

National Aeronautics and
Space Administration

Aerocapture to Reliably Reduce Inertial
Velocity With Aerodynamics and Lift



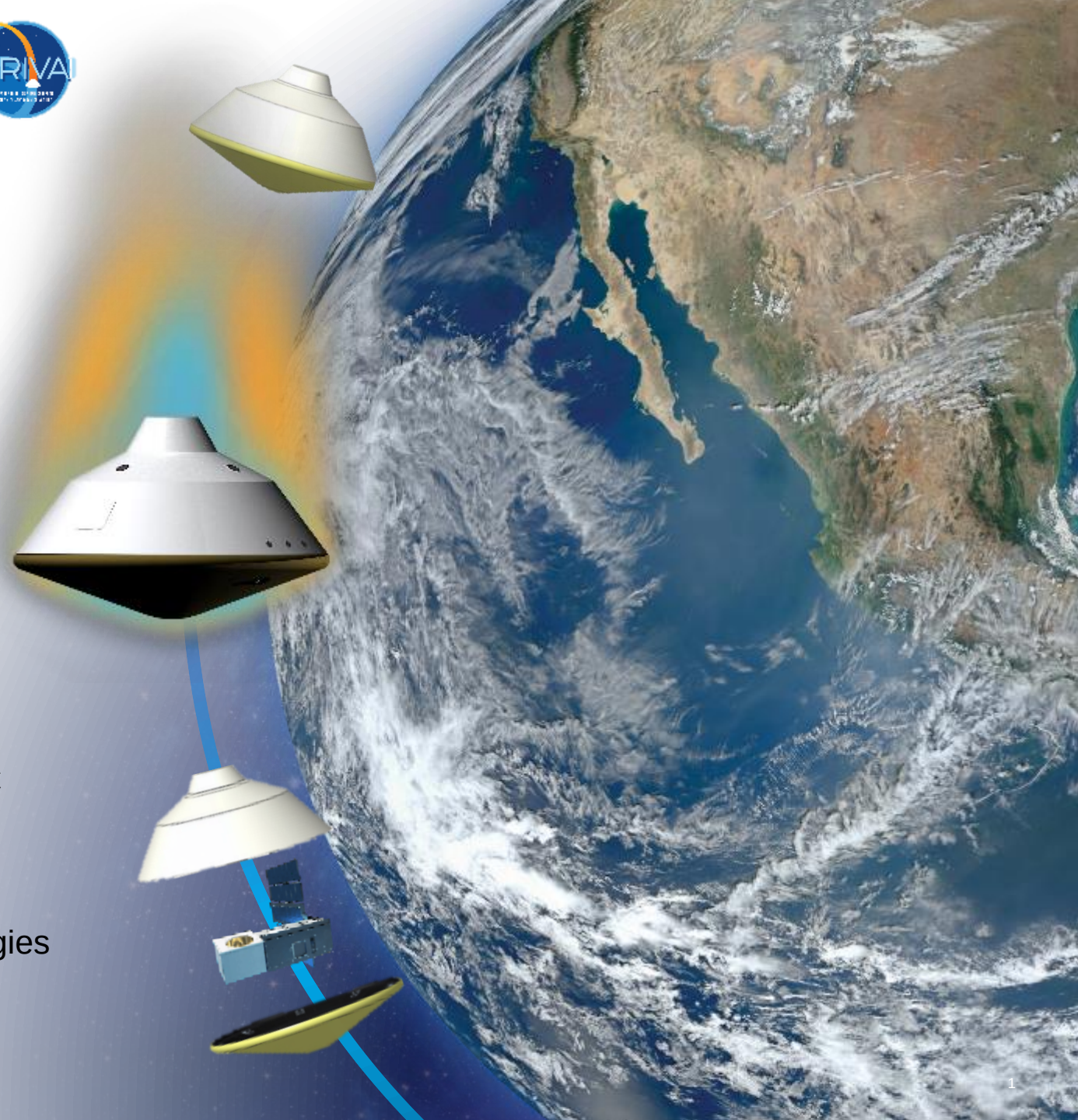
Comparison of Earth SmallSat Aerocapture Demonstration Trajectory Opportunities

AIAA SciTech Forum 2026

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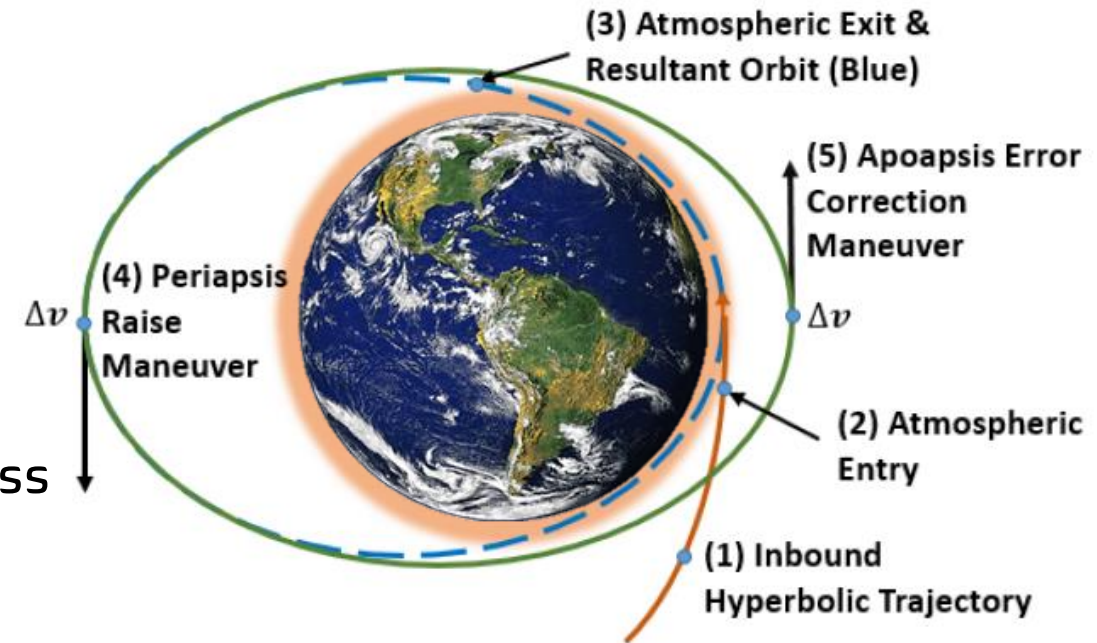
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What is Aerocapture?

