

Aerocapture Earth Demonstration Design to Support Future Planetary Mission Needs

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Aerocapture is an orbital insertion maneuver that allows a spacecraft in hyperbolic flight to use aerodynamic forces within an atmosphere to reduce its energy and enter a captured orbit. Past research has shown that despite aerocapture systems needing a heatshield, the maneuver could save substantial overall mass in terms of orbital insertion fuel. Additionally, for many planetary destinations of interest, such as Uranus, Neptune, Venus, and Mars, aerocapture-based missions can take a more direct route to the planets, achieve orbit insertion with less propulsive mass, cut substantial operation time during cruise, and enable missions that have constrained budgets and ambitious science timelines. However, aerocapture has not been demonstrated at any planetary destination, so there is an impetus to showcase the maneuver at Earth to reduce implementation risks for planetary missions. This work describes a lower risk mission design for an aerocapture demonstration vehicle at Earth, using a small satellite as a chassis, but still demonstrating capabilities needed for planetary aerocapture missions and reducing the system risks associated with the concept.

I. Introduction

THE 2022 Planetary Decadal Survey identified several challenging, but scientifically interesting targets for planetary science for the coming decades. Exploration of the Ice Giants, Uranus and Neptune, were especially highlighted as top flagship class destinations [1]. Exploration of the outer planets via traditional mission design approaches, where fully-propulsive chemical orbit insertion maneuvers would be required for orbit capture, lead to mission timelines of several decades and missions with launch mass with 60-70% fuel for the propulsive burns [2, 3]. These mission designs can be improved in terms of increasing science mass fractions to orbit and shorter mission timelines by using innovative orbit insertion maneuvers.

NASA has also recently increased its interest in establishing a presence on Mars via robotic and human-scale missions. As part of the Moon to Mars architecture, several missions are being considered in the near future, such as

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a Mars Telecommunications Orbiter [4] and high-mass, robotic-scale landers to supply infrastructure to the planet's surface. Past studies [5–7] have shown that the performance of these missions could be augmented by orbit insertion maneuvers that can handle fast entry velocities coming from interplanetary trajectories with fast transits.

Aerocapture is an orbit insertion maneuver where the aerodynamic forces in the atmosphere of the planet are used to decrease orbital energy and achieve a target orbit. Aerocapture is especially adept for these challenging missions, with a 2022-2024 study showing aerocapture as an enabling technology for shorter Uranus orbiter and probe missions [8, 9] and NASA studies from the early 2000's showing the capabilities of an aerocapture system for Mars missions [10]. The Uranus study and similar papers [11] have shown that feasible aerocapture designs based on heritage technologies borrowed from the entry, descent, and landing community can put the next generation of NASA missions into their desired science orbits.

However, since aerocapture technology has not been demonstrated, mission proposers are reluctant to make aerocapture the main orbit insertion technology. A demonstration of aerocapture at Earth would alleviate many of those risks and make aerocapture a technology that can be infused into future planetary missions. This paper looks at the structure of an aerocapture demonstration mission at Earth to enable future planetary missions.

II. What is Aerocapture

Aerocapture is an atmospheric maneuver that uses the drag generated during an atmospheric pass to decelerate a vehicle in order to capture a spacecraft into an elliptical orbit from an interplanetary trajectory. As seen in Fig. 1, the spacecraft starts the maneuver during an arrival at the planet from an interplanetary trajectory. After cruise stage jettison, the aerocapture vehicle includes the aeroshell and the payload, usually an orbiter. The spacecraft continues to the planet's atmospheric interface, at which time the aerodynamic forces begin to build and enough energy is dissipated for the spacecraft to be in a captured orbit. After atmospheric exit, the aeroshell is jettisoned and the orbiter is deployed. There are still two additional maneuvers, first at the first apoapsis to raise the periapsis and then at the next periapsis to clean-up any apoapsis error. The total process is conducted over one period of the captured orbit.

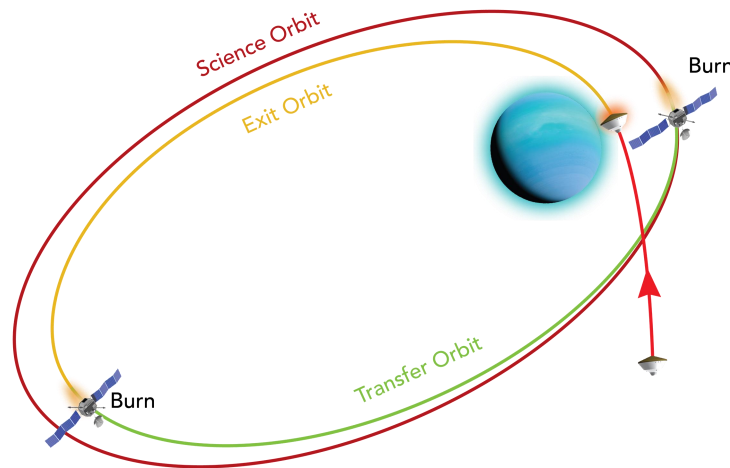


Fig. 1 Nominal concept of operations for aerocapture.

