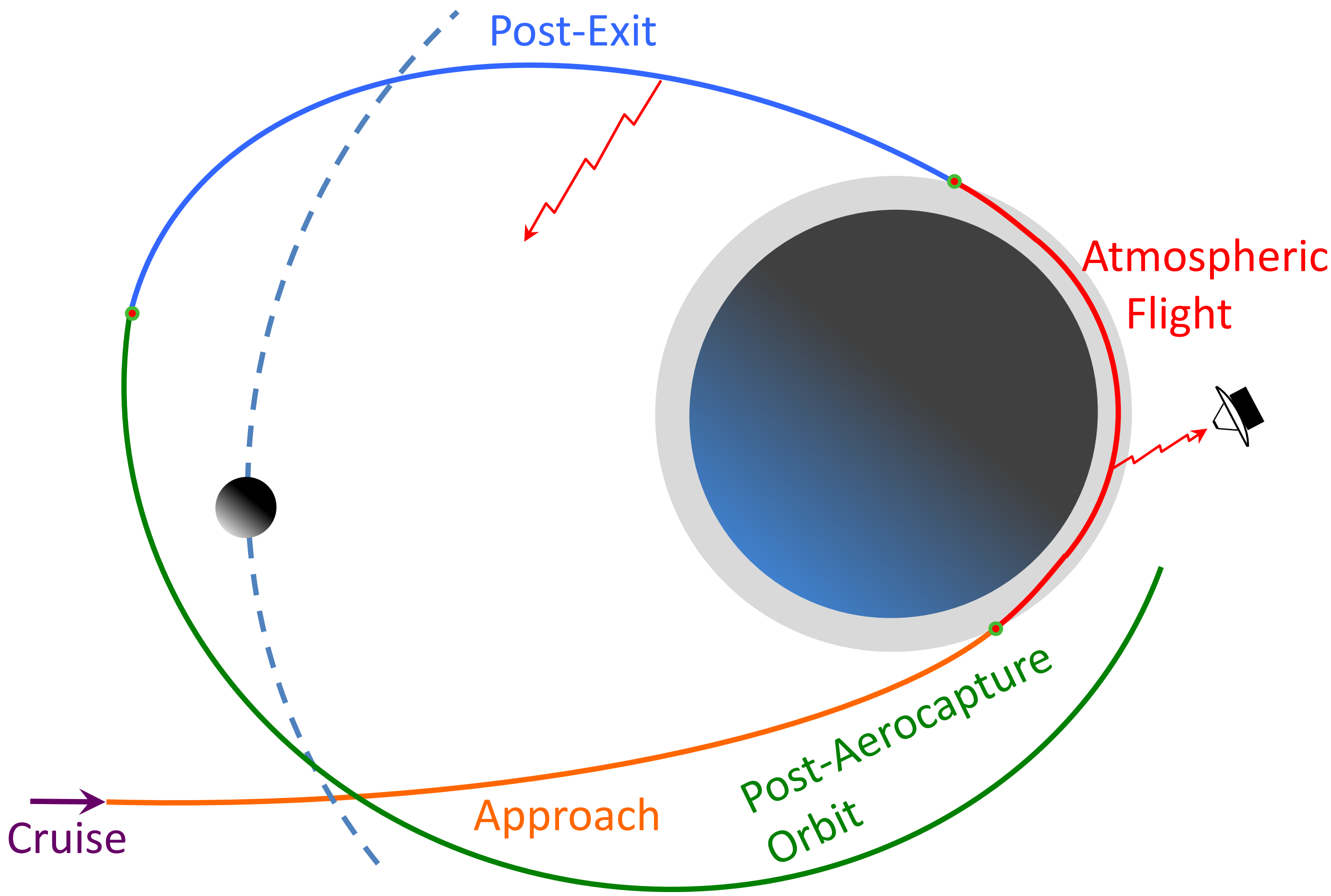

An Assessment of Aerocapture and Applications to Future Missions

February 13, 2016

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

An Assessment of Aerocapture and Applications to Future Missions

Jet Propulsion Laboratory, California Institute of Technology
for
Planetary Science Division
Science Mission Directorate
NASA

Work Performed under the Planetary Science Program Support Task

D-97058

February 13, 2016

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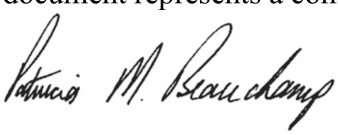
Foreword

Aerocapture has been proposed for several missions over the last couple of decades, and the technologies have matured over time. This study was initiated because the NASA Planetary Science Division (PSD) had not revisited Aerocapture technologies for about a decade and with the upcoming study to send a mission to Uranus/Neptune initiated by the PSD we needed to determine the status of the technologies and assess their readiness for such a mission. The output of this study can feeds directly into that study and thus allow the team to make intelligent trades between the available technical options. However, in order to make this a broad assessment, we did not limit the planetary destination and examined Aerocapture at multiple objects.

Participants representing all aspects of Aerocapture technologies were invited to participate in an A-team study at JPL to encourage an honest and open dialogue to assess the state of the art and determine if more work needed to be done prior to use on a mission. Those that could not attend were asked to review the initial draft document and their edits have been incorporated. This document represents a consensus from those attendees and reviewers.



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February 13, 2016

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A-Team Aerocapture Study
October 7–8, 2015

1 Introduction

Aerocapture technologies have the potential for enabling orbital missions to the outer planets and their satellites with shorter trip times than is practical when achieving orbit capture using conventional chemical propulsion. Aerocapture centers on the judicious use of aerodynamic forces in a planetary atmosphere to guide the spacecraft to a desired captured trajectory. NASA's Space Technology Mission Directorate (STMD) is investing in aeroassist technologies in response to the needs of human Mars exploration. The purpose of this study was to determine both the applicability of the STMD-developed technologies to robotic exploration and what other aeroassist technology and risk reduction investments would benefit robotic exploration, as well as assess the readiness of aerocapture technologies for potential robotic missions.

1.1 Study Goals and Objectives

The study's overarching goals were:

- Identify what technologies are needed for a future orbital mission using aerocapture
- Determine if a technology demonstration mission is required prior to its first use for a science mission

The primary study objectives were:

1. Characterize the current status of aerocapture technologies for Science Mission Directorate (SMD) missions
2. Determine NASA actions needed to ensure that proposed missions can use these technologies
    a. Determine if near- or far-term aerocapture missions need technology developments
    b. Determine these technology gaps, if any
    c. Determine the potential advantages of technologies using deployables or inflatables
3. Provide a technology roadmap to the PSD and STMD if developments are required
4. Identify the recommended path forward for NASA HQ
5. Determine if an aerocapture demonstration is required before using it for an actual science mission
6. Determine if we need more modeling and/or simulations, such as improved computational fluid dynamics (CFD) to support aerodynamic and aerothermal databases, or Monte Carlo simulations addressing system performance at Neptune

Objective 5 has two subparts: If the study's conclusion is that a flight demonstration is not required, is that conclusion a universally accepted consensus among the participants? Is the evidence for not requiring a demonstration convincing?

