produce shorter transit times for earlier science data return [22]. For these short transit time trajectories, the fully-propulsive design may require an increased propellant mass that eliminates mass dedicated to science payload or require a higher performance launch vehicle. Some of the benefits of aerocapture over fully-propulsive orbit insertion maneuvers include transit times less than 10 years which are not



(a) Fully-Propulsive [18]

(b) Aerobraking [18]

Fig. 4 Concept of operations of typical orbit insertion techniques used. MOI refers to Mars Orbit Insertion, as these figures reproduced here from Ref. [18] are depicted for Mars.

feasible without aerocapture [23, 24]. Aerocapture can allow for reduced launch costs without significant compromise to the delivered science payload.

Studies looking at aerocapture for Ice Giants have consistently shown to deliver more on-orbit science payload (more than 40%) over traditional, fully-propulsive planetary insertion maneuvers and the interplanetary trajectories are 2 to 5 years shorter [4]. However, when some of these studies were considered 15 years ago, the aerocapture technologies, especially in the realm of thermal protection system, guidance, control, and navigation, meant a new class of entry vehicle would have to be developed to meet the goals for Ice Giants missions. Recent technological developments show that aerocapture at the Ice Giants may not require a new class of entry vehicles [5, 21, 23]. In fact, these new capabilities make heritage entry vehicle configurations flown at Earth, Mars, Venus, Titan, and Jupiter feasible for conducting Ice Giants aerocapture with robust performance.

III. Uranus Orbiter and Probe

The primary design of a Uranus mission for the Decadal Survey was the UOP mission [3]. The mission included a 13-year interplanetary cruise with a Jupiter fly-by. The baseline launch date was 2031 with a backup opportunity for 2032. The mission was designed to be achievable with a Falcon Heavy Expendable or a Vulcan Centaur. One of the innovations in mission design for UOP was 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 [2, 25, 26], which separated 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 had a long cruise phase with a Jupiter fly-by to reduce the approach velocity at Uranus, the Uranus Orbit Insertion (UOI) maneuver required approximately 1000 m/s of ΔV. This meant the single UOI maneuver required 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.

Figure 5 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.

The smaller volume form-factor of the actual scientific instruments is one of the key components of the aerocapture systems analysis being conducted under the auspices of the STMD-funded Early Career Initiative project. Using the UOP orbiter as the payload, the STMD-funded project will look at leveraging aerocapture technology to design a mission which will reduce launch mass while getting to the Uranian system faster than a fully-propulsive mission. Focus will be on improving key performance metrics such as propellant mass and interplanetary cruise phase. The configuration is similar to the artist rendering in Fig. 6, where the UOP orbiter and probe, along with critical elements such as the HGA

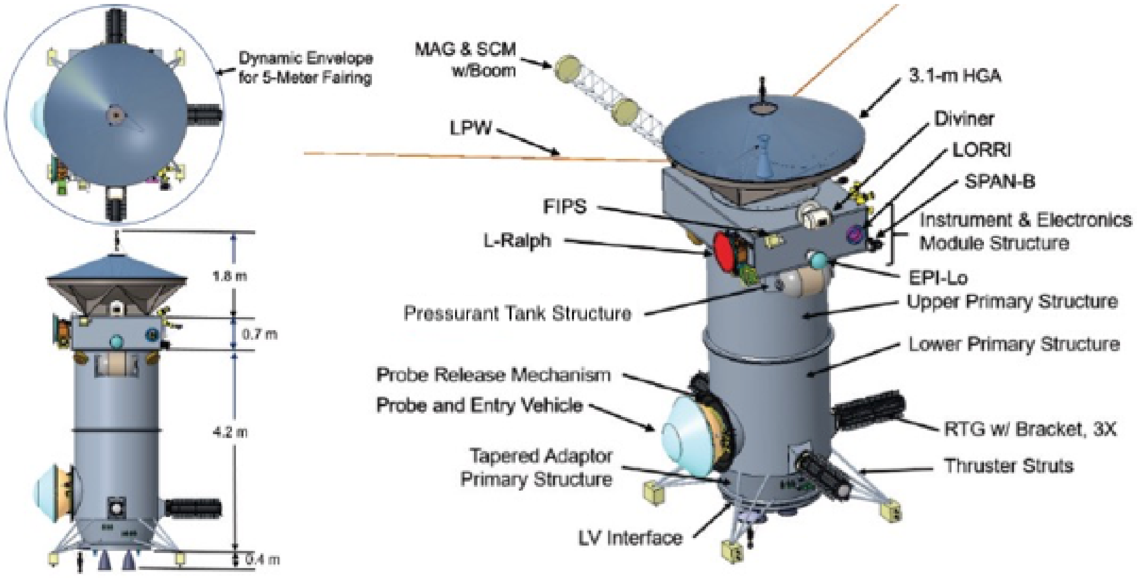


Fig. 5 Spacecraft for the Uranus Orbiter and Probe Mission [3]

and the RTGs, are encapsulated in an aeroshell during the aerocapture maneuver.

