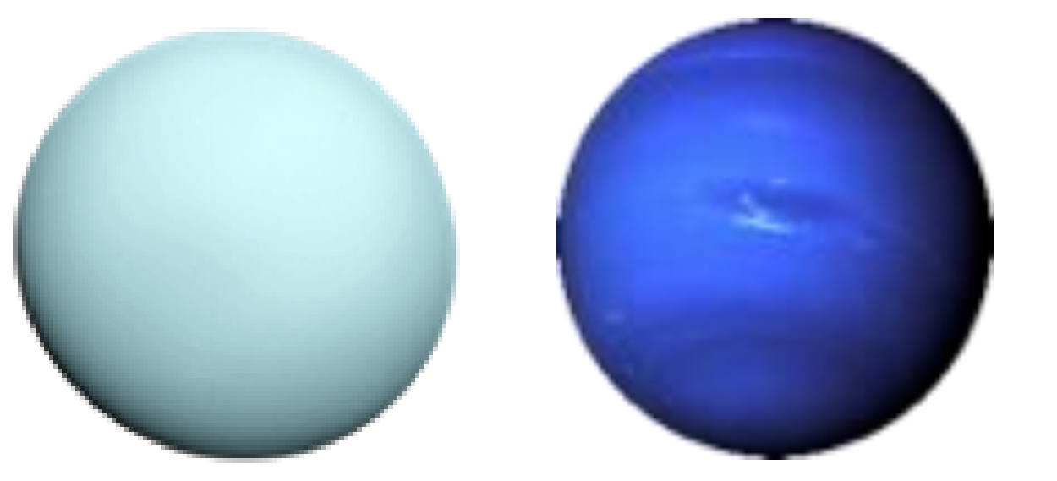
Investigation of Aerocapture Earth-Based Demonstration Options

Soumyo Dutta,[1] Rohan Deshmukh,[1] Evan Roelke,[2] Alejandro Pensado,[2] Min Qu,[2] and Nicholas Vitullo[2]
[1]NASA Langley Research Center, Hampton, VA, USA
[2]AMA at NASA Langley Research Center, Hampton, VA, USA