1.2 Study Participants and Schedule

The study was conducted at JPL on October 7 and 8, 2015 and included participants from the Jet Propulsion Laboratory (JPL), Langley Research Center (LaRC), Ames Research Center (ARC), and the Johnson Space Center (JSC). The following presentations were made on the first day of the study:

- Pat Beauchamp (JPL, study lead) – Introductory remarks
- Michelle Munk (LaRC) – Overview of current state of aerocapture
- John Elliott (JPL) – Mission needs, systems engineering
- Dick Powell (LaRC) – Vehicle Capabilities and Guidance: Comparisons from past studies (Titan vs Neptune, primarily); through improved guidance strategies, achieving with lower Lift-to-Drag ratio (L/D) vehicles the performance of higher L/D vehicles
- Ron Sostaric (JSC), via teleconference – Similarities and differences between Orion skip guidance, Mars Science Laboratory (MSL) hypersonic guidance, and aerocapture guidance; assess current guidance status, given what we have accomplished over last 10 years since the last aerocapture study
- Parul Agrawal (ARC), via teleconference – Recent Uranus study and recent analysis that demonstrates the impacts of uncertainties of atmospheric models
- Neil Cheatwood (LaRC) – Hypersonic Inflatable Aerodynamic Decelerator (HIAD) for Titan Aerocapture; benefits, assessment of readiness, gaps
- Helen Hwang (ARC) – Thermal Protection System (TPS) Capabilities: Heatshield for Extreme Entry Environment Technology (HEEET)
- Paul Wercinski (ARC) – Adaptable, Deployable Entry Placement Technology (ADEPT) for Titan, Uranus and Neptune Aerocapture; benefits, assessment of readiness, gaps

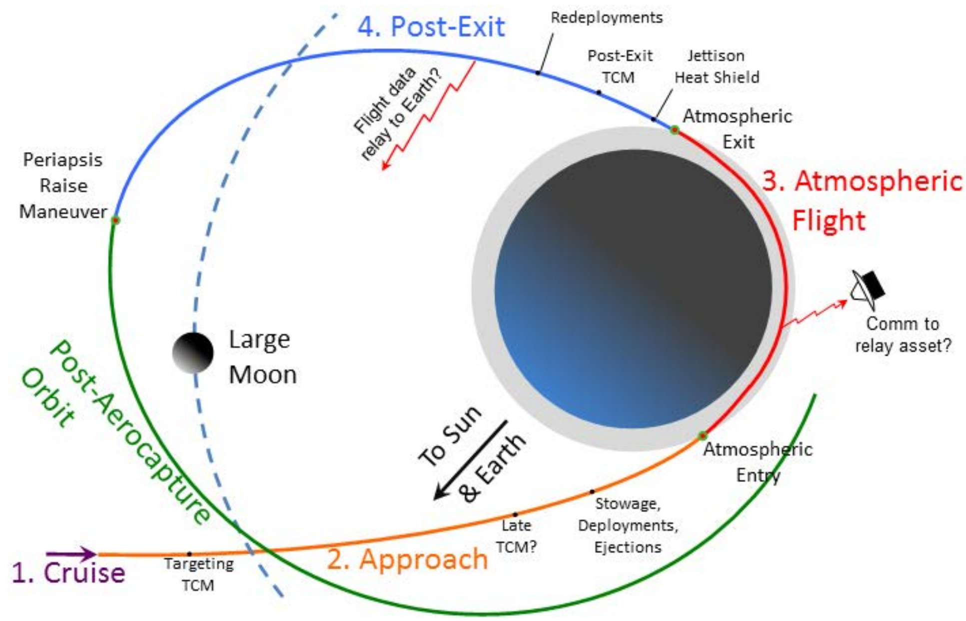
Following the presentations was a general discussion of the status of aerocapture technologies for SMD missions and what NASA needs to do to ensure that proposed missions can use the these technologies. Second day activities focused on the timeline of aerocapture activities and the risks inherent in each. Mitigations were identified for each risk. In addition, the team addressed the need for an aerocapture technology demonstration mission. The risk results and technology demonstration results are shown below in the *Primary Risks of Aerocapture* subsection of this section, and in Section 4, *Key Findings*. Prof. Bobby Braun of the Georgia Institute of Technology reviewed and edited this final report.

2 Fundamentals of Aerocapture

2.1 Aerocapture Concept and Terminology

At the simplest level, aerocapture is the judicious use of aerodynamic forces (e.g., lift and drag) generated during a vehicle's controlled flight through a planetary-sized body's atmosphere to change an unbound (hyperbolic) approach orbit into a desired bound (captured) orbit. Thus it is a means of achieving orbit insertion at the body without reliance on a propulsive maneuver, usually performed with rocket engines, for the majority of the ΔV required. The concept of aerocapture is not new [1] but has yet to be implemented on a space flight mission.

Figure 1 illustrates the profile of a typical aerocapture maneuver. It begins with a spacecraft's hyperbolic approach to its destination. During this period the operations team navigates the spacecraft to a trajectory providing an atmospheric entry within the acceptable *entry corridor*, the range of entry conditions (such as flight path angle and speed) over which the flight system can guide to an acceptable exit state. Several aspects influence establishing the entry corridor, including vehicle constraints such as maximum deceleration, navigation and approach trajectory



	Knowledge Required	Actions Required	Driving Technologies
Cruise	(nothing unique to aerocapture)	RPS waste heat rejection (if RPS is used inside aeroshell)	(nothing unique to aerocapture)
Approach	Destination gravity field, & atmospheric structure & its uncertainties	TCMs; deployments, stowage, & ejections; attitude determ'n & control; late TCM?	Restowable solar array (if used); autonomous navigation & maneuver execution for late TCM
Atmospheric Flight	Destination gravity field; atmosphere, its uncertainties, & gas dynamics; aeroshell hypersonic aero-dynamics	Autonomous navig'n (knowledge & algo-rithms) & flight path control [actuators] to exit; rejection of RPS waste heat	Aeroshells & TPS; autonomous navigation code; flight control actuators; inertial sensors
Post-Exit	Destination gravity field; satellite ephemerides	Attitude determ'n & control; autonomous exit state verific'n & TCM; reconfiguration	Spacecraft extraction frm aeroshell, redeploy; autonomous navigation & maneuver execution

Figure 1. Aerocapture maneuver sequence and fundamental functional requirements. Color-coded table rows correspond to the figure's flight phases. "Driving Technologies" are technologies central to an aerocapture maneuver.

control accuracies, and uncertainties in the destination's atmospheric structure and the aerothermodynamics of its gas mixture, and the vehicle's mass properties, aerodynamics, and TPS response. This navigation task makes use of knowledge of the planet's gravitational field and its *ephemeris*, its location in space as a function of time. As with a lander mission this likely involves late navigation measurements and trajectory correction maneuvers (TCMs), possibly done autonomously by the spacecraft. Beginning a few hours or days before entry the spacecraft performs any reconfigurations needed for entry and comes to the proper entry attitude. This might involve ejections of now-unneeded hardware, such as a solar electric propulsion (SEP) stage, deployments to provide aerodynamic force modulation, or stowage of hardware that is needed after aerocapture but that must be protected during the aerocapture maneuver.

