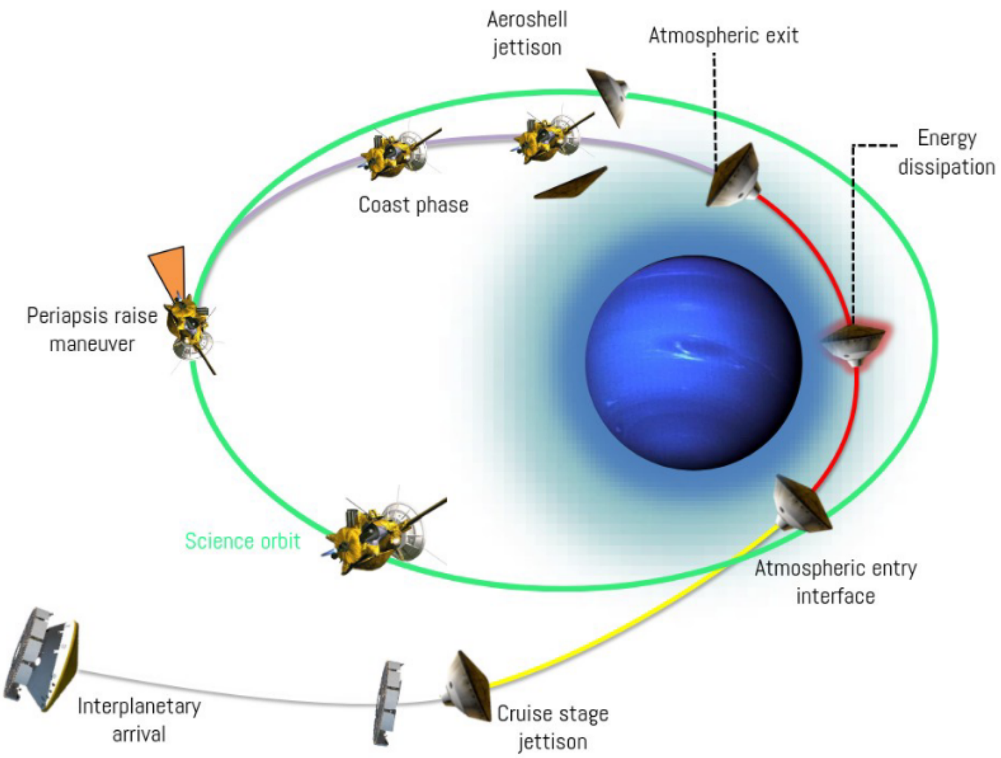
Technology Recommendations for Enabling Future Planetary Science Missions with Aerocapture

Prepared by: Dr. Athul Girija



December 31, 2023

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Technology Recommendations for Enabling Future Planetary Science Missions with Aerocapture

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Executive Summary

Aerocapture offers an efficient and near-propellantless method of orbit insertion at almost all atmosphere-bearing planetary destinations. Compared to propulsive insertion, aerocapture offers considerable savings in propellant mass which could be used to accommodate more scientific payload. To protect the spacecraft from the aerodynamic heating during the maneuver, the spacecraft must be enclosed in a protective aeroshell or deployable drag device which also provides aerodynamic control authority to target the desired post-aerocapture conditions at atmospheric exit.

For inner planets such as Mars and Venus, aerocapture offers a very attractive option for inserting small satellites or constellations into very low circular orbits such as those used for imaging or radar observations. The large amount of propellant required for orbit insertion at outer planets such as Uranus and Neptune severely limits the useful payload mass that can delivered to orbit as well as the achievable flight time. For outer planet missions, aerocapture opens up an entirely new class of short time of flight trajectories which are infeasible with propulsive insertion.

As with any space mission, aerocapture involves multiple disciplines and analyses: science, mission design, interplanetary trajectory, atmospheric guidance, navigation, and control, vehicle and spacecraft design, thermal protection system design, atmospheric models, satellite tour design, as well as programmatic, cost, and risk considerations. Aerocapture is particularly attractive for low-cost interplanetary small satellite mission concepts. This report provides recommendations for developments in each of these disciplines and aims to inform space technology policy in prioritizing investments in the development of aerocapture technology for future science missions.

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December 31, 2023

Aerocapture has been the subject of study for over six decades, since the early 1960s [1, 2]. Figure 1 shows the number of aerocapture publications, indicating that aerocapture has been investigated at every atmosphere-bearing Solar System destination over the years [3, 4]. Although it has never been flown, aerocapture continues to be the subject of research by academic and government research centers, as shown in Fig. 2. This report explores the highly interdisciplinary aspect of aerocapture missions, and provides some recommendations on future research directions.

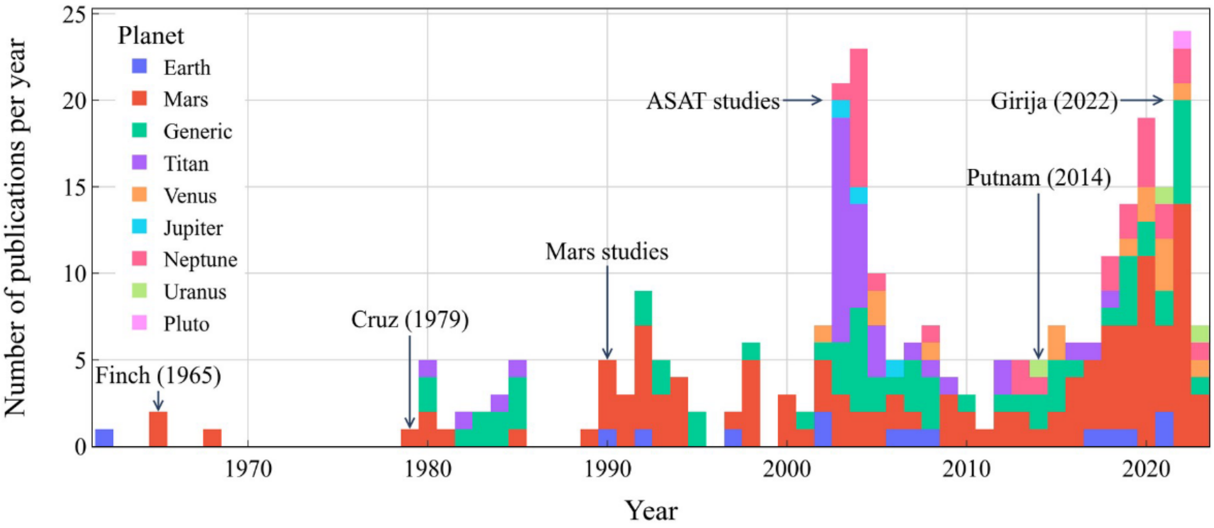

Fig. 1 Aerocapture publications over time, colored by destination.

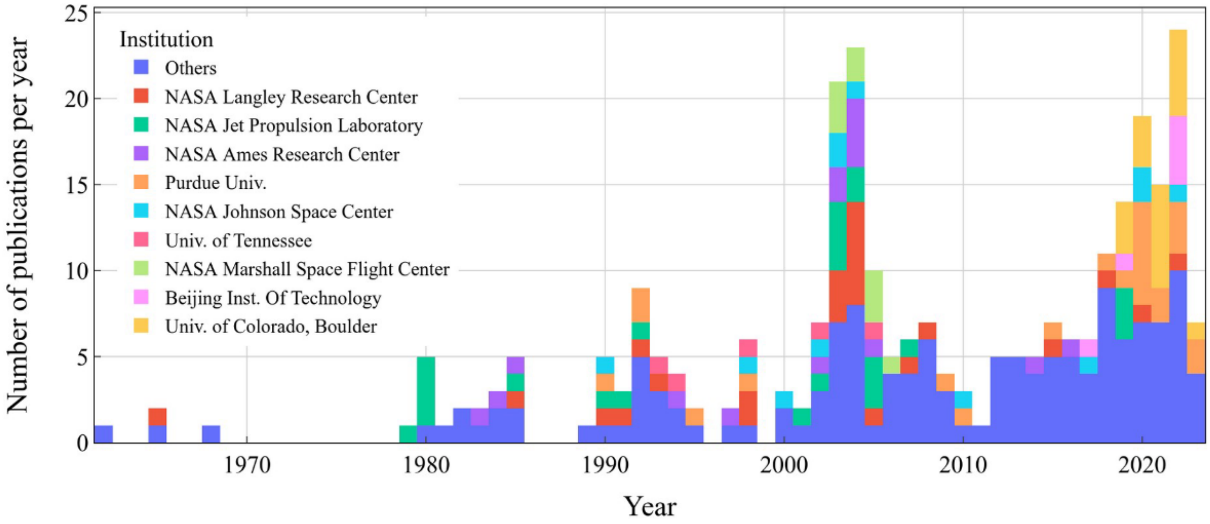

Fig. 2 Aerocapture publications over time, colored by institution.