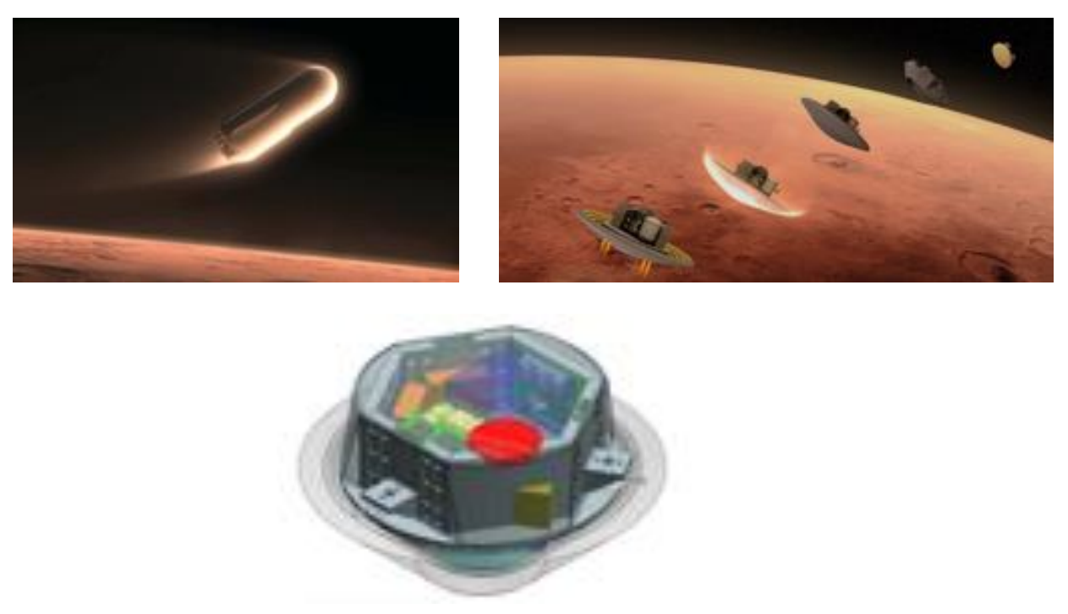
Submission ID: 32

Motivation

Aerocapture is an **atmospheric maneuver** that utilizes **aerodynamic forces** within a planetary atmosphere to **decelerate** a spacecraft and **achieve orbit insertion**. This maneuver reduces the level of propulsive maneuvers needed to achieve the desired capture orbit. Aerocapture is a **single pass** as opposed to aerobraking where multiple passes are required to target an orbit.



Uranus was selected in 2022 as the top destination for a future Flagship-class mission by the Planetary Decadal Survey[1]. The **Uranus Orbiter and Probe (UOP)** study, identified as the flagship mission of this decade, proposed a 2031 launch and utilized a fully propulsive orbit insertion design with a transient times ranging from 13 to 15 years. Ref. [2] investigated the impact of using aerocapture for a Uranus mission and demonstrated potential mass savings, increased launch opportunities (launch every 2 years through the 2030's and 2040's) including at high arrival velocities, and reduced transient time (2-3 years).



Besides Uranus, aerocapture can be an enabling technology for other scenarios: small satellite orbiter **constellations at Mars** to support **human-scale Mars missions**; deceleration of **low and mid lift-to-drag entry bodies for human-scale Mars** at a lower percentage of propellant mass; small satellite orbiter missions to **Venus** and **Titan**; and Earth orbit insertion of **cislunar assets** in **near-Earth exploration.**

Since aerocapture has never been demonstrated at any planetary destination, NASA, through the Aerocapture Demonstration Relevance Assessment Team **(ADRAT)**[3] and other studies[4], has demonstrated an interest in an Earth demonstration that can answer questions for applying aerocapture at other destinations and buy down risk. This work discusses what a mission like that might look like. **Table 1** lists some of the steps achievable by an Earth demonstration mission.

Table 1. Steps needed for aerocapture at planetary destinations and goals for Earth demonstration

Requirements	Demonstration
Hypersonic guidance for target orbit	Demonstrated on Mars (MSL/Mars2020) and Earth (EFT1). **Relevant demonstration with Earth demonstration.**
Thermal Protection System (TPS)	Necessary TPS (PICA/C-PICA) already demonstrated on Mars/Earth or selected (3MDCP) for future missions. **Used on Earth demo and perhaps at relevant conditions.**
Autonomous periapsis raise burn	**Will be demonstrated with Earth demonstration**
Control systems demonstration	**Earth demo can demonstrate relevant control systems (reaction control systems (RCS) or aerodynamic surfaces)**
Aeroshell release post-aerocapture	**Can be demonstrated with Earth demonstration**
Target tight entry corridors (entry flight path angle) using optical navigation	Not within scope of Earth demonstration, but technology has been proven on missions like Deep Space 1 (DS1)
Packaging science instruments, etc. within aeroshell	Feasibility has been shown in mission studies for planetary destinations[2]