Once sufficiently dense atmosphere is encountered the vehicle begins its atmospheric flight phase. Using knowledge of the planet's gravity field, the atmosphere's composition and density profile and their uncertainties, and inertial data from onboard sensors (e.g., acceleration and attitude), the spacecraft autonomously controls its atmospheric flight to dissipate the desired amount of energy, emerging from the atmosphere at the desired atmospheric exit point state conditions. There might be a programmatic requirement that the vehicle must report its progress and performance to Earth during this phase. In case of a catastrophic failure, critical event telecom provides the project team with data that could be key in diagnosing the failure's cause. If the atmospheric flight phase includes periods where communication to Earth is not possible because the planet occults the communication path, it might be necessary to provide a relay asset that remains outside the atmosphere, receiving the flight vehicle's data for relay to Earth , similar to the MarCO (Mars Cube One) CubeSats being used in combination with InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) at Mars. This data link has no ground-in-the-loop control duties at all. Even if communication interruptions could be reliably prevented, the time delay inherent in communications to Earth from distant destinations makes such control irrelevant. Relay of these data can be done after the fact, possibly well after atmospheric exit.

Upon atmospheric exit certain actions must be accomplished quickly. For large heat loads, the heat-soaked aeroshell must be ejected to prevent damage to the orbiter spacecraft; other ejections might be necessary as well. Navigation measurements must be made, probably autonomously, to verify the accuracy of the vehicle's exit state, and to design and execute a post-exit TCM. The closer to the planet the TCM is executed, the smaller is the ΔV required, so prompt action saves propellant mass. This TCM is particularly important if the desired exit speed is very near escape speed, as is the case in past studies of aerocaptured missions to the Neptune system [2,3]. In the relatively unlikely event that errors in the aerocapture maneuver are large enough that the actual exit speed is greater than escape speed, a TCM should be executed to reduce the orbit energy to a captured state. A post-exit TCM also can adjust the apoapsis altitude for the most efficient subsequent maneuvers to the desired science orbit, including the periapse raise maneuver (PRM), and adjust the "wedge angle" that is related to the argument of periapsis.

Other post-exit activities can occur on a somewhat less pressing time scale than the initial post-exit TCM. Any hardware stowed for the aerocapture maneuver must be redeployed, and any deployments of previously unused hardware, such as a deployable high gain antenna (HGA), might be done. During the flight from atmospheric exit to apoapsis, the spacecraft could relay to Earth more detailed data about the aerocapture maneuver's performance. Upon atmospheric exit the departure orbit has a periapsis radius that is within the planet's atmosphere. The PRM at apoapsis raises the periapsis to prevent re-entry into the atmosphere, and typically would raise it to the desired periapsis for the initial science mission orbits. For short-period post-aerocapture orbits this could be a canned maneuver. For long-period orbits, ground control might be involved. Typically, one or more subsequent propulsive maneuvers would fine-tune the initial science orbit.

If the destination body has one or more large satellites, the propulsive PRM could possibly be replaced by a gravity-assist flyby of a large satellite, designed to raise periapsis as needed, saving the propellant mass for up to hundreds of m/s of ΔV. This requires very tight control of the atmospheric flight phase and very accurate post-exit navigation and TCMs to ensure an accurate satellite flyby. Missions to bodies with such large satellites would certainly target close flybys of at least one of them, and would probably use one or more of the moons as "tour engines", using multiple planned gravity assists to effect a comprehensive "tour" of the entire system, much as the *Cassini* spacecraft is using Titan to explore the Saturn system. However, there is no fundamental requirement for the first outbound orbit leg to encounter a large moon. The PRM can be performed propulsively, in a way that allows subsequent orbital evolution and TCMs to provide a later initial satellite flyby that begins the tour. A first outbound leg encounter with a large moon could save much propellant, but that must be weighed against the increased risk.

A hybrid aerocapture/propulsive approach is a relatively new concept under consideration. This would have aerocapture provide the majority, but not all, of the ΔV needed for orbit insertion, and have a rocket propulsion system provide the remainder. An example application would be aerocapturing at Neptune to an apoapsis lower than that of the planned science orbit to avoid the accidental escape scenario, then propulsively boosting the apoapsis to the desired radius. Although currently not scheduled, future studies might determine if this technique offers potential risk or performance advantages.

2.2 Related Techniques

Aerocapture is one form of *aeroassist maneuver*, a general category that also includes such techniques as *aerobraking*, *entry*, and *aerogravity assist* maneuvers. In the past, instances of references to a maneuver that would be properly called an *aerocapture* maneuver as an *aerobraking* maneuver have led to confusion. The two are distinctly different concepts.

Aerobraking is the repeated use of a body's atmosphere to evolve a spacecraft's orbit from a larger eccentricity to a smaller eccentricity. This is accomplished over many passes through the atmosphere, with only small changes to the orbit during any single pass. Notably, unlike aerocapture, during a single aerobraking pass both the spacecraft's initial state and the final state are bound orbits at the primary, while for aerocapture the initial state is an unbound (hyperbolic) orbit that approaches from deep space. The aerobraking technique was first demonstrated in the 1990s by the Magellan spacecraft at Venus and has been used repeatedly since.

Atmospheric entry is entry into a planet's atmosphere from either a bound or unbound orbit to a fully decelerated state. There are many variants on this general concept. One is direct entry, where the entry vehicle's altitude decreases monotonically throughout the entry maneuver. This can be followed by landing on a solid or liquid surface (if the destination has one), or completion of the mission while still in the atmosphere, for instance giant planet entry probes or a Venus balloon. Another variant is "skip entry", in which the vehicle enters the destination's atmosphere and only partially decelerates, exiting and then re-entering for a final deceleration. This method is often applied to very high-energy entries, allowing both more gradual deceleration and increased landing location accuracy. Direct entry can be implemented without flight path control if the particular location of the final, fully decelerated state is not important. If that location is important and has relatively small tolerances a guided entry might be more appropriate, with navigation and flight path control during the entry and descent. This is generally regarded as a more challenging technical task than aerocapture. The Mars Science Lander, renamed "Curiosity," used guided entry to landing, including flight path control during the hypersonic phase of the entry. Skip entry, also deemed more challenging than aerocapture, has been applied in multiple cases including human missions, beginning with Apollo. NASA's Orion vehicle is designed for skip entries, with a flight test scheduled for 2017. Robotic missions have used skip entry, dating back to the Soviet Luna missions returning samples from the moon in the late 1960s and early 1970s.

Aerogravity assist uses aerodynamic forces generated during a vehicle's flight through a planetary-sized body's atmosphere (in addition to the gravitational forces the body imposes upon the vehicle) to change the vehicle's orbital energy relative to a third body. This is particularly useful at a body with a relatively weak gravitational field that cannot provide the hyperbolic bending angle needed for a near-optimal gravity assist maneuver, but with an atmosphere sufficiently thick that a vehicle passing through it can generate aerodynamic forces sufficient to achieve that increased bending angle. Unlike aerocapture, both the approach and departure orbits of an aerogravity assist maneuver are unbound with respect to the body whose atmosphere is used, so the vehicle's ultimate destination is usually elsewhere. Most examples in the literature describe aerogravity assist as a means to achieve extremely high heliocentric velocities (on the order of 50–100 km/s) or high-energy trajectories to the outer solar system [4,5], applications that would require significant advances in thermal protection system technology. But an aerogravity assist maneuver can also *decrease* a vehicle's orbital energy relative to a third body. For example, a spacecraft could use a relatively gentle aerogravity assist in Titan's atmosphere to capture into Saturn orbit. Aerogravity assist has not yet been demonstrated in flight.