1. Mission Design Tools

Aerocapture concepts utilize two main mission design tools: an interplanetary trajectory search software, and an atmospheric entry trajectory simulation software. The interplanetary search tool is often the starting point for any mission study. Such tools take in a set of constraints such as launch window, launch C_3, maximum time of flight, minimum hyperbolic arrival mass, maximum arrival V_∞ etc. along with a list of planetary flyby sequences to be searched for and returns a set of trajectories which satisfy these constraints. Several interplanetary search tools exist such as the Satellite Tour Design Program (STOUR) [5], JPL-STAR [6], and the Evolutionary Mission Trajectory Generator (EMTG) [7] though these tools are generally not publicly available. PyGMO and PyKEP [8] are two open source projects developed at the ESA Advanced Concepts Team.

Atmospheric trajectory simulation software start with the initial vehicle state vector at entry interface and propagates the trajectory throughout the atmospheric phase of the flight. Examples include Program to Optimize Simulated Trajectories II (POST2) [9], JPL Dynamics, Simulator for Entry, Descent and Surface landing (DSENDS) [10] software.

The Aerocapture Mission Analysis Tool (AMAT) is a dedicated tool for aerocapture trajectory analysis, and can act as a bridge between interplanetary trajectory tools and high-fidelity atmospheric trajectory codes to obtain end-to-end trajectories for aerocapture [11]. AMAT can inform initial constraint values for the interplanetary search tools such as STOUR, shortlist a set of feasible trajectories from the result catalog, perform preliminary aerocapture simulations to evaluate vehicle performance, and provide a reference initial state vector for higher-fidelity tools such as POST2.

The study recommends technology investments in the following areas with respect to preliminary mission design for aerocapture concepts:

- Compile an searchable online catalog of interplanetary trajectories to all Solar System destinations over the next several decades for a wide range of launch and arrival conditions. Hughes [12] has initiated efforts towards compiling such a trajectory catalog. An online trajectory database exists at the NASA Ames Trajectory Browser website*, though the search query parameters are quite limited. The tool returns only a limited number of

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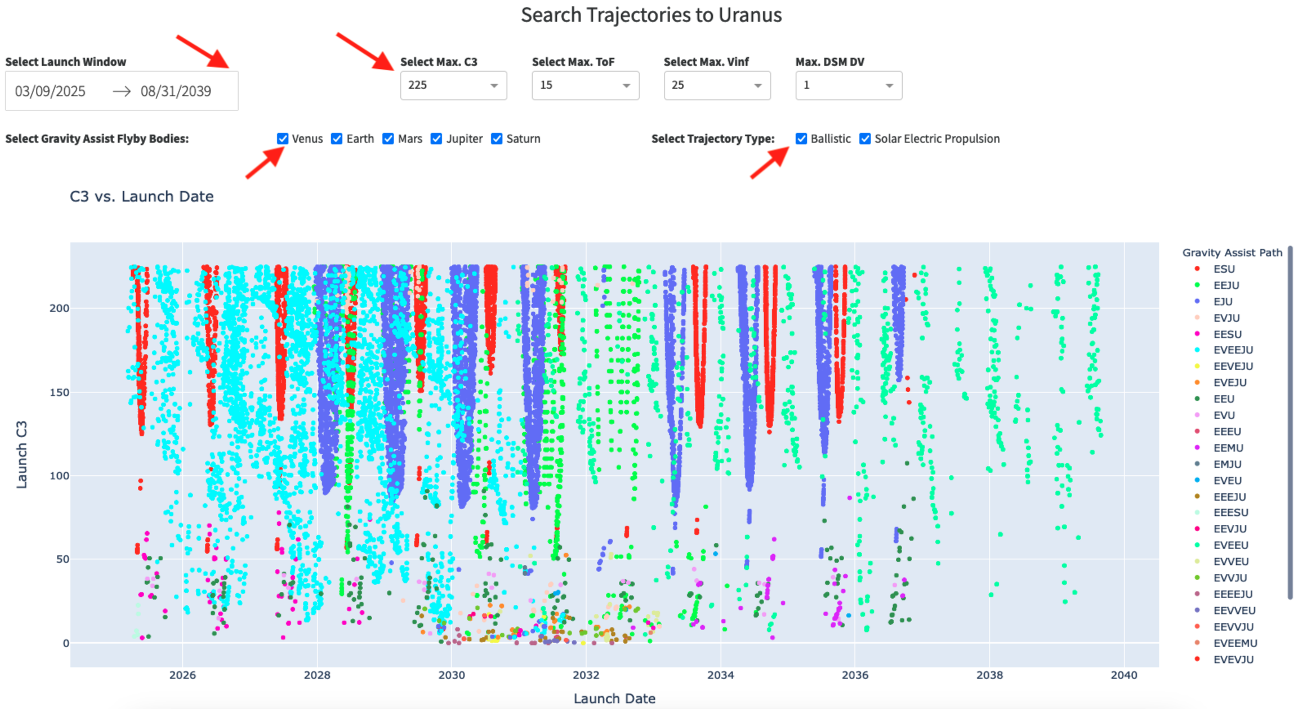
*https://trajbrowser.arc.nasa.gov/

trajectories all of which are pre-computed. A more extensive trajectory catalog which permits more query parameters and can also search for new trajectories in addition to the pre-computed trajectories will aid rapid mission design studies. Such a catalog will when combined with tools such AMAT can help identify promising aerocapture trajectories, especially for outer planet missions. A preliminary effort in this direction has been initiated with Planetary Science Mission Architecture Tool (PLASMA) pilot phase study at Purdue University [13]. Figure 3 shows the interplanetary trajectory search tool. Such interplanetary data, when combined with a launch performance tool, shown in Fig. 4 can provide quick insights into the feasible missions with aerocapture [14].

- Compile a list of promising design reference aerocapture missions to various destinations, and include aerocapture discipline experts in the early stage of mission studies to inform both the capabilities offered and risks incurred by aerocapture.



Search Trajectories to Uranus

Select Launch Window: 03/09/2025 → 08/31/2039

Select Max. C3: 225

Select Max. ToF: 15

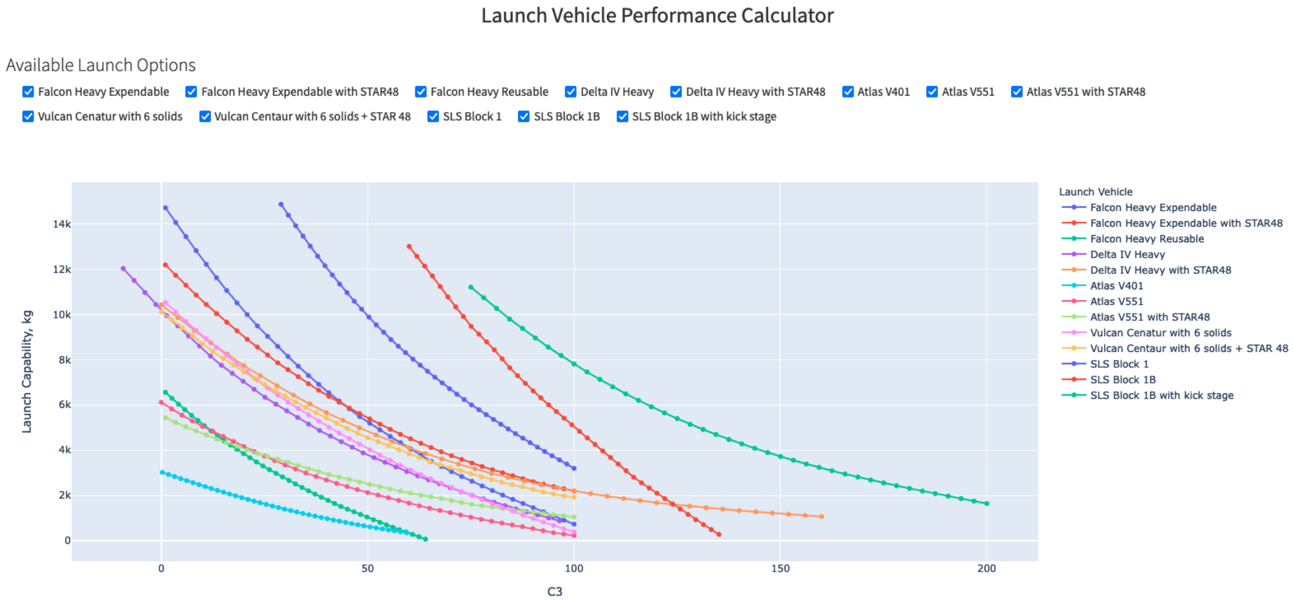
Select Max. Vinf: 25

Max. DSM DV: 1

Select Gravity Assist Flyby Bodies: ☑ Venus ☑ Earth ☑ Mars ☑ Jupiter ☑ Saturn

Select Trajectory Type: ☑ Ballistic ☑ Solar Electric Propulsion

Fig. 3 Interplanetary trajectory search tool from the PLASMA pilot phase study.