Concept of Operations

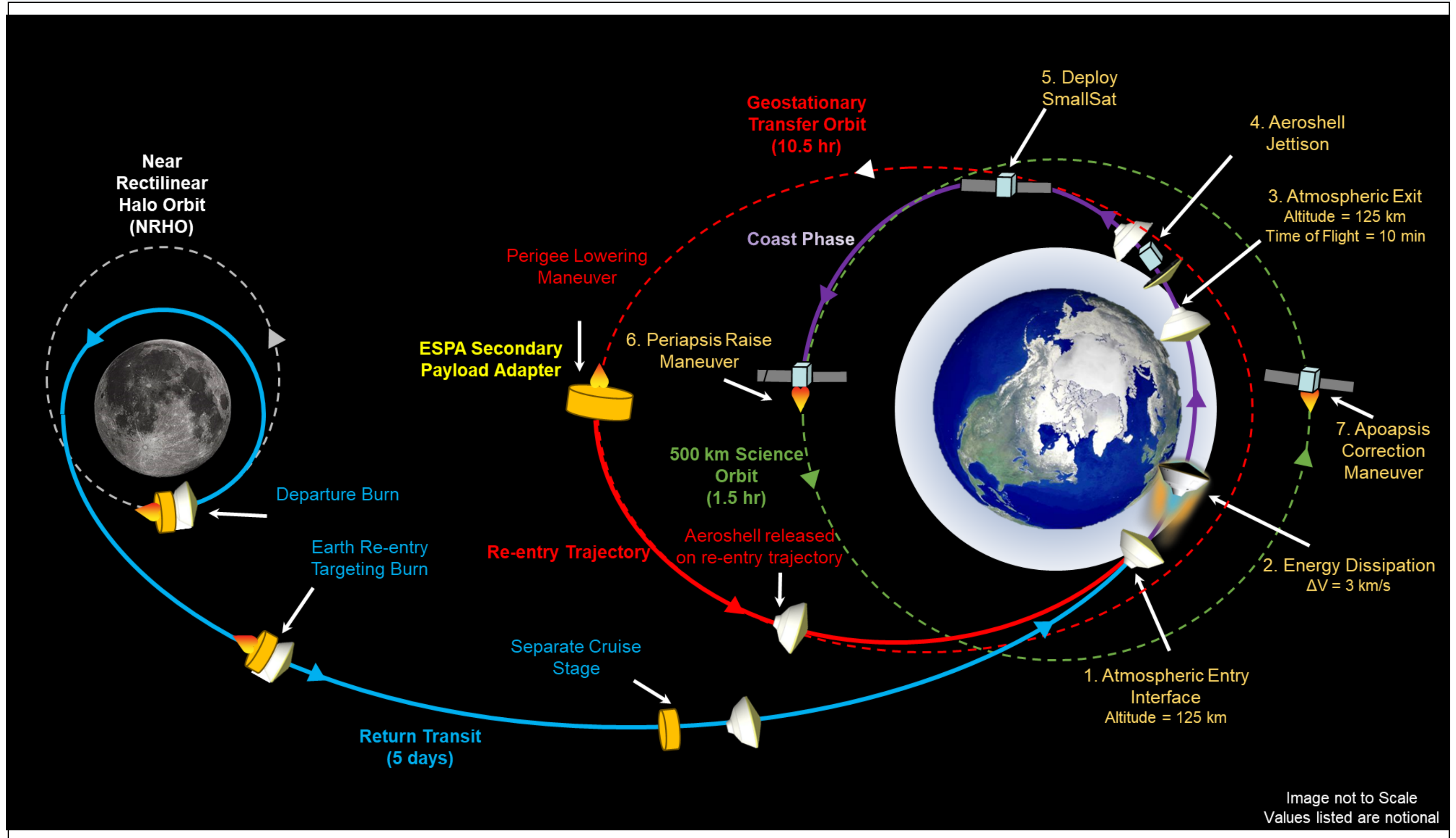


Fig. 1. Earth Aerocapture trajectories from Geostationary Transfer Orbit (GTO) or Lunar Return