- Capture into enclosed orbit with single atmospheric pass from inbound hyperbolic trajectory
- Requires thermal protection and active guidance, navigation, and control (GNC).
- Potential benefits of aerocapture:
 - Reduce interplanetary transit times
 - Reduced orbit insertion burn $\rightarrow$ more on-orbit mass
 - Enable certain missions (e.g. outer ice giants)



An Earth aerocapture technology demonstration mission (TDM) – ARRIVAL – could buy down perceived risks of the maneuver to increase applicability for use at other planetary bodies

Benefits of an Earth aerocapture TDM discussed more in Soumyo Dutta et. al (AIAA SciTech 2026)



Outline

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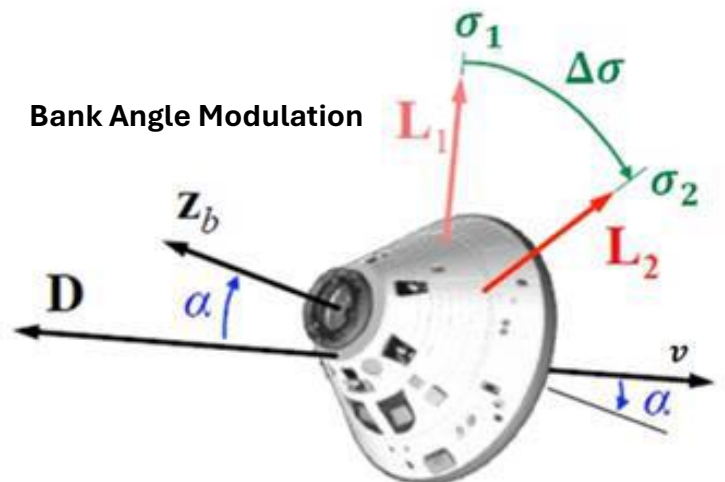
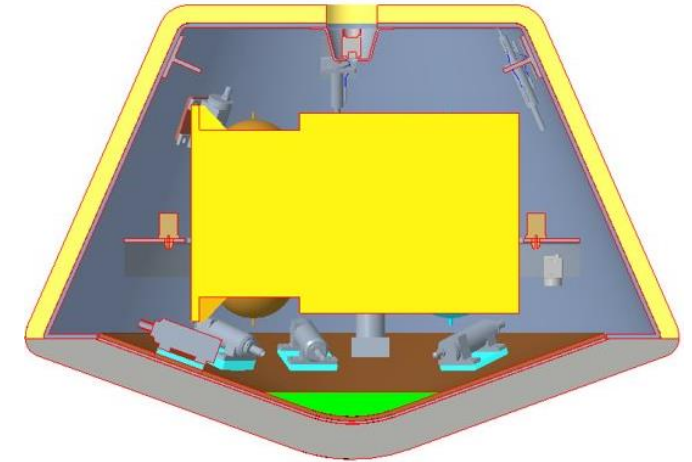


- Aerocapture mission overview
- Mission Concept of Operations (CONOPs)
- Trajectory option overview/qualitative comparison
- Simulation development overview
 - Sub-discipline overviews
- Sensitivity studies
- Nominal results
- Monte Carlo results
- Monte Carlo trade study results

What is ARRIVAL?

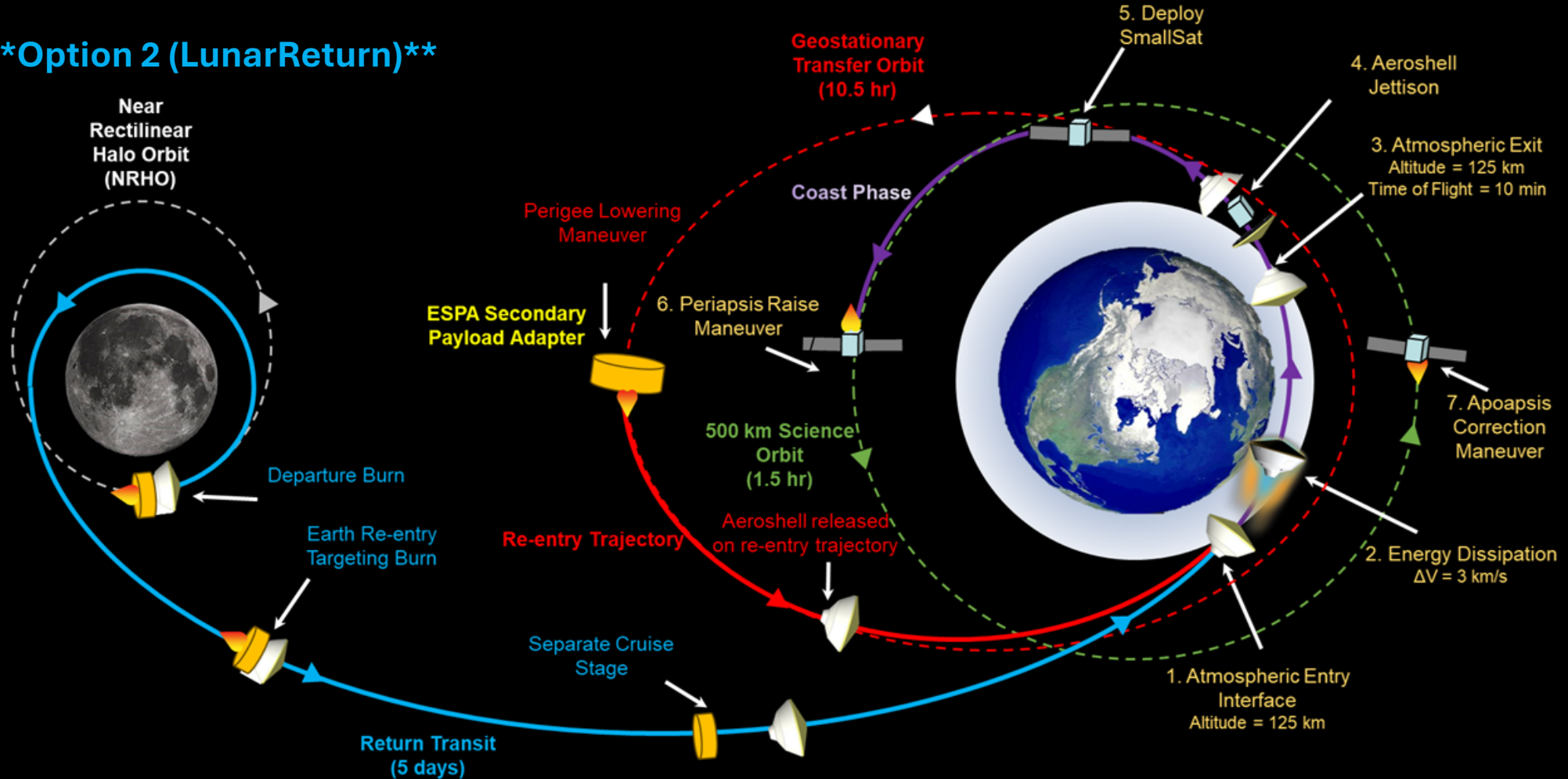
- **ARRIVAL: Aerocapture to Reliably Reduce Inertial Velocity with Aerodynamics and Lift**
 - Technology demonstration mission to execute an end-to-end aerocapture mission
 - Respond to perceived risks from 2022-2023 Aerocapture Demonstration Relevance Assessment Team (ADRAT) report
 - Leverage heritage aeroshell design (70deg spherecone) and control architecture (bank modulation via reaction control system)
 - Designed to fit CAPSTONE-sized payload (12u CubeSat)
 - Strong emphasis on enabling aerocapture applicability to a wide range of planetary destinations and missions (e.g. Mars, Titan, Uranus, Venus, Earth return)
- First year of development considered two “Pre-Phase A” Earth entry options:
 - Return from geostationary orbit (GTO)
 - Return from Lunar near-rectilinear halo orbit (NRHO)
 - Ballistic Lunar Transfer (BLT):
 - Smaller departure ΔV
 - Higher orbit energy $\rightarrow$ Faster entry speed
 - Longer travel time (90-150 days)
 - Fast Lunar Return (FastLunar):
 - Powered lunar flyby
 - Shorter interplanetary travel time (5-8 days)

ARRIVAL Aeroshell concept



CAPSTONE = Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment

Option 2 (LunarReturn)