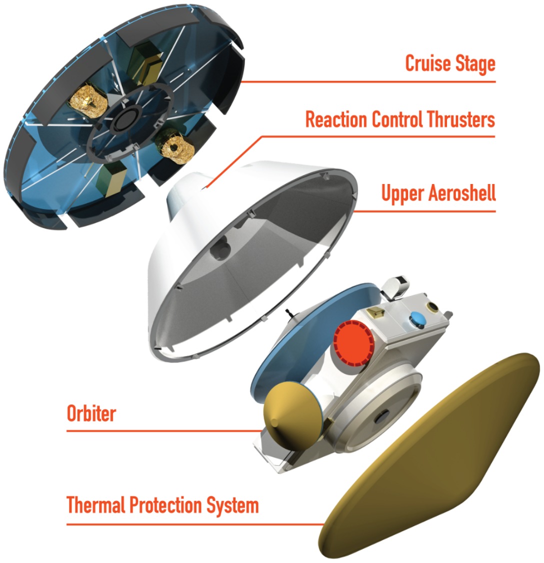


Fig. 6 Rendering of the aerocapture vehicle using UOP as a payload.

IV. Aerocapture Systems Analysis

Aerocapture vehicles are an integrated system, similar to Entry, Descent, and Landing (EDL) vehicles. Performance is highly coupled with the delivery errors and interplanetary navigation concept of operations (for example, when data cutoffs are staged and trajectory correct maneuvers are performed). Mechanical systems and TPS affect the overall size and mass of the vehicles, which further influences the flight performance. During the hypersonic phase of flight, the guidance and control system control the vehicle to stay within the corridor width of the feasible trajectories, all the while inaccuracies in atmospheric modeling can create biases from the reference trajectory. Since entry velocities are high during the hyperbolic approach, aeroheating and aerodynamic concerns are relevant.

This paper will briefly describe the various subsystem design implications involved in the planning of an aerocapture vehicle for a Uranus aerocapture mission. However, references will be added for the reader to find more information in other papers associated with the STMD-funded project.

A. Mission Design and Navigation Implications

The UOP report considered only the fully-propulsive design space to reach Uranus with launches starting in the late 2020's and continuing to the late 2030's. Most of the viable trajectories that met the mass thresholds of a Uranus orbiter and reached the planet in less than 18 years required a Jupiter fly-by, as seen in Fig. 7 where the bold options have Jupiter in the sequence.