Spacecraft Design

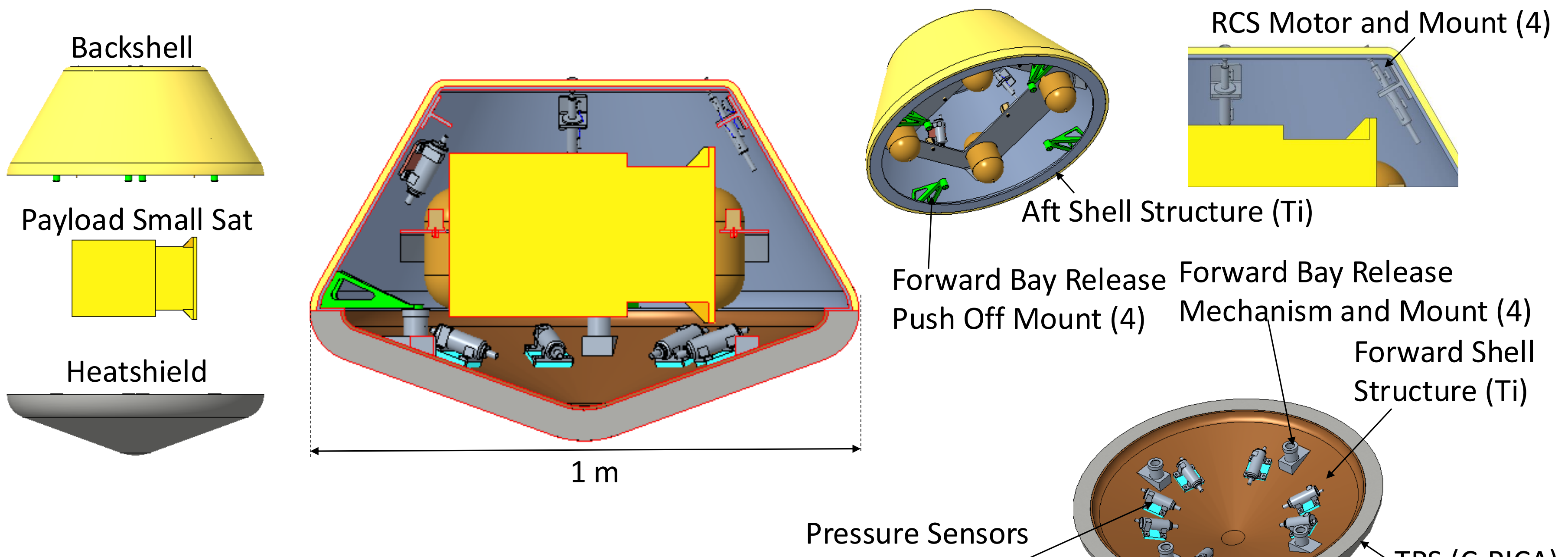


Fig. 2. Small satellite form-factor aerocapture demonstrator for ESPA and Falcon payload adapters

*Not pictured: Thermocouple plugs (7)

References

[1] Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032, The National Academies Press, 2022, 10.17226/26522 [2] Soumyo Dutta et al., Aerocapture Solutions for Uranus Flagship-Class Orbiter and Probe, AIAA SciTech 2025,AIAA 2025-1508, Orlando, FL [3] E. Dukes, et al., Report of the Aerocapture Demonstration Relevance Assessment Team (ADRAT), NASA STMD, 2023 [4] Civil Space Shortfall Ranking, NASA STMD, 2024. [5] Rohan Deshmukh et al., 6-DoF Uranus Aerocapture Trajectory Analysis, AIAA SciTech 2025, AIAA 2025-1510, Orlando, FL [6] Pardha Sai Chadalavada et al., Onboard Navigation Error Analysis for Aerocapture at Uranus, AIAA SciTech 2025, AIAA 2025-1707, Orlando, FL

Modeling and Simulation

Performance analysis of the pre-phase A concept was conducted in Program to Optimize Simulated Trajectories II (POST2) using best practices used for planetary missions and the Uranus aerocapture study.[5,6]

- The following sub-discipline data/models are included:
  - Mission Design and Navigation (MDNAV) at Entry Interface (EI) minus 10 mins initial conditions
  - Guidance, Navigation, and Control (GNC) with Fully Numerical Predictor Corrector Aerocapture Guidance (FNPAG) guidance delivered from Entry Guidance team
  - No active lateral logic for GTO
  - Aerodynamics tailored for Earth 70 deg sphere-cone
  - Aerothermal database for aerocapture conditions