Launch Vehicle Performance Calculator

Available Launch Options

☑ Falcon Heavy Expendable ☑ Falcon Heavy Expendable with STAR48 ☑ Falcon Heavy Reusable ☑ Delta IV Heavy ☑ Delta IV Heavy with STAR48 ☑ Atlas V401 ☑ Atlas V551 ☑ Atlas V551 with STAR48
☑ Vulcan Cenatur with 6 solids ☑ Vulcan Centaur with 6 solids + STAR 48 ☑ SLS Block 1 ☑ SLS Block 1B ☑ SLS Block 1B with kick stage

Fig. 4 Launch performance from the PLASMA pilot phase study.

2. Navigation and Guidance

Two areas of particular interest to aerocapture missions are interplanetary approach navigation near the target planet and the on-board guidance algorithm which steers the vehicle during the atmospheric flight. Currently, interplanetary approach navigation is done with the ground in the loop. The spacecraft state is determined using ranging, Doppler, and optical navigation images which are transmitted to Earth, using which ground controllers determine appropriate manuevers and then command the spacecraft to perform these manuevers. For missions such as those to the outer planets, the one-way light time is substantial and hence it is not feasible to have the ground in the loop during the final days or hours of the planetary approach which are critical in determining the delivery error at atmospheric interface. NASA has been developing the AutoNav technology which automatically determines the spacecraft state (for example, using optical navigation images) and commands necessary maneuvers to achieve the desired entry conditions [15]. Spacecraft autonomy is also critical post-aerocapture, for the spacecraft to determine its capture orbit, perform propulsive burns to raise the periapsis outside the atmosphere and correct apoapsis targeting errors. The second area of interest is the development of advanced flight control methods and guidance schemes for atmospheric flight. Traditionally entry vehicles have only used bank angle modulation which gives limited aerodynamic control. In addition to the bank angle, the angle-of-attack, sideslip angle and trim tabs can be actively commanded to provide more aerodynamic control [16].

- The study recommends NASA support efforts to continue the development of AutoNav and related spacecraft autonomy technologies, particularly for outer planet missions where accurate delivery of the vehicle to the atmospheric interface and performing autonomous post-aerocapture propulsive burns are critical. Fig. 5 shows an illustration of how autonomous optical navigation using the Uranian moon system on approach to deliver the aerocapture vehicle into the entry corridor to minimize delivery error [17].

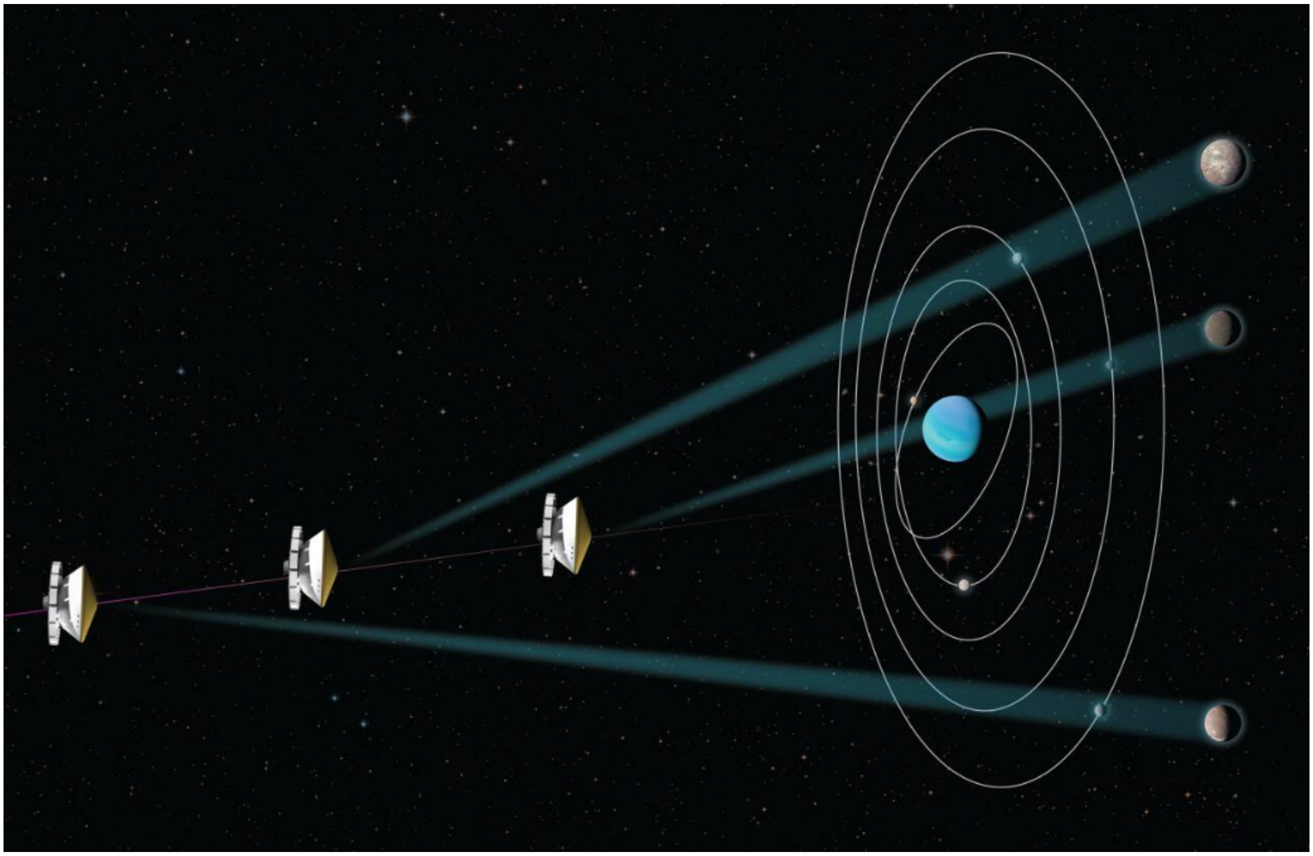


Fig. 5 Illustration of optical AutoNav for a Uranus aerocapture mission, Dutta at al. [17].

- The study recommends continued research and development in the areas of advanced flight control methods for aerocapture vehicles, and robust and reliable guidance schemes which can steer entry vehicles in uncertain atmospheric environments. Of particular interest are on-board algorithms to estimate the atmospheric density during entry, and using deep learning models to accurately predict the atmospheric exit state [18].

3. Aerocapture Vehicle Design

Derivatives of lifting entry vehicles such as MSL, Apollo, and Orion can be readily used for aerocapture missions with some modifications such as the adapting the aeroshell jettison mechanism to work outside of the atmosphere. The spacecraft design would also need to fit within the aeroshell. Recent work on Uranus aerocpature by Dutta et al. have realized orbiter configurations that can fit within the existing MSL aeroshell design as shown in Fig. 6 [17].

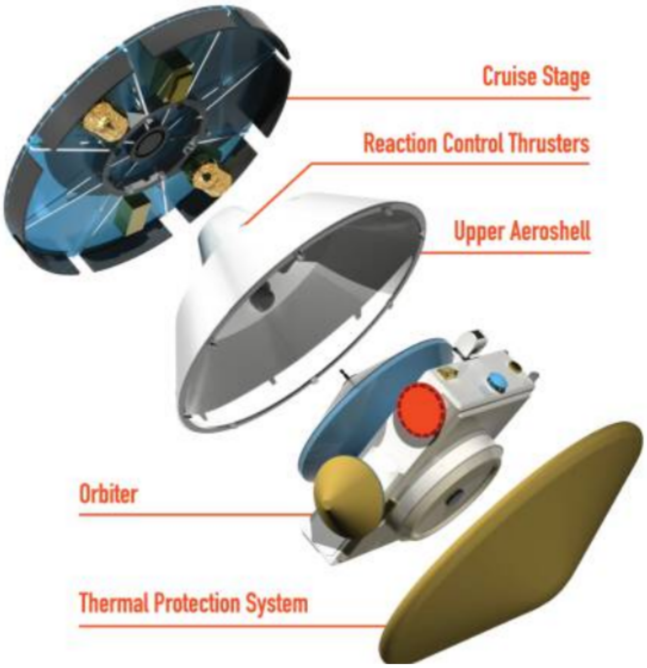


Fig. 6 Illustration of Uranus orbiter packaging in the MSL aeroshell. Dutta et al. [17].

