Report of the Aerocapture Demonstration Relevance Assessment Team (ADRAT)

Commissioned by the Chief Technologist

Science Mission Directorate

NASA

Work Performed under the

Terms of Reference for the Aerocapture Demonstration Relevance Assessment Team

February 10, 2023

FOREWORD

In August 2022 as put forth in the "ADRAT Terms of Reference (TOR)"[1], the Aerocapture Demonstration Relevance Assessment Team (ADRAT) was established at the discretion of the Chief Technologist, Science Mission Directorate, following consultation with the Assistant Deputy Associate Administrator for Research, Science Mission Directorate, as well as the Associate Administrator, Science Mission Directorate.

The purpose of the team is to "examine the utility of an aerocapture demonstration mission to reduce the risk on outer planets missions, focusing on how NASA can use this technology to more effectively meet the nation's science and exploration goals." Specifically, NASA's Space Technology Mission Directorate (STMD) has proposed the use of a small spacecraft (less than ~200 kg) performing aerocapture into Earth's orbit as a suitable demonstration to both reduce risks for large spacecraft and to demonstrate the capability for future small spacecraft missions. The team's task was to determine the potential relevance of the STMD-proposed demonstration mission to reduce risks for a large spacecraft to the outer planets and other solar system destinations. This task focused on answering four questions that were posed in the TOR:

1. What are the top risks associated with using aerocapture on future NASA missions to the outer planets?
2. What architecture(s) and requirements are necessary for a tech demo to retire identified risks for various aerocapture techniques?
3. Would a demonstration of aerocapture using a small spacecraft in Earth's atmosphere buy down any of those risks? If so, what data would be most beneficial to collect?
4. There are at least two fundamental concepts to control a spacecraft during aerocapture: drag modulation and lift modulation. Is one of these clearly more beneficial to demonstrate as risk reduction to the outer planets?

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1. Introduction and Summary

Aerocapture is a technique to slow down a spacecraft on a hyperbolic approach to a destination to effect capture into orbit using a single pass through the atmosphere. Previous studies[2] have shown that use of aerocapture at the outer planets provides potential mission benefits in areas including mission duration and mass delivery to orbit. NASA is considering an Earth aerocapture demonstration for advancement of the aerocapture technology and reduction of the risks to future missions that may use aerocapture.

The team assessed the aerocapture risks at the outer planets. It was determined that the risks are real (not just perceived), dominated by uncertainty in the destination's atmosphere and environment. It was further determined that these risks need to be mitigated before an aerocapture mission to the outer planets can be undertaken. These risks are detailed in Section 4. Specific recommendations for mitigating these risks are provided in Section 2. An assessment of the adequacy of an Earth demonstration to mitigate these risks was performed. The assessment is detailed in Section 6. A summary of the findings is presented here.

As the team assessed the risks and technology, it became clear that a mission design effort is needed in order to provide a frame of reference for an aerocapture technology trade study. The risks and the appropriate aerocapture technology are destination dependent, science objective dependent, and mission design dependent. In order to perform a detailed assessment of the mission risks and to determine the best aerocapture approach for a specific destination, a representative mission is required for comparative assessment.

The team concluded that steps can be taken to advance the necessary technologies and reduce uncertainty to relieve the implementation burden on the future project independent of the mission design. These steps include increased observation and modeling of outer planet atmospheres and ground testing of various materials in the H_2/He environment including atmospheric trace constituents (e.g., CH_4). These steps and others are discussed in more detail in Section 2.

Earth aerocapture technology demonstrations are useful for raising the Technology Readiness Level (TRL) of the various techniques and associated Thermal Protection System (TPS) materials. Raising these TRLs will provide more options for outer planet aerocapture missions. A SmallSat Earth demonstration provides a means to raise the TRL of specific design implementations. For example, a recent assessment of the Adaptable, Deployable Entry Placement Technology (ADEPT) TRL for drag-modulated aerocapture assessed the critical technologies as TRL 4. A successful hypersonic flight test is needed to mature ADEPT beyond TRL 5.[3] These technologies include drag skirt stowage and deployment, drag skirt separation, Guidance Navigation and Control (GNC) algorithms, and deployed drag skirt design robustness.

An Earth demonstration would also provide benefits for an aerocapture mission at destinations with a well-understood atmosphere where the risks are not dominated by atmospheric uncertainty. An Earth demonstration provides a means to raise the integrated technology to TRL 6, enabling infusion into missions at Venus or Mars. An Earth demonstration could also provide important data for validation of design tools for predicting aerothermal performance and could provide information on proper scaling for engineering correlations. These models could then be used to more confidently extrapolate performance to other destinations.

However, there are many specific, high-risk aspects of aerocapture for an outer planet mission that cannot be addressed in an Earth demonstration. As stated above, these risks are dominated by uncertainty in the environment and particularly by uncertainty in the atmosphere. Other aspects of outer planet aerocapture that cannot be demonstrated at Earth include high approach velocity, ephemeris uncertainty, material interactions with a H_2/He atmosphere, and increased autonomy due to long communications delays. These aspects are further discussed in Sections 6 and 7.

2. Recommendations

2.1. Recommendations to Address Risks

NASA can invest in technology development now that would reduce uncertainty and reduce the burden on the implementing project[4]. Among these efforts, the team recommends performing a relevant reference mission design study for the outer planets including Titan in order to address specific risks and in order to enable a direct comparison of the various aerocapture methods. However, the reference mission should be chosen to carefully weight NASA's priorities because the aerocapture implementation will be destination dependent and may result in different aerocapture risks, mitigations, and approaches.

Data collection on a precursor orbiter/probe mission that is specifically targeted to enabling subsequent aerocapture-based missions would provide valuable information that would greatly reduce the atmospheric uncertainty and associated risk of a future aerocapture mission.

Probe data would serve to reduce the most fundamental of the aerocapture risks, which is the knowledge of the properties of the target atmosphere:

- In-situ measurements of atmospheric mass density and composition versus altitude
- Winds via Doppler measurements (probe-to-orbiter) for enabling separation of vertical winds. These measurements would potentially be enhanced by a probe-to-Earth link.
- Data on TPS/environment performance and non-equilibrium turbulent flow from an instrumented heat shield
- Remote sensing instruments on the orbiter to observe the probe entry location for cross-calibration of probe and orbiter measurements

Orbiter data could provide:

- Information regarding temporal and spatial variations through radio, stellar, and solar occultations, particularly with a precessing orbit that provides observations that sample a large fraction of the planet
- Multiple wavelength instruments including ultraviolet and infrared (IR) instruments to provide data at various atmospheric altitudes
- Measurement of methane bands at visible wavelengths and in the near-IR wavelengths

To address risk-associated TPS performance with respect to atmospheric composition, the team recommends acceleration of ground testing and analysis of TPS behavior in an H_2/He environment. This testing and analysis should include environments with trace constituents (e.g., CH_4) that are present in outer planet atmospheres. Attention should be given to formation of CN radicals and their radiative effects on aeroshell heating. Further, the team recommends incorporation of the results of this testing into aerothermodynamic models and simulations of aerocapture in the H_2/He environment.

Modeling capability will be key to the development of a mission concept; requirements verification will most likely rely on simulation and analysis grounded in the aforementioned testing. The team recommends continuation of tool development for dynamic Computational Fluid Dynamics (CFD) analysis because it is important to understand how these vehicles will dynamically interact with the environment.

To address the key risk related to propulsion performance in extreme atmospheric conditions, the team recommends a study to characterize thruster performance in a relevant aerocapture environment (i.e., behind a hypersonic shock).

At the mission level, there remains significant uncertainty with respect to the required margins of system performance given the large uncertainties in the models of the target atmospheres. The team recommends that NASA continue to explore aerocapture technology enhancements in order to improve margin position and consider which technologies provide the largest margin against the most significant atmospheric uncertainties. Enhancements to improve performance of aerocapture technologies could improve margins and reduce risk.

For example, drag modulation with a continuously variable ballistic coefficient might improve success rates relative to high uncertainties or variability in density. Such control over the ballistic coefficient might be implemented by, for example, a flexible drag skirt with a frontal projected area that is continuously variable. However, much more design and analysis are needed to assess the effectivity and robustness. If the drag skirt is flexible (e.g., the ADEPT system) reducing the cone angle without some complex mechanism to maintain the tension on that material could result in the material "flapping in the breeze."

New technologies are being explored such as deployable ballutes and decelerators that could greatly reduce the mass of the aerocapture system for the same drag efficiency. Technology demonstration missions such as the Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) and developments such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) provide new options for future missions. These technologies should be examined and prioritized relative their ability to address risk relative to atmospheric uncertainty.