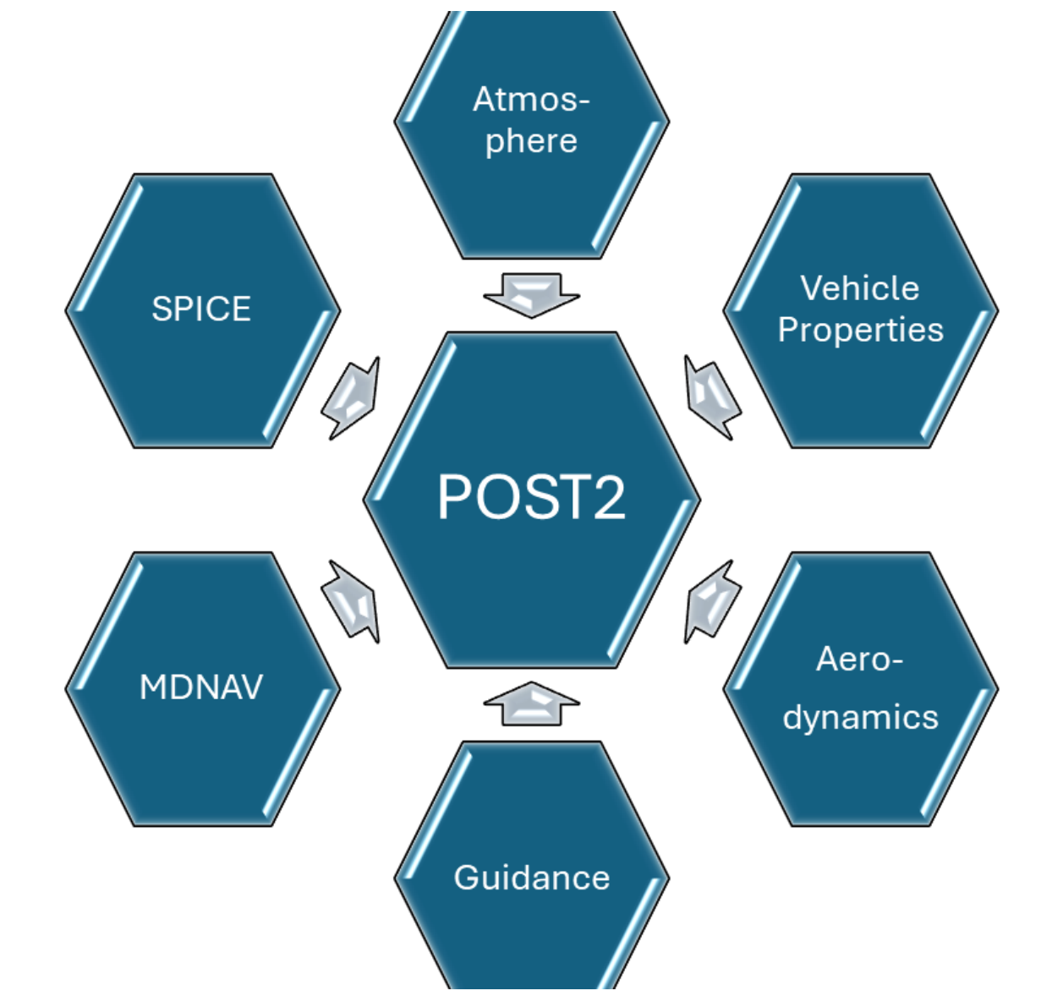


Fig. 3. Overview of the models incorporated for the integrated performance simulation

- Vehicle Properties:
  - 70 deg. sphere cone
  - 1 m reference diameter
  - 0.25 m nose radius
  - 180 kg Maximum Possible Value mass
  - 163 kg/m^2 ballistic coefficient (β)
  - Lift-to-drag ratio L/D = 0.25
- Atmosphere Properties:
  - Gram Suite v2.1
  - Sutton-Graves Constant: 1.7623x10^{-4} √kg/m
- GNC Target:
  - 500 km circular target orbit