2.3 Destination Dependence

One characteristic of aerocapture as a general technique is that, much like propulsive insertion, sizing of the required hardware depends upon the destination. Important characteristics include: planetary mass; atmospheric composition and structure; uncertainty in our knowledge of atmospheric structure and its variability; and uncertainty in planetary ephemerides. In our solar system the characteristics of planetary-sized bodies with usable atmospheres cover a huge range, from Mars with its relatively low mass and thin CO_2-dominated atmosphere, to massive Jupiter with its thick H_2-He atmosphere (at altitudes appropriate for aerocapture). The contrast in planetary masses leads to an order of magnitude range in atmospheric entry speeds, from as little as 5 km/s to over 50 km/s. That and atmospheric chemistry determine heating rates, radiative/convective balance, shear loads, and other entry conditions that determine important hardware characteristics such as the aeroshell geometry and the TPS material required, either of which, in extreme cases, might require technology developments; see Section 3.

Uncertainties in our knowledge of solar system atmospheres, and even planetary ephemerides, also vary significantly from body to body, and this influences approach navigation requirements and as such, the required lift and/or drag control authority of the aerocapture vehicle. Assuming the use of lift as the atmospheric flight control mechanism, aerocapture at a body such as Neptune, with a relatively poorly-constrained atmosphere model, or at a body where the body's position uncertainty means entry circumstances (e.g., entry flight path angle) are more uncertain might require more control authority than for a more well-known atmosphere and ephemeris such as Titan's.

Similarly, tighter control of drag-modulation systems is required in such cases. Destination-imposed requirements for higher performance also can influence requirements for maneuvering rates, such as rates at which bank angle, attack angle, or drag force can be changed. These requirements can influence the choice of actuators used to implement that control authority. Destination dependence is the primary source of differences in specific technology needs among potential aerocapture missions. Where technology needs are challenging there is generally more risk. This is why aerocapture at Titan currently involves less risk than at Neptune.

The significance of potential advantages of aerocapture over other orbit insertion techniques is also destination dependent. This is discussed in the following section on potential aerocapture benefits.

Despite these destination-dependent differences, aerocapture maneuvers at the various bodies have much in common. Notably, the software involved is very similar among the destinations. The primary difference in the software involves the specific inputs and models used in development of the control method. But the core guidance algorithms, the routines that navigate through the atmospheric flight phase and make autonomous decisions as to how best to achieve the desired exit state, are essentially identical for all destinations using the same guidance methods. As such, validation of the core software has general applicability: validation at one destination validates it for others. Atmospheric data coverage and uncertainties are of course destination dependent.

2.4 Potential Benefits of Aerocapture

There are three categories of potential benefits from using aerocapture instead of propulsive orbit insertion. The first is that given a particular launch vehicle, aerocapture can often deliver more payload mass to orbit at the destination. In those cases, the mass of the hardware needed for the aerocapture maneuver and ancillary propulsive maneuvers is less than the mass of propulsion hardware and propellant needed to perform the insertion entirely propulsively. This difference is available for increased science payload and spacecraft subsystems to support it.

The second category of benefits is that given a particular launch vehicle, aerocapture can reduce the trip time from launch at Earth to the destination. This arises from the fact that as a consequence of the higher V_∞ of approach that results from shortening a mission's trip time, the ΔV for orbit insertion increases. For a purely propulsive insertion the propellant mass needed for that ΔV increases quasi-exponentially with ΔV, while the mass of the hardware needed for aerocapture increases approximately linearly with ΔV. Thus for distant destinations such as Neptune, the transfer orbit from Earth can arrive with a higher V_∞ of approach that would drive an all-propulsive insertion to an impractical propellant mass, while an aerocaptured insertion could accommodate the higher ΔV with relatively modest increases in aerocapture hardware mass. In some cases, a mission could benefit from both of the first two categories, delivering more mass to orbit with a shorter trip time.

The third category of benefits is that given a fixed science payload and trajectory, aerocapture could allow launching on a less costly launch vehicle.

The magnitude of these potential benefits depends strongly upon the destination, especially the destination's heliocentric distance. Studies by NASA's Aerocapture Systems Analysis Team (ASAT) [3] indicate that the increase in delivered payload can range from about 15% at Mars, to more than 200% at Titan and Uranus, to more than 800% at Neptune. These results were for designs that emphasize the first benefit category (increased delivered mass). For Uranus and Neptune the studies assumed a time limit for the transfers from Earth to the destination. They also assumed that a propulsively inserted mission would fly the same trajectory as an aerocaptured mission and use direct delivery to the science orbit immediately after orbit insertion. A more realistic approach, not taken by the ASAT studies, would have the propulsive-only mission optimize its trajectory for propulsive insertion, possibly using a longer transfer and lower V_∞ of approach, and when possible would use gravity assists at satellites to decrease the ΔV costs of achieving the science orbits. While increasing the time required to reach the initial science orbit, this would also increase the delivered mass. A 2013 study at NASA's Ames

Research Center [6] examining the 2012 Planetary Science Decadal Survey (PSDS) atmospheric entry probe mission at Uranus was expanded to include using aerocapture for the orbiter part of that mission, and included that more realistic approach for the propulsive-only version of the mission. They concluded that the propulsively inserted version would require a launch mass that is 42% greater than the aerocaptured version, not 200% greater, but a project manager would still consider that increased payload capacity substantial. Though outer solar system missions stand to gain more from aerocapture, a Mars mission's project manager would not ignore a potential 15% increase in delivered payload capacity.

2.5 Technologies Associated with Aerocapture

Aerocapture involves many technologies, all of which are used in other aeroassist techniques such as atmospheric entry probes, guided entry, descent, and landing (EDL), and skip entry. As mentioned above, some of these technology needs are destination-dependent. For instance, any technique involving hypersonic flight in atmospheric regions where the mass density is more than a few tens of micrograms per cubic meter will involve aeroshell and TPS technologies. Aerocapture is no exception. In particular, flight control and TPS technologies needed are a strong function of the destination. At Titan, where the entry speeds can be low and the atmosphere is well characterized, current TPS materials with high flight heritage are sufficient. Also sufficient is a high-heritage, rigid, blunt-body aeroshell, or a deployable (ADEPT) or inflatable (HIAD) decelerator (see ADEPT and HIAD later in this section). At Neptune, where entry speeds might be near 30 km/s and atmosphere models carry much more uncertainty, higher-performance TPS materials are needed and the vehicle might need significantly greater control authority than possible with a rigid blunt body [2]. At any aerocapture destination a sufficiently accurate understanding of the atmosphere and its uncertainties is required. The atmospheres of some destinations, such as Uranus and Neptune, are less well characterized, and aerocapture missions there would benefit from further work on improved atmospheric models. Knowledge of an atmosphere's composition and structure (temperature, pressure, and mass density vs. altitude) as well as the hypersonic aerothermodynamics of the gas must be known, or sufficient margin added to cover the uncertainty.

In most cases the hypersonic aerothermodynamics cannot be accurately modeled by derivation from first principles or extrapolation of laboratory experiments at lower Mach numbers; it must be measured in appropriate laboratory facilities. For some destinations, such as Titan, Mars, and Venus, the hypersonic aerothermodynamics of the atmospheric gas mixtures is known to sufficient accuracy that no further aerothermodynamics experiments are needed. But for destinations with more demanding entry circumstances, such as Uranus and Neptune, laboratory experiments in previously untested flow regimes might be needed.