NASA has been supporting the development of a rigid drag skirt drag modulation aerocapture flight system which could be flown to Venus, Mars, and Titan in the near term. Of particular interest for drag modulation aerocapture is the drag skirt jettison event, during which a clean separation which minimizes any risk of recontact is essential. Compared to a rigid drag skirt, a deployable drag skirt can be stowed during launch and cruise and can be deployed just before aerocapture. This minimizes the volume footprint, particularly for rideshare satellites on the host spacecraft. Additional studies are required to understand the separation dynamics and recontact risk for deployable drag skirts in hypersonic flight. Figure 7 shows experimental results from wind tunnel tests to understand the separation dynamics of aerocapture drag skirts [19].

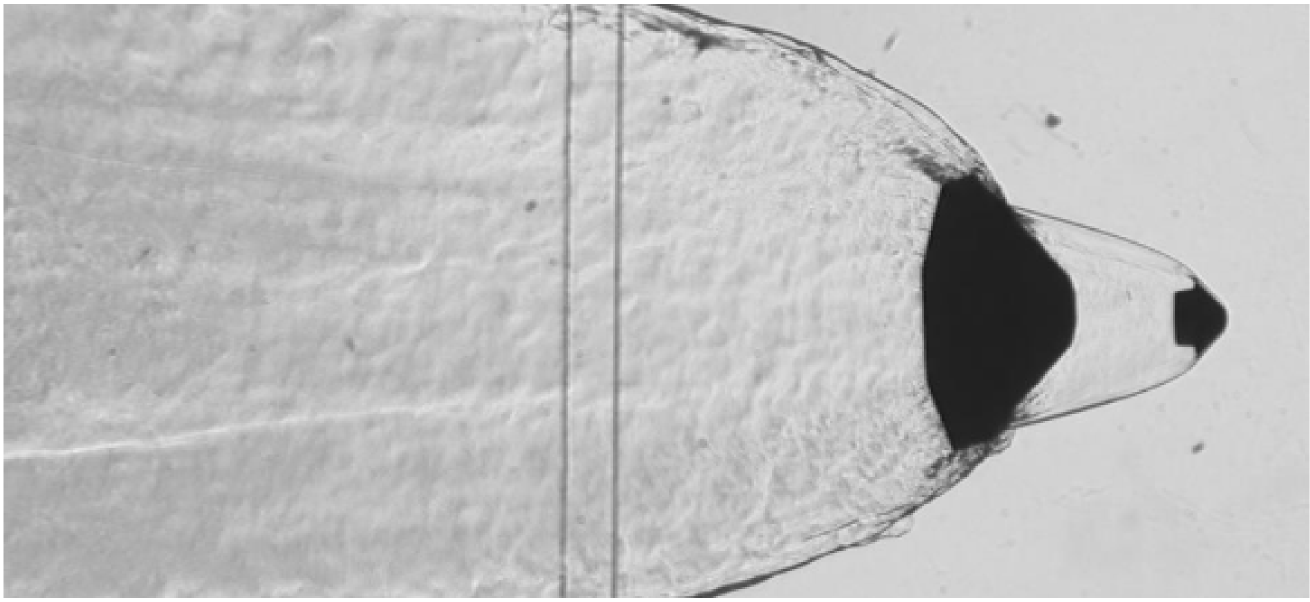


Fig. 7 Shadowgraph image of scale drag skirt separation in wind tunnel test. Wilder et al. [19]

It is anticipated that both rigid aeroshells and deployable skirt aerocaptuee vehicles will use accelerometer data to construct a real-time atmospheric density profile during the descending leg of aerocapture is of significant interest for aerocapture. Advanced and efficient on-board data processing algorithms are required to denoise the data and reconstruct a near real-time atmospheric profile during the maneuver for use by the guidance algorithm in apoapsis targeting.

- The study recommends continued NASA support for computational and experimental efforts to realize a feasible small satellite drag modulation aerocapture flight system which minimizes risk of recontact and ensure a clean separation.
- The study recommends support for efforts to realize a deployable drag skirt for drag modulation aerocapture which could enable CubeSat sized rideshare interplanetary spacecraft to achieve orbit insertion at Mars, Venus, and Titan.
- The study recommends the continued development of advanced on-board data processing algorithms to denoise the accelerometer data and construct a real-time atmospheric profile for accurate post-aerocapture orbit targeting in unceratain atmospheres.

4. Thermal Protection Systems

Existing flight-proven thermal protection system materials such as PICA are sufficient for aerocapture at Mars, Titan, and Uranus [20, 21]. HEEET is the another candidate TPS for aerocapture at Uranus and Neptune, and has been tested under laboratory conditions for these entry environments. However due to facility limitations, often the combined effect of stagnation-point heat rate and stagnation pressure is difficult to replicate. Computational models can complement such parameter regimes where experimental testing is difficult or cost prohibitive. Figure 7 shows the representative TPS requirements for lift and drag modulation mission concepts [22].

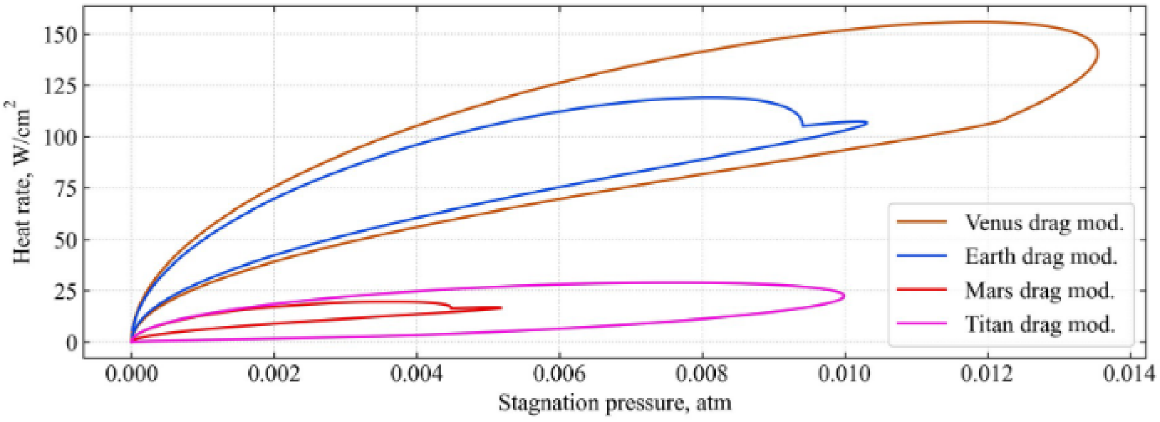


Figure 11. TPS requirements for drag modulation aerocapture.

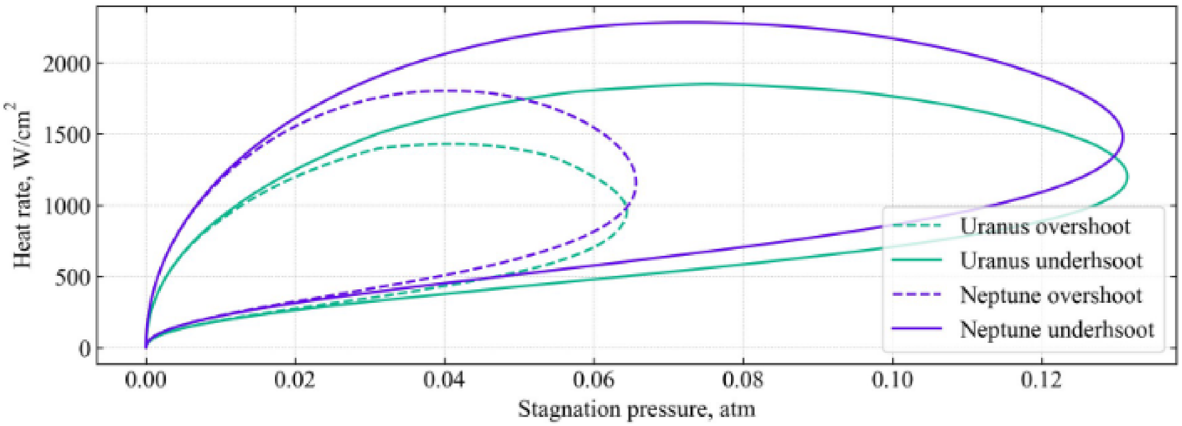


Figure 12. TPS requirements for lift modulation aerocapture at Uranus and Neptune.

Fig. 8 Representative thermal protection requirements for aerocapture missions.