2.2. Atmosphere Characterization Recommendation

This recommendation addresses the need to establish that uncertainties in environmental parameters are sufficiently understood for aerocapture. A primary concern is uncertainty in atmospheric density profiles that vary across small and large time scales, and across small and large spatial scales. Rossby waves, atmospheric gravity waves and turbulence are responsible for variations on small spatial and temporal scales. Seasonal effects and, to a smaller extent, solar-cycle variations are responsible for variations on large temporal and spatial scales. A secondary concern is the compositional uncertainty, insofar as the H_2/He ratio is related to atmospheric density and to how hydrocarbon molecules may interact with nitrogen in the aeroshell (for Uranus and Neptune) or in the atmosphere (for Titan). These interactions can lead to shock production of CN radiative heating of the aeroshell. For Uranus and Neptune, Voyager data has provided density profiles and compositional information at high spatial sampling from radio and UV solar occultations, but these data are inadequate to address environmental uncertainties. Considerable knowledge of environmental variability exists for Titan thanks to the long-duration, heavily-instrumented Cassini mission and the Huygens Probe. In the set of recommendations that follow, it is implicit that the effort needs to focus on the pressure/altitude levels and the time and latitude frames that are relevant to an aerocapture mission.

- ✦ Convene a panel of experts to assess environmental uncertainties relative to what is needed for aerocapture evaluation.
  - As part of that task, the panel could examine the assumptions of how uncertainties were derived and used for aerocapture studies that have already been performed and archived or published.
  - An example of this task is the panel convened by the Cassini Project (i.e., the Saturn Atmosphere Working Group [SAMWG]) to assess environmental trends and uncertainties. These assessments were used to plan final orbits at Saturn that were designed to sample (at periapsis) the high atmosphere using in situ measurements (mass spectrometer), and measurements using the magnetometer and Radio Science. The Project needed to know what altitude/density would be unsafe (i.e., would trigger spacecraft tumbling). The SAMWG assessment was documented and archived.
- ✦ Update and improve the fidelity of Global Reference Atmospheric Models (GRAMs) for the outer planets and Titan (see more on this in Section 4.2.1.2). The following are examples that can be used to perform this effort:
  - Existing/archived and future observations from the Hubble Wide Field Camera 3, the Spitzer Infrared Spectrometer (IRS), and ground-based thermal images, near-IR images and spectra. Orton et al. (2022)[5] illustrated a best-case example using infrared observations of Jupiter. Observations taken using ground-based telescopes over a forty-year period revealed “periodicities of 4, 7–9 and 10–14 years that involve different latitude bands and seem disconnected from seasonal changes in solar heating.”
  - Leverage long-term ground-based efforts such as those used by Orton et al. (2022) and space-based efforts such as the Outer Planet Atmospheres Legacy (OPAL) program to continue Hubble Space Telescope (HST) observations on an annual basis through Hubble’s lifetime. Because Uranus has an especially low brightness temperature and is sometimes not seen in ground-based thermal-IR spectra, it would be valuable to institute an OPAL-like program including spectroscopy from the James Webb Space Telescope (JWST).

An example of the evolving knowledge and complexity is illustrated by the following table and graphic showing the derived columnar abundances in the Uranus atmosphere from Spitzer observations*[6].

Molecule	Column abundance (molecule-cm^{-2})	Pressure of maximum contribution function (bars)
CH_4	$4.5 +1.1/-0.8 \times 10^{19}$	1.8×10^{-4}
C_2H_2	[a]$6.2\pm1.0 \times 10^{16}$	1.8×10^{-4}
C_2H_6	$3.1\pm0.4 \times 10^{16}$	2.1×10^{-4}
CH_3C_2H	$8.6\pm2.6 \times 10^{13}$	4.4×10^{-4}
C_4H_2	$1.8\pm0.3 \times 10^{13}$	3.7×10^{-4}
CO_2	$1.7\pm0.4 \times 10^{13}$	1.4×10^{-4}
CH_3	[b]$<3.3 \times 10^{12}$	1.5×10^{-4}

[a]from fit to the SL1 spectrum; a 24% increase is required to fit the LL2 spectrum
[b]3σ upper limit

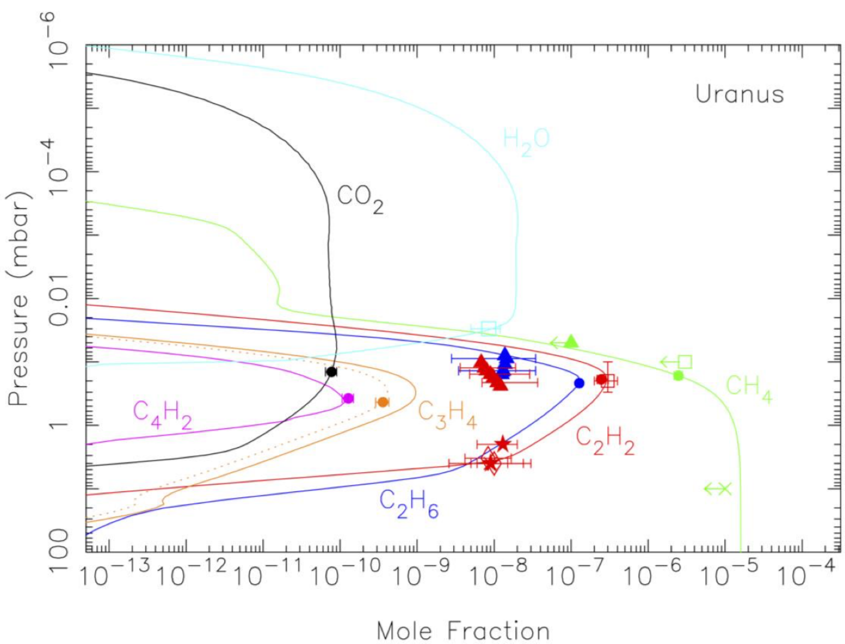

Figure 1: Mid-Infrared Spectroscopy of Uranus Results

Information as shown above will improve the outer planet GRAM models (see Section 4.2.1.2) and can be used to improve environmental assessment for aerocapture, but it must be remembered that more is needed in order to understand temporal and spatial variations. Methane is condensable in the atmospheres of Titan, Uranus, and Neptune. Hydrocarbon mole fractions are therefore sensitive to atmospheric upwelling and downwelling, which can vary in time and space. Furthermore, mid and high latitudes in one or the other hemisphere are not visible from Earth, especially for Uranus, depending on orbital phase. Near- and mid-infrared spectra and images to be obtained in the near future from JWST could be especially informative about hydrocarbon mole fractions and atmospheric temperatures. Ground-based near-infrared images using adaptive optics on the largest telescopes may also be useful. As with the HST imagery, however, these images may be of limited use for aerocapture assessment if the observed cloud features pertain to atmospheric pressures that are too deep to be helpful for aerocapture.

- ✦ Consider special opportunities for future ground-based or Earth-orbital observations, such as stellar occultations.
  - Stellar occultations of Uranus, Neptune, and Titan are rare and are sensitive to very low pressures and limited latitude coverage. For these reasons, these occultations may not be of much use for aerocapture studies. Other considerations such as ephemerides improvements may be important.
  - Consider the possibility of one or more occultations of cosmic radio sources to probe deeper levels than are accessible from stellar occultations.
- ✦ Consider precursor remote sensing and/or a probe either as a stand-alone mission or as part of an aerocapture mission. Probe data are unsurpassed for establishing abundances of well-mixed constituents such as He but provide only point-source (in space and time) data on constituents that vary with location and time. Probe measurements of wind and an atmospheric temperature/pressure profile are also especially valuable as “ground truth” and can give indicators of wave activity at a specific location and time. These measurements may also be used to calibrate and assess the fidelity of temperatures derived from orbiter instruments if done in conjunction with such instruments. Remote sensing observations (including radio and stellar occultations) from one or more orbiting satellites (including CubeSat class) can be valuable. Multiple radio and stellar occultations covering many latitudes and occurring over an extended time period were invaluable at Saturn to assess latitude and time variations for planning of the final Cassini orbits (i.e., SAMWG). These measurements provided unique and valuable science data.

2.3. Recommendation for Mission Study

A large part of the problem regarding evaluation of the feasibility and benefit of the application of aerocapture to an outer planet mission is the wide range of assumptions that have gone into the studies to date. As such, collapsing the design space to a manageable size with consistent assumptions would be extremely valuable for future design exercises and trade studies.