Depending upon the destination and need for aerodynamic lift, knowledge of the lift, drag, and ablation characteristics of a candidate geometry, including how those characteristics change with the shape change due to ablation, can be important to a successful aeroshell design. A small number of aeroshell geometries have been tested under a wide range of conditions and in flight, and are ready for use on an aerocaptured mission. The blunt-body geometry, used for a large number of atmospheric entry probes, EDLs, and human missions, is the best example of this technology. But the L/D available from that family of geometries is limited to approximately 0.4 or less. If an aerocapture maneuver requires a larger L/D, or if a blunt body will be used in a flow regime well outside the currently validated envelope, testing in an appropriate facility, such as a hypersonic wind tunnel facility, might be required. In some cases, such as atmospheric flight during aerocapture at Neptune, the conditions needed for useful tests challenge or exceed the capabilities of existing facilities.

Knowledge of an atmosphere's composition and structure, its aerothermodynamics, and vehicle hypersonic aerodynamics, is necessary but not sufficient for aerocapture maneuvers. An aerocapture vehicle's atmospheric flight must be guided and controlled from its state at any given time to an exit at an acceptable state. To do so, navigation inputs from various sensors, such as accelerometers and gyroscopes, are used to estimate the vehicle's current state, and the actual characteristics of the atmosphere. From there, an atmospheric guidance algorithm, informed by various models of the atmosphere (themselves informed by the measured characteristics), the vehicle's aerothermodynamics, its aeroshell aerodynamics, control authorities, etc., determines the best flight control sequence to the desired exit state. Currently there are three primary types of guidance algorithms: reference-based guidance routines, analytic predictor-corrector routines, and numerical predictor-corrector routines. Reference-based routines are the simplest and least computationally intensive of the three, relying on a pre-determined reference trajectory the routine attempts to maintain along the entire path. Apollo re-entries used reference-based guidance, but for demanding destinations whose atmospheres have large uncertainties they are probably too inflexible. Analytic predictor-corrector routines are more flexible in the face of an atmosphere significantly different from that expected. They are not bound to a pre-determined trajectory, but instead continuously recalculate the best flight path from the current state to the desired exit state, based on analytical models and the measured characteristics of the atmosphere already encountered. They are more computationally intensive and more accurate than reference-based routines, and are sufficient for aerocapture maneuvers. Numerical predictor-corrector routines also continuously recalculate the best flight path from the current state to the desired exit state, but they calculate full numerical solutions to the fundamental equations of motion instead of evaluating analytical models. They are the most computationally demanding and are more accurate than analytic predictor-corrector routines. This might be enabling for some of the more demanding aeroassist techniques, but not for aerocapture. If such routines were implemented onboard the vehicle, the increased accuracy would likely reduce post-exit ΔV requirements. Implementing the flight path determined by a navigation routine requires using a control technique to control the vehicle's interaction with the atmosphere.

There are multiple techniques, of varying ranges of control authority, being considered for implementing the atmospheric flight control needed for a successful aerocapture. The simplest is drag modulation (DM), wherein the vehicle generates no lift but controls its drag vs. time profile to dissipate the required amount of energy. One method for controlling the drag is to deploy a large tethered inflatable device such as a ballute that generates significant drag in relatively thin regions of the atmosphere, where dynamic heating is relatively low. Control is achieved by releasing the device when the onboard software predicts that after release the relatively small energy losses from drag on the vehicle alone, through the remaining atmospheric flight path, will yield the desired orbital energy at exit. Multi-event DM systems are possible, yielding more continuous control. Other inflatable approaches use inflatable devices secured to the vehicle instead of towed, such as NASA's experimental HIAD. Another technique under study at NASA would use non-inflated devices such as the ADEPT to control drag by altering the vehicle's effective area via geometry or attitude changes. Drag modulation methods likely are sufficient for destinations such as Titan, Venus, and Mars. Studies addressing its applicability to aerocapture at Uranus or Neptune have not yet been done. One potential advantage of DM methods for aerocapture maneuvers with relatively low heating rates (both convective and radiative) is that the vehicle might use an open backshell architecture, not fully enclosing the orbiter spacecraft. This could simplify dealing with a variety of potential issues, such as packaging constraints and science instrument availability for cruise science. This approach could be available with any of the ballute, HIAD, or ADEPT technologies.

Another flight control technique, bank angle modulation (BAM), uses lift generated by a lifting body shape at a fixed angle of attack, then controls the bank angle to provide the desired flight path. The magnitude of the lift vector is not controlled, changing only slowly in response to slowing flight speeds and ablative changes in vehicle geometry. BAM controls only the bank angle, the "clock angle" direction of the lift vector perpendicular to the vehicle's velocity vector. The onboard guidance system achieves control by turning the lift vector in either the "lift up" or "lift down" orientation, depending upon whether less dense or more dense atmosphere is needed to fly the vehicle to the proper exit position and state. If neither is needed, having the vehicle maintain a constant roll rate cancels the effect of the lift vector. Control authority is limited to some extent by the vehicle's roll-rate capability, which determines how quickly it can change the lift vector direction in response to a changing atmospheric environment. There are a variety of roll control methods possible, including external thrusters, aerodynamic actuators such as body flaps, internal mass shift, etc. NASA's Mars Science Laboratory (renamed *Curiosity*) used this technique for the hypersonic guidance phase of its precision entry to landing. The ASAT study [2] found that BAM, along with the hardware technologies available at the time, is sufficient for aerocapture at Neptune if an aeroshell with an L/D of 0.8 is available.

A third technique, direct force control (DFC), also uses lift, but actively controls the magnitude of the lift vector as well as its direction. That magnitude can be changed rapidly by changing the vehicle's angle of attack. There are various means of controlling the angle of attack, including shifting the vehicle's center of mass by internal mass movements or shifting the vehicle's center of pressure (or other aspects of its external geometry) via body flaps or other external actuators. This technique promises the highest maneuverability.

2.6 Primary Risks of Aerocapture

The study team generated a set of technical risk elements following the phases during the execution of an aerocapture maneuver in time order. Proper execution of each phase, and thus reduction of the risk involved, requires specific knowledge elements and actions. These phases, along with the required knowledge and actions, include:

- Cruise
    - Knowledge required: (nothing unique to aerocapture)
    - Actions required: rejection of Radioisotope Power System (RPS) waste heat (if RPS is inside an aeroshell)
- Approach
    - Knowledge required: destination's ephemeris and gravity field; destination's atmosphere and its uncertainties
    - Actions required: trajectory correction maneuver(s); deployments, stowage and ejections; attitude determination and control; potentially, late-stage autonomous navigation and trajectory correction maneuver(s)
- Atmospheric flight

- Knowledge required: destination's gravity field; destination's atmosphere, its uncertainties, and its hypersonic aerothermodynamics; vehicle hypersonic aerodynamics (including actuators)
- Actions required: autonomous navigation (knowledge and algorithms) and flight path control (actuators) to exit; rejection of RPS waste heat (if RPS is used inside an aeroshell); communication of flight progress and status (if required)

- Post-exit
  - Knowledge required: destination's gravity field
  - Actions required: attitude control; navigation (verification of exit state); autonomous critical reconfigurations and maneuvers; communication of detailed flight performance data

Each risk was then evaluated in light of the risk mitigation activities that are required. The methods and timing for addressing these mitigations include three general categories, listed in order from the earliest to the latest in the project development cycle:

- early feasibility and trade space analysis,
- risk reduction required prior to project start, and
- project development support (i.e., project directly funds development effort).

Table 1 below organizes these risks by their appearance in the aerocapture activity sequence and the approach recommended for addressing these risks.