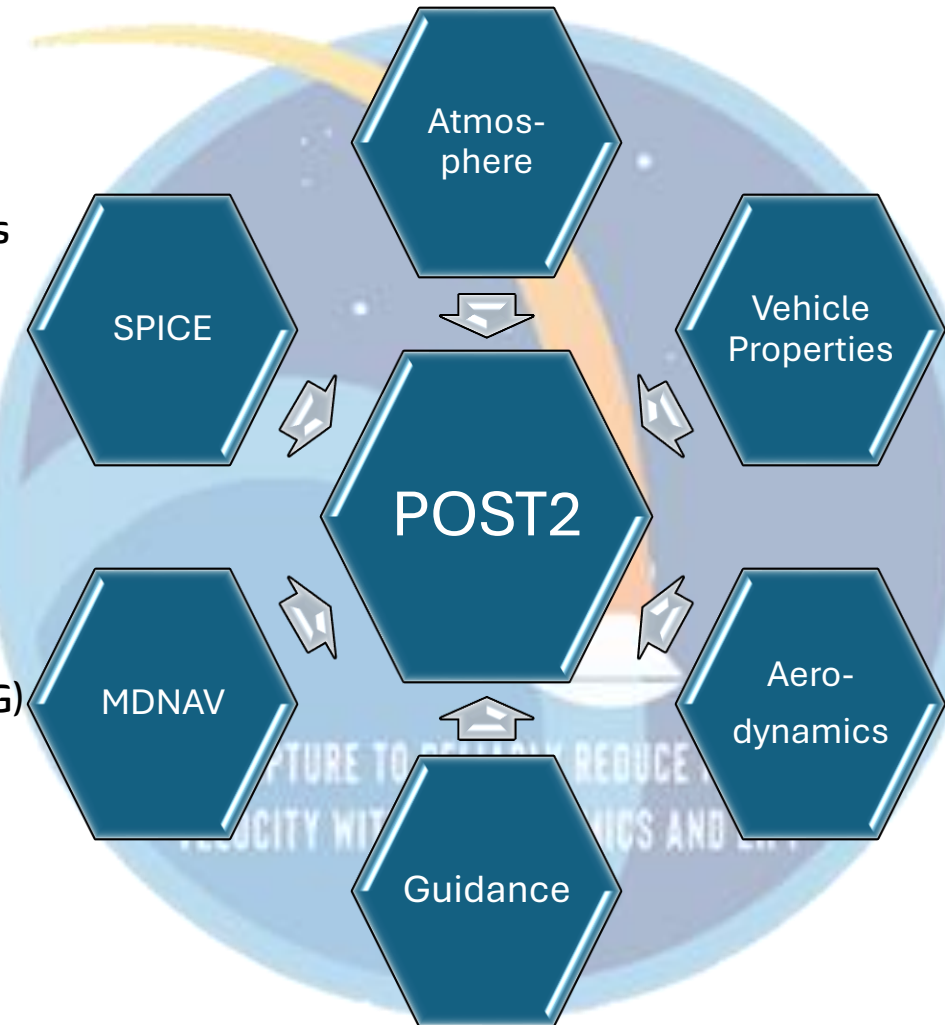
Option 1 (GTO)

Category	GTO	Lunar Return	Notes
Entry Speed	– Lower	+ Higher	Lower entry speed means less controllability, total aerocapture ΔV
Aerothermal	≈ Less stressing	≈ More stressing	Stressing thermal materials might support technology advancement
Launch opportunities	+ Currently more opportunities – Fewer expected	– Currently fewer opportunities + More expected	Currently more GTO opportunities due to established market. Growing market for Lunar return
In-space transit	+ Short	– Long	In-space radiation environment, micro-meteorite impacts, heat source for instruments, etc
Cruise stage	+ No cruise stage required	– Requires a cruise stage	Cruise stage adds mass/complexity

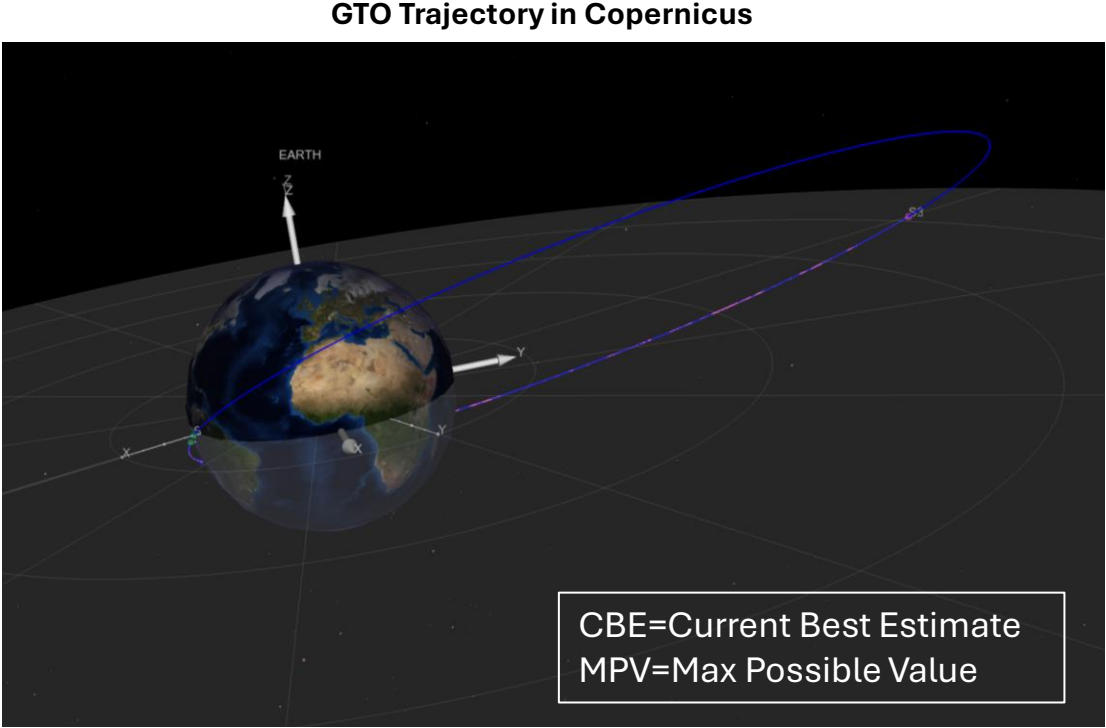
– = less desirable
 + = more desirable
 ≈ = neutral

- **Program to Optimize Simulated Trajectories II (POST2)**
 - Incorporates all sub-discipline data/models into end-to-end aerocapture simulation
- **Atmosphere:**
 - Global Reference Atmospheric Model (GRAM) Suite v2.1
 - Standardized atmosphere for Knudsen, Reynolds number calculations from atmospheric composition data
- **Vehicle Properties:**
 - 1m diameter, 70deg sphere cone
 - 0.25m nose radius
 - 180 kg and 255 kg masses considered
 - Trim AOA of -17deg → continuum L/D = 0.25
- **Aerodynamics: ARRIVAL aerodatabase (ADB) v1.0**
- **Guidance: bank angle modulation**
 - Fully Numerical Predictor-corrector for Aerocapture Guidance (FNPAG)
 - 500 km circular orbit target
 - See Julia Briden et. al (2026) for more details
- **Mission Design Navigation (MDNAV)**
 - Copernicus generates entry interface (EI) and EI-10min initial states
- **SPICE - Consistent planetary ephemeris/frame definitions across different tools**

ARRIVAL POST2 Flight Mechanics Simulation



- Modeled in Copernicus
- Target desired entry state at entry interface (EI)
 - Entry flight-path angle (EFPA) target determined from open-loop lift-up and lift-down solutions
- Four vehicle configurations considered
 - Representative of various design cycle iterations