Realistic assumptions regarding launch readiness date are the first set of assumptions that should be clarified. This assumption primarily affects the type of cruise to the outer planet and whether Jupiter is available as a flyby option for a Uranus mission. The decade of the 2030s is essentially divided into a timespan when Jupiter is available during the first half and not available during the second half. Two mission profiles should therefore be considered, including one with and one without Jupiter as a flyby opportunity for the target of near-term interest (i.e., Uranus). Two baseline trajectories should be agreed upon. A similar approach should be considered for the other targets of interest (i.e., Neptune, Titan) to determine when Jupiter is available to provide a gravity assist and to determine a baseline trajectory in the appropriate timeframe. There is non-optimality when selecting a “one size fits all” approach to trajectory design, but the benefit of removing this variability from future studies may outweigh the penalty.

In addition to the launch readiness date, a realistic assessment and estimate of the launch vehicle or the expected performance of future vehicles is needed for a consistent evaluation of trajectory options and mass assumptions. The transit time from launch to delivery into orbit about the target planet is a reflection of the urgency of the science and the budget for a mission, and future studies would therefore benefit from some clarification. In rough terms, the corners of the box for Uranus could be defined as a fast transfer (~11 years) and a slow transfer (~16 years). The assumed launch vehicle capability directly feeds into launch C3 and subsequent arrival V_∞, which impacts arrival conditions such as heating rates. Clarification of the anticipated launch vehicle capability with regard to the cruise trajectory is critical. The assumption that aerocapture is relatively insensitive to arrival velocity often drives mission studies to assume a faster transit to the destination. However, if no launch vehicle exists to launch onto such a trajectory, the study is flawed.

The selection of the target and a general clarification of the desired science orbit about that body is also essential to any study. For example, the high obliquity of Uranus has implications related to the types of orbits that a spacecraft can insert into. Whether or not the science of a Neptune mission is focused on the moon Triton (which orbits in a retrograde direction) will affect the entry conditions of the aerocapture mission. With its relatively slow arrival velocity, a Titan orbiter will have different requirements than either of the previous targets. Definition of the desired science orbit about the primary targets of interest will therefore help determine the most suitable aerocapture implementation. Additionally, knowing the type of science (e.g., imagery, radar) planned will be valuable to evaluate other mission parameters such as the power source and the implications of heat dissipation from within the aerocapture vehicle.

A large contributor to the delivery uncertainty of a spacecraft entering the atmosphere of a body is the state uncertainty at the entry interface point. A realistic assessment of the flight path angle uncertainty for each target should be made so that subsequent aerocapture studies have a consistent understanding of this important parameter. Ephemeris knowledge of the target body, navigation accuracy, atmospheric modeling accuracy, and attitude control capability all contribute to flight path angle accuracy. In the studies reviewed, entry corridor assumptions varied from less than 1 degree to more than 2 degrees (see Appendix 1: Bibliography). The addition of optical navigation and autonomous Trajectory Correction Maneuver (TCM) generation and execution may improve the delivery accuracy, but the availability of moons for navigation differs by target. A consistent and realistic assessment of the entry flight path angle uncertainty due to all error sources is needed for each target. Values of uncertainty under various conditions could be generated such as assuming use of radio navigation, optical navigation with ground generated TCMs, or optical navigation with autonomous maneuver generation and execution. Such assessment will provide a set of consistent values that can be used in subsequent Monte Carlo simulations as the various aerocapture approaches are evaluated.

These mission design parameters are all dependent variables that together define the aerocapture conditions. The entry corridor width, peak deceleration, peak stagnation-point heating, and total heat load are all functions of the arrival V_∞ and vehicle L/D. Conversely, the L/D of the vehicle to achieve the mission is dependent on the arrival V_∞ and corridor width that in turn set the deceleration and heating rates. A consistent set of mission design assumptions are needed prior to performing aerocapture design trades and feasibility assessment.

3. Team Conduct

The ADRAT was formed of Subject Matter Experts (SMEs) with expertise across a wide range of fields related to aerocapture. A kickoff meeting was held July 29, 2022. Weekly meetings were held thereafter with specific agenda topics each week. These topics included presentations from SMEs, discussion of TOR questions, and other related topics.

A full list of the presentations follows:

- *Status and Overview of Aerocapture Technology*, Michelle Munk
- *Outer Planet Global Reference Atmospheric Model (GRAM) Upgrade Status*, Hilary Justh
- *TPS Readiness Assessment for Aerocapture – Ice Giants and Other Solar System Destinations*, Ethiraj Venkatapathy
- *Aerothermal Readiness Assessment for Aerocapture*, Michael Barnhardt
- *Lessons Learned from the Cassini Saturn Atmosphere Working Group,* Darrell Strobel
- *Drag Modulation Aerocapture Technology Development Overview and Future Plans*, Alex Austin
- *Aerocapture Technology Demonstration – Lift-Modulation Concept*, Soumyo Dutta

In addition to weekly meetings, the team reviewed many papers that addressed various aspects of aerocapture including methods, previous technical assessments, guidance algorithms, etc. (see Appendix 1: Bibliography). Information gleaned from these papers was included in the weekly discussions and reflected in the report.

The team synthesized all of the information from papers and presentations in order to formulate responses to the TOR questions. A presentation of the results was provided to SMD on November 29, 2022. This document constitutes the final report.

4. Question 1: What are the top risks associated with using aerocapture on future NASA missions to the outer planets?

The team examined concerns that would keep an outer planets aerocapture mission from being successful. "Success" was considered in the broadest terms without regard for a specific mission implementation based on the team's collective knowledge (both prior to and acquired during this study) of what is required to perform aerocapture at an outer planet. Development risks and mission risks were considered in the team's analysis.

The largest risk is uncertainty in the environment. Uncertainty in the environment encompasses multiple facets. The two primary concerns are:

1) Uncertainty in the vertical profiles of fundamental atmospheric conditions including mass density and composition (insofar as composition affects the balance of radiative/convective heating input to the spacecraft)
2) Uncertainty in the aerothermodynamics of the atmospheric mix of gases flowing at hypersonic speeds around a hypersonic vehicle within the atmosphere. The equation-of-state of the gas/plasma (i.e., the relationship among pressure, temperature, and density) and the radiative character of the gas mixture at the different pressures, temperatures, densities, and Mach numbers to be encountered are not known for the outer planets, particularly the ice giants Neptune and Uranus.

In addition to considering the risks, the team also considered the question, "What are the barriers to technology infusion?" The greatest barrier to infusing aerocapture into an outer planet mission is the inability to sufficiently characterize the environment in order to produce a mission with an acceptable level of risk, in terms of development risks and mission risks.

The risks presented herein are meant to apply to any aerocapture mission to the outer planets. Before a detailed risk assessment can be performed for a specific mission implementation, the following will need to be addressed:

- How is success defined, and what probability of success is acceptable? Is success defined by capturing into any orbit? Is success defined by achieving the desired apoapsis altitude within tolerance? Is success defined by achieving the desired science orbit in terms of altitude, inclination, phasing, etc.?
- Timing the mission so that the first orbit is in the plane of the satellites puts a strong constraint on the launch widow. This timing may preclude use of a Jupiter gravity assist. This is especially a concern for Uranus because of its large obliquity.
- Subsequent tour planning (e.g., Triton observations for a Neptune mission) will require a much more flexible initial phase than deterministic tour missions (e.g., Cassini). Previous missions relied upon being in a specific orbit at a specific time with other alignments. Aerocapture can get a spacecraft close to the desired orbit but won't provide the same level of position and timing precision as missions using a controlled propulsive orbit insertion.

Many Monte Carlo (MC) analyses were performed during the various studies examined by the team (see Appendix 1: Bibliography). A non-zero number of cases failed to capture into orbit. Most analyses used post-capture apoapsis altitude with a large tolerance as a measure of success. Few analyses addressed meeting a desired science orbit. Some studies assessed propulsive capability needed post-capture for orbit refinement.

Multiple studies used MC to justify that current technology is sufficient and that the probability of mission success would be acceptably high. Unfortunately for Uranus and Neptune, there is no measure of realism for the assumptions on atmospheric variations included in the calculations.

4.1. Risk List

The final risk list is shown in Table 1. Eight high-level risks were identified, including four development risks and four mission risks. A three-level risk scale of High, Medium, and Low was used to distinguish the relative importance or level of impact. Each of the identified risks is discussed in detail in the following sections.

Table 1: Top Risks Identified

	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

4.2. Risk Details

The following sections address each risk in detail. A description of the concern is provided along with how the recommendations could mitigate these risks.