A point of emphasis is that aerocapture is different from another similar maneuver called aerobraking. In aerobraking, the spacecraft does not have an external aeroshell for heating protection. Additionally, the spacecraft is first inserted into a highly elliptical orbit from interplanetary transit. Then, the aerobraking maneuver slows down the vehicle in the upper atmosphere with the vehicle's drag from its solar arrays. Due to the small amount of drag generated in the upper atmosphere by the solar arrays, aerobraking involves several passes of the atmosphere and the total concept of operations can involve months or years [12]. Aerobraking was first demonstrated by the Magellan spacecraft at Venus [13], and has since been used by Mars Odyssey [14] and Mars Reconnaissance Orbiter [15].

Aerocapture, the one-pass brethren of aerobraking, has been studied extensively for the past 50 years, as documented in the extensive bibliography in Ref. [16], but it is not a demonstrated maneuver. Aerocapture has been selected as the primary orbit insertion technology for some missions [17] but missions were not completed. There is a perception of

higher risk of aerocapture over other orbital insertion methods like chemical propulsion or aerobraking [18] although past studies have shown that on the contrary aerocapture has reduced risk compared to other types of maneuvers [12].

The objective of this paper is to discuss how integrating aerocapture into the design of planetary spacecraft can be beneficial and how a demonstration at Earth can potentially reduce the overall risk posture.

III. Current Risk Posture for Aerocapture

A. ADRAT report

Since aerocapture has not been demonstrated at any planetary destination, there are actual and perceived risks associated with implementing the maneuver on planetary missions. NASA's Science Mission Directorate (SMD) spearheaded a 2022-2023 study team named Aerocapture Demonstration Relevance Assessment Team (ADRAT) [19] that identified some potential risks associated with the aerocapture concept when applied to future planetary missions. Figure 2 summarizes the risks and prioritizes them in terms of risk level.

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

Fig. 2 Risks identified by the ADRAT report for aerocapture missions (adapted from Ref. [19]).

From the report, the main risks are associated with high atmospheric uncertainties at the target planets, implementation costs of aerocapture if uncertainties are too high, and if the aerothermodynamic environment of the target body is poorly understood.

For some planetary destinations, like the Ice Giants, where the atmospheric knowledge is poor, environmental uncertainties are certainly potential risks an aerocapture system has to overcome. However, these environmental risks exist for other mission components, like the probe mission, which is equally important part of the proposed mission. Thus, only downgrading the risk posture of the aerocapture mission is not a fair assessment. Additionally, newer studies documented in Refs. [9, 20, 21] show robust aerocapture performance is possible with certain design choices even with large atmospheric and environmental uncertainties.

Most importantly, the ADRAT report recommended an aerocapture demonstration mission at Earth to be traceable to the outer planets mission applications. This key recommendation is the crux of the study summarized in this paper.

B. Past studies

Aerocapture as a concept has been proposed for decades, with studies looking at proposed atmospheric maneuvers for orbital transfers at different planetary bodies since the 1960's [22–24]. These proposed studies often included innovative vehicle shapes to provide the aerodynamic forces for orbit insertion. Fig. 3(a) shows a large inflated drag surface that trails the orbiter as it captures around a planetary body. Another unique shape is the ellipsed mid lift-over-drag concept in Fig. 3(b) used to generate high lifting force to attain energy dissipation for orbit insertion.

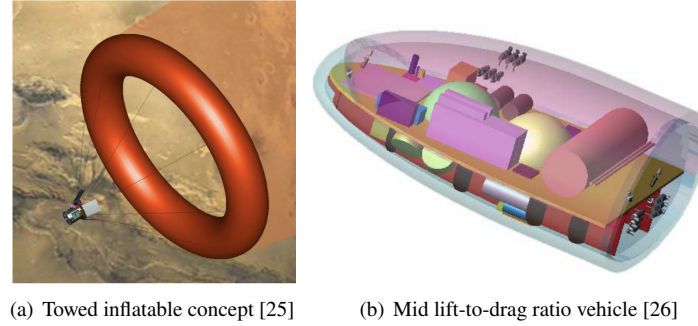


Fig. 3 Historical vehicle concepts for aerocapture.

In the last twenty years, NASA conducted systems analysis reference studies in the early 2000's for Venus [27], Mars [10], Titan [28], and Neptune [26]. The studies demonstrated the feasibility and robustness of aerocapture, but a drawback was the design and qualification of a new entry vehicle configuration. Most past aerocapture designs necessitated the use of a vehicle that had not flown in any planetary setting.

More recently, some aerocapture concepts have suggested using solely the drag force as the control mechanism for orbit insertion. Instead of modulating the lift force, like concepts in Fig. 3(b), one can control only the drag of the vehicle with drag modulation (see Fig. 4). Control is maintained by modulating the ballistic coefficient (β) by going from a high drag system to a lower drag system, such as by shedding a drag skirt [29, 30]. However, robustness of control for these drag-only systems might be lower [31] than those with lift-modulation, especially in situations where environmental uncertainties are high.