Table 1. Aerocapture activities and risks organized by flight phase, with potential risk mitigations and their timing with respect to a project's schedule. Flight phase color coding corresponds to that in Figure 1.

Mission Phase, Characteristics, & Risks	Risk Mitigation Activities	Feasibility & Trade Studies	Risk Reduction prior to Project Start	Project Development Effort
CRUISE				
Heat rejection	Investigate the complexity, reliability, & lifetime of heat rejection systems	■		
APPROACH				
• Navigation errors • Need OPNAV(s)? • Late maneuvers? • Equipment failures	Determine whether OPNAV or a late autonomous maneuver is needed	■		
	Quantify flight path angle errors	■		
Deployments, stowage, & ejections				
• Mechanism failures • Environmental issues • Warming up electronics	Develop redeployables, including solar panels, if needed	■		■
Attitude determination & control	Aerocapture introduces no additional risk			■

Table 1 (cont'd). Aerocapture activities and risks organized by flight phase, with potential risk mitigations and their timing with respect to a project's schedule. Flight phase color coding corresponds to that in Figure 1.

Mission Phase, Characteristics, & Risks	Risk Mitigation Activities	Feasibility & Trade Studies	Risk Reduction prior to Project Start	Project Development Effort
Atmosphere & gravity field knowledge & uncertainty				
• Temperature, density, & pressure profiles • Composition	Increase atmosphere & rings modeling efforts	■		
	Advocate opportunistic stellar occultations	■	■	■
	Take spacecraft-based measurements on approach			■
	Send an advance scout probe			■
	Improve knowledge with Earth- & space-based observations			■
• Gravity field	Aerocapture introduces no additional risk			■
ATMOSPHERIC FLIGHT				
Survival				
• Heating • Pressure • Shear • Turbulence (including "pot holes" and buoyancy waves) • Acceleration	Establish a peak acceleration requirement	■		
	Determine CFD aerothermal model quality		■	
	Understand uncertainty on radiative heating component		■	
	Work on high-velocity physics development		■	
	Expand/build aerothermal & hypersonic turbulent flow test facilities		■	
	Develop heat shields: flexible TPS, carbon phenolic, woven TPS, deployable carbon fabric		■	
	Investigate long-term storage & protection of heat shields			■
	Analyze & test roughness effects			■
	Identify cold & micrometeoroid survival means			■

Table 1 (cont'd). Aerocapture activities and risks organized by flight phase, with potential risk mitigations and their timing with respect to a project's schedule. Flight phase color coding corresponds to that in Figure 1.

Mission Phase, Characteristics, & Risks	Risk Mitigation Activities	Feasibility & Trade Studies	Risk Reduction prior to Project Start	Project Development Effort
Flight control—knowledge & algorithms				
Vehicle aerodynamics database	Improve/expand hypersonic wind tunnel capability			
• Knowledge (attitude & initial deceleration) • In-flight guidance algorithms	Aerocapture introduces no additional risk			
Flight control—actuators				
Actuators	Determine whether anything beyond heritage hypersonic control is needed			
Flaps or other shape change	Analyze & wind-tunnel test			
CG change	Analyze & wind-tunnel test or low-cost flight test			
Deployable drag modulation through release or adjustment	Research, analyze, & wind-tunnel test for different drag conditions			
• Thrusters • Mass modulation	Aerocapture introduces no additional risk			
POST-EXIT				
• Attitude control • Critical reconfigurations & maneuvers (escape avoidance cleanup, periapsis raise) • Non-critical reconfigurations & maneuvers (additional cleanup)	Aerocapture introduces no additional risk			
Aerocapture communications (any flight phase)				
• Occultation issues • Relay asset? • Direct-to-Earth semaphores/low data rates/Doppler • Engineering performance & instrumentation data	Aerocapture introduces potential mission constraints but no additional risk			

Section 4 shows key findings regarding these aerocapture risks. In addition to these technical risks, aerocapture has faced programmatic risks for decades. This risk environment involves changing policies and priorities, and changing attitudes concerning a requirement (or not) for an end-to-end flight demonstration before implementing aerocapture for a science mission.

2.7 Relevant Demonstrations Already Accomplished

Although no aerocapture maneuver as defined above has been attempted, multiple missions have demonstrated aeroassist maneuvers directly relevant to aerocapture. In the 1960s, the Apollo 4 and Apollo 6 missions demonstrated the hypersonic navigation and control necessary for a skip-entry into Earth's atmosphere from a lunar return trajectory. These demonstrations were sufficiently successful for the Apollo Program to certify the technique *for human crews*. Successful skip-entry is a more challenging task than aerocapture. At roughly the same time, Soviet Zond spacecraft returning samples from the moon also used skip-entry successfully. More recently, in August 2012 NASA's MSL demonstrated highly accurate autonomous hypersonic guidance in the martian atmosphere to a precision landing on the martian surface, a task significantly more challenging than aerocapture. The MSL Project adopted and certified this approach with NASA approval, *without a precursor technology demonstration flight*. Finally, in October 2014 the Chinese space agency launched the Chang'e 5-T1 mission that demonstrated a skip-entry to Earth from a lunar return trajectory.

2.8 Planned Relevant Demonstrations

Further demonstrations of aeroassist maneuvers relevant to aerocapture, and end-to-end aerocapture technology demonstrations, are planned. NASA's Orion development program plans a 2017 demonstration of trajectory control under hypersonic conditions in Earth's atmosphere. A FY 2016 JPL Strategic University Research Partnership (SURP) Program grant has a joint JPL and Georgia Institute of Technology team working toward an aerocapture demonstration flight using a CubeSat-based system riding as a secondary payload on a geostationary transfer orbit (GTO) launch. After deployment it would steer itself to atmospheric entry and atmospheric flight to exit, designed to yield more than 3 km/s of ΔV in its single pass. In recent conferences representatives of the Japan Aerospace Exploration Agency (JAXA), the space exploration arm of the Japanese government, have presented fairly detailed technical plans for flying a mission demonstrating aerocapture at Mars, but with no indication of schedule [7].

3 Aspects of Aerocapture Needing Additional Research or Development

3.1 Destination Dependence

As discussed above, the technological demands imposed upon an aerocapture flight system are strongly dependent upon the destination, so the need for research or technology development is strongly dependent upon the destination as well. To avoid invalid generalizations about development needs this section treats each potential aerocapture destination in our solar system individually. The five destinations considered here are Titan, Venus, Mars, Uranus, and Neptune. Jupiter and Saturn are also potential aerocapture candidates, but the entry and atmospheric flight conditions at those planets are so harsh that aerocapture there is considered a longer-term goal. A 2012 JPL publication [8] gives much cogent information about the wide range of entry circumstances involved in these destinations. With surface pressures of only a few microbars, Triton and Pluto might be candidates for some forms of aeroassist, but with current or developing technologies aerocapture there would involve considerably more risk than other destinations.

3.2 Titan

Titan, whose N_2/CH_4 atmosphere has a surface pressure of almost 1.5 bars, has a sufficiently dense atmosphere for aerocapture. Titan's relatively low mass and unexpectedly warm middle- and upper-atmospheric temperatures contribute to large atmospheric scale heights and relatively low entry speeds, possibly as low as 5 km/s. These make Titan the least demanding aerocapture destination in our solar system. Having data from the *Huygens* probe EDL and multiple flybys by *Cassini* brushing the upper atmosphere, bolsters confidence that atmospheric models there are fairly well understood and accurate. The overwhelming consensus of this study was that current technologies can accomplish Titan aerocapture, so it would require no developments aside from the usual engineering developments common to any space flight mission. Titan is also unique in that entry conditions are so benign that the same aeroshell might be used first for an aerogravity assist into Saturn orbit for a Saturn-orbiting phase of a mission, then again for an aerocapture from Saturn orbit into Titan orbit for a Titan-orbiting phase, and yet again to deliver a Titan landing, roving, floating, or flying vehicle.