4.2.1. Risk 1

	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

How large is the atmospheric uncertainty? Current outer planet GRAMs are the best available but are based on limited data. There is also limited information available on the calculation of the uncertainties contained in the models and the magnitude of these uncertainties. There is limited or no information on spatial and temporal variability available for Neptune or Uranus. Terrestrial planets and to some degree Titan have better models. In general, however, the team put more emphasis on Neptune and Uranus in its risk assessment. A more detailed discussion of the outer planet GRAMs and the current and future status are provided in Section 4.1.1.2. Seasonal and latitude variations are particularly important for Uranus due to the high obliquity (tilt) of its axis of rotation.

Knowledge of the magnitude of the uncertainty is needed to determine whether the margin assumptions for a mission are adequate. The results of any MC analyses are only as good as the fidelity of the models and inputs assumed. Many of the papers that the team reviewed concluded that aerocapture at the outer planets is feasible for L/D ratios consistent with the blunt-body heritage (L/D~0.4) as opposed to the initial Neptune study[7] that indicated need for a larger L/D (i.e., 0.6-0.8). Atmospheric variations used in MC calculations to date are primarily based on theory; fidelity to actual variations is unknown. However, the team did not find studies that performed analysis of the sensitivity to the atmospheric profile or studies that used variations outside those provided in the outer planet GRAMs. Limited observations are available for validation of atmospheric models in the altitudes of interest to aerocapture as detailed in Section 2.2. To the team's knowledge, comparison studies on model fidelity or quantification of error estimates have not been performed for the outer planets

Cassini mission experience from planning the proximal orbit passes illustrates this concern. The intent was to choose an altitude for these passages that would stay within the attitude control capability with 100% margin ("half-tumble density"). The initial Saturn atmosphere model was based on Voyager stellar occultation and VIRS data. This data was reanalyzed in 2015. Direct observations from the Cassini Ultraviolet Imaging Spectrograph (UVIS) and radio occultation measurements resulted in an updated Saturn thermospheric model to match the new observations. Significant changes linked to the solar cycle between 2005 and 2011 were observed in the UVIS data. The in-situ measured density during the final plunge was higher than predicted, but control was maintained during the proximal orbit passes due to the large margin. Cassini experience indicates that more observations over longer time scales are needed to accurately model these gaseous atmospheres in order to avoid carrying such large margins.

4.2.1.1. Risk #1 Implications

Recent studies conclude that capabilities in aerothermal modeling, TPS, and GNC strategies have made aerocapture at Neptune more feasible[8]. Advances in GNC algorithms (i.e., Numerical Predictor-Corrector) and alternate control methodologies (e.g., Direct Force Control, Drag Modulation) indicate that trajectories can be flown with heritage blunt-body L/D configurations (~0.4). However, the Numerical Predictor-Corrector (NPC) algorithms fit the density estimation based on assumptions about other parameters (e.g., winds) since only deceleration can be directly measured during the aeropass.

Are we fooled that outer planet aerocapture can be performed with heritage configurations because we implicitly believe the models, including uncertainty? Such belief avoids an expensive development program for higher L/D configurations and enables use of the existing database and experience with the blunt-body configuration rather than the need for an extensive development program.

In order to assess this risk level and consequent mission margins, an assessment of the aerocapture sensitivity to modeling uncertainty is needed. An assessment of the pressure levels where most of the deceleration and lift occur informs the assessment of the atmospheric model uncertainties in the regions of interest as discussed in Section 4.3. Uncertainty requires that a mission carry large margins as discussed in Risk #4 (Section 4.2.3).

4.2.1.2. Current Outer Planet GRAM Status

The GRAMs are engineering-oriented atmospheric models that estimate mean values and statistical variations of atmospheric properties for numerous planetary destinations. GRAMs are frequently used toolsets and are vital in assessing effects of atmospheres on interplanetary spacecraft during the program lifecycle process. Outer planet GRAMs are currently available for Neptune, Uranus, Jupiter, and Titan. The outer planet GRAMs are included in the GRAM Suite, which is available through the NASA Software Catalog (https://software.nasa.gov/software/MFS-33888-1).

The atmospheric input data for Neptune-GRAM are from figures in *Neptune and Triton*[9] that are based on observations from Voyager radio science, Infrared Interferometer Spectrometer and Radiometer (IRIS), and the Ultraviolet Spectrometer (UVS).[10] The data consist of profiles of average, minimum, and maximum temperature values. Additional thermodynamic values have been derived from the data using hydrostatics and the ideal gas law. The data have been extended in altitude by utilizing a simple thermospheric model that includes diffusive separation. Neptune-GRAM includes a minimum-to-maximum envelope of Neptune data that contains variations of the mean with respect to latitude, season, and time of day. This envelope bounds the Neptune-GRAM estimate of uncertainty given the available data.

Neptune-GRAM includes data for total number density, number densities of hydrogen, helium, and methane, mass density, air pressure, and air temperature. Neptune-GRAM also contains a basic zonal wind model from Ingersoll et al[11]. However, as noted in the Neptune GRAM User Guide[12], "due to the lack of data at Neptune, Neptune-GRAM is not a 'global reference' model in its current form." Future versions of Neptune-GRAM will include more comprehensive data as modeling techniques improve and additional data become available.

Uranus-GRAM atmospheric input data is based on data from the Uranus Atmospheric Model developed by the NASA Ames Research Center (ARC)[13]. The ARC Uranus Atmospheric Model is based on Voyager radio science, IRIS, and UVS data from three seminal papers about the Uranus atmosphere regarding observations from the Voyager 2 flyby of Uranus that occurred on January 24, 1986[14].

Uranus-GRAM includes atmospheric density, temperature, pressure, and chemical composition data for helium, hydrogen, and methane, but does not include wind data since the winds on Uranus are currently unknown. There is evidence for significant seasonal variation in the thermal profiles (to be expected since Uranus' axis-of-rotation is nearly in its orbital plane) that are not represented in the current ARC Uranus Atmospheric Model. The ARC Uranus Atmospheric Model was created by combining the mole fraction, pressure, and density data from the three papers, which provides the information necessary to define the equilibrium atmospheric state. The Chemical Equilibrium with Applications (CEA) program was then used to calculate all of the remaining thermodynamic and transport properties contained in the ARC Uranus Atmospheric Model.

Jupiter-GRAM atmospheric input data is based on Galileo probe Atmospheric Structure Instrument (ASI) data[15]. Jupiter-GRAM includes atmospheric density, pressure, and temperature, but does not include chemical composition, a perturbation model, or wind data.

Titan-GRAM atmospheric input data is based on (1) Voyager radio science, IRIS, and UVS observations from Yelle et al.[16] or (2) Titan General Circulation Model (GCM) data from Hourdin et al[17]. and Mueller-Wodarg et al[18]. The input data utilized in Titan-GRAM depends on the input parameter chosen by the Titan-GRAM user[19]. The Voyager radio science, IRIS, and UVS data profiles provide an adequate fit (per Yelle et al.) to all three of the following sources of variations and uncertainties: (1) uncertainties in the analysis of the Voyager data, (2) estimated range of latitudinal variations in atmospheric structure, and (3) temporal changes in the atmosphere due to seasonal and diurnal variations.

Titan-GRAM includes a minimum-to-maximum envelope of Titan data that contains variations of the mean with respect to latitude, season, and time of day. This envelope bounds the Titan-GRAM estimate of uncertainty given the available data. Titan-GRAM includes Huygens Atmospheric Structure Instrument (HASI)/Doppler Wind Experiment (DWE) and Cassini Composite Infrared Spectrometer (CIRS) auxiliary profiles produced by a Titan-GRAM Comparison Study by Justh and Justus[20]. These auxiliary profiles allow Titan-GRAM to better replicate the HASI/DWE and CIRS observational data.

Releases of the GRAM Suite, upgrades of the existing outer planet GRAMs, and development of new outer planet GRAMs are continuing and are led by the GRAM Upgrade Team at LaRC and MSFC. The GRAM Upgrade Team has established a contract with JHU/APL to develop a Dragonfly atmospheric profile for use in a future Titan-GRAM upgrade. NASA LaRC is developing Jupiter, Saturn, Uranus, Neptune, and Titan global models that will provide data for use in future GRAM Suite upgrades. The GRAM Upgrade Team is aligning the outer planet GRAM upgrades with planetary mission needs and with priorities identified by the Planetary Science and Astrobiology Decadal Survey 2023-2032.

4.2.2. Risk 2

	Risk Statement	Type	Level of Risk
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

The design of a TPS for an aerocapture mission is definitely not a "one size fits all" task. TPS designs are very different depending on the destination, mission design, and aerocapture implementation. Destination dependencies include the range of entry velocities, which vary greatly for planets of very different masses, sizes, rotation rates, atmospheric composition, and atmospheric structure. Mission design dependencies involve the approach orbit circumstances (declination of the approach asymptote with respect to the equatorial plane and V_∞), and the target orbit parameters including inclination (is it prograde? polar? retrograde?), apoapsis altitude, and the desired orientation of the initial line of apsides.