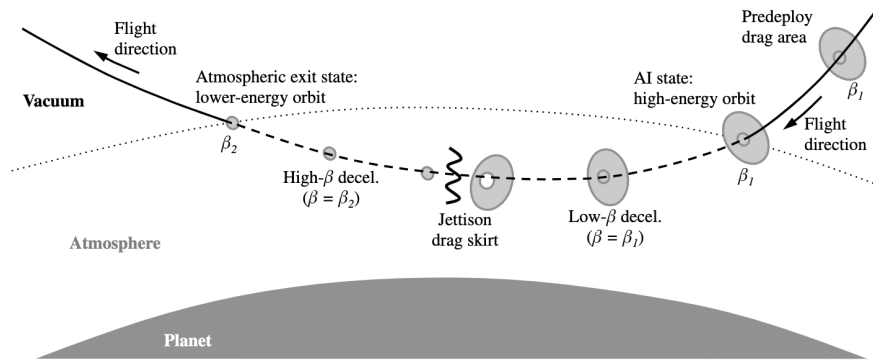


Fig. 4 Conceptual design of drag modulation aerocapture (adapted from Ref. [29])

In 2023-2024, in response to the selection of Uranus as the top flagship destination in the 2022 Planetary Science Decadal survey, a two-year study [8, 9] considered the use of heritage, blunt-body capsules and lift-modulation control (flight-proven control strategy at Mars and Earth) to design an orbit insertion system for an Uranus orbiter and probe spacecraft. The resulting aerocapture vehicle, as seen in Fig. 5, leveraged existing and tested technologies. The

design was a feasible vehicle that can encapsulate the desired science payload while reducing implementation risks for a flagship-class mission. Since aerocapture already has some perceived risks, the goal of the study was to utilize flight-proven strategies from the EDL community that require no additional innovation while still achieving the mission enabling benefits aerocapture can provide for these planetary missions.

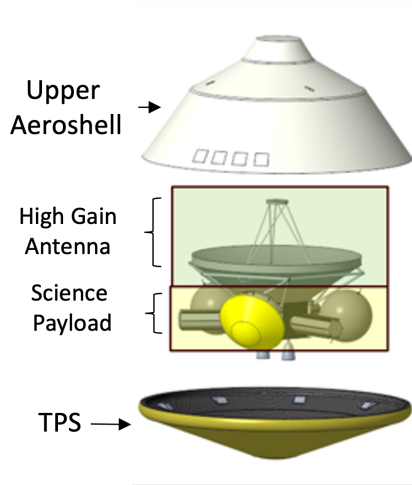


Fig. 5 Aerocapture concept for Uranus with the science payload and other necessary components (adapted from Ref. [9]).

The aerocapture study also showed the robustness of the high-heritage concept for a large range of atmospheric conditions (see Ref. [20]) and to various different launch opportunities without sacrificing feasibility of the underlying technology components, like the thermal protection system (TPS). Fig. 6 adapted from Ref. [9] shows a large range of different mission design and navigation launch opportunities (from 2031 to 2042) that lead to various entry speeds (V_∞) available to the Uranus aerocapture design. Despite the large range of conditions, most of the opportunities still remain feasible within the capabilities of the TPS material, which in this case was Conformal Phenolic Impregnated Carbon Ablator (C-PICA).

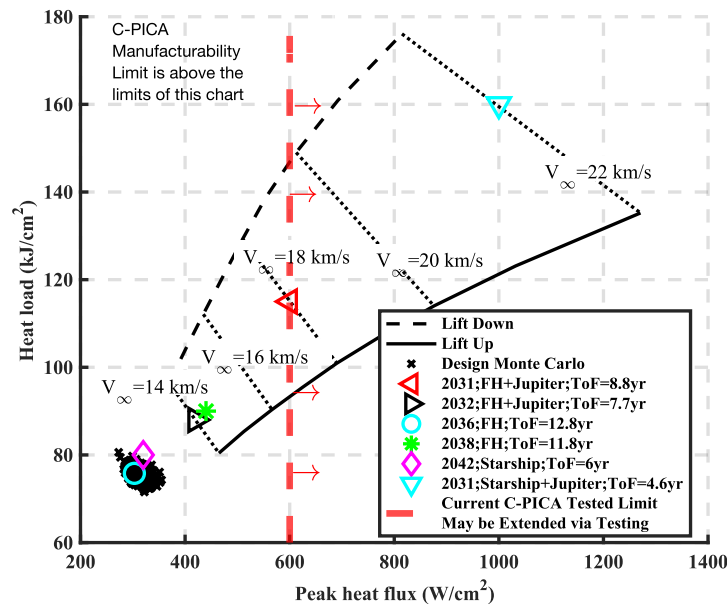


Fig. 6 Comparison of various Uranus aerocapture opportunities and heating environments (adapted from Ref. [9])

This recent study showed that aerocapture does not always require new entry vehicle design or untested control mechanics. There are possibilities of using heritage concepts from entry, descent, and landing (EDL) missions that can achieve mission requirements while also making aerocapture more palatable to mission designers.

C. Risk reduction through Earth demonstration

As seen in these past, detailed aerocapture studies, aerocapture is a conglomeration of technologies like guidance, navigation, and control and TPS that have individually been demonstrated in many relevant environments and may have a high technology readiness level, but together the aerocapture technology has a lower readiness level. Based on the points highlighted by past studies and the ADRAT report, an aerocapture demonstration can drive down risks in several key areas and make the technology ready to be infused for future planetary missions.

The aerocapture demonstration has been proposed at various planets, such as at Venus or Mars [32], but an Earth-based demonstration provides a potentially faster time horizon for the mission since the cadence of missions to Earth orbit is higher than planetary missions to Venus and Mars. Additionally, studies like those discussed by Werner et al. [33] have recommended using a small satellite chassis to make the development and build cycle faster.