Drag modulation aerocapture systems using PICA TPS are well understood and require no additional developments. However, deployable drag skirts using materials such as carbon cloth can benefit from additional modeling and arc jet testing efforts. Figure 9 shows the arc-jet testing of woven carbon cloth TPS for ADEPT. Aerothermodynamic environments at the ice giant planets are the most challenging due to the relatively high entry speeds (20–30 km/s). No accurate sizing relations are available to estimate the TPS mass fraction for aerocapture at these destinations, and presents a major challenge for conceptual studies. The study recommends NASA support the following efforts for advancing TPS technology for aerocapture missions:

- Perform computational studies to assess the aerothermodynamic environment for aerocapture at Uranus and Neptune, and refine empirical relations for computing heat rates, and TPS mass fraction to better predict the mass benefit offered by aerocpature.
- Support development efforts to realize a deployable and jettisionable drag skirt which serves as both the structure and TPS for a drag modulation aerocapture flight systems.
- Models to estimate the cost of small deployable TPS systems to be incorporated into small satellite mission planning for Mars and Venus rideshare opportunities.

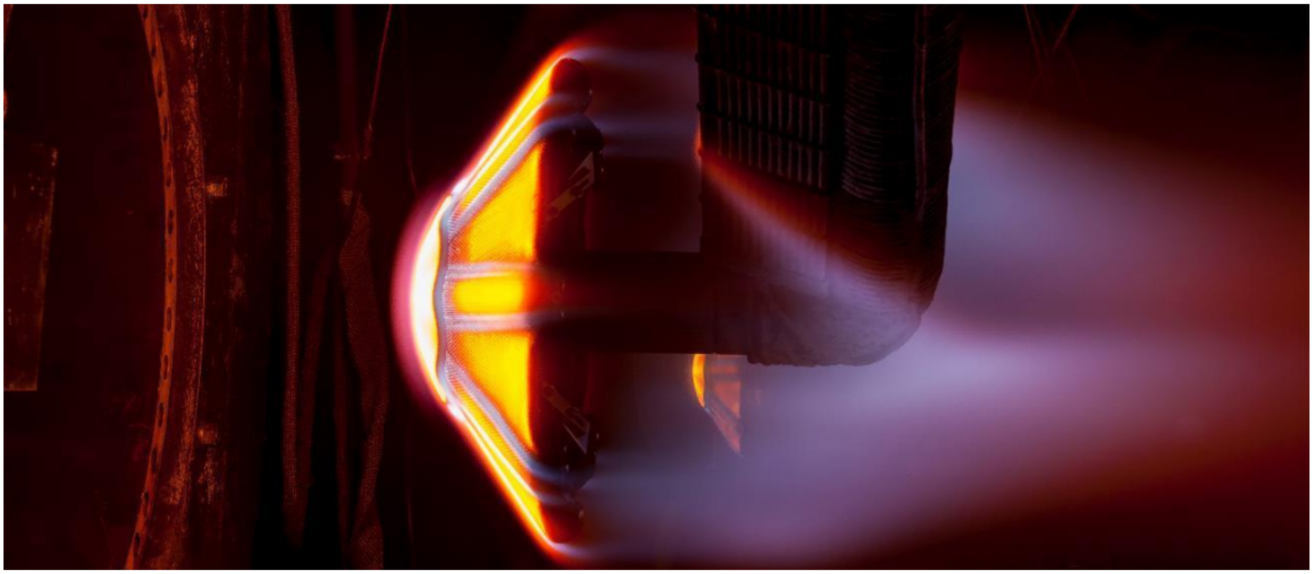


Fig. 9 Arcjet testing of Woven Carbon Cloth which could be used for drag modulation aerocapture [23].

5. Spacecraft and Probe Design

The fact that the spacecraft needs to be enclosed in an aeroshell for lift modulation aerocapture (and at least partially for drag modulation aerocapture) will be a design driver for the spacecraft. Prior to the aerocapture maneuver, an MSL-like cruise stage may provide communications and propulsion capability for the spacecraft which is inside the aeroshell. Four outer planet missions, the spacecraft almost certainly will carry an entry probe which either needs to be accommodated inside the aeroshell and be released post aerocapture, or mounted externally and be released prior to the main spacecraft performing aerocapture. Recent studies by Dutta et al. [17] have chosen to carry the probe inside the aeroshell and deploy it after orbit insertion, as shown in Figure 10.

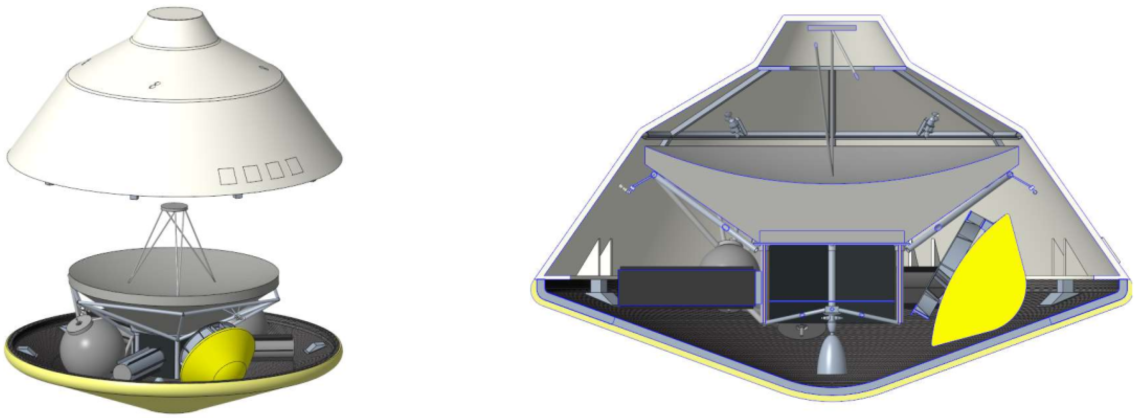


Fig. 10 Packaging of aerocapture orbiter and probe inside the aeroshell. Dutta et al. [17].

After the aerocapture maneuver, the heat soaked aeroshell must be jettisoned immediately and the spacecraft must activate its deployables such as antennae, instruments, and sensors so as to obtain attitude control and orbit determination. The spacecraft must also almost immediately prepare for the periapsis raise and apoapsis correction burns (likely autonomous). The study recommends the following technology developments for aerocapture spacecraft and probe design:

- Perform studies to better understand the operational requirements for the spacecraft immediately after aerocapture such as the time constraints for heat shield and aeroshell jettison, antenna deployment, detumbling and attitude stabilization, orbit determination, preparation for propulsive burns to establish a stable initial capture orbit, and report critical telemetry to ground stations.

6. Atmosphere Models

To the extent required for aerocapture, the atmospheres of Venus, Mars, and Titan are well constrained and do not require any advances over the GRAM models [24]. Our knowledge is most lacking for Uranus and Neptune, whose atmospheres have large uncertainties as a result of the lack of any in situ measurements, and the mission design must accommodate large uncertainties [25].

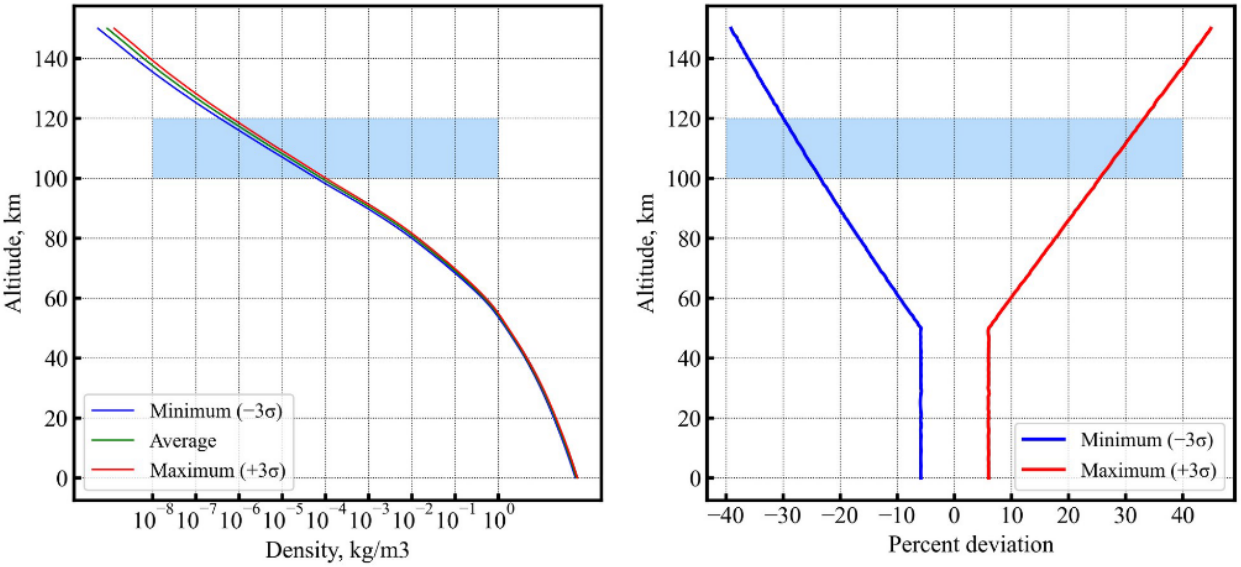


Fig. 11 Nominal min-max atmospheric uncertainties at Venus.