Aerocapture Performance

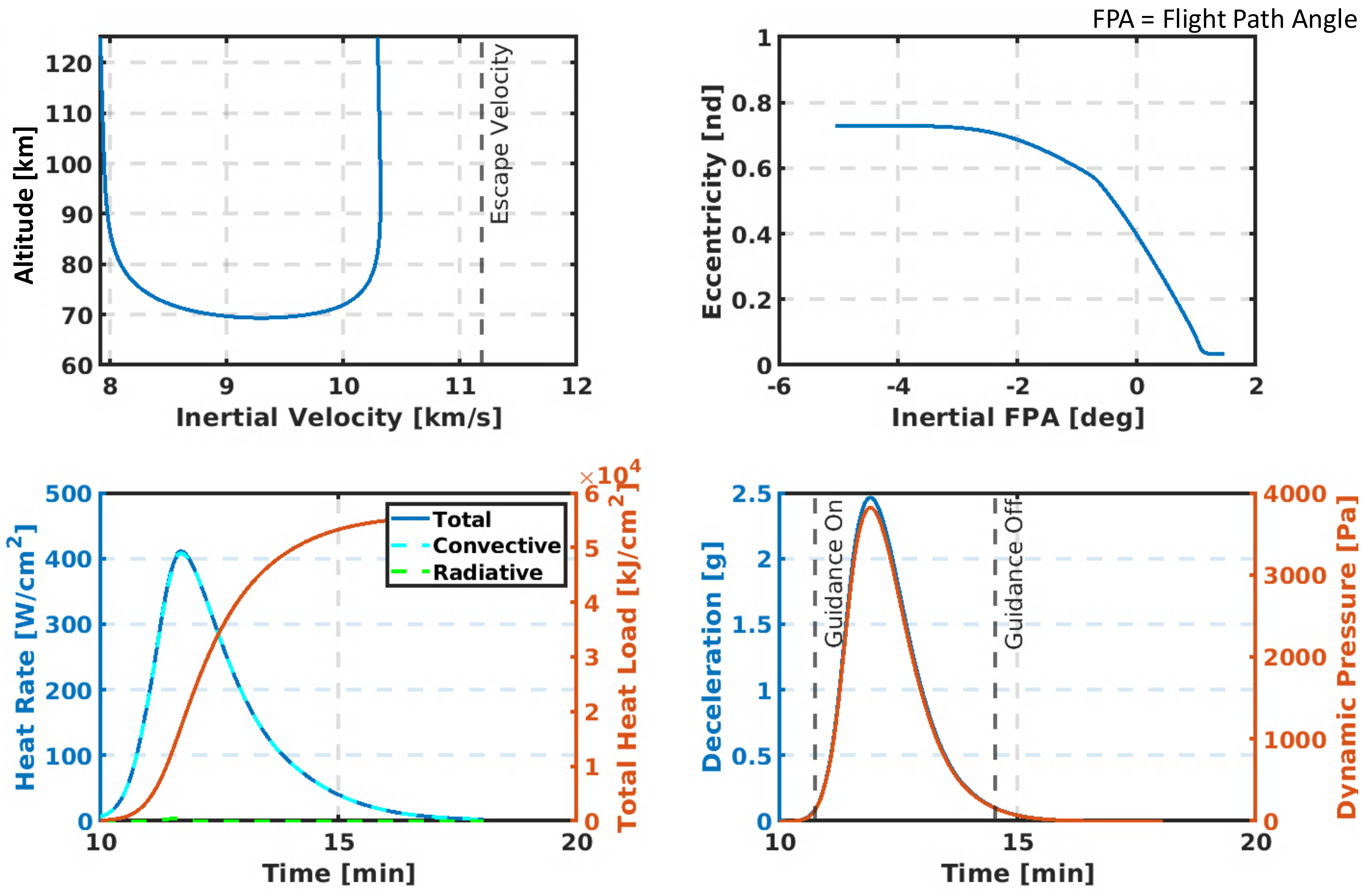


Fig. 4. GTO concept of operations aerocapture performance

Table 2. Monte Carlo simulation results for Earth GTO concept and Uranus aerocapture