Combining both of these suggestions – Earth-based demonstration and a small satellite chassis – while demonstrating lifting aerocapture concepts needed for planetary missions creates a strong mission concept to reduce aerocapture risks. Table 1 distills the main areas and technologies that an aerocapture system must demonstrate to be used at planetary destinations. These areas are then mapped to what can be demonstrated with an Earth-based demonstration.

Table 1 Decomposition of functional areas needed for aerocapture usage at planetary destinations

Requirements for planetary missions	Earth-based demonstration behavior
Hypersonic guidance for target orbit	Demonstrable. Aerocapture guidance is similar to guidance already demonstrated at Mars (Mars Science Laboratory (MSL) and Mars 2020) [34] and Earth (Exploration Flight Test 1) [35]. Relevant guidance scheme can be demonstrated in an Earth-based test without constraints.
Thermal Protection System (TPS)	Demonstrable. Potential TPS materials for planetary aerocapture missions, like PICA and C-PICA, have already been demonstrated on Mars [36] and Earth [37]. These TPS materials can also be demonstrated on an Earth-based test but potentially not at equivalent planetary mission conditions.
Autonomous periapsis raise maneuver	Demonstrable. Can be demonstrated in an Earth-based test without constraints.
Control systems demonstration	Demonstrable. Relevant control systems, whether reaction control systems (RCS) or any other control schemes can be demonstrated in an Earth-based test without constraints.
Aeroshell separation after aerocapture	Demonstrable. Can be demonstrated in an Earth-based test without constraints.
Targeting tight entry corridor	Limited demonstration. Tight entry flight path corridors needed for planetary missions are achieved using optical navigation (opNAV) and autonomous navigation (AutoNAV) campaigns over multiple weeks. A short time duration Earth-based demonstration may not provide the time spans for these opNAV campaigns. However, both opNAV and AutoNAV have been demonstrated in missions such as Deep Space 1 (DS1) [38] and Double Asteroid Redirection Test (DART) [39].
Packaging payload in aeroshell	Not demonstrable. Planetary aerocapture missions may involve tight fitting of planetary payloads enclosed within aeroshell, as seen in the 2022-2024 Uranus orbiter study [9]. This would not be demonstrable in a small satellite chassis of the Earth-based demonstration but is a mechanical challenge handled in many other planetary missions.

As summarized in the table, most of the key areas needed for a planetary aerocapture mission, such as hypersonic

guidance, TPS, autonomous maneuvers, and control system usage, can be executed in an Earth-based demonstration. Some of the lingering areas, like targeting tight entry corridors, involve technologies that have been executed in other successful planetary missions and are portable to various aerocapture scenarios. An Earth-based aerocapture demonstration to reduce risks seems feasible and maps favorably to the functional areas that will be needed for a planetary aerocapture mission.

IV. Aerocapture Demonstration at Earth Concept of Operations

When looking at demonstration of aerocapture at Earth, there are a few options for the concept of operations. The current study looking at the aerocapture demonstration design has considered two sides of the range – geostationary transfer orbit (GTO) (Fig. 7) and lunar transfer (Fig. 8).

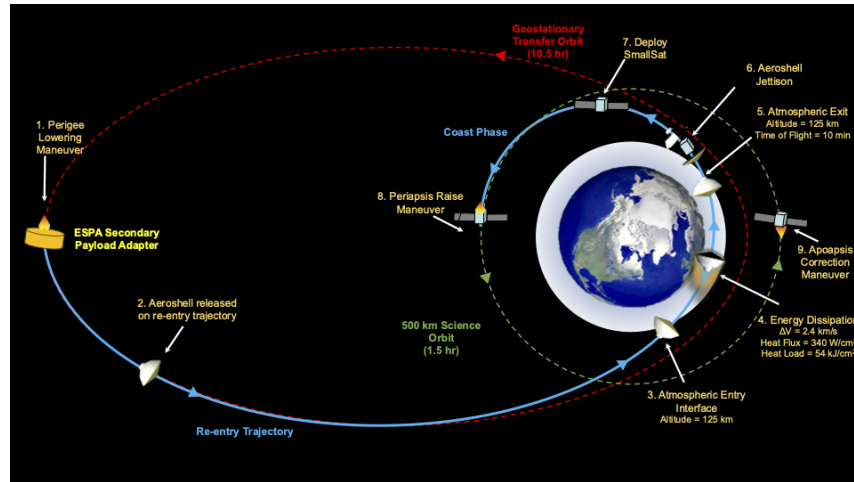


Fig. 7 Concept of operations for an aerocapture demonstration from a geostationary transfer orbit.