3.3 Venus

At Venus the high molecular weight atmosphere (dominated by CO_2) and Earthlike gravity yield a relatively small atmospheric scale height at altitudes relevant to aerocapture. Its heliocentric location, well inside Earth's orbit at about 0.72 AU, yields a minimum entry speed of about 11 km/s, making aerocapture at Venus more demanding than at Titan. With the wealth of data about Venus's atmosphere from multiple entry vehicles and the Magellan aerobraking campaign the uncertainties in Venus atmosphere models are relatively small, so Venus aerocapture is still within the capabilities of a blunt-body aeroshell. No new technology developments are needed, though investments in aerothermal analysis and higher-performance TPS materials could yield further increases in delivered payload mass fraction.

3.4 Mars

Mars's heliocentric location is slightly more distant from Earth than Venus's, but Mars's much smaller mass makes atmospheric entry speeds there much slower than at Venus. Mars exhibits a large range of atmospheric variability, with both time and location. Nonetheless, in the 1990s the analysis-based confidence in the reliability of aerocapture at Mars was sufficiently high that the Centre National d'Études Spatiales (CNES, the French national space agency) chose it as the orbit insertion technique for their part of a multinational Mars sample return (MSR) mission concept. The role of that orbiter would have been to rendezvous with vehicles carrying samples from Mars's surface into orbit, placing them into Earth re-entry vehicles, and returning them to Earth for re-entry and recovery of the samples. This is a very mass-intensive mission profile, so the delivered mass advantage offered by aerocapture was a significant factor in that choice. Since then data from numerous lander and aerobraked orbiter missions have refined Mars atmosphere models to the point that aerocapture at Mars into low-energy orbits is within the capability of a blunt-body aeroshell without further technology developments. Using those models, in 2012 MSL demonstrated, with a blunt-body aeroshell, accurate hypersonic guidance to a precision landing at Mars, a more difficult task than aerocapture into low-energy orbits at Mars. The Human Spaceflight Architecture Team (HAT) is considering high-energy target orbits (1–5 sol periods) from low approach speeds, a task that might require a higher level of control authority.

3.5 Uranus

Uranus is the destination for the "Uranus Orbiter with Probe" (UOP) mission, the PSDS third-ranked flagship mission for the decade 2013–2022. It is an ice giant planet of about 15 Earth masses with an atmosphere dominated by H_2 and He at altitudes relevant to aerocapture. That mass produces a deep gravity well, which results in much higher minimum entry speeds than at Titan or any of the inner planets. Its location in the solar system, at an average heliocentric radius of 19.2 AU, makes travel times from Earth an issue. Efforts to reduce trip times typically increase the V_∞ of approach, increasing atmospheric entry speeds above the minimums shown in Spilker et al. [8]. Uranus has a unique combination of traits in the solar system: a rotation rate that makes atmospheric rotation speeds significant, and an obliquity, the angular offset of the equatorial plane from the heliocentric orbit plane, of 97.7°, so its rotational poles are nearly in its orbit plane, causing significant seasonal variation in spacecraft arrival declinations. Uranus's orbit period is 84.4 years, so over a 21-year period arrival directions change from nearly pole-on to nearly equatorial.

Uranus's large heliocentric distance hinders accurate measurement of its atmospheric characteristics. To date the only spacecraft visit to the Uranus system was the *Voyager 2* flyby in 1986, providing only two closely-spaced (in time) snapshot views of the troposphere and middle atmosphere with radio occultation experiments, and lower-resolution data from infrared and ultraviolet instruments, leaving many questions and thus much uncertainty about atmospheric variability. Optical-wavelength stellar occultations provide some added information about the atmosphere at very high altitudes, but extrapolating those to altitudes relevant to aerocapture carries large uncertainties. These uncertainties in Uranus atmospheric models impose more demanding performance requirements on aerocapture there as compared to Titan and the inner planets. During its 2014 study of aeroassist missions at Uranus the ARC study team found considerable disagreement among several atmospheric models from the scientific community in the 0.1 to 1 mbar pressure levels, a region that is important for aerocapture. For study purposes the team generated their own engineering model atmosphere from a combination of the scientific models, but future work would gain from a collaborative effort between the scientific and engineering communities to improve the models.

Prospects for using aerocapture at Uranus would improve if various technology and modeling tasks are undertaken. Continued development of NASA's HEEET TPS material would address survivability under the entry conditions stemming from the high-speed entries typical at Uranus. Laboratory testing of the materials and the associated hypersonic gas dynamics would reduce flight control uncertainties and thus reduce risk. Analysis of the expected performance could determine whether or not the control authority of a rigid blunt-body aeroshell would suffice for Uranus aerocapture. If not, development of mid-L/D aeroshells would need to be done, including laboratory testing of the actual performance of candidate shapes and their robustness to ablative shape and texture change. None of these developments require a flight demonstration.

The high entry speeds characteristic of aerocapture at ice giant planets lead to anticipated packaging issues for orbiters there. Those high entry speeds make it more likely that the aeroshell will fully enclose the orbiter, i.e. will have a full backshell. Typically large spacecraft components such as high gain antennas and possibly even solar arrays will need to fit within the aeroshell during aerocapture. This drives interest in such components that are stowable and redeployable. If the orbiter's electric power subsystem is based on an RPS instead of a solar power system, packaging with a thermal subsystem such that the significant waste heat from the RPS can be rejected outside the aeroshell becomes an issue.

The technological pathway to aerocapture at Uranus is not restricted to a single narrow approach. There are multiple options for dealing with some of the more demanding aspects. For example, one option for addressing atmospheric uncertainty is to do scientific research that improves the fidelity of atmospheric models, so they better predict the conditions a vehicle would actually encounter. Another approach is to design sufficient control authority into the system to handle large uncertainties. Yet another is to send one or more small pathfinder vehicles (possibly CubeSats) ahead of the aerocapture vehicle, to sample the actual state and structure of the atmosphere and communicate that knowledge to the aerocapture vehicle. This would allow it to make pre-entry adjustments to targeting or other parameters. Studying such options would be very useful in our efforts to understand which are the most cost-effective approaches for reducing mission cost and risk.

3.6 Neptune

The PSDS "deferred" an orbital mission to Neptune to later decades, but recent NASA activities underscore the continued high levels of interest in such a mission. These activities include expressions of interest by NASA's Outer Planets Assessment Group (OPAG) and the initiation in FY2016 of ice giant mission studies at JPL. Like Uranus, Neptune's atmosphere is dominated by H_2 and He at altitudes relevant to aerocapture. Despite the outward similarities, at 17 Earth masses Neptune has a somewhat deeper gravity well than Uranus, increasing atmospheric entry speeds, and at an average heliocentric distance of 30.1 AU the trip time issue is more pronounced than for Uranus. To date the only spacecraft visit to the Neptune system was the *Voyager 2* flyby in 1989, which gave us our only high-resolution data about the atmosphere at altitudes relevant to aerocapture, and those data represent only a snapshot in time, leaving much uncertainty about its time variability. Models of it have higher uncertainties than those of Titan or the inner planets. These uncertainties might drive a need for advanced aeroshell development that is robust to ablation effects. Advanced flight control options might allow Neptune aerocapture with the lower L/D of a higher-heritage blunt body aeroshell. If analysis shows that implementing such advanced flight control is impractical for the foreseeable future, or that even with such advances a mid-L/D aeroshell is needed, research and testing in hypersonic wind tunnels is needed on candidate aeroshell geometries, to characterize their performance and to measure the sensitivity of that performance on the changes resulting from ablation. Some aspects of such a research program depend on the decision of which initial Neptune orbit option to use.