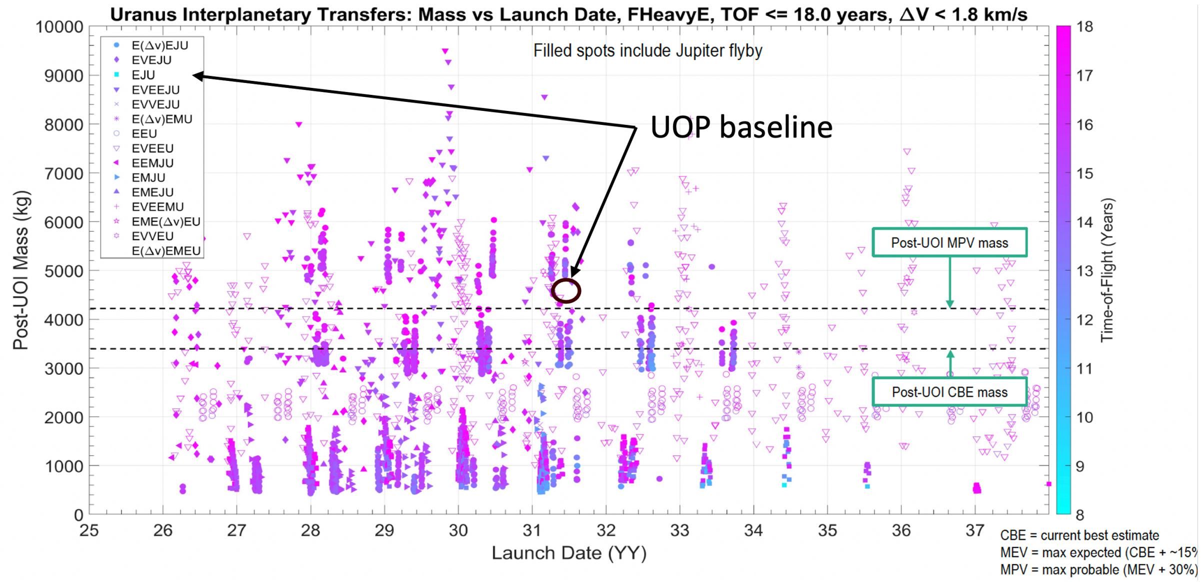


Fig. 7 Mission design space for only fully-propulsive options considered by the Uranus Orbiter and Probe proposal [3]. The legend shows the fly-by sequences used, including Earth (E), Venus (V), Jupiter (J), and deep space manuevers (ΔV) to get to Uranus (U) for a fully-propulsive capture. Bold options include Jupiter fly-by. The fully-propulsive UOP baseline is highlighted.

The scarcity of arrival options with a Jupiter fly-by after a 2033 launch date in Fig. 7 shows that, due to planetary alignment, Jupiter will be hard to access on the way to Uranus for mid-2030's launch. Additionally, the available fully-propulsive options after a 2033 launch have lower mass capabilities and also take upwards of 18 years for cruise, making them unappealing.

The aerocapture maneuver in the Uranus atmosphere can dissipate large amount of energy, making the maneuvers more tolerant of high speeds at Uranus entry interface. Thus, the interplanetary trajectories needed to reach Uranus can be more direct and take less cruise times. Ref. [24] discusses these interplanetary options in more details, providing details of solutions where launch occurs as late as 2038 but can reach Uranus before the end of the 2040's in time of the Northern Spring equinox in 2050, a time scientists are keen to observe [15].

Summarizing work discussed in more detail in Ref. [24], aerocapture trajectories can be decomposed into four specific bins based on the permutation of using heavy lift vehicles (e.g. Falcon Heavy and Vulcan) or super heavy lift vehicles under development (such as the Space Launch System (SLS) and Starship), as well as the ability to do a Jupiter fly-by or not. As mentioned earlier, heavy lift launches before 2033 can incorporate a Jupiter fly-by, but the odds of having a Flagship-class orbiter by 2033 are slim. Super heavy options such as SLS and Starship can boost the chances with Jupiter options further to 2035. However, there is then a reliance on launch vehicles with large logistical needs, such as multiple launches, and on systems not currently available. Fully-propulsive options realistically end in this time frame until post-2040 launch opportunities, but the long cruise phase of these missions makes reaching Uranus during the desired equinox impossible. Aerocapture maneuvers can thus fill a gap in launch opportunities in the mid to late 2030's, by which time a realistic Flagship-class orbiter can be constructed, while also achieving the scientific goal of reaching Uranus near the equinox.

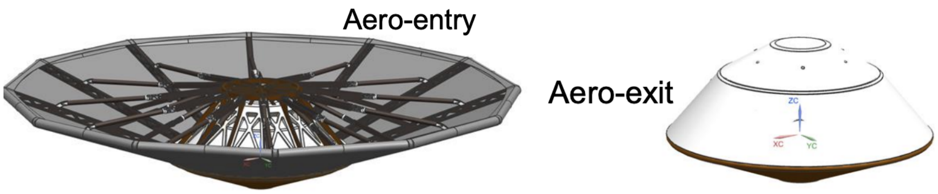
The navigation concept of operations is also crucial to study for a Uranus aerocapture (or fully-propulsive) case. The one-way-light time is approximately 4 hours from Earth to Uranus, meaning ground-in-the-loop analysis for trajectory correction maneuver (TCM) or entry parameter update will have a significant lag-time between the data cutoff used in doing the analysis and the time the command is received by the spacecraft. The entry flight path angle uncertainty needed for successful aerocapture also necessitates late-breaking ranging information to resolve errors in planetary ephemeris of Uranus. Previously, optical navigation and even autonomous navigation (AutoNAV) were part of the solution space discussed for aerocapture at the Ice Giants [27].

Results from recent work done for this project, discussed in Ref. [24], shows that ground-in-the-loop ranging along with an OpNAV campaign based on the moons of Uranus might be sufficient for the design space of aerocapture trajectories that are being considered. A reasonable TCM schedule of a few days before entry interface might be sufficient for aerocapture. Even more time-sensitive TCM and parameter updates less than a day before entry could be executed. Additionally, AutoNAV, a demonstrated technology for deep space missions, can build an improved delivery and knowledge state covariance by processing on-board the vehicle range and optical data taken within a few hours of entry. However, for the aerocapture scenarios being considered for Uranus, this capability might not be needed.