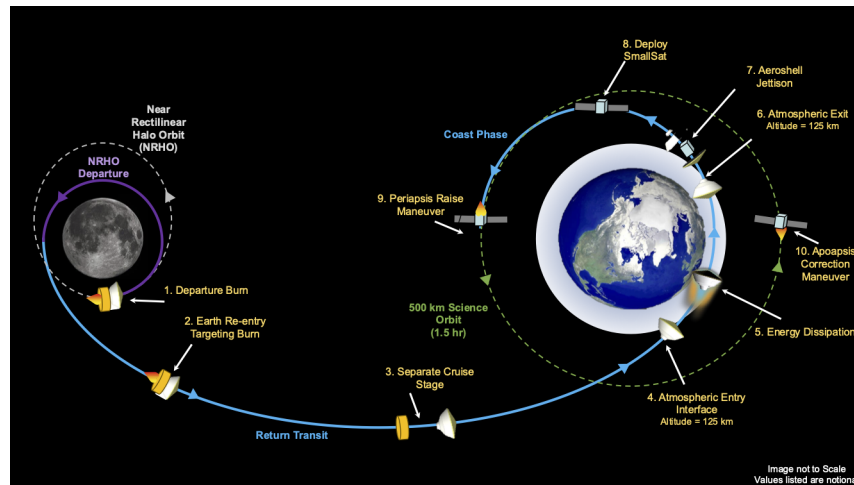


Fig. 8 Concept of operations for an aerocapture demonstration from a lunar return trajectory.

Similar to what was described for the general aerocapture scenario, for the Earth aerocapture demonstration the spacecraft with an aeroshell enters the planetary atmosphere, performs aerodynamic maneuvers to dissipate energy (with ΔV of 2.4 and 3.2 km/s occurring for these two concepts, respectively), exits the atmosphere to shed the aeroshell and deploy the payload, and ends with two final, smaller propulsive maneuvers occurring at the first apoapsis and the next periapsis.

Some key differences in these two scenarios are the initial conditions. The GTO concept spacecraft (Fig. 7) originates after a perigee lowering maneuver during the geostationary transfer orbit (approximately 37,000 km altitude), and for this study, the spacecraft is ejected from an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). All of the spacecraft operations, from ESPA-ejection, aerocapture pass, and smallsat propulsive maneuvers are done within a 24-hour time period.

For the lunar return case, the initial orbit selected was Near Rectilinear Halo Orbit (NRHO) around the Moon, since it is being considered for the human-scale missions and the Gateway space station [40]; thus, it is a potential trajectory for a rideshare. The aeroshell and an associated cruise stage exits NRHO after a departure burn and transits to Earth. Prior to a few minutes before atmospheric entry, the aeroshell is released from the cruise stage to start the aerocapture pass similar to the GTO concept. The lunar return concept of operations can be of variable time period depending on the lunar transit orbit chosen, and some of the various options considered are described in Ref. [41]. Nevertheless, lunar return will require a cruise stage and the whole operation will be a multi-day effort.

In both cases, the definition of aerocapture is extrapolated, as for both GTO or lunar return scenarios the spacecraft is already in an elliptical, captured orbit around Earth. However, both scenarios still allow the vehicle to enter the Earth atmosphere in a high-energy state, deplete orbital energy, and target a lower energy orbit similar to an aerocapture concept of operations at planetary destinations. As seen in Fig. 9, which shows entry velocity and ΔV expended during aerocapture, the GTO and Trans Lunar Injection (TLI) conditions that represent the lunar return scenarios capture requirements for various planetary missions. Other Earth concept of operations potential for an aerocapture demonstration, like middle Earth orbit (MEO), Sun-Earth Lagrange Point 1 (L1), and Ultraviolet Explorer (UVEX), fill in the range of the design space. GTO and lunar return cover a large swath of the region needed for planetary missions of interest and thus were picked for concepts considered in this study. Please see Ref. [41] for a detailed comparison of the two concepts.

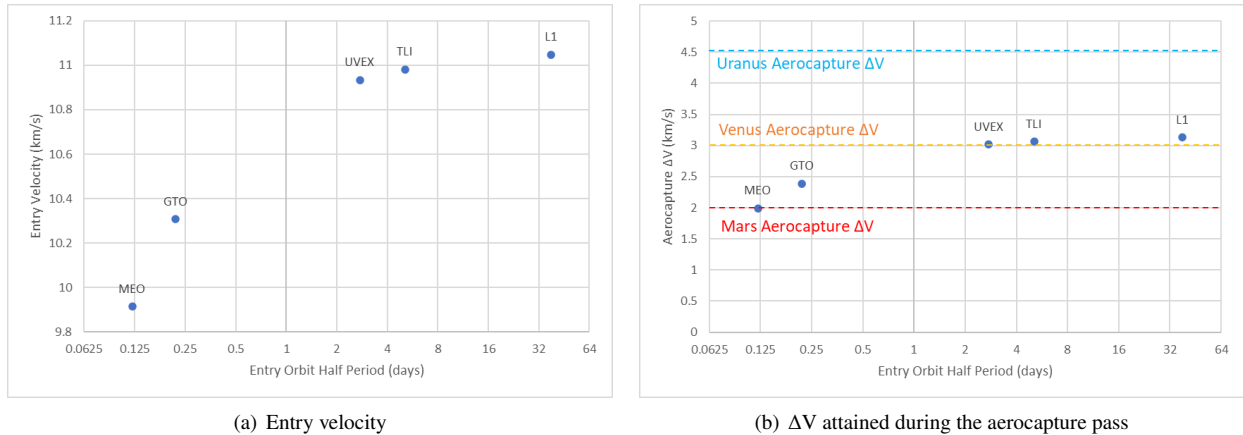


Fig. 9 Demonstration ranges of aerocapture concept of operations.

V. Aerocapture Demonstration Design

The previous sections discussed the motivation and necessary components of an Earth-based aerocapture demonstration vehicle. This section provides a summary of the aerocapture demonstration vehicle after one year of pre-phase A design study. The reader is also encouraged to look at papers that accompany this current paper, specifically Refs. [41–43], for more information on the detailed design.