There are two very different options for the initial target orbit at Neptune, and they impact the quality of some high-priority science objectives in the Neptune system. One approach is to have the science orbit be prograde with respect to Triton's orbit, which is retrograde with respect to Neptune's rotation (inclination 157°). Such an orbit would minimize the V_∞ of approach to Triton, making the most efficient use of Triton as a tour engine and providing the best Triton science. The other approach is to make the initial orbit prograde with respect to Neptune's rotation, providing somewhat better science at Neptune and its smaller, inner moons. Aerocapture into a Neptune-prograde orbit involves atmosphere-relative entry speeds in the 23–26 km/s range. But aerocapture into a Triton-prograde orbit requires a retrograde atmospheric entry at Neptune, with atmosphere-relative speeds in the 28–30 km/s range, and this brings technological challenges. Atmospheric flight conditions for those entries involve flow speeds, heating rates, and especially a convective/radiative mix, that are beyond the range of current hypersonic facilities. Even the Neptune-prograde entry speeds are sufficiently high that aerocapture at Neptune shares with Uranus aerocapture the possible need for a fully-enclosing aeroshell, and thus spacecraft packaging could be an issue.

As is the case for Uranus, prospects for using aerocapture at Neptune would improve if various technology and modeling tasks are undertaken. Some of the tasks for Neptune push technologies and knowledge slightly farther than analogous tasks for Uranus, so completing them for Neptune meets Uranus requirements as well. TPS materials and mid-L/D aeroshells (if needed) are obvious examples. Analysis of the expected performance of various flight control approaches for Uranus and Neptune would be very similar. Also analogous to the Uranus case, the technological pathway to aerocapture at Neptune is not restricted to a single narrow approach. Studying technology options and their ramifications would be very useful in our efforts to understand which are the most cost-effective approaches for reducing mission cost and risk.

4 Key Findings

The study identified a number of key finding to help guide NASA’s plans for using aerocapture for planetary missions.

1. **An aerocapture demonstration is not needed to reduce risk prior to flight implementation.** This conclusion is the overwhelming consensus of the study participants. Multiple successful demonstrations of aeroassist techniques that are more demanding than aerocapture, by multiple nations’ space agencies, support it. See *Relevant Demonstrations Already Accomplished* under *Primary Risks of Aerocapture* above. Any flight demonstrations required would test specific subsystems; an end-to-end aerocapture demonstration would have limited utility.
2. **Within the time frame considered, aerocapture at the destinations of interest is feasible with no or modest technical developments.** No developments are needed for aerocapture at Titan, Venus, or Mars. For other destinations, continued heat shield development is needed. Depending upon the destination this would involve TPS material development or higher-L/D aeroshell development (Uranus and Neptune). With the possible exception of Neptune, heritage hypersonic guidance and control technologies may be sufficient.
3. **Aerocapture can be used at Uranus and Neptune to reduce the time of flight, bring additional science payload to the destination, and/or reduce overall mass.** Of all potential solar system destinations, the ice giant planets, with their large heliocentric distances, stand to benefit the most from using aerocapture. The benefit for other destinations, though somewhat smaller, is nonetheless significant.
4. **Trade studies and Design Reference Mission (DRM) developments are needed to determine any developments required in advance of a project.** In the light of the range of potential flight control techniques and aeroshell configuration options, these studies would better define technology requirements such as the required control authority. This might allow use of higher-heritage, lower-L/D aeroshell geometries (blunt bodies). For the widest range of applicability continued focus on low L/D blunt body shapes is appropriate, with the caveat that Uranus and Neptune might require higher performance, depending upon the outcome of DRM-based studies. Improved models of the mass requirements for aerocapture systems would increase the fidelity of these trade studies.

5. **The following would be beneficial risk mitigation activities:**
   - Update and improve atmosphere and ring models
     - Most important for Uranus and Neptune; improvements at Venus, Mars, and Titan might be enhancing but are not enabling
     - Identify opportunistic stellar occultations of Uranus and Neptune, especially using the *Kepler* spacecraft's extended mission, for improving atmosphere models
   - Quantify and constrain the complexity, reliability, and lifetime of heat rejection systems
   - Develop redeployable solar panels, if needed
   - Determine whether any techniques beyond heritage hypersonic guidance and control are needed
   - Identify potential mission constraints arising from aerocapture data capture requirements, if any
   - Determine whether late autonomous maneuvers would be needed (destination-dependent)
   - Quantify achievable flight path angle errors at Uranus and Neptune from practical approach navigation accuracies and planetary ephemeris uncertainties

5 Summary

This study conducted an extensive review of the aerocapture technique and the state of technologies needed for its implementation at multiple solar system destinations from Venus to Neptune. This included a detailed examination of the time sequence of an aerocapture maneuver, from long before the approach phase begins until a stable orbit is established, describing and evaluating the potential risks at each step. The study team's overwhelming consensus is that NASA is technologically ready to use aerocapture at Titan, Mars, and possibly Venus *now*. Notably, **no flight demonstration is needed**, a conclusion strongly supported by the fact that multiple highly successful flight implementations of aeroassist techniques significantly more challenging than aerocapture have already occurred. At all destinations considered in this study, aerocapture promises to reduce the total spacecraft launch mass and/or the trip time, or increase the delivered payload. Although the improvements are greatest for outer solar system missions, those for the inner solar system are not insignificant. As with any project, trade studies and DRM developments and studies are needed to determine which, if any, unique developments would be required in advance of project start for an aerocapture mission. The study team developed a list of beneficial risk mitigation activities for the near- to mid-term; see Finding 5 in the *Key Findings* section above.

6 Acronyms

ADEPT	Adaptable, Deployable Entry Placement Technology
ARC	Ames Research Center
ASAT	Aerocapture Systems Analysis Team
BAM	Bank Angle Modulation
CFD	Computational Fluid Dynamics
CNES	Centre National d'Études Spatiales

EDL	Entry, Descent, and Landing
GTO	Geostationary Transfer Orbit
HAT	Human Spaceflight Architecture Team
HEEET	Heatshield for Extreme Entry Environment Technology
HGA	High Gain Antenna
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
L/D	Lift-to-Drag Ratio
LaRC	Langley Research Center
MarCO	Mars Cube One
MSL	Mars Science Laboratory
MSR	Mars Sample Return
OPAG	Outer Planets Assessment Group
PRM,	Periapse Raise Maneuver
PSD	Planetary Science Division
PSDS	Planetary Science Decadal Survey
RPS	Radioisotope Power System
SEP	Solar Electric Propulsion
SMD	Science Mission Directorate
STMD	Space Technology Mission Directorate
SURP	Strategic University Research Partnership
TCM	Trajectory Correction Maneuver
TPS	Thermal Protection System

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