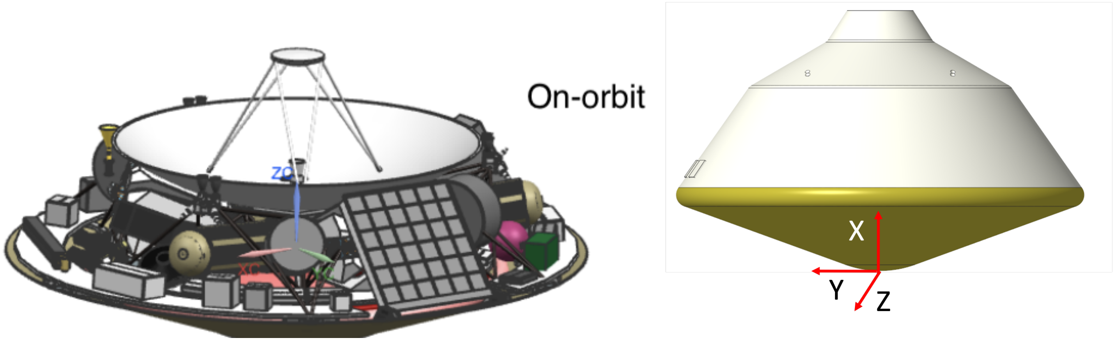
The mission design and navigation implications are further looked at in Ref. [24].

B. Mechanical and Thermal Design Implications

An aerocapture mission to Uranus will involve containing the science payloads, the orbiter, and the probe within a heatshield during the atmospheric portion of the mission. With a large HGA and multiple RTGs, the UOP concept, shown earlier in Fig. 5, provides a design challenge. A past study had looked at incorporating a mature orbiter design, which included a HGA and RTGs, into an aeroshell [28], but that particular vehicle used a deployable heatshield, allowing the vehicle trajectory to have lower deceleration loads. For the current project, the baseline vehicle is a 70° sphere-cone, similar to what was flown for previous Mars missions like Mars Science Laboratory and Mars 2020. Figure 8 shows a comparison aeroshell shapes from Ref. [28] and the current project. The present project relies on heritage entry configurations without the need of lower technology readiness level vehicles such as deployables. The payload for the aeroshells consists of the UOP orbiter, instruments, probe, HGA, and the 3 RTGs, which were shown in Fig. 5. The only parts not included are the two cylindrical tanks for propellant and the associated structure. Since aerocapture requires a lot less propellant than the UOP fully-propulsive concept, the fuel for the aerocapture mission will be contained in smaller spherical tanks. The mechanical design and its implications are further considered in Ref. [29].



(a) Past Project-Entry Configuration [28]　　(b) Past Project-Exit Configuration [28]



(c) Past Project-Post Separation [28]　　(d) Present Project-Entry Configuration

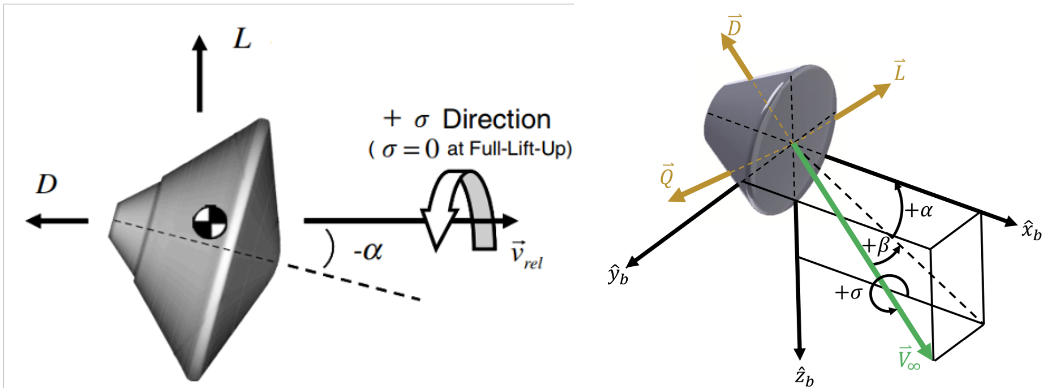
Fig. 8 Aeroshell configuration for aerocapture missions to Uranus based on past [28] and present projects.

The thermal solution for incorporating three RTGs within the confines of an enclosed aeroshell, even for a cruise phase of 9-10 years as opposed to 13-15 years for fully-propulsive missions, is a big sensitivity to consider. The current project has not completed the thermal control design, although current plans lean toward a passive control system. The project can also draw upon the experience of prior missions like Mars Science Laboratory and Mars 2020, both of which incorporated an RTG within an aeroshell, albeit for 8-9 months of cruise phase. The upcoming Dragonfly mission to Titan will also incorporate an RTG within an aeroshell with cruise phase of several years. The thermal control design for Dragonfly can be a more accurate surrogate of conditions expected by the Uranus aerocapture mission.