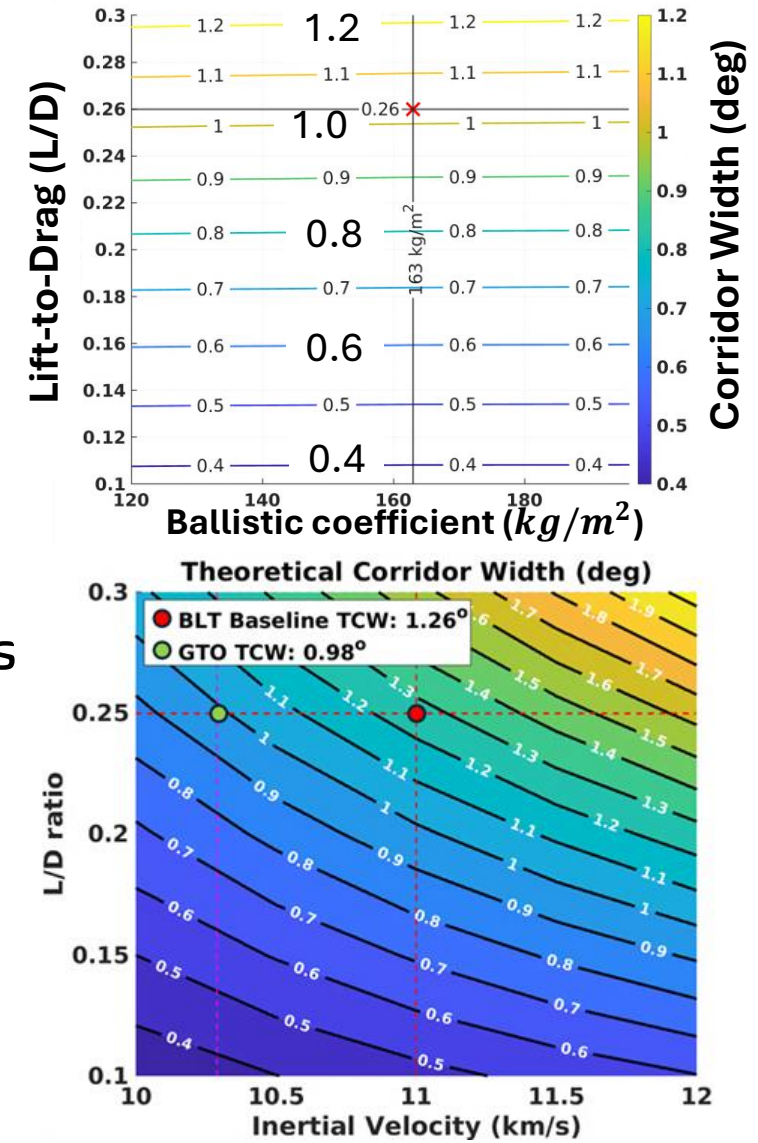


Scenario	Mass (kg)	L/D	Entry Velocity (km/s)	EFPA Target (deg)	EFPA 3 σ (deg)
GTO-CBE	180	0.25	10.3	-5.06	0.37
FastLunar	180	0.25	10.9	-5.57	0.38
BLT	180	0.25	11	-5.61	0.36
GTO-MPV	255	0.25	10.3	-5.14	0.37

Tradespace Analysis

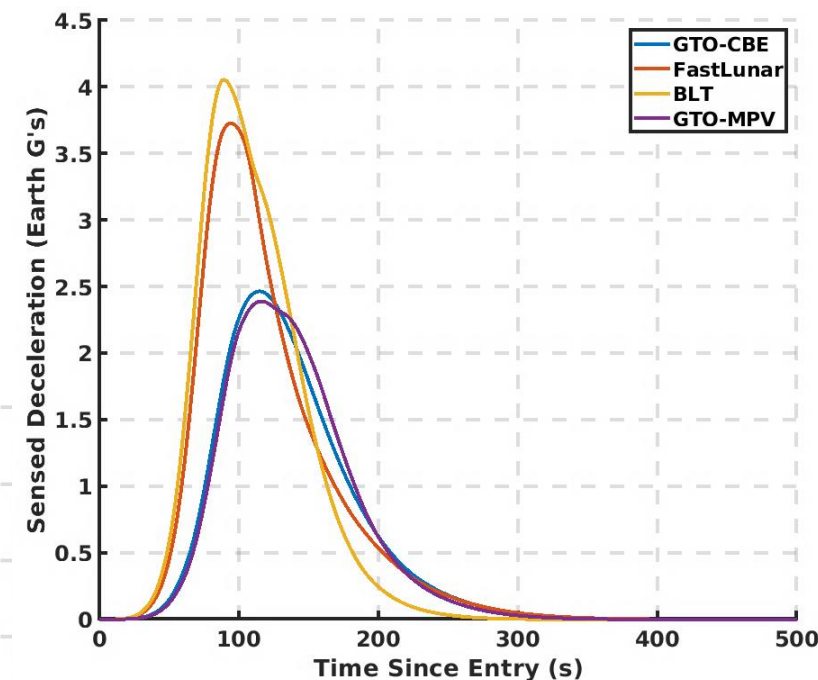
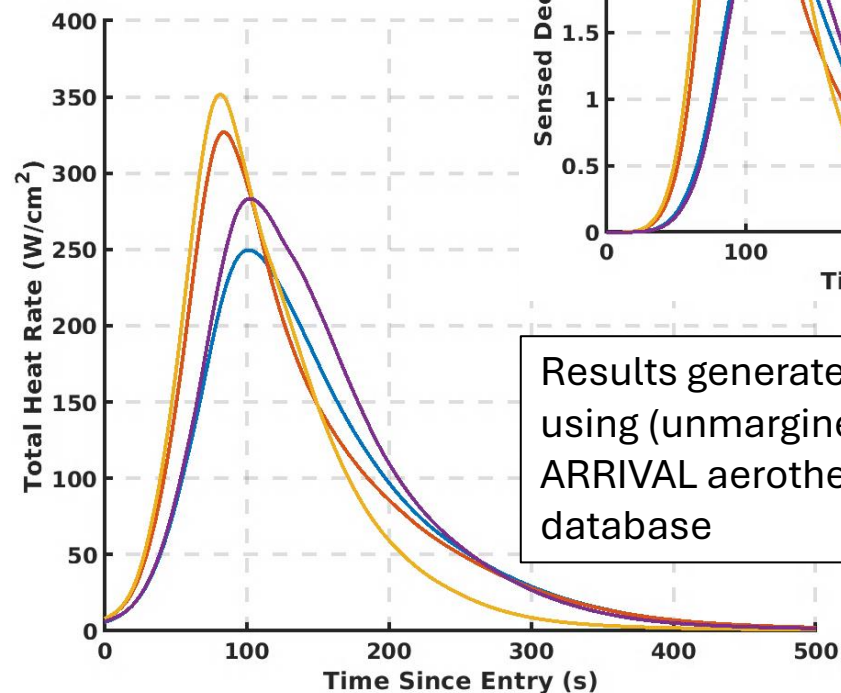
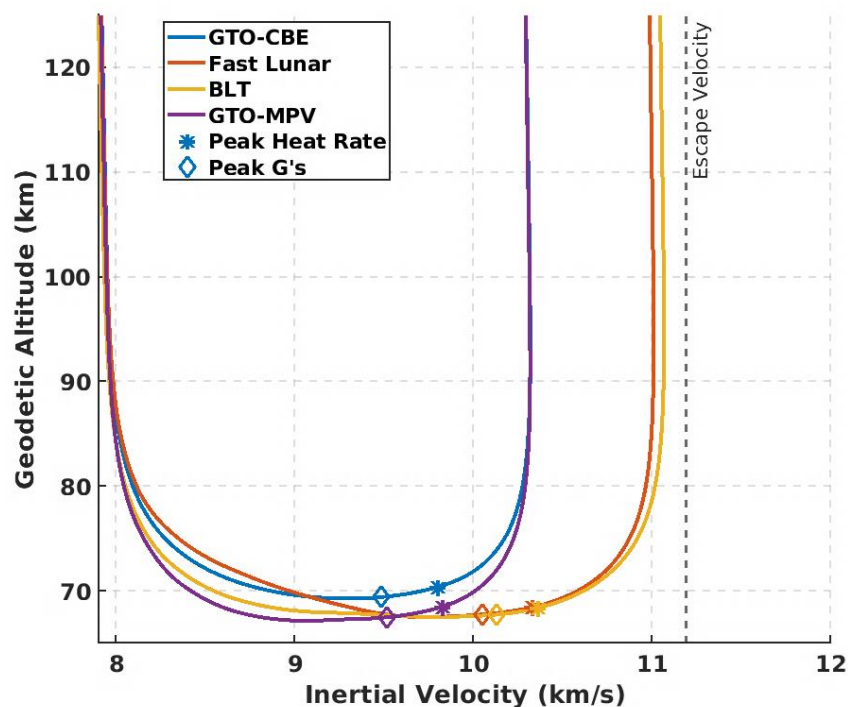
- Theoretical corridor width (TCW) defines fly-able corridor to still attain apoapsis target (with active guidance and control)
 - Metric to quantify vehicle's control authority
- Trade studies on TCW help inform future design iterations
 - For example, TCW is largely insensitive to small mass changes
 - Ballistic coefficient, $\beta = \frac{m}{C_D A_{ref}}$
 - Can quantify changes in TCW for design parameters such as L/D, entry velocity to understand e.g. uncertainty margins