The diversity of the solar system's planetary bodies results in a huge range of requirements imposed on TPS designs. "TPS mass fraction can be as low as 5% of entry mass to as high as 67% of entry mass, depending on the relative approach velocity and the reduction in velocity required.[21]" Not only do these diverse requirements affect TPS mass, they can also affect the aeroshell geometries available to implement the L/D needed for a given mission. Some aerocapture maneuver designs are possible with the well-studied, well-characterized, and flight-proven "blunt body" geometry, while others would require more exotic geometries such as the "ellipsled." This ellipsled has not been qualified for flight or even tested in wind tunnels or ballistic ranges.

The presentations and papers analyzed various Neptune mission and system designs. The designs' estimated heating rates (peak stagnation) varied over a huge range, from ~225 W/cm^2 (drag modulation[22]) to >8000 W/cm^2 (lift modulated[23]). The team assesses that the mission peak heating rate for a Neptune mission is currently limited by Heatshield for Extreme Entry Environment Technology (HEEET) testing to 4000 W/cm^2, after accommodating appropriate margin.

However, there are many unknowns regarding how different TPS materials will behave in an H_2/He atmosphere. Aerothermal (thermochemistry) analyses of TPS response in different atmospheric gas mixtures are limited and may impact TPS sizing. As an example, the Galileo Probe at Jupiter showed far more recession than predicted in an unanticipated area (on the flank near backshell) and far less recession than predicted at the stagnation point. Even current models developed 25 years later fail to accurately predict that TPS performance[24].

Minor atmospheric constituents at the outer planets, especially at the ice giant planets, complicate the picture. These constituents are not well characterized in either composition or vertical abundance profiles and may have unexpected impacts on TPS performance. The balance between radiative and convective heating is important for TPS design. That balance is strongly impacted by the atmosphere's constituents including some relatively minor ones such as the aforementioned CH_4. For example, most minor constituent interactions with carbon-based TPS materials have not been analyzed, yet radiative heat flux is known to be very sensitive to methane[25], especially in the presence of nitrogen. Carbon-based volatile species are ubiquitous in the solar system's planets and Titan. “The Spitzer/IRS spectra of Uranus show evidence for emission from CH_4, C_2H_2, C_2H_6, CH_3C_2H, C_4H_2, CO_2, and possibly CH_3” (see Figure 1). Carbon-containing species have the potential to interact with nitrogen in the atmosphere or in the heatshield. This interaction results in high radiative heating at short wavelengths (violet and UV) and can deposit heat at depth in the TPS material, causing highly inefficient spalling instead of efficient ablation of the material.

All of these unknowns will need to be characterized, and margins will need to be adjusted accordingly. If the characterization includes a large amount of uncertainty, then large TPS margins will be needed. As previously stated, large TPS margins equate directly to mass. Large TPS mass increases the structure mass needed to support the entry system. These mass increases may limit the mission assumptions regarding LV performance or limit the payload mass, decreasing the gains expected from aerocapture.

4.2.3. Risk 3

	Risk Statement	Type	Level of Risk
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

As the aerocapture mission enters formulation and the environmental requirements become more defined, there may be surprises. Although NASA may take steps to reduce the risk of the aerocapture technology, the implementation burden will fall on the project. Integrating the aerocapture technology with other elements of the mission and spacecraft design may result in unforeseen development issues. Resolving these issues will require time and money to develop engineering solutions. The aerocapture design will drive much of the environment including heating rates, heating duration, spacecraft symmetry, center-of-mass, static and dynamic loads, and mechanical packaging.

Concerns include but are not limited to:

- Packaging of the orbiting spacecraft inside the heat shield while accommodating the required thermal dissipation will require an iterative design. The spacecraft that have been packaged in a heatshield to date have been landers and atmospheric entry probes.

- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) packaging and cooling is a significant issue. It is assumed that any flagship-class mission to the outer planets will use a nuclear power source. Packaging inside the heatshield will require thermal cooling for heat dissipation in addition to operating through all mission modes. Late access for integration will also drive placement and access design.
- There is uncertainty in how much heat will need to be dissipated (see Risk #7).
- G-load mitigation may be needed for sensitive components. Static entry loads from high entry velocity are large, and the dynamic loads that result from turbulence are unknown. Initial studies assuming high arrival velocity indicate that g-loads may be on the order of 30 g's or about twice the design envelope of MSL. Instruments that have been traditionally designed for orbiters (e.g., UV spectrometers) have not been qualified to those levels. The re-qualification effort and potential redesign for these sensitive components will drive cost and schedule.
- Systems for communication over large distances including antenna design may need deployable/retractable mechanism development. Communications prior to aerocapture (during cruise) will require a fairly large antenna to achieve reasonable downlink rates. New antenna designs, mechanism designs, or duplicate (e.g., cruise and orbit) antennas may be required.
- Mechanism design for aerocapture implementation needs to be robust to entry loads and flow-field interactions. Existing separation system designs may not be adequate to handle the higher expected entry loads, and this may require a significant design and qualification effort.

4.2.4. Risk 4

	Risk Statement	Type	Level of Risk
4	If the aerocapture uncertainties are too high, then the cost ($, mass) of implementation with sufficient capability will be too high.	Development	High

An outer planet mission that relies on aerocapture will be of a mission class that is required to maintain a conservative risk posture with significant margins against uncertainties. The large uncertainty in the target atmosphere will drive mission designers to establish requirements that bound the projected uncertainties. In turn, the derived requirements on key elements of the aerocapture system will demand performance under a wide range of conditions. Specifically, large margins will be needed on TPS, control authority, heat rejection systems, and mechanism reliability. Realistic constraints on component margin likely limit the altitude target in order to ensure heating and control margin, thereby decreasing the efficiency of aerocapture. Moreover, high entry loads may drive re-qualification and/or redesign efforts of heritage systems and instruments.

Without substantial investment in uncertainty reduction, the implementation burden will fall on the project, which is unlikely to be feasible under a cost-capped, PI-led mission paradigm (e.g., New Frontiers). An extended Phase A is likely needed with potential for many design iterations. For comparison, Europa Clipper had ~2.5 years of pre-Phase A followed by a 20-

month Phase A. Mission Concept Review was held during Pre-Phase A, and the duration from KDP-A to Mission PDR was three years.

Pre-Phase A studies will likely be required to identify additional key technology developments, which will further drive cost and schedule. The potential for aerocapture technologies to reduce spacecraft mass to the outer planets may result in attempts to do too much in one mission. On the other hand, being too conservative reduces the reward for adoption of aerocapture.

All parties interviewed by the team voiced a need for relevant mission design(s) against which to evaluate the technologies and drive trade studies and design/investment decisions (as discussed in Section 2). The combination of the lack of a specific, outer planet target and the atmospheric uncertainties inherent in all outer planet targets leaves the trade space too wide-open to make effective technology investment decisions. For example, a mission to Uranus that involves capture into the plane of satellites may drive a different implementation than capturing into the ecliptic. A mission to Neptune that includes observations of Triton will drive additional orbit design requirements. The team urges the prioritization of an outer planet target such that the large atmospheric modeling uncertainties can be specifically addressed for that target.

4.2.5. Risk 5

	Risk Statement	Type	Level of Risk
5	If the aerothermodynamics of the target body are not well understood/modeled, then heat shield performance will be compromised.	Mission	High

The aerothermodynamics of the destination's atmosphere will have a significant impact on how the spacecraft interacts with the atmosphere during the aerocapture pass. If these interactions are not well understood then the heat shield design may be incorrect (e.g., not the right thickness or shape). Unexpected interactions of the heat shield with the atmosphere could lead to loss of control and not achieving the desired orbit (e.g., due to shape changes), or loss of mission (e.g., due to burn-through).

The current knowledge base for TPS behavior is primarily based on Earth's atmosphere with additional data from Mars and Venus missions (CO_2-based atmospheres). The atmospheric composition of the outer planets is very different from Earth's. Neptune and Uranus have an H_2/He atmosphere with verified carbon-based minor constituents, while Titan has a primarily nitrogen atmosphere with a small but non-trivial amount of methane that qualifies as something more than “minor.” While the outer planets also have nitrogen-bearing ammonia, that constituent is not as volatile as methane and is constrained to lower altitudes by the cold trap at the tropopause. In cases when N_2 is also present, it is possible that non-trivial quantities could be lofted to levels that an aerocapturing vehicle might reach.