C. Guidance, Navigation, and Control Implications

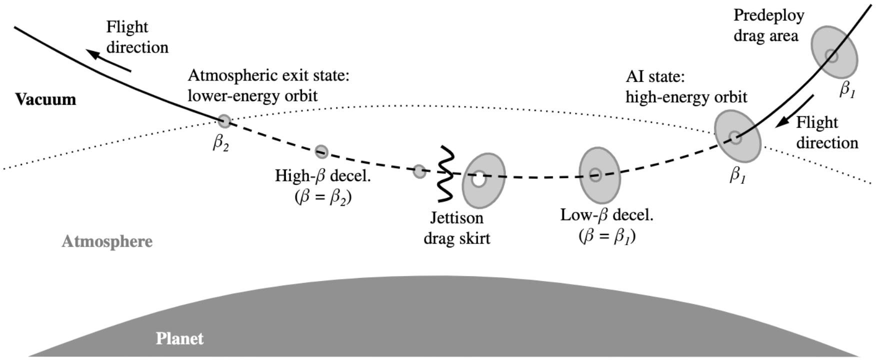
Past aerocapture mission studies [4, 30] to the Ice Giants relied on reference-based, analytical guidance schemes. These Apollo-era guidance schemes require tuning parameters off-line to follow a reference profile and then use control gains based on expected perturbations for flight to guide the vehicle close to the pre-planned reference trajectory. These analytical schemes are less computationally expensive and provide deterministic results. The schemes for these past aerocapture studies are similar to guidance schemes flown on Apollo, Artemis, and the recent Mars missions.

One drawback of the past analytical schemes is that they are tuned based on pre-flight estimates of environmental conditions, such as atmosphere. For Uranus, the knowledge in the atmospheric profile is low. Hence, an adaptive aerocapture guidance scheme that can respond to in-situ atmospheric estimates to update the on-board commands can vastly improve capture success rate and performance for the Ice Giants. Recent developments in aerocapture guidance have moved towards similar goals, especially with the advent of Predictor-Corrector guidance schemes such as the Fully-Numerical Predictor-Corrector Aerocapture Guidance (FNPAG) [31, 32].



(a) Bank Angle Modulation [33]

(b) Direct Force Control [20]



(c) Drag Modulation [34]

Fig. 9 Conceptual design of various flight control techniques for aerocapture.

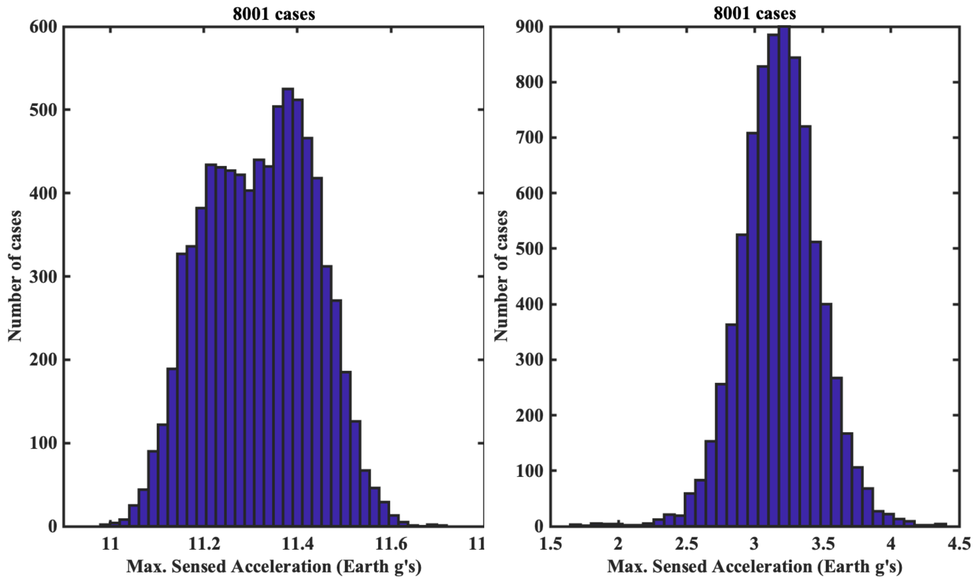
FNPAG and similar predictor-corrector guidance schemes [20, 21] propagate the trajectory equations of motion for several command profiles and the current states at each guidance call. Then, the optimal command is selected to meet the target objective. The process is repeated at every guidance call. These predictor-corrector schemes are computationally more intensive, but have flown successfully on Artemis I [35]. Additionally, these predictor-corrector schemes could utilize parameterized atmospheric models to use the information gained during the entry leg of aerocapture to improve the predictions on the exit leg of the aerocapture, and hence improve capture success rate and performance [36, 37].