Scenario	L/D	v_{entry} (km/s)	TCW (deg)	EFPA 3σ (deg)
GTO-CBE	0.26	10.25	1.02	0.37
FastLunar	0.25	11	1.26	0.38
BLT	0.25	11	1.26	0.36
GTO-MPV	0.25	10.25	0.98	0.37



Nominal Performance

- Lunar return has higher entry speeds $\rightarrow$ more stressing to TPS
- GTO MPV increases mass over CBE
 - Steeper EFPA $\rightarrow$ lower periapsis altitude
 - Peak Heat Rate increases from $\sim 250 \text{ W/cm}^2$ to $\sim 290 \text{ W/cm}^2$
- Peak deceleration environment is relatively benign



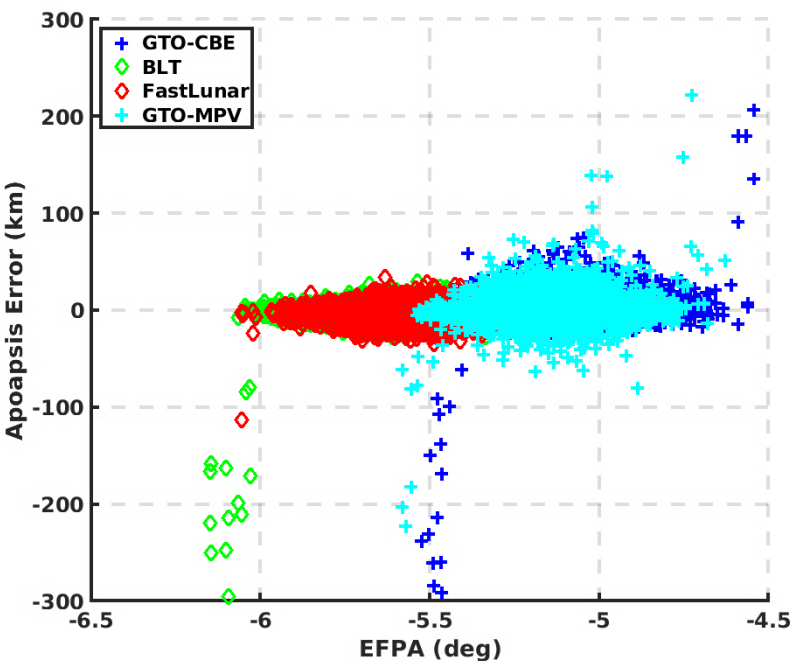
Results generated
using (unmargined)
ARRIVAL aerothermal
database



Baseline Monte Carlo Results



- Monte Carlo dispersion sources:
 - Initial States – MDNAV dispersed initial states
 - Atmosphere – GRAM Suite model
 - Mass - $\pm 10\%$ normally distributed
 - Aerodynamics – Aerodatabase
- Lunar return scenarios appear more robust in apoapsis targeting, but have highest PRM costs due to lowest periapsis altitudes
- Can see cases starting to exceed entry corridor limits at both steep & shallow ends
 - Steep side exceedances less favorable due to risk of surface impact



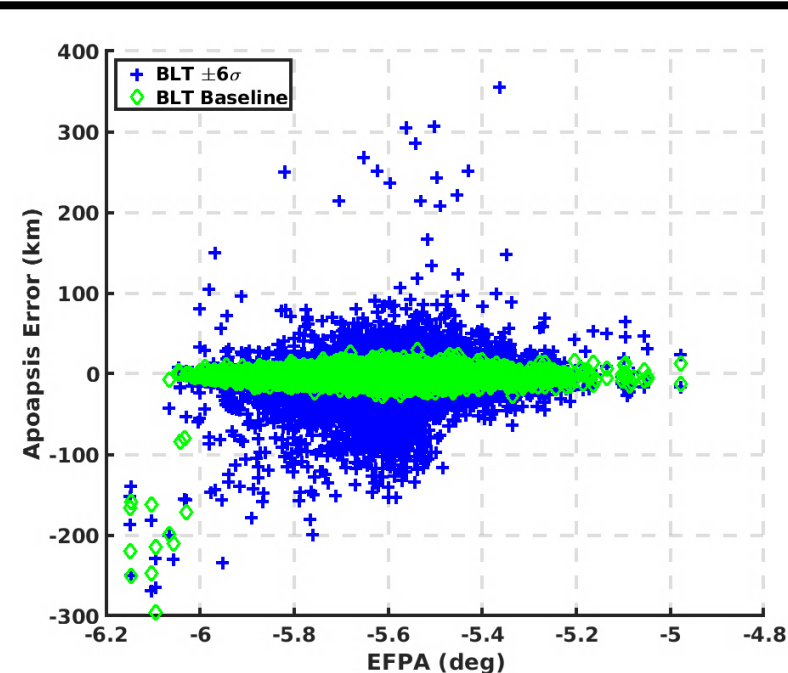
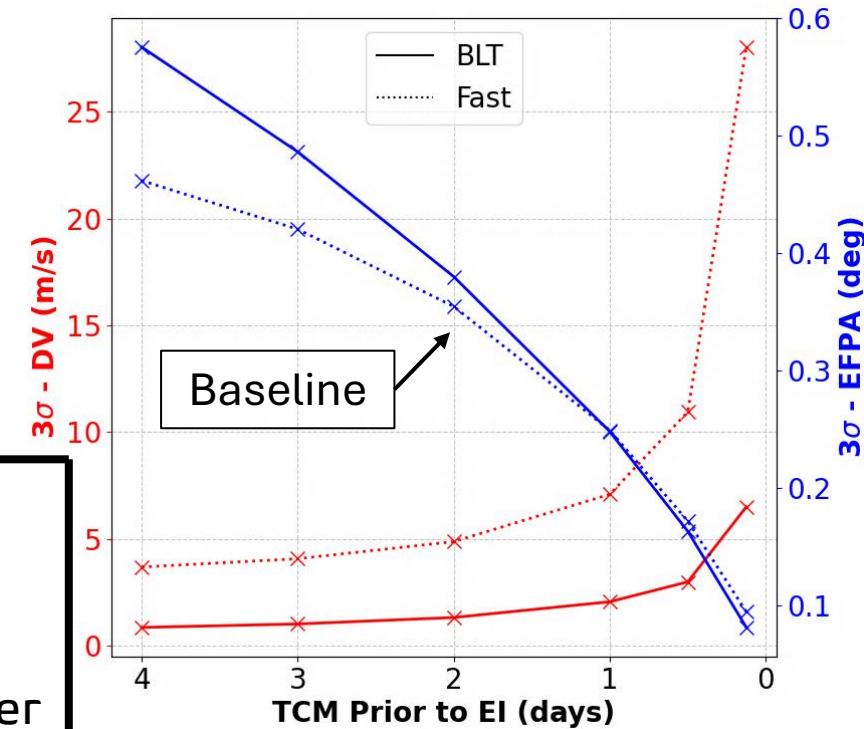
- No surface impacts
- All 99 %-tile apoapsis errors less than 50 km (10% of apoapsis target)