A. Mechanical design

A key design choice for the aerocapture demonstration vehicle is to fit within the small satellite chassis in order to keep development costs low and potentially expedite the demonstration schedule. Many small satellites are deployed from secondary payload adapters, with ESPA and SpaceX's Falcon adapters being the most popular and available carriage structures. Both ESPA and SpaceX have defined payload volume constraints. The limiting dimension in these payload volume constraints is 46 inches (or 1.168 m) which constrains the size of the aeroshell diameter.

Fig. 10 shows different views of the design of the aerocapture demonstration vehicle. The aeroshell shape is chosen to be the 70-degree sphere-cone shape that is a known aerodynamic quantity and has heritage in many planetary missions. The diameter was varied between 1.0 and 1.1 m, with Fig. 10(a) showing the larger design. Fig. 10(c) shows a simplified view of the internal components. The payload consists of a commercial-off-the-shelf (COTS) small satellite, and for the design study the NASA CAPSTONE spacecraft is assumed as the placeholder.

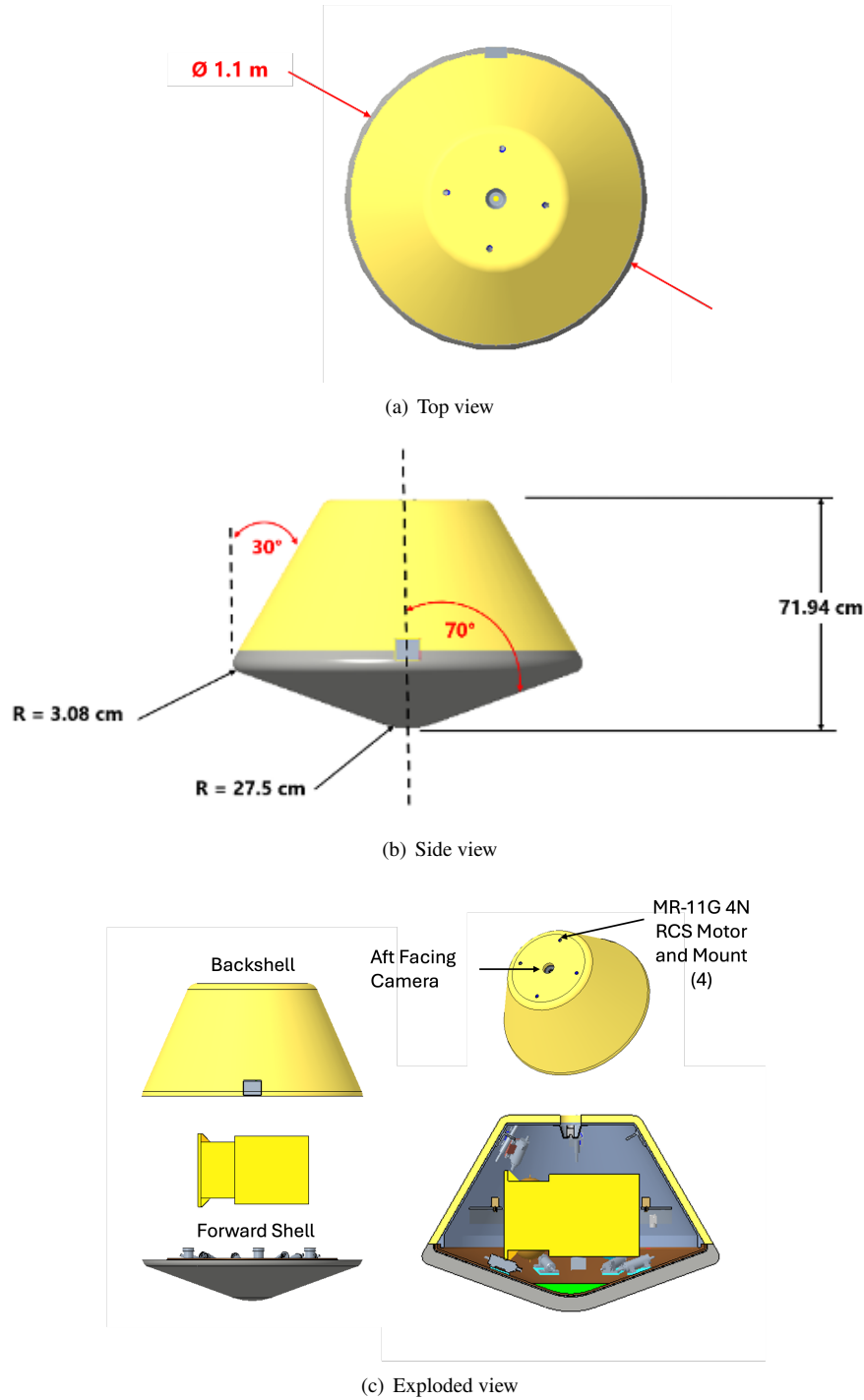


Fig. 10 Aerocapture demonstration vehicle design.

Both titanium and carbon fiber composite were considered for the structure of the vehicle. If titanium was used, the

overall mass of the vehicle was slightly higher and the thermal protection system design required a strain isolation pad. Ultimately, a carbon fiber layup was selected for the current iteration of the design, but structural loading analysis is ongoing, potentially changing the final design.