For the current aerocapture design for Uranus, FNPAG was taken as the baseline guidance scheme. Ref. [38] discusses the design and tuning of the guidance for this application.

There are several options that can be used for the control strategy during aerocapture. EDL missions with hypersonic guidance have employed bank angle modulation (see Fig. 9(a)), where the vehicle stays at a constant angle of attack (α) and constant lift (L) and drag (D), while the bank angle (σ) is revolved around the velocity (v_{rel}) vector to move the lift vector from vertical direction to lateral direction to control downrange and crossrange. Similar methodology can be applied to aerocapture to use the bank angle to control the energy of the orbit and the wedge angle of the final orbit [31]. Direct force control (see Fig. 9(b) is another lift modulation strategy. However, instead of a constant lift and drag value, the angle of attack and sideslip angle (β) are modulated to change the drag, lift, and side force (Q). The separate control of angle of attack and sideslip angle allows the aerocapture vehicle to control energy of the orbit and the wedge angle independently, and potentially improving trajectory control compared to bank angle modulation [21]. Finally, instead of modulating the lift force, one can control only the drag of the vehicle in drag modulation (see Fig. 9(c)). Control in this method is achieved by modulating the ballistic coefficient (also labeled as β) by going from a high drag configuration to a lower drag configuration by shedding a drag skirt [34, 39] or a ballute [30].

Bank angle modulation control was chosen for the current aerocapture concept for Uranus due to its flight heritage and higher technology readiness level. Bank angle control has heritage from the Mars hypersonic guidance [40] and can be implemented using reaction control system (RCS) actuators instead of using systems like center of gravity modulation, trim tabs, or hypersonic separation of deployables. The goal, as with similar subsystems, was to use systems that have been demonstrated in past missions to reduce the number of innovations needed for Uranus aerocapture. Further information about the guidance and control strategies needed for the aerocapture as well as system sensitivities can be found in Ref. [38].

D. Aerocapture Performance



(a) Mars 2020 [41]

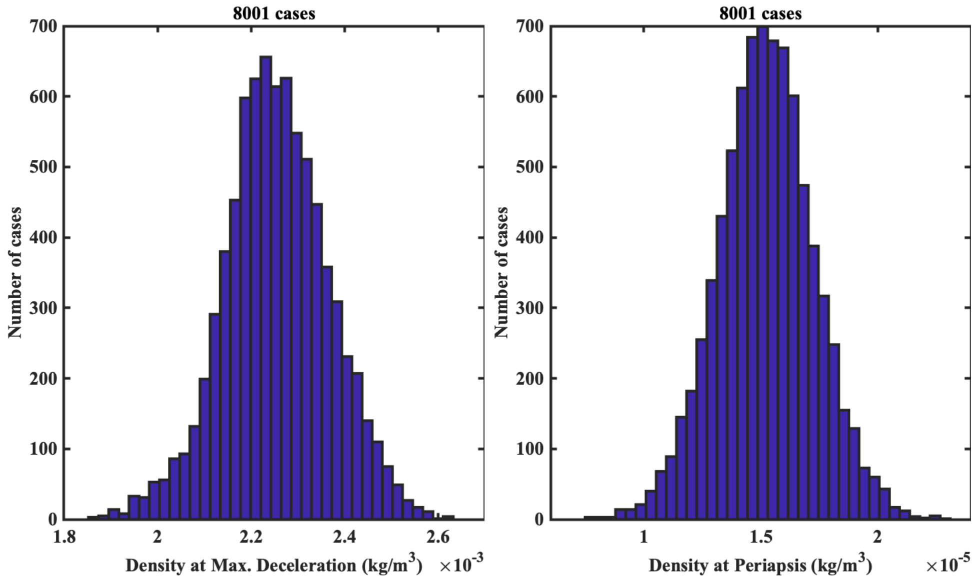
(b) Uranus Aerocapture

Fig. 10 Comparison of maximum deceleration for Mars EDL and Aerocapture at Uranus.

In order to quantify aerocapture performance, an end-to-end flight mechanics simulation with guidance and control in-the-loop is traditionally used along with Monte Carlo analysis. Such uncertainty quantification with software-in-the-loop methods are used to look at metrics such as peak heating, total integrated heat load, maximum deceleration, and total ΔV needed in the post-aerocapture propulsive maneuvers. The primary metrics for aerocapture performance are the capture success rate (how many cases were captured around the planet) and the percentage difference from target orbit in terms of either orbital energy or apoapsis. These key metrics for the aerocapture design for Uranus are shown in Ref. [42].