	Surface Impacts	Apoapsis Error 99%-tile (km)	PRM 99%-tile ΔV (m/s)
GTO-CBE	0 (0%)	36.8	140.3
BLT	0 (0%)	17.4	159.2
FastLunar	0 (0%)	21.8	159.2
GTO-MPV	0 (0%)	40.7	153.5

PRM = Periapsis Raise Maneuver

• Lunar Return TCM Timing

- Gives insight into entry performance as a function of TCM burn timing/magnitude
- FastReturn option shows higher ΔV costs with diminishing EFPA uncertainty benefit



• High Atmospheric Density Study: $\pm 3\sigma$ vs $\pm 6\sigma$

- Atypically-large density uncertainties demonstrate aerocapture robustness for other planetary bodies
- Larger, but not prohibitive, targeting errors suggest that the ARRIVAL design is robust to high density environments
- Responds to a high-risk item from the ADRAT report



Summary

- Aerocapture can be used to reduce orbit insertion costs and/or support additional on-orbit mass
- Earth technology demonstration mission, ARRIVAL, developed to increase viability of aerocapture at other destinations
- Both GTO and Lunar Return options assessed both qualitatively and quantitatively
- Lunar Return options showed better apoapsis targeting performance, but lower periapsis altitudes increased PRM costs compared to GTO
- Results show aerocapture can be successfully demonstrated by all considered trajectory options



Thank you!

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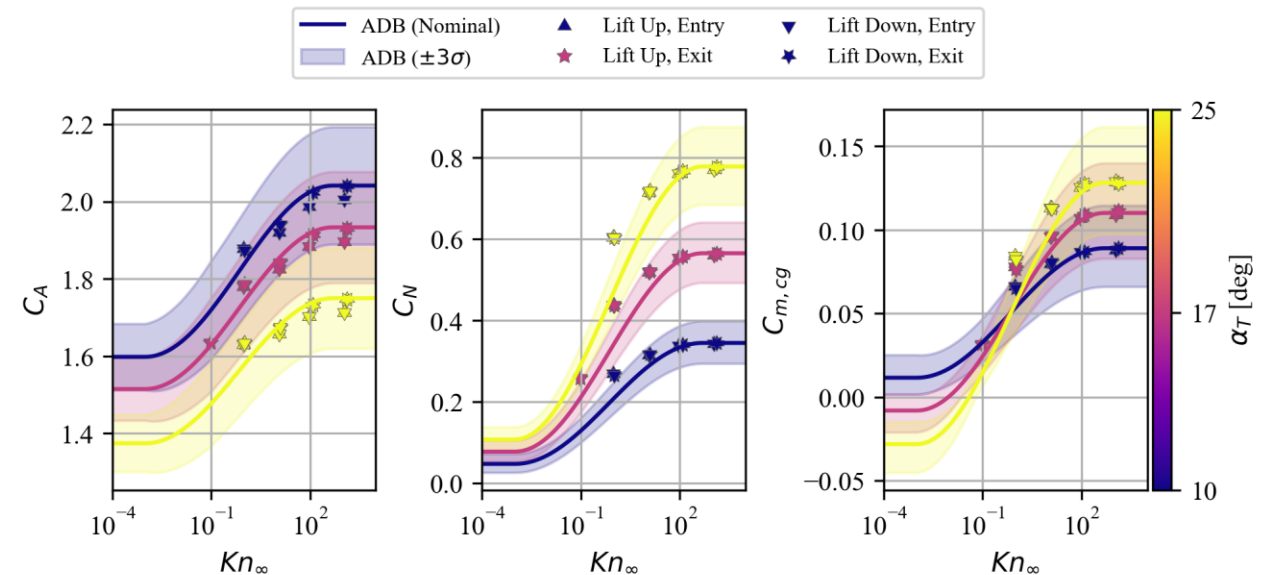
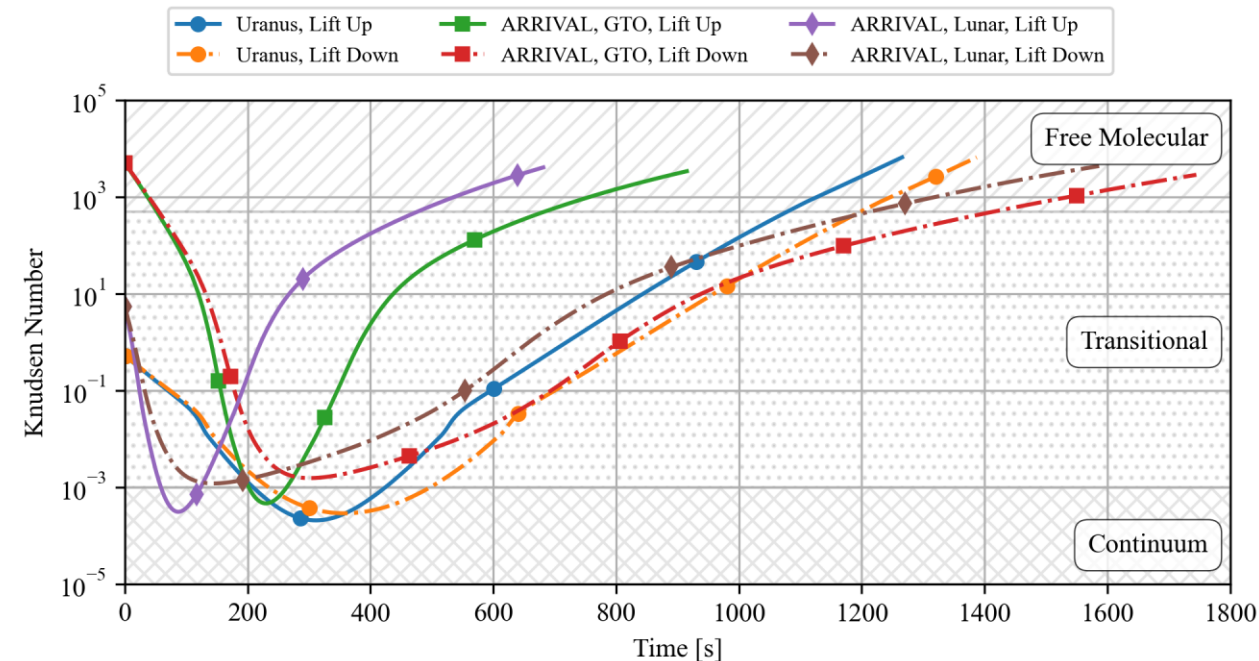


Questions?