The overall vehicle mass, in current best estimate (CBE) sense, was less than 200 kg, especially with the carbon fiber composite structure. However, considering mass growth allowance and pre-authority to proceed (ATP) mass property rules of standards like AIAA-S120A [44], the maximum expected value (MEV) was set at 255 kg for analysis for other design areas, such as trajectory and TPS design.

B. Trajectory design

The aerocapture trajectory design spanned the whole domain of the aerocapture mission, starting at spacecraft release from the primary spacecraft, either at geostationary transfer orbit apoapsis or NRHO, all the way to the periapsis raise maneuver post aerocapture pass. The Copernicus trajectory design and optimization program was used for the non-atmospheric portion of the trajectory design [45], while the Program to Optimize Simulated Trajectories II (POST2) [46] was used to model the atmospheric portion of the simulation.

Copernicus was used to characterize possible dispersed initial states at aeroshell release and 10-min prior to atmospheric entry. These conditions were based on conservative assumptions about orbit lowering execution errors, although this is an area that requires additional work in the future. Ref. [41] discusses some of these assumptions and also possible ways these uncertainties can be better quantified in the future.

An integrated guidance and control algorithm, described in the following section, was also implemented in POST2 to simulate a controlled trajectory during the atmospheric pass, and Monte Carlo simulations were conducted with aerodynamic, atmospheric, mass, and initial condition dispersions to characterize the statistical flight performance. These performance statistics included capture success rate (most scenarios were at 99%+) and the required ΔV needed for post-aerocapture propulsive maneuvers. Although the trajectory simulations were using three degree-of-freedom analysis, higher fidelity models, like rate and acceleration limits of controllers, were modeled and the overall level of fidelity of the results were above the pre-phase A level of the project.

Roelke et al. [41] discusses the trajectory modeling and simulation in more detail and also provides examples of several trades conducted to analyze the aerocapture design space.

C. Guidance and Control strategy

Heritage concepts of controls were used, including bank angle modulation achieved using reaction control systems (RCS). Instead of novel control schemes, like drag modulation, which requires aeroshell separation during hypersonic flight, or direct force control, where aerodynamic control surfaces are actuated during hypersonic flight, the aerocapture demonstration design stayed with tried and true RCS controls that have been demonstrated at Earth and Mars, with COTS components available for the design. Fig. 10(c) shows the current iteration of the RCS design and motor selection, although optimization of this system is an ongoing design effort.

For guidance, the Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) scheme [47] is selected as one of the state-of-the-art numerical predictor corrector guidance schemes. These numerical predictor-corrector schemes have been shown to be robust to environmental and design conditions [47], such as atmospheric or aerodynamic uncertainties, and even have some heritage such as being flown successfully on Artemis I [48].

Briden et al. [42] discusses the guidance and control strategies in more detail and provides details on the trade space and tuning parameters used in the study.

D. Aerodynamic, Aerothermodynamics, and thermal protection system design

The aerodynamic database for the aerocapture demonstration was developed using computational fluid dynamics (CFD)-based data and best practices followed on prior EDL missions and the Uranus aerocapture study [49]. Tools like the Langley Aerothermal Upwind Relaxation Algorithm (LAURA) and Multiphysics Algorithm with Particles (MAP) were used to generate aerodynamic force and moment data for hypersonic continuum and rarefied regimes. The aerocapture demonstration vehicle, due to its small diameter and reference area, spends a large portion of the atmospheric pass in a high Knudsen Number (rarefied) regime of the flight, making Direct Simulation Monte Carlo (DSMC) tools like MAP a big driver of the aerodynamic database. Ref. [41] discusses the aerodynamic database in greater detail and also provides trades and sensitivities observed in the spacecraft performance due to the aerodynamics.

The aerothermodynamic environment for the aerocapture demonstration was also developed using CFD tools similar

to what was used for aerodynamics, like LAURA, Hypersonic air radiation algorithm (HARA), and MAP, and then an aeroheating database was created. The techniques were very similar to past work used for Uranus aerocapture analysis (see. Refs. [50, 51]) including the use of surrogate modeling to span a large range of entry conditions, from relatively high energy lunar return conditions to lower energy GTO.

The CFD analyses used to build the aeroheating database conducted both convective and radiative heating, and various turbulence models were also considered. The GTO trajectories did not have significant radiative heating, but for higher energy trajectories that radiative component of total heating was more significant. One of the pleasant observations was that due to the relatively small nose radius of the small satellite-scale aerocapture demonstration vehicle, the peak heating values are of the order of magnitude seen by full-scale aerocapture aeroshells needed at planetary destinations, like Uranus [51], and also seen in Fig. 6. The total integrated heat load achieved by aerocapture trajectories at Earth are still far lower than their equivalent for planetary destinations at the Giant and Ice planets, but the Earth-based demonstration will achieve similar peak heating conditions to those needed for planetary missions.

The aeroheating database was integrated with the end-to-end trajectory simulations to interrogate a plethora of potential heating trajectories. These heating time histories from the aeroheating database and trajectory simulation were then used in the TPS design to define thermal conditions at various body points over the forebody and aftbody of the vehicle. The Fully Implicit Ablation and Thermal response program (FIAT) along with other associated tools were used to develop the TPS stack-up for the aeroshell. Similar to the experience of TPS sizing of the aerocapture aeroshell for planetary destinations like Uranus, the flight-proven and relatively lower density C-PICA was found to be apt material for the forebody of the aeroshell. C-PICA was also chosen as the aftbody material, but some lower density but high performing TPS materials are under development and can be good candidates for the relatively lower heating seen in the aftbody.