In the above sections, aerocapture has been compared with EDL at planetary bodies. The comparison is especially pertinent to Earth and Mars missions where hypersonic guidance has been used, such as Apollo, Artemis I, Mars Science Laboratory, and Mars 2020. Similarities especially exist when looking at the guidance and control strategies [30, 40].

However, to many readers, aerocapture missions may engender worries about extreme environments. Atmospheric entry velocities at the Ice Giants are high compared to their Earth and Mars EDL counterparts (atmospheric relative velocities of 27 km/s for Uranus vs. 8 km/s at Earth and 6 km/s for Mars), primarily due to the larger gravity wells of Uranus and Neptune compared to the terrestrial planetary bodies. For Uranus aerocapture, the deceleration occurs at higher altitude and lower density than for EDL, since the vehicle is slowing down only enough to enter a captured orbit, which results in a more benign environment than planetary EDL. This comparison can be seen by looking at Monte Carlo analysis-based predictions of peak deceleration (Fig. 10) and density at peak deceleration (Fig. 11) for Uranus aerocapture and Mars EDL. Ref. [42] provides results for the aerocapture case, while Ref. [41] was used for the Mars 2020 results as an example of Mars EDL performance. One can see that maximum deceleration for aerocapture is an order of magnitude lower, mostly since peak deceleration is happening at atmospheric densities orders of magnitude lower than in EDL. Aerocapture, despite the high entry conditions, is in family with EDL and in some cases can have a more benign environment. Aerocapture performance and constraints for metrics such as heating and deceleration are tied closer to entry initial conditions, such as flight path angle, than environmental conditions as can be seen in Ref. [42].



(a) Mars 2020 [41]

(b) Uranus Aerocapture

Fig. 11 Comparison of density at maximum deceleration for Mars EDL and Aerocapture at Uranus.

Concerns have been also raised if the aerocapture performance is significantly sensitive to the atmospheric model assumed by the guidance and control algorithms. This is an apt worry since there are large uncertainties in Uranus atmosphere, which is primarily built on Earth-based observations and Voyager 2 data [43]. However, the models and simulations developed under the aegis of this study have stressed tested this situation. For example, by tuning the guidance on an older Uranus atmosphere while testing the truth simulation with newer models of Uranus atmosphere, one can quantify a potential performance degredation at Uranus. Ref. [42] explores this situation in greater detail, but the summary is that although performance is degraded, the capture success rate is only nominally affected, and the correction for the situation is to carry slightly larger amount of fuel for the clean-up burns which is within the allocations made for this study. An actual aerocapture mission will benefit from any improved atmospheric modeling during the cruise phase of the flight and would tune its on-board guidance to the best atmospheric knowledge.

Details on the specifics of the simulation used to characterize aerocapture performance, as well as additional metrics, can be further found in Ref. [42].

E. Aerosciences and Thermal Protection System Implications

The characterization of aerodynamic and aerothermal environments of an aerocapture vehicle at Uranus are challenging due to the novel H_2-He atmosphere at the Ice Giants, compared to the N_2 rich atmospheres at Earth and Titan or the CO_2 abundant atmospheres at Venus and Mars which are typically studied for EDL vehicles. The gas chemistry models for NASA tools for H_2-He are not as well developed as the N_2 and CO_2 counterparts [17]. Nevertheless, recent shock tunnel data and computational tools improvements [44] can be leveraged to quantify the aerodynamic and aerothermal predictions of aerocapture at Uranus.

As the Mars Science Laboratory and Mars 2020 entry vehicle shape was retained as the baseline for this study, the aerodatabase for the Uranus aerocapture mission is comparable to its Mars counterpart [45]. Special consideration has been made by Ref. [46] to adapt the aerodynamic solutions to the unique chemistry of Uranus, and emphasis has been made for rarefied aerodynamics since a significant portion of the aerocapture trajectory traverses free molecular and transitional regimes of flight [42]. One observation from the aerocapture aerodatabase development has been the very different speed of sound and mean free path in H_2-He atmosphere. The rarefied flow regime is significant at a very high altitude ($\sim$ 4000 km geodetic altitude) and simulations have to capture atmospheric effects from such higher altitudes.

Due to the large entry velocities, aerothermal analysis also has to consider radiative heating in addition to convective heating [44]. Fortunately, due to the H_2-He atmosphere, radiative heating is very low at nominal aerocapture entry velocities such as 27 km/s, but if faster interplanetary cases are considered, the effect of radiative heating can increase [44]. Another consideration in the aerothermal analysis is the presence of CH_4 which can enhance radiative heating [17]. Such enhancements have been considered for Titan planetary vehicles, such as Huygens and Dragonfly, but the CH_4 preponderance at Uranus at altitudes well below the lower altitude range of aerocapture [44].