- Biggest Aerocapture Risks:
1. Atmospheric Density Uncertainty
 2. Aerocapture uncertainties (e.g. vehicle properties, post-aerocapture burn targeting)
 3. Poorly –understood aerothermal environment (risk to TPS)

	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

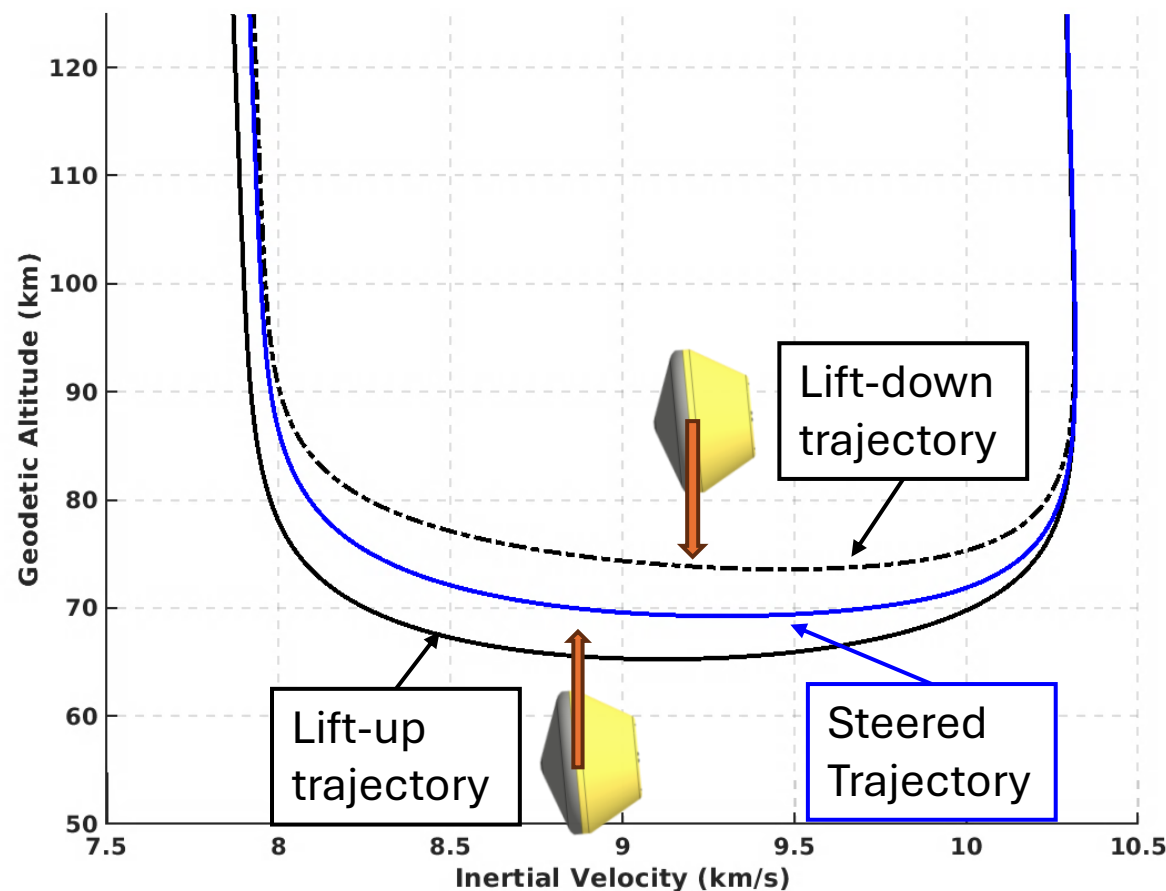
- ARRIVAL-specific aerodatabase (ADB) developed to characterize steady and unsteady aerodynamics of the aeroshell
- MSL-like forebody and Stardust-like backshell allows heritage aerodatabase use
- Vehicle spends considerably more time in rarefied/transitional flow regimes (as opposed to continuum) compared to typical entry vehicles
 - Similar Knudsen number profiles to Uranus aerocapture simulation supports assertion that Earth aerocapture demo improves applicability to other planetary destinations
- Leverage tools such as the Multiphysics Algorithm with Particles (MAP) to obtain Direct Simulation Monte Carlo (DSMC) solutions in these regimes to augment heritage data



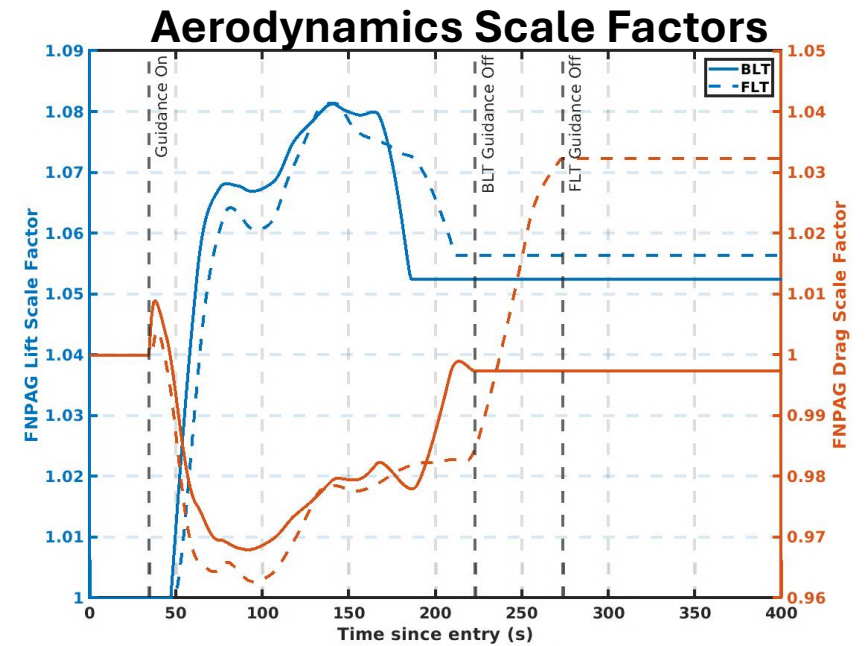
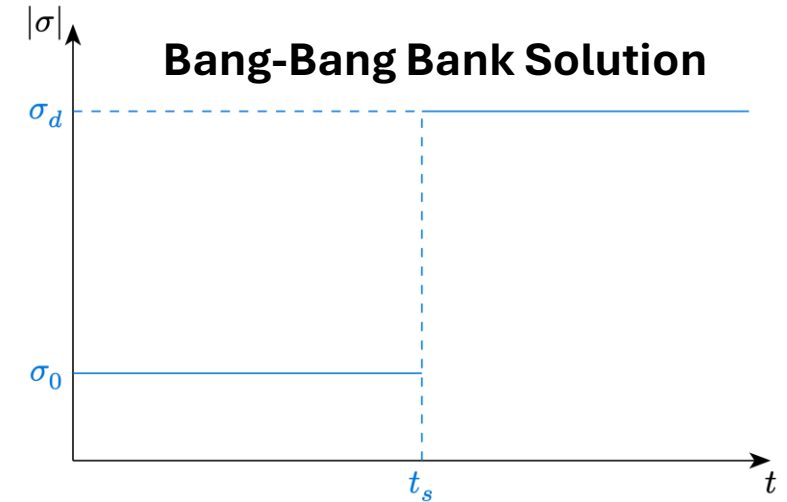
MAP static aero uncertainty bounds