Understanding the ablation behavior of the TPS is important for determining the thickness and shape of the heatshield. Post-flight analysis of the Galileo probe's heatshield performance highlighted key physics associated with H_2/He atmosphere interactions with the carbon-based TPS. Designers were surprised by observing less ablation than expected at the fore-shell stagnation point (at the nose) and significantly more ablation than expected at the fore-shell flank; only generous thickness margins prevented burn-through and loss of the mission. The post-shock environment of Galileo was almost entirely equilibrium and CH_4 was insignificant at probe altitudes, which may not be the case at the outer planets. Aerocapture at ice giants may be partially non-equilibrium, resulting in greater uncertainty in radiative heating[26].

Non-equilibrium surface chemistry for coupled ablation modeling has very limited analysis. Only one ground test has been performed in H_2/He mixture. As interest in performing aerocapture in this environment has increased, some work on understanding the chemistry has been initiated. For example, a three-year academic grant was recently awarded to Prof. Guillaume Blanquart of CalTech for theoretical modeling of shock layer radiation uncertainties.

How the surface ablates relative to the shape is also a concern as discovered in the Galileo analysis. Uneven surface ablation (nose to flank) can change the shape, impacting the L/D of the body. This potential change will need to be accommodated through margin or controller design as it changes the spacecraft dynamics.

Surface ablation can also change the surface roughness, resulting in changes from laminar flow to turbulent flow. Most entry analysis to date has assumed laminar flow. Turbulent flow can double the heating rate through "heating augmentation". The coefficient of lift changes in the different flow regimes, further magnifying any changes to the L/D. These effects have not been studied or incorporated into current analyses.

Improved coupling between Computational Fluid Dynamics (CFD) models and TPS material models is critical to accurately assessing thermal soak-back. This interaction is particularly important for aerocapture at outer planets where heat rejection is a major mission driver. Iteration between CFD and material response models is not normally done but will be critical in order to understand the performance in these various atmospheres. This iteration is not normally done for current entry missions (e.g., Mars landers) but will be critical. Attempts to perform these analyses in a traditional uncoupled approach can yield very non-physical temperatures on the surface[27].

Another important modeling advancement needed is dynamic high-fidelity CFD modeling. Traditional CFD models analyze a static configuration. Models are run for various configurations (e.g., angles-of-attack). This modeling is important to understand backshell heating. At the expected high mach numbers, the wake closure can also radiate heat to the backshell. Further, it will be necessary to understand how the forces and heating change dynamically. For example, the separation dynamics for drag modulated control (e.g., drag skirt jettison) will require significant dynamic modeling. High-fidelity CFD modeling development for dynamic modeling is in work, but current implementations are still modeling discreet points (e.g., before and after separation).

4.2.6. Risk 6

	Risk Statement	Type	Level of Risk
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

All of the various approaches to aerocapture rely on some manner of interaction with the atmosphere in order to adjust the trajectory by introducing a lift vector or adjusting the ballistic coefficient of the spacecraft during the aeropass. Understanding the atmosphere of the target body is critical toward evaluating the ability of the vehicle to execute its desired flight profile. If the needed control isn't available when expected, then the spacecraft's ability to follow the desired flight profile will be compromised. Additionally, the shape of the vehicle and its resultant flow field complicate the analysis, particularly if the angle-of-attack is modified during the aeropass.

The performance of the control actuators must be understood. The predicted performance is used in pre-flight simulations and analyses with subsequent implementation in GNC algorithms. Thruster firings behind a shock wave are difficult to model, and the resultant dynamic behavior of the vehicle may vary dramatically based on the flight regime. Articulated drag panels will also change the flow field and would need to be characterized. The separation event of a drag-modulated vehicle introduces a discontinuity that is also difficult to characterize using CFD or wind tunnel tests. In all cases, the atmosphere of the ice giants is different from our experience base in molecular composition. The entry environment will be much more severe given the greater entry velocities. Efforts to understand the differences and how those differences affect the way the spacecraft control interacts with the atmosphere are important for any progress on an outer planet aerocapture architecture. Given the uncertainty in the atmosphere, the control margin for all of these approaches will have to be expanded. It is questionable whether the control margins can be made large enough to accommodate the expanded performance uncertainties.

4.2.7. Risk 7

	Risk Statement	Type	Level of Risk
7	If the entry heating (integrated heat flux and soak-back) cannot be accommodated, then components may overheat resulting in failures.	Mission	Medium

In addition to the thermal design for steady-state conditions, the thermal design to accommodate entry heating will be a challenge that may require significant development effort. For example, heat rejection systems for an MMRTG may not be operable during entry (e.g., radiators blocked or heated, high loads prevent fluid pumping). The duration of the entry pass determines the total heat load. This duration has to be traded against peak heat flux.

Heating and subsequent thermal soak-back assessment relies on understanding of CFD and TPS material model coupling as captured in Risk 5. Once the heating and thermal soak-back are modeled, insulation and isolation of the spacecraft from the heat load may require new solutions that exceed capabilities of the heritage systems. Key components may need to be qualified to higher temperature limits. If the modeling error is too large, components may exceed their temperature limits during entry and become permanently damaged.

4.2.8. Risk 8

	Risk Statement	Type	Level of
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

Optical navigation (OpNav) is used to improve the knowledge of a body's location by identifying the body's barycenter through centroiding and the apparent diameter of the body. The body's location is typically measured relative to the background stars. Moons with well-known ephemeris (e.g., Phobos at Mars) can also be used as reference points. This type of navigation has been demonstrated for rocky bodies on missions such as Deep Impact, OSIRIS-REx, and DART. However, it is one thing to use OpNav on a solid body, and quite another thing to use OpNav on a body with an extended atmosphere. The Cassini Project initially planned to perform OpNav using Titan, but was unable to do so because of the fuzzy nature, non-sphericity, and variable nature of the high atmosphere including haze layers that could be seen at the limb but not modeled sufficiently a priori.

Precise navigation is needed for aerocapture to meet the entry corridor requirement (as discussed in Section 2.3). For planets with well characterized atmospheres (e.g., Mars), the uncertainties of the atmosphere at and below the entry interface point have been reduced to the point that radio-based navigation is a viable option for delivering the vehicle to the desired radius and flight path angle at the entry interface. In order to use OpNav for entry estimation at the outer planets, atmospheric modeling must correctly correlate the optical images to the planet barycenter and then from that barycenter to the predicted atmospheric environment at the entry location. Ideally, such a model could predict atmospheric conditions affecting the observables that OpNav uses. Those conditions could assist the OpNav software in properly assessing the limb figure and translating that assessment to a barycenter location. This modeling must be performed onboard with updates close to the time of entry due to the long distances and communications delays, resulting in the need for autonomous OpNav (AutoNav).

The observational capability necessary to verify the model input parameters, as well as to understand atmospheric behavior well enough to generate reliable predictions from the inputs, are capabilities that are not demonstrated by previous OpNav applications. It may be that the problem is too complex to allow reliably predicting atmospheric behavior (e.g., the Cassini experience), despite engulfing the problem with all of the measurements possible from the spacecraft itself, from other spacecraft, and from other ground-based and near-Earth assets. It is possible that locating the barycenter and predicting atmospheric structure near the entry site to the requisite accuracies will be beyond the current modeling capabilities.

If the OpNav system cannot locate the planet's barycenter to the requisite accuracy, then the control authority of the aerocapture guidance would have to be inflated to account for an additional uncertainty component that may be difficult to quantify. Alternatively, this scenario may introduce a new requirement on the spacecraft to not only provide optical observations for determination of its state relative to the planet, but also to observe the atmosphere for determining whether the atmosphere is behaving as predicted. An atmosphere that is significantly less dense than predicted would require some adjustment of the trajectory to deliver the spacecraft to a different flight path angle in order to avoid skip-out. It is unclear whether an onboard optical system could provide this capability with the necessary accuracy, and it will be difficult to validate the performance prior to flight.

4.3. Risk Implications by Method

Different approaches to aerocapture have varying sensitivities to the relative uncertainties. The atmospheric levels where aerocapture is most sensitive to uncertainty depend on the aerocapture technique, the profile strategy used, and the aerocapture systems' ballistic coefficient(s). The driving considerations are the pressure levels at which most of the deceleration and lift occur. Other considerations include the peak heating and total heat load on the spacecraft as determined by altitude and entry pass duration, maturity of the technology, and complexity of the implementation.

Three potential aerocapture approaches are described below along with assessment of their risk postures relative to the identified risks. All three approaches share similar risks for packaging, approach navigation, and increases to development costs. Differences in other risks are driven primarily by the mass density (altitude) at which entry occurs and the duration of the entry pass. The system heritage also drives differences in the implementation risks. Tables 2 through 4 provide a summary of the pros and cons of each method.