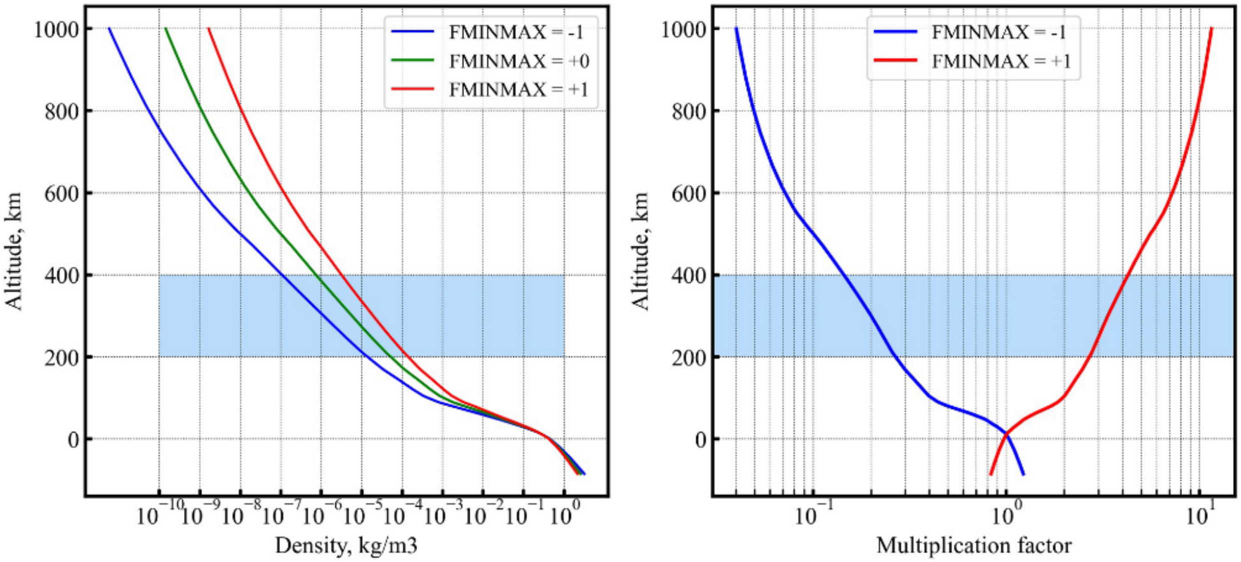


Fig. 12 Nominal min-max atmospheric uncertainties at Neptune.

Large atmospheric model uncertainties impose more aerodynamic control demands on the aerocapture vehicle to allow the vehicle to compensate for these uncertainties during the maneuver. If the control variable becomes saturated and the vehicle is not able to achieve the desired exit conditions, the spacecraft risks not getting captured and will lead to an almost certain loss of mission. The large atmospheric uncertainties remain one of the major hurdles for aerocapture at the ice giants. Since in-situ measurements are not forthcoming until a probe enters their atmosphere, remote sensing observations using telescopes and opportunistic stellar occultation measurements for Uranus and Neptune remain the only way to probe these atmospheres and provide constraints for engineering models as shown in Fig. 13. The study recommends the following technology efforts:

- Provide continued support for GRAM model development and upgrades, incorporating new datasets into models for Venus, Mars, and Titan from recent missions.
- Support efforts to use Earth and space-based telescopes, and opportunistic Earth-based stellar occultations for observations of the atmospheres of Uranus and Neptune.

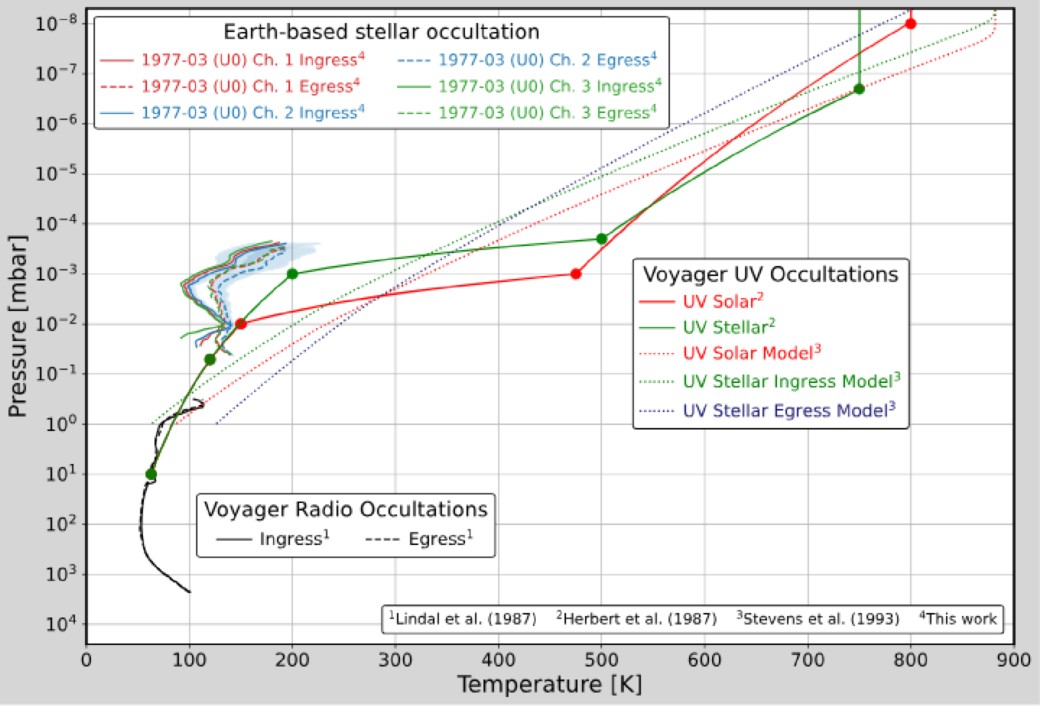


Fig. 13 Uranus stellar occultation results. (Saunders et al. [26])

7. Satellite Tour Design

Once captured into orbit, missions such as those to the Saturn-Titan system or the Neptune-Triton system will use planetary moon flybys to change the orbit without using propellant. Such targeted moon flybys will allow close observations of various latitudes and longitudes on both the moon and the planet as demonstrated by the Galileo and Cassini missions. Specialized tools such as Mystic Low-Thrust Trajectory Design and Visualization Software are available for designing and optimizing moon tours. The initial orbit for aerocapture has to be selected considering the orbit requirements for such tours. The selection of a prograde vs. retrograde orbit at Neptune has important implications for the subsequent Triton tour and vehicle aerothermal loads. A retrograde orbit minimizes the Triton relative flyby speed, but results in much higher planet relative entry speed and aerothermal load compared to a prograde entry. Satellite tours are of particular interest for missions to the Saturn, Uranus, and Neptune where there is significant scientific interest for the spacecraft to perform close targeted flybys of the satellites and rotate the orbital plane to access new regions.

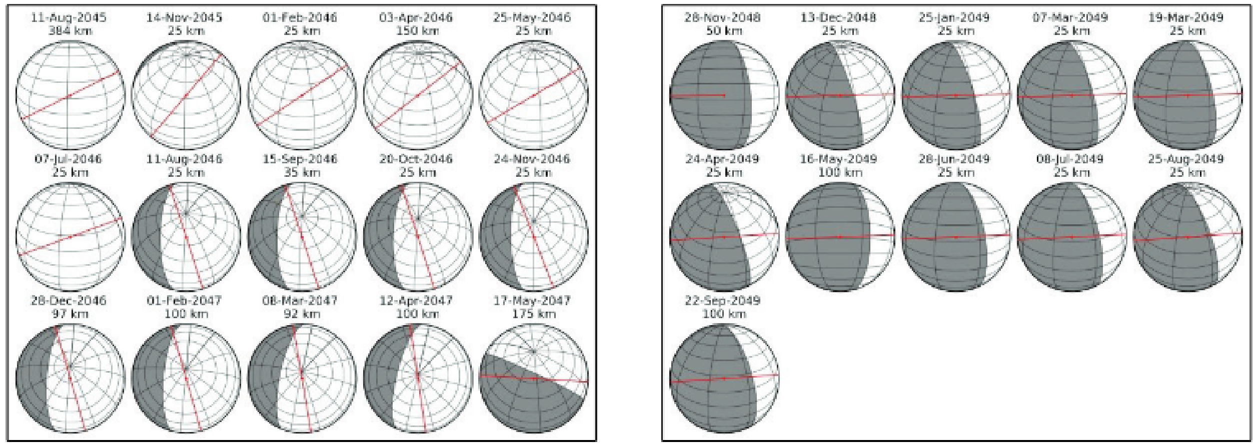


Exhibit 3-39. *Titania flybys used to equatorialize the orbiter trajectory.*

Exhibit 3-40. *Ariel flybys used to reduce Uranus-relative periapsis for subsequent spacecraft disposal.*

Fig. 14 Uranus moon tour using Titania and Ariel flybys. (NASA/Simon et al. [27])

The feasibility of performing such moon tours with an aerocapture mission architecture is not well understood, with the exception of Neptune-Triton system for which preliminary studies exist. The Saturn system offers a plethora of possibilities such as using aerocapture or aerogravity assist at Titan to place a spacecraft into orbit around Titan or Saturn and also flyby the various moons and ring systems. The study recommends the following efforts for moon tour design with aerocapture:

- Assess the viability of performing moon tours at Saturn, Uranus, and Neptune for aerocapture missions considering the constraints from interplanetary arrival trajectory, probe delivery, and post-aerocapture orbit targeting accuracy.