	Earth (GTO Concept)	Uranus
Dissipated ΔV (km/s)	3 (99%-tile)	4.5 (99%-tile)
Peak Total Heat Flux (W/cm^2) (margined)	480 (99%-tile)	320 (99%-tile)
Integrated Heat Load (kJ/cm^2)	70 (99%-tile)	80 (99%-tile)
Peak Deceleration (G's)	3.65 (99%-tile)	1.75 (99%-tile)
Time of Flight within Atmosphere (min)	10 (99%-tile)	13 (99%-tile)
Percent Success in Captured Orbit	99+%	99+%

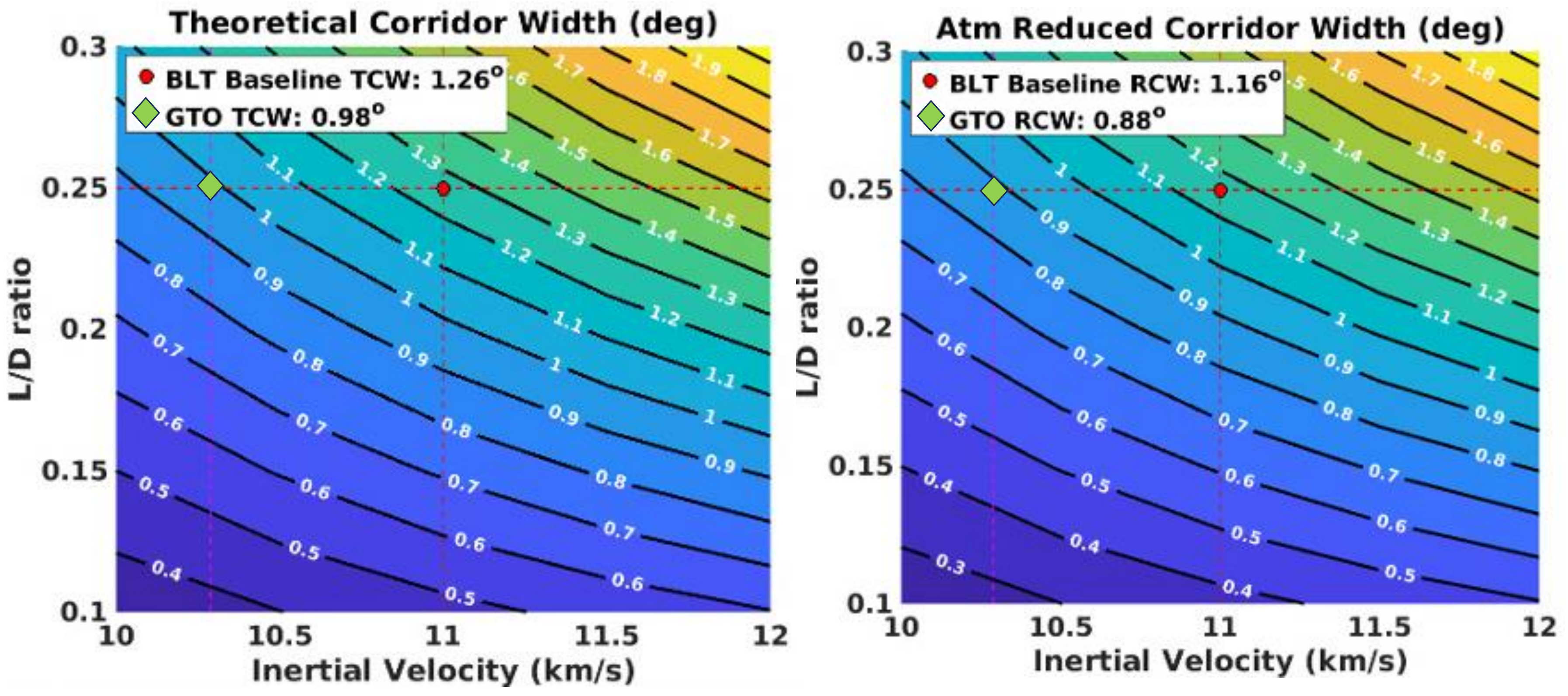


Fig. 5. Comparison of GTO and Lunar Return (BLT) theoretical corridor width (TCW) and reduced corridor width (RCW) to understand aerocapture guidance performance and margin