4.3.1. Lift Modulation (minimize total heating)

This approach uses lift modulation (Bank Angle Modulation [BAM]) to affect a flight profile that minimizes the total heat load on the TPS with entry at a relatively steep Entry Flight Path Angle (EFPA). The roll angle of the spacecraft is controlled to point the lift vector to the desired angle where the vector pointed to zenith is “lift-up.” The approach in this case is to remain lift-up modulated in order to establish level flight at a density where the aerothermal conditions are at the maximum for the heat shield rating (with margin). This approach produces maximal deceleration rates. The spacecraft is then rotated to a lift-down orientation in order to maintain flight at that density level. As the speed decreases, the spacecraft might move slightly downward to a higher atmospheric density. Onboard navigation is used to determine the discreet transition points in the entry profile. The spacecraft remains in lift-down orientation until the navigation software determines that it is time to begin the exit maneuvers. This determination is based on atmospheric parameters measured during entry that indicate the desired deceleration has been achieved. The spacecraft is then rotated to the lift-up orientation in order to perform an exit from the atmosphere.

This approach minimizes the mass of the heat shield but allows the spacecraft to descend to higher atmospheric densities where the uncertainties are greatest. This approach therefore has the highest risk level due to atmospheric uncertainty. The entry profile also results in larger deterministic (non-turbulence-induced) inertial forces and higher heating rates, thereby increasing the TPS risk and the risk of needing g-load mitigation. This approach also results in uncertainties in the post-aerocapture orbit due to larger uncertainties in important parameters of the exit state including the location of the exit and the exit FPA. These exit state parameters affect the orientation of the orbit's line of apsides and its eccentricity, both of which may require additional ΔV post-aerocapture in order to refine the orbit. However, this method has the most heritage and is the simplest to implement, which mitigates some of the development risks.

Table 2: Lift Modulation BAM Pros/Cons

Method	Pros	Cons

Lift Modulation - Bank Angle Modulation (BAM)	❖ Method demonstrated by hypersonic entry with recent experience on Mars Perseverance
	❖ Hypersonic guidance was human rated for Apollo. Many guidance techniques have been investigated and are relevant.
	❖ Leverages aerodynamic shapes and existing databases for low L/D requirements
	❖ Provides limited inclination control (< 10 deg, possibly much less)
	❖ Lowest hardware implementation complexity
	❖ Retain control authority throughout aeropass
		❖ Relies on inherent L/D of body for control authority
		    ❖ Higher L/D requirements will require new, less mature shapes and relevant testing
		❖ Slow response time to affect lift vector through roll-angle direction change using thruster control
		    ❖ Controls lift vector by rotating the entire vehicle with no control on angle-of-attack
		    ❖ Interaction between thruster plumes and flow field must be well understood.
		❖ Higher heating rates relative to drag modulation
		❖ After exit condition achieved, the non-lifting configuration could be achieved by spinning the vehicle, to average out the lift, requiring de-spin
		❖ This method has medium relative propulsive needs to compensate for delivery errors

4.3.2. Lift Modulation (optimize exit state)

This approach also uses lift modulation but uses a flight profile that optimizes the exit state and therefore optimizes the final orbit parameters. Given the slow response time of BAM, Direct Force Control (DFC) is needed to implement the continuous entry profile. Two main options for DFC are currently under study including external tabs to modulate the lift vector or an internal mechanism to dynamically offset the center-of-gravity (cg) location. The profile begins similarly to the previous case but at a less steep EFPA. The spacecraft remains primarily in lift-up orientation with the angle modulated to establish level flight at a density where the navigation software determines the highest probability of exit at the desired exit state. This determination is made through forward propagation of the exit paths from the established level flight orientation. Using the atmospheric profile sampled by entry, the navigation software computes an optimal exit path to the exit point. The navigation software also computes the associated exit path corridor (akin to the entry corridor) that ensures the vehicle's control system can guide the vehicle to the desired exit state. The lift vector is dynamically controlled to steer to that exit path corridor. The spacecraft's control system handles deviations from the pre-measured atmospheric conditions in order to maintain the optimal path.

Using this approach limits the descent to levels yielding mass densities less than those yielded by maximal deceleration, producing a less extreme heating environment and lower deterministic inertial forces. The most sensitive portion of the flight profile is at lower mass densities (i.e., higher altitudes) than the previous case. This approach therefore lowers the risk due to atmospheric uncertainty by flying higher and by providing more ability to compensate for variations in the atmosphere. This approach also provides better control of the exit state parameters and the resulting orbit (eccentricity and apsides), reducing the post-aerocapture ΔV required. However, this approach also results in a higher heat shield mass due to the higher total heat load from a longer-duration aerocapture maneuver. This higher mass therefore lowers the TPS risk while raising the heat dissipation risk. DFC implementation has not been proven and requires technical development, increasing the risk of ancillary system development.

Table 3: Lift Modulation DFC Pros/Cons

Method	Pros	Cons
Lift Modulation -Direct Force Control (DFC)	❖ Provides improved control authority via quick response time of lift vector adjustments compared to BAM ❖ Provides limited inclination and line-of-apsides control ❖ Retain control authority throughout aeropass ❖ Transitioning to no-lift configuration is achieved with zero angle-of-attack and no need to spin ❖ Provides the most accurate delivery accuracy, thereby reducing the post-aerocapture propulsion requirements to compensate for delivery errors	❖ Has not been demonstrated by US (limited demonstration by Chinese Mars lander) ❖ Additional mechanism complexity for either tab or cg control ❖ May require additional roll control ❖ Modifies the aeroshape, which will require additional aerothermal analysis downstream of the flaps that may limit the maximum L/D ❖ Aerothermal analysis downstream of the control tabs needs analysis to accurately characterize the control moments applied by the tabs at different Mach numbers and flow regimes ❖ Higher heating rates relative to drag modulation

4.3.3. Drag modulation (single jettison)

This approach uses an external appendage to provide aerodynamic control through a change in ballistic coefficient and zero lift. Spacecraft control to the target orbit is provided by the ratio of the ballistic coefficient pre- and post-jettison. A low initial ballistic coefficient (higher L/D) provides higher initial drag. Current studies have assumed a drag skirt that is either fixed or can be stowed and deployed post-launch. Other options that are still in the study phase include deployed ballutes or other deployable decelerators. The spacecraft enters at a relatively shallow EFPA, limiting the mass density of the atmosphere encountered to relatively low values (relative to lift modulation). Using the atmospheric profile sampled during entry, the navigation software estimates an optimal jettison time for the drag skirt that achieves the desired deceleration and initiates the jettison. After jettison, the spacecraft continues unguided for the rest of the flight profile until exit.

Using drag modulation limits the descent to levels with atmospheric mass densities that are considerably smaller than those of the other two cases. The most sensitive portion of the flight profile is at considerably higher altitudes where uncertainties in the atmosphere are lower, resulting in lower risk due to atmospheric uncertainty. The lower density also provides much lower heating rates, mitigating the TPS risk. However, there is no control of the orbit's line of apsides or eccentricity, both of which will add ΔV to the post-aerocapture propulsive requirements. Drag modulation implementation has not been proven and requires technical development, increasing the risk of ancillary system development.

Table 4: Drag Modulation - Single Jettison Pros/Cons

Method	Pros	Cons
Drag Modulation - Single Jettison	❖ Provides improved control authority prior to jettison (set by ratio of ballistic coefficients pre- and post-jettison) ❖ Reduces aerocapture system mass carried to orbit ❖ Simple mechanical design if fixed skirt ❖ Lowest heating rates due to higher altitude of aeropass ❖ Requires no roll control during aeropass ❖ Caveat: even a minor asymmetry could induce significant roll rates and result in a fast-spinning vehicle at exit, so may need roll rate limiters ❖ Leverages aerodynamic shapes and existing databases with zero angle of attack	❖ No control authority after jettison, so no ability to react to atmospheric variation relative to pre-jettison atmosphere and predicts ❖ Additional mechanism complexity for deployment and jettison of the skirt ❖ Larger delivery errors will require larger post-aerocapture propulsive capability to achieve science orbit ❖ No control of inclination or line-of-apsides ❖ Drag skirt non-uniformity can result in spin-up of the vehicle ❖ This method has the highest relative propulsive needs to compensate for delivery errors

5. Question 2: What architecture(s) and requirements are necessary for a tech demo to retire identified risks for various aerocapture techniques?