Williams et al. [43] provides a more in-depth discussion about the aeroheating environment and TPS sizing for the aerocapture vehicle, and also provides information on potential TPS material trades that are still ongoing.

E. Entry systems instrumentation

A key goal of the aerocapture demonstration mission is to gather data to understand the flight performance of the vehicle during the aerocapture maneuver and then validate key models, such as aerodynamics, aerothermodynamics, and thermal response, which would be essential for design of the planetary missions. To such end, the aerocapture demonstration vehicle is designed to contain several different measurement packages as part of the entry systems instrumentation (ESI) suite.

The small satellite payload is expected to contain an inertial measurement unit (IMU) and global positioning system (GPS) receivers which will allow the reconstruction of the trajectory of the vehicle. In addition, the aerodynamics and thermal response of the aeroshell during the atmospheric pass would be captured with pressure transducers and thermocouple plugs that can capture the pressure distribution and in-depth temperature profile at various locations in the forebody and aftbody of the vehicle. Table 2 summarizes the ESI sensor list, while Fig. 11 shows a view of the various ESI sensors on the the forebody aeroshell. The arrangement is based on the methods developed for the successful ESI suites flown on the MSL and Mars 2020 missions known as the MSL/Mars 2020 Entry, Descent, and Landing Instrumentation (MEDLI) [52].

Table 2 Possible entry system instrumentation list

Sensors	Location	Sensor Count
Low-pressure pressure sensors	Forebody	7
Diaphragm resistance temperature detector pressure sensors	Forebody	7
TPS plugs	Forebody	7
Low-pressure pressure sensors	Backshell	2
Diaphragm resistance temperature detector pressure sensors	Backshell	2
TPS plugs	Backshell	2
Forward-facing camera	Backshell	1
Aft-facing camera	Backshell	1
Payload camera	Payload	1

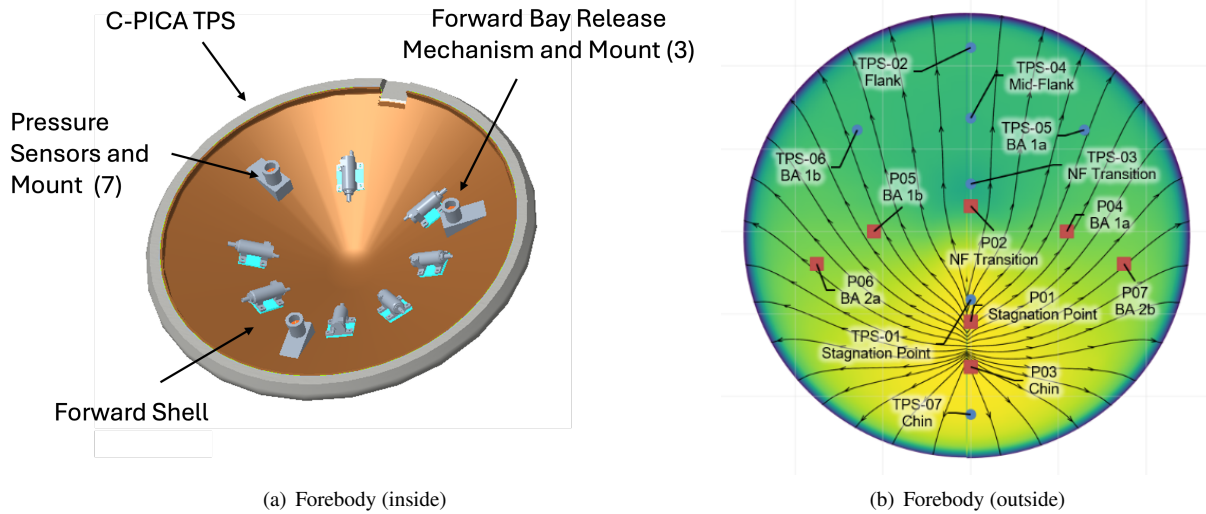


Fig. 11 Notional arrangement of ESI suite on the forebody of the aerocapture demonstration vehicle.

In addition to the pressure transducers and thermocouples, the ESI suite will contain three context cameras, with one facing forward, one facing aft, and one imaging from the small satellite payload. These context cameras can provide invaluable data regarding the trajectory and aerodynamic flow during the atmospheric pass and have shown great success in recent missions [53].

VI. Conclusions

Aerocapture is a promising orbit insertion strategy that can be mission enabling at various planetary destinations. However, the maneuver is undemonstrated and although some components of the underlying techniques have heritage, the overall concept has some risks associated with it. Recent studies have suggested an aerocapture demonstration to reduce risks that can enable mission infusion into future missions. This paper showed the design of a potential Earth-based aerocapture demonstration using flight-heritage lifting control and a small spacecraft chassis. Leveraging lower risk choices, such as a heritage blunt-body capsule design, using lifting control and bank angle modulation, utilizing proven TPS like C-PICA, all within the shell of a small satellite chassis could lead a demonstration that can make aerocapture appealing to future mission designers.

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