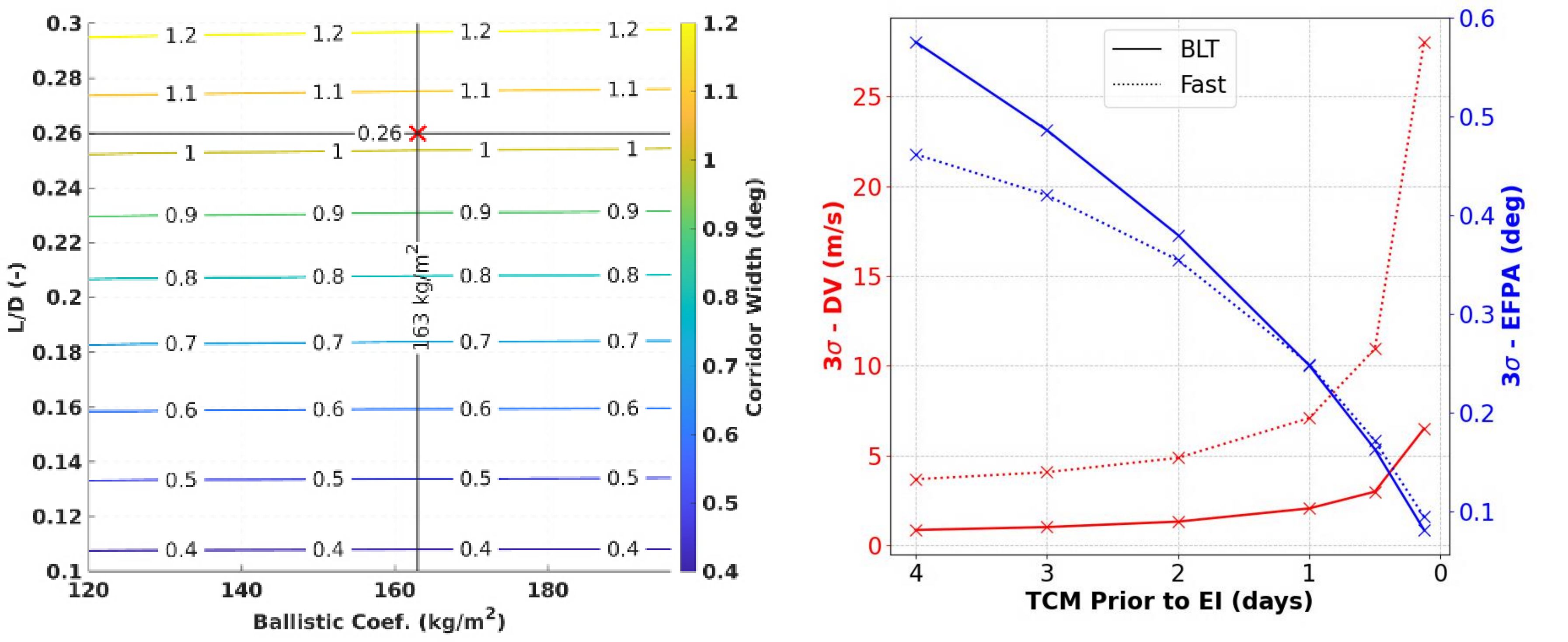


Fig. 6. Aerocapture performance sensitivity due to ballistic coefficient and entry flight path angle (EFPA) possibilities based on MDNAV design with a variety of trajectory correction maneuver (TCM) choices