8. Programmatic, Cost, and Risk Considerations

Most of the work presented so far concerns the 'technical' aspect of aerocapture missions. However, NASA program managers, in addition to the technical aspects are naturally concerned about the programmatic, cost, and risk considerations of using aerocapture. Very little literature exists about these aspects of aerocapture. For example, consider a hypothetical scenario[†] [‡] where the science community is planning to insert a Flagship-class orbiter into orbit around Neptune. The program manager is presented with two design alternatives: #1) a relatively modest science package inserted into orbit using conventional propulsive orbit insertion; and #2) a well-instrumented and fairly comprehensive science package inserted into orbit using aerocapture.

Option #1 relies on a proven conventional orbit insertion technique which carries very low technical, cost, and schedule risk. Because the science package is modest, the returned total science data volume is low. However, there is a very high probability that certain key measurements can be performed within only few months of orbit insertion. Because the mission uses a heavy-lift launcher, the cost of this mission is higher than option #2.

Option #2 involves the hitherto untested aerocapture maneuver which carries at the very least moderate and worst case high technical, cost, and schedule risk. Because the science package is comprehensive, the returned total science data volume is much higher than option #1. However, if the aerocapture maneuver fails (eg: the spacecraft burns up or fails to capture into orbit) there is a risk of no data being returned at all. The shorter transit time allows a longer science orbit duration for an extended mission and follow up observations. Overall, while this mission architecture promises a greater total science data volume and more science per dollar, there is risk of no science returned at all as well as cost and schedule risks.

[†] Based on the example presented in NASA Risk Management Handbook [28].

[‡] The scenario and numbers used are hypothetical and for the purpose of discussion.

As pointed out by the 2023 Planetary Science Decadal Survey, “*because aerocapture is not being proposed for use in missions, it is considered a ‘dormant‘ technology that is perceived as high risk in a mission competitive environment.*” This is reminiscent of the “*technology death valley*” concept in the startup ecosystem, in the where promising ideas fail to fully materialize because a new technology, while promising, struggles to progress from the research stage to operational implementation. In some sense, aerocapture technology is in a similar state after several decades of basic research having proven the technical capabilities. The Decadal Survey notes, “*Aerocapture is a technology that is ready for infusion and that can enhance/enable a large set of missions, but that will require special incentives by NASA to be proposed and used in a science mission.*”

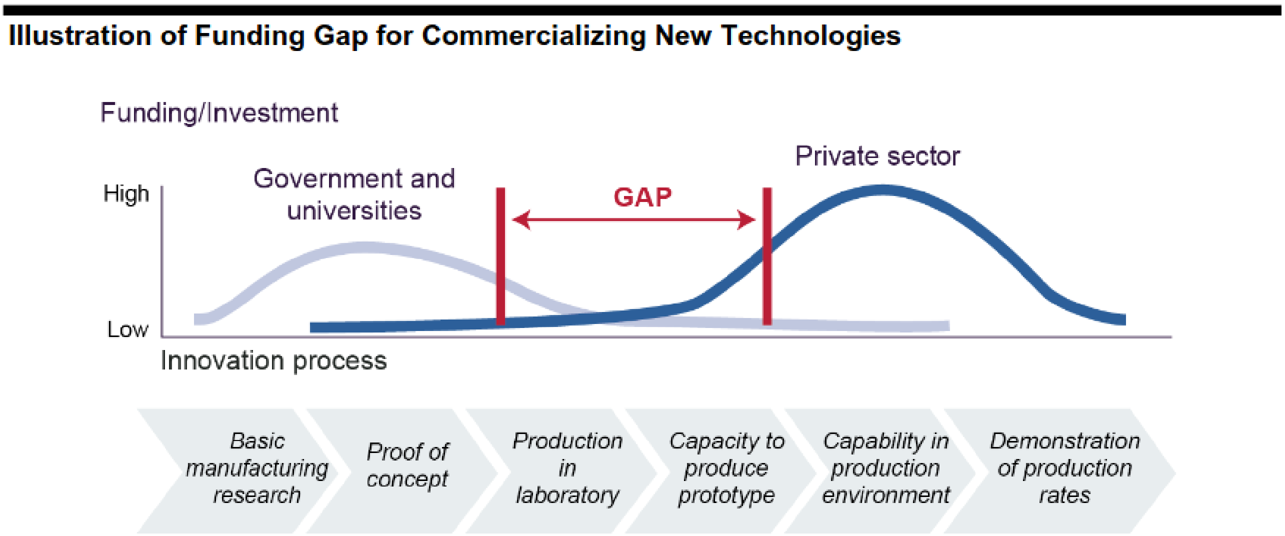


Fig. 15 Technology Death Valley. Department of Energy, GAO-21-202.

The study recommendsthe following efforts to make informed decisions regarding cost and risk:

- Assess the technical, cost, and schedule risks associated with aerocapture missions for various destinations. For example technical risks could be the spacecraft burning up or skipping out due to higher than or lower than expected atmospheric density. Cost risks include new spacecraft design and testing efforts potentially overshooting the budget.
- Perform independent cost and risk assessments of aerocapture mission concepts to avoid bias. Tchnologists trying to ‘push’ aerocapture as a technology for future missions will have a bias toward favoring the technology and portraying it as low cost and low risk.

9. Small Satellite Constellations

Small satellite constellations such as those operated by Planet Labs, SpaceX (Starlink), OneWeb and ICEYE (SAR constellation) have demonstrated their cost-effectiveness and great utility in near real-time global imaging, communications, and radar observations over the past decade. Constellations of CubeSats and SmallSats (< 180 kg) can enable a new paradigm in planetary exploration by enabling global imaging and radar observations of Mars and Venus at a fraction of the cost and much less risk than that of a large mission. Such missions may also provide communication and positioning services to future manned missions to Mars. Until now, orbit insertion has been a formidable challenge for small satellites due to their small form factor. However, with maturation of drag modulation technology over the last several years, the possibility to insert small satellites into very low circular orbits at Mars and Venus as rideshare payloads has opened up.

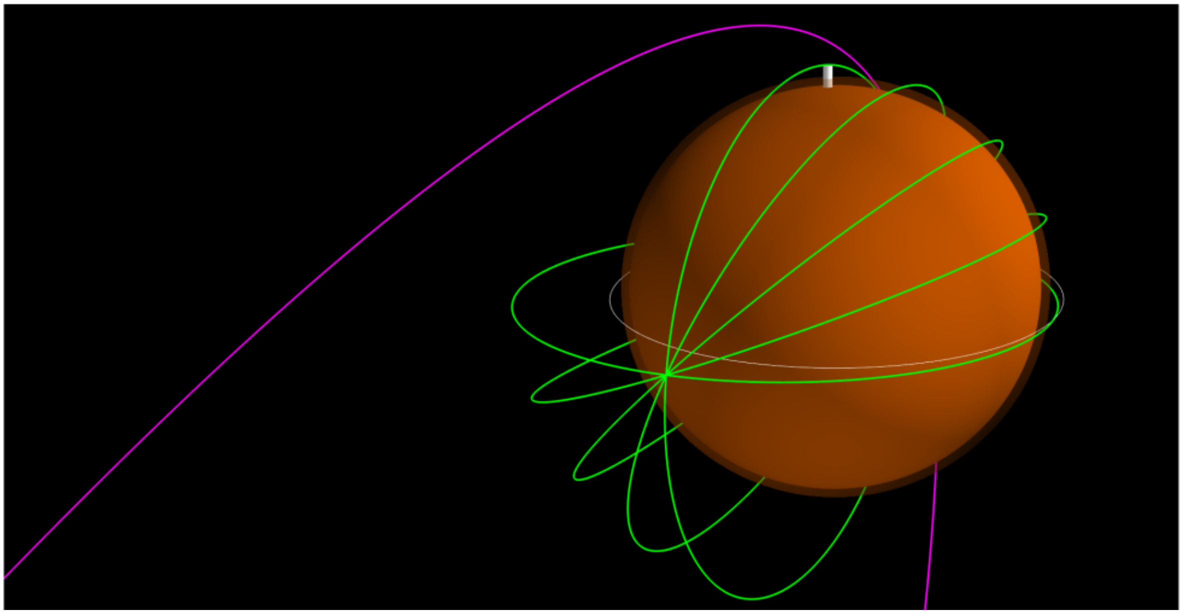


Fig. 16 Mars small imaging satellite constellation in 200 × 2000 km orbits with various inclinations from equatorial to polar (green), and the host orbiter in 250 × 70,000 km polar orbit.