Finally, the aerothermal environment is mapped to the thermal protection system material response prediction, which in turn is used to size the TPS for the vehicle. For the aerocapture vehicle at Uranus, the TPS of choice is Conformal Phenolic Impregnated Carbon Ablator (CPICA) [47] which is a lightweight version of PICA. Although CPICA has not flown on any missions, its close relative, PICA has flown on 2006 Stardust, 2012 Mars Science Laboratory, 2021 Mars 2020, and 2023 Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer (OSIRIS-REx). The aeroheating and pressure environments for aerocapture are well within the predicted capabilities of CPICA, and the current TPS design also meets the manufacturing tolerances [47]. However, the aerothermal environments are benign enough for Uranus aerocapture that the TPS does not strongly ablate, which usually is the most efficient way for the TPS to dissipate heat [47]. Instead, the TPS sizing is dominated by the length of the atmospheric pass ($\sim$ 10 mins) during which CPICA acts largely as an insulator. Thus, the time of the heatshield separation after atmospheric exit from aerocapture is a strong driver in the TPS size. Analysis has shown that a 5-8% increase in TPS thickness is needed for every ±5 mins difference in heatshield separation time [47].

The readers are referred to Ref. [44] for aerothermal and Ref. [46] for aerodynamic considerations behind the aerocapture system design for Uranus. Ref. [47] discusses the TPS implications of the aerothermal environment expected by the Uranus aerocapture vehicle.

V. Forward Work

A major obstacle to aerocapture not becoming a baseline design concept since the late 1990's is a perception of risk associated with the maneuver. Although similar guidance and control architectures have been demonstrated during hypersonic guidance during EDL at Earth and Mars, many studies look at aerocapture concepts with trepidation that the orbiter will be lost during the atmospheric phase of flight. Similar atmosphere-utilizing maneuvers such as aerobraking do not evince as much worry. If aerocapture's risks for Uranus could be quantified via a probabilistic risk assessment to compare it in even keel against fully-propulsive maneuvers and aerobraking, potentially the perception of risk could be lowered. A similar effort [18] was also attempted during the systems analyses of the early 2000's, but the focus of the current effort will be purely Uranus-centric.

In 2022, the need for aerocapture for the Ice Giants mission and other planetary exploration had been considered by the Aerocapture Demonstration Relevance Assessment Team (ADRAT) commissioned by NASA Science Mission Directorate [17]. The team found aerocapture as a viable option for the Ice Giants and other planetary missions, such as small satellite planetary exploration. However, the team concluded that an Earth demonstration of aerocapture would reduce risks. An example of such an Earth aerocapture demonstration is discussed in Ref. [48]. Although the particular implementation in Ref. [48] uses drag modulation for aerocapture trajectory control, the paper discusses a concept of operations of using a geosynchronous transfer orbit as an initial state from which to conduct aerocapture. A similar approach could be used with bank angle modulation or direct force control as well, and can show that a captured orbit around Earth could be attained. The successful demonstration of aerocapture end-to-end can alleviate many perceived risks of the technology.

VI. Conclusion

The 2022 Planetary Science Decadal Survey has identified an orbiter and probe mission to Uranus as the next Flagship-class target. The baseline mission chosen in the Decadal Survey is a fully-propulsive mission, with a launch date of 2031 or 2032, and launch mass that is 60-70% propellant mass, with a major component of that fuel devoted to the large Uranus orbit insertion burn. Additionally, the mission will take 13 years from launch to reach Uranus. On the other hand, aerocapture, an orbit insertion maneuver that uses the atmosphere to decelerate, can reduce the propellant load needed for a captured orbit and can reach the planet several years faster in most circumstances. The NASA STMD-funded project has been formed to look at an aerocapture system design for a Uranus Flagship-class mission. Using the payload of the mission recommended by the Decadal Survey, the project shows many improvements over the baseline fully-propulsive mission. These improvements include a shorter cruise phase, flexibility in launch opportunities late into the 2030's while reaching Uranus before the 2050 equinox for the desired science opportunities, and lower propellant mass needs. Additionally, the concept uses a lower risk, heritage entry vehicle configuration that has been used for Mars entry, descent, and landing for the aerocapture vehicle.

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. The authors would like to acknowledge the project mentors at NASA Langley Research Center, Ames Research Center, and the Jet Propulsion Laboratory. Additionally, the authors would like to 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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