Many interlinked technology efforts are needed to address and mitigate the identified risks. These efforts include:

- Improved atmospheric model fidelity informed by new data or reassessment of existing data
- Aerothermal response modeling including TPS surface and flow-field chemistry, and coupled TPS material response modeling
- TPS development of rigid body (e.g., HEEET) and 3D woven (e.g., ADEPT) structure, depending on mission implementation (e.g., higher heating rates, larger structure, integrated system)
- Control actuator development and performance assessment
- TRL advancement of Numerical Predictor-Corrector (NPC) algorithms for this application
- Density estimation algorithms for control and/or jettison timing
- Verification is needed that these algorithms can be supported by current platforms (e.g., for C&DH computational resources and timing, sensor accuracy and noise)
- Autonomous Optical Navigation (AutoNav) for a gaseous planet is needed for targeting of outer planets to compensate for poor ephemeris

Some of these technologies may be addressed by a precursor probe mission as discussed in the team's recommendations. However, a probe development won't address all of the risks due to differences in the aerocapture implementation. An entry probe has only a subset of the aerocapture requirements. A probe typically has a zero angle-of-attack with a large tolerance for variability and no need for L/D control. Because there is no target exit state, navigation and control requirements are greatly reduced. A probe could provide some valuable information on TPS performance in the H_2/He atmosphere and could provide at least a single data point on atmospheric conditions deeper in the atmosphere.

Although OpNav with ground-in-the-loop has been demonstrated on several deep space missions (e.g., Stardust, OSIRIS-REx) and AutoNav was used on DART, an outer planet implementation will be more complex. Differences in hard body detection versus outer planet implementation will need assessment due to the fuzzy edge. Use of satellite occultations or stellar occultations observed from the approaching spacecraft to refine the atmospheric profile at the limb could be explored. In addition, enhanced capability to perform complex computations onboard are needed due to the long communication delays.

A technology demonstration that addresses all or even a majority of these technology developments would have to be performed at an outer planet. The atmospheric composition and dynamics are an important component of aerocapture that can't be simulated at Earth. The high arrival velocity and entry Mach numbers also can't be demonstrated at Earth. A demonstration at Mars or Venus could advance some of the aerocapture technology but would still fall short due to their differing atmospheric compositions compared to the outer planets.

6. Question 3: Would a demonstration of aerocapture using a small spacecraft in Earth's atmosphere buy-down any of those risks? If so, what data would be most beneficial to collect?

An Earth demonstration would not directly address the outer planet aerocapture risks, which are dominated by the uncertainty of the target environment. As stated in the previous section, an Earth aerocapture demonstration can't meet the high heat fluxes or entry velocities (>20 km/s) to simulate the hypersonic conditions of an outer planet entry. Demonstration missions under consideration assume a Geostationary Transfer Orbit (GTO) or Lunar rideshare opportunity, thus limiting entry velocity.

However, this does not mean that an Earth demonstration would not be valuable. An Earth demonstration could improve the integrated system TRL for aerocapture methods of Lift Modulated Direct Force Modulation or Drag Modulation. An Earth demonstration would also provide valuable data for model correlation, thereby improving model fidelity and providing more confidence in the extrapolations and scaling needed for an outer planet aerocapture. The TRL advancement and model correlations would provide substantial benefit to destinations with a well-understood atmosphere and approach velocities similar to the demonstration velocity (e.g., Mars, Venus).

Many elements of the integrated system would be demonstrated in an Earth demonstration. Candidates for demonstration include drag tab control algorithms and mechanisms, heating rate modeling, center-of-gravity (cg) change control algorithms and mechanisms, skirt stow/deploy, jettison, packaging, mechanisms, and jettison timing control algorithms (i.e., NPC algorithms). For drag modulation, a demonstration could validate dynamics modeling of the separation event. A hypersonic flight test is needed to mature ADEPT beyond TRL 5 since aeroheating and the separation event can't be adequately tested on the ground.

Through instrumentation and post-flight analysis, data for CFD and TPS model correlation would improve scaling approaches and improve confidence in extrapolation to uncertain environments. Scaling from a SmallSat to the larger interplanetary spacecraft is an important consideration. Limited studies have been done through scaled ground testing in air, but a flight demonstration would provide improved data. Concerns about laminar-to-turbulent flow regimes could be addressed. There are onboard instrumentation techniques (e.g., thermocouples and heating rates) that can determine the transitions between laminar and turbulent flow regimes

Other than the data needed to address the overall aerocapture technology development and the specifics for that demonstration, there is no additional specific data collection relative to an outer planet demonstration that would be beneficial.

7. Question 4: There are at least two fundamental concepts to control a spacecraft during aerocapture: drag modulation and lift modulation. Is one of these clearly more beneficial to demonstrate as risk reduction to the outer planets?

There is not a clear preference of implementation for an outer planet aerocapture application, primarily due to the differences in the destinations, the atmospheric environments, and the requirements for the science observations at the destination. The most direct path to obtaining some clarification to this question is to perform a comparison using the baseline mission designs described in Section 4.3. This comparison may indicate that one implementation is preferable at a specific target.

The maturity of specific technologies may also guide the selection of one technique over another. For example, a lift-modulated system will experience a more extreme thermal situation, so the maturity of thermal protection systems that can tolerate such heat rates will be a critical point of consideration. Conversely, a drag-modulated system would benefit from increased drag area in order to provide large guidance control authority margins. The maturity of deployable heatshield systems would be a critical point of consideration for the evaluation of this technique.

Finally, the choice of system may be strongly influenced by the desired target body. One technique that works well at Titan may not be the best choice for Uranus. Both architectures should continue to be pursued in order to provide more options in the mission toolbox.

8. Conclusions

The team assessed the aerocapture risks at the outer planets. It was determined that the risks are real (not just perceived), dominated by uncertainty in the destination's atmosphere and environment. It was further determined that these risks need to be mitigated before an aerocapture mission to the outer planets can be undertaken.

The relevance of Earth aerocapture demonstration missions to potential aerocapture applications at the outer planets is limited to technology advancement and model correlation, which can improve confidence in models for extrapolation in scaling.

The Earth aerocapture demonstration missions would reduce the risk of aerocapture to other solar system destinations that have well-known atmospheres where there is high confidence in scaling and model extrapolation.

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Appendix 2: Acronyms

3D	Three-dimensional
3MDCP	3D Mid-Density Carbon Phenolic
ADEPT	Adaptable, Deployable Entry Placement Technology
ADMIRE	Aerocapture Drag Modulation Integrated Rapid Explorer
ADRAT	Aerocapture Demonstration Relevance Assessment Team
ARC	Ames Research Center
ASI	Atmospheric Structure Instrument
AutoNav	Autonomous Optical Navigation
BAM	Bank Angle Modulation
C&DH	Command and Data Handling
CalTech	California Institute of Technology
CEA	Chemical Equilibrium with Applications
CFD	Computational Fluid Dynamics
cg	center-of-gravity
CIRS	Composite Infrared Spectrometer
DART	Double Asteroid Redirection Test
DFC	Direct Force Control
DWE	Doppler Wind Experiment
EDL	Entry, Descent, and Landing
EFPA	Entry Flight Path Angle
GCM	General Circulation Model
GNC	Guidance Navigation and Control
GPS	Global Positioning System
GRAM	Global Reference Atmospheric Model
GSFC	Goddard Space Flight Center
GTO	Geostationary Transfer Orbit
HASI	Huygens Atmospheric Structure Instrument
HEEET	Heatshield for Extreme Entry Environment Technology
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HST	Hubble Space Telescope
IR	Infrared
IRIS	Infrared Interferometer Spectrometer and Radiometer
IRS	Infrared Spectrometer
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KDP	Key Decision Point
LaRC	Langley Research Center
L/D	Lift over Drag
LOFTID	Low-Earth Orbit Flight Test of an Inflatable Decelerator
LV	Launch Vehicle

MC	Monte Carlo
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory
NPC	Numerical Predictor-Corrector
OPAL	Outer Planet Atmospheres Legacy
OpNav	Optical Navigation
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
PDR	Preliminary Design Review
PI	Principal Investigator
SAMWG	Saturn Atmosphere Working Group
SMD	Science Mission Directorate
SME	Subject Matter Expert
STMD	Space Technology Mission Directorate
TCM	Trajectory Correction Maneuver
TOR	Terms of Reference
TPS	Thermal Protection System
TRL	Technology Readiness Level
UV	Ultraviolet
UVIS	Ultraviolet Imaging Spectrograph
UVS	Ultraviolet Spectrometer
V_∞	V Infinity (approach Velocity)
VIRS	Visible and Infrared Scanner
WFC3	Wide Field Camera 3

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