Drag modulation technology is particularly attractive to small satellites as the deployable drag skirt can be stowed during launch and cruise, and can be deployed just prior to atmospheric entry eliminating the need for an aeroshell and RCS thrusters required for lift modulation aerocapture. Just as a single launch vehicle routinely launches several constellation satellites into Earth orbit, a single interplanetary cruise stage can deliver multiple small satellites into different orbits (for example, different inclinations) to form a constellation. The study recommends the following to support small satellite constellations for future planetary science missions:

- Perform mission concept studies to assess the feasibility, cost, and technical challenges of inserting multiple imaging or SAR satellites from a single interplanetary cruise stage into different inclination orbits at Mars and Venus.

10. Design Reference Missions

Design reference missions are intended to provide science investigators and mission planners with an optimized baseline mission concept from the plethora of options available for a mission architecture [29]. Such mission concept studies provide the high-level mission architecture (launch vehicle, interplanetary trajectory, arrival geometry etc.) along with the flight system design (spacecraft and aerocapture system). Examples include an Earth flight test to demonstrate aerocapture, small satellite aerocapture demonstration at Mars [30], and an aerocapture small satellite mission to Titan.

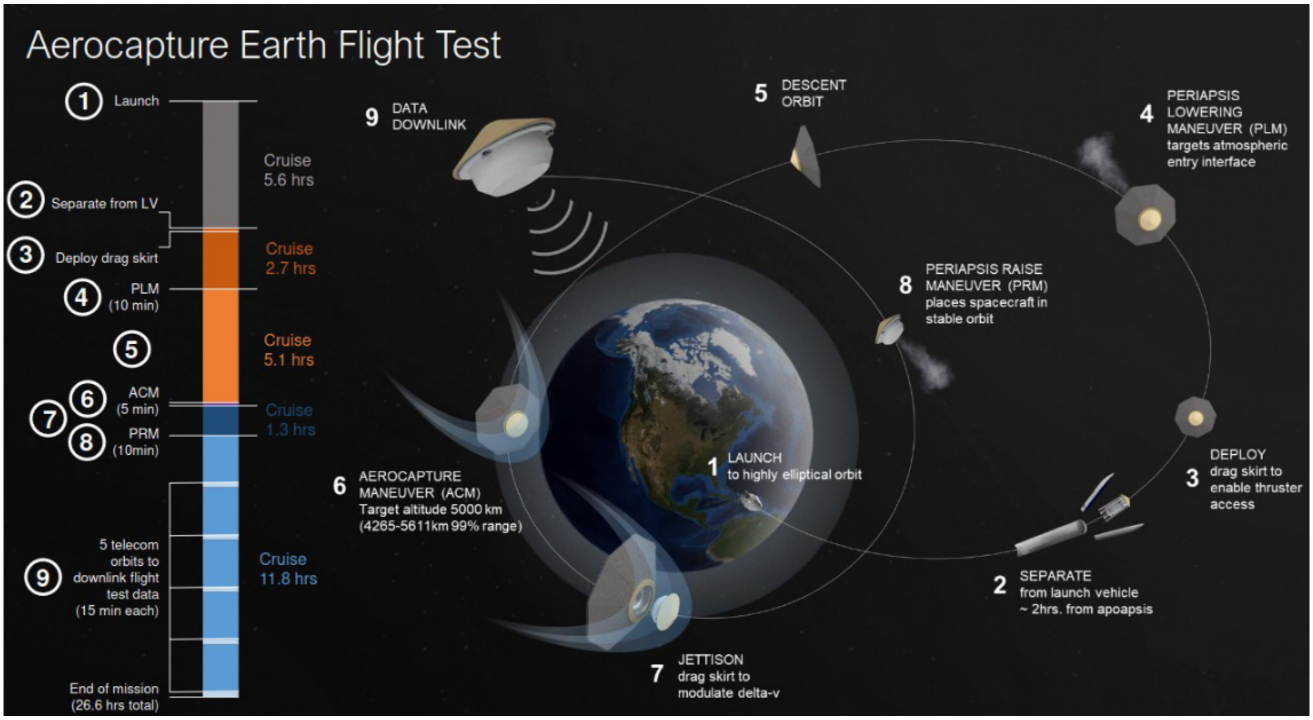


Fig. 17 Aerocapture Flight Technology Demonstrator at Earth.

The study recommends the following end-to-end design reference aerocapture mission concept studies:

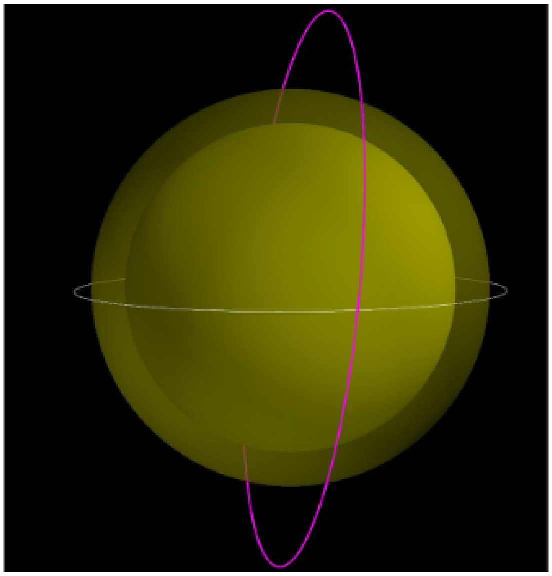


Fig. 18 Titan small satellite aerocapture mission concept.

- Demonstration of aerocapture at Earth using a low-cost drag modulation system launched as a secondary payload on a GTO mission or a lunar return mission.
- Inserting a small satellite (CubeSat or SmallSat) into a low circular orbit (400 km) at Mars or Venus using a drag modulation flight system.
- Inserting small satellite(s) into orbit around Venus which serve as a data relay for an aerial platform or a long-lived lander delivered on the same mission.
- Inserting multiple small satellite constellations into different inclination low circular orbits around Mars and Venus for optical imaging or SAR constellations from a single interplanetary cruise stage such as that flown on MSL.
- Delivering a lander, rover, or rotor-craft to Titan's surface along with one or more small satellites into Titan orbit which serve as both science platforms and data relays for a Flagship-class mission following the Dragonfly mission.
- Delivering a Flagship-class orbiter and atmospheric probe to explore the Uranus system using a low-L/D blunt-body aeroshell within a $2B cost-cap.
- Delivering a Flagship-class orbiter and probe to explore the Neptune system and perform multiple Triton flybys using a low-L/D blunt-body aeroshell within a $2B cost-cap.

11. Implications for Future Missions

Aerocapture has far reaching implications for future planetary science missions from small satellites at Venus and Mars, to Flagship-class orbiters at Uranus and Neptune [31, 32]. In the near term, aerocapture can enable small low-cost orbiters and constellations around Mars and Venus [33]. With the exception of Jupiter and and Saturn, aerocapture has been shown to be useful at every atmosphere-bearing destination [34]. Missions to the outer planets have been heavily constrained in both instrument mass and transit time due to conventional orbit insertion [35, 36]. The benefits of aerocapture are the greatest at the ice giants, Uranus and Neptune whose large heliocentric distances imply long transit times and high orbit insertion ΔV [37]. Aerocapture opens up entirely new classes of fast trajectories to the ice giants without the constraint of a large orbit insertion ΔV [38]. Titan, with its thick atmosphere and low gravity offers an ideal setting for both large and small spacecraft missions using aerocapture [39]. A flight demonstration of aerocapture at Earth from a GTO rideshare payload, or a spacecraft returning from the moon can raise the technology from a concept to one with flight heritage, and facilitate its adoption into planetary science missions.

12. Summary

This report provided a list of recommended technology development in the areas of mission design, navigation and guidance, aerocapture vehicle design, thermal protection systems, spacecraft and probe design, atmosphere models, and satellite tour design for future aerocapture missions. A brief discussion of the programmatic and risk considerations of aerocapture from a program management perspective is presented. The importance of small satellite constellations using aerocapture, enabling a new paradigm of planetary science mission is discussed, and a recommended list of design reference missions is provided for future aerocapture mission concept studies.

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