Entry State Targeting

- Fly-able corridor bounded by full lift-up and full lift-down trajectories
 - Defines a 'theoretical corridor width' (TCW)
 - Quantified by the difference in entry flight-path angles (EFPAs) of the respective trajectories that achieve desired apoapsis altitude target
- Atmosphere, aerodynamics, mass property, etc dispersions further reduce corridor ('Reduced corridor width', or RCW)
- Higher L/D ratio increases the TCW size, making it a convenient metric for quantifying vehicle control authority

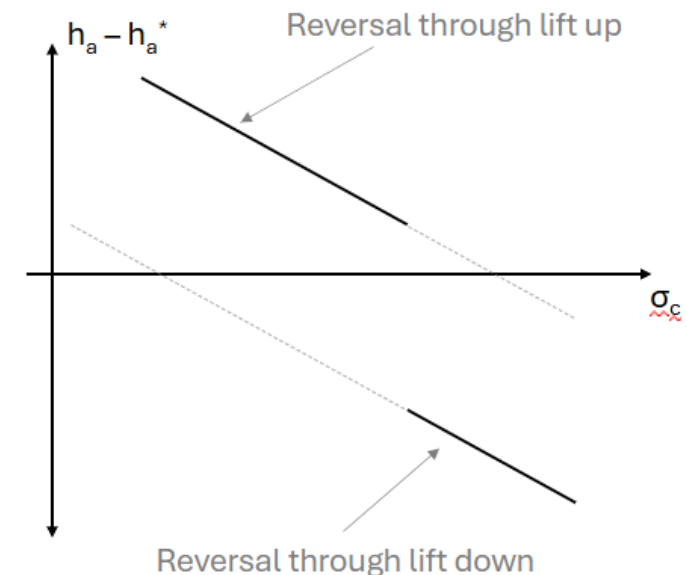
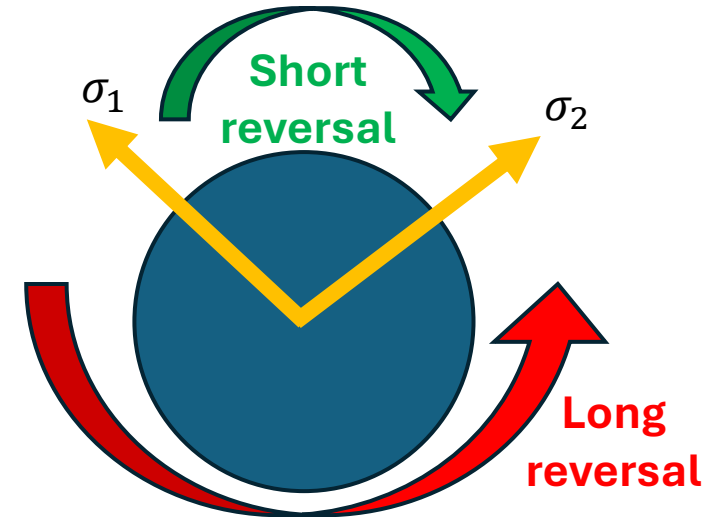


- Active guidance is needed to steer the vehicle through the atmosphere to mitigate vehicle and atmospheric uncertainties
- Fully Numeric Predictor-corrector Aerocapture Guidance (FNPAG)¹
- Two-phase guidance to target a final apoapsis
 - Phase 1 commands lift up, propagates using the user-defined σ_d , and solves for t_s (optimal bang-bang solution)
 - Phase 2 solves for a constant bank angle command
- Estimators use sensed acceleration to scale the on-board models of density and aerodynamics
- Guidance team uses their simulation tool, Genesis, for guidance algorithm tuning
- See Briden et. al (2026) for more details



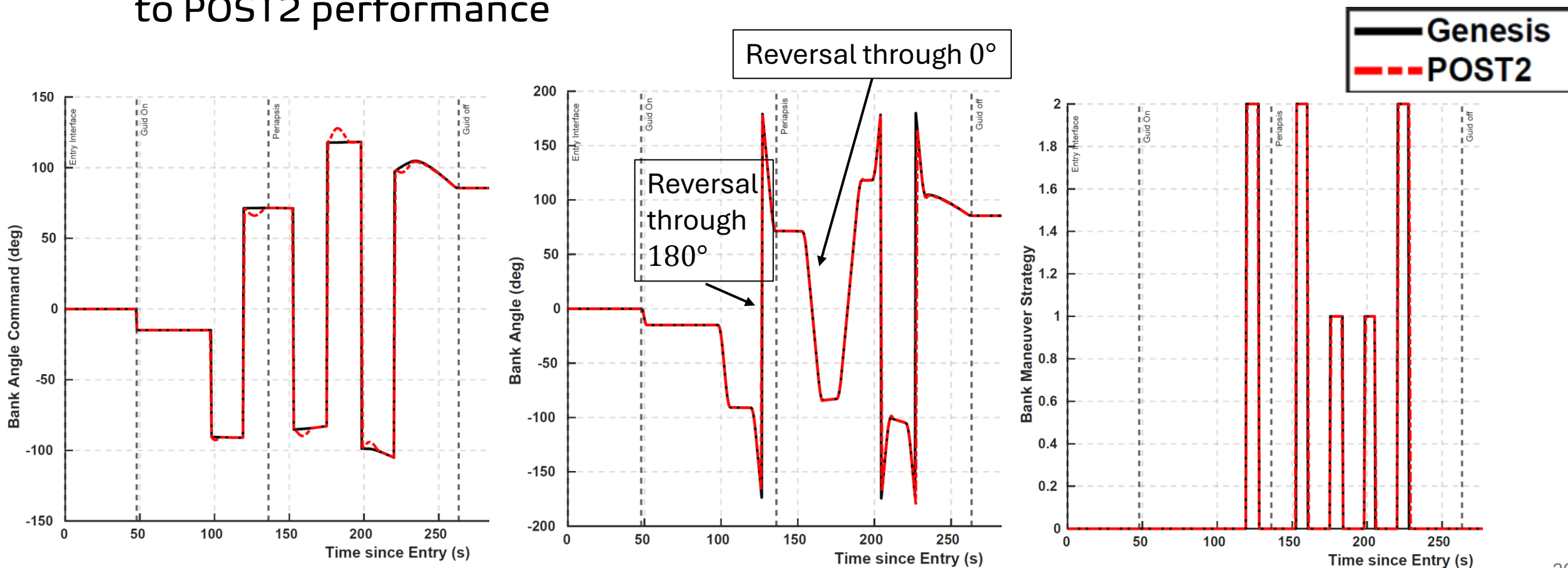
¹Ping Lu et al., "Optimal Aerocapture Guidance," Journal of Guidance, Control, and Dynamics (2015). DOI: 10.2514/1.G000713

- Bank reversals to manage inclination error
- User specifies a target inclination and target longitude of ascending node
- Geometric reduction in lateral error using no more than a user-specified number of reversals²
 - Predicts both with and without a reversal and compares the ratio of lateral errors to a trigger value
 - Sensitivity studies performed to determine ideal number
- Predictor models finite bank rate and acceleration
- Guidance team has augmented the original algorithm to consider the ideal direction of the reversal
 - Prioritizes shortest reversal duration since it is an open-loop control event
 - Relevant to the goal of turning the entry guidance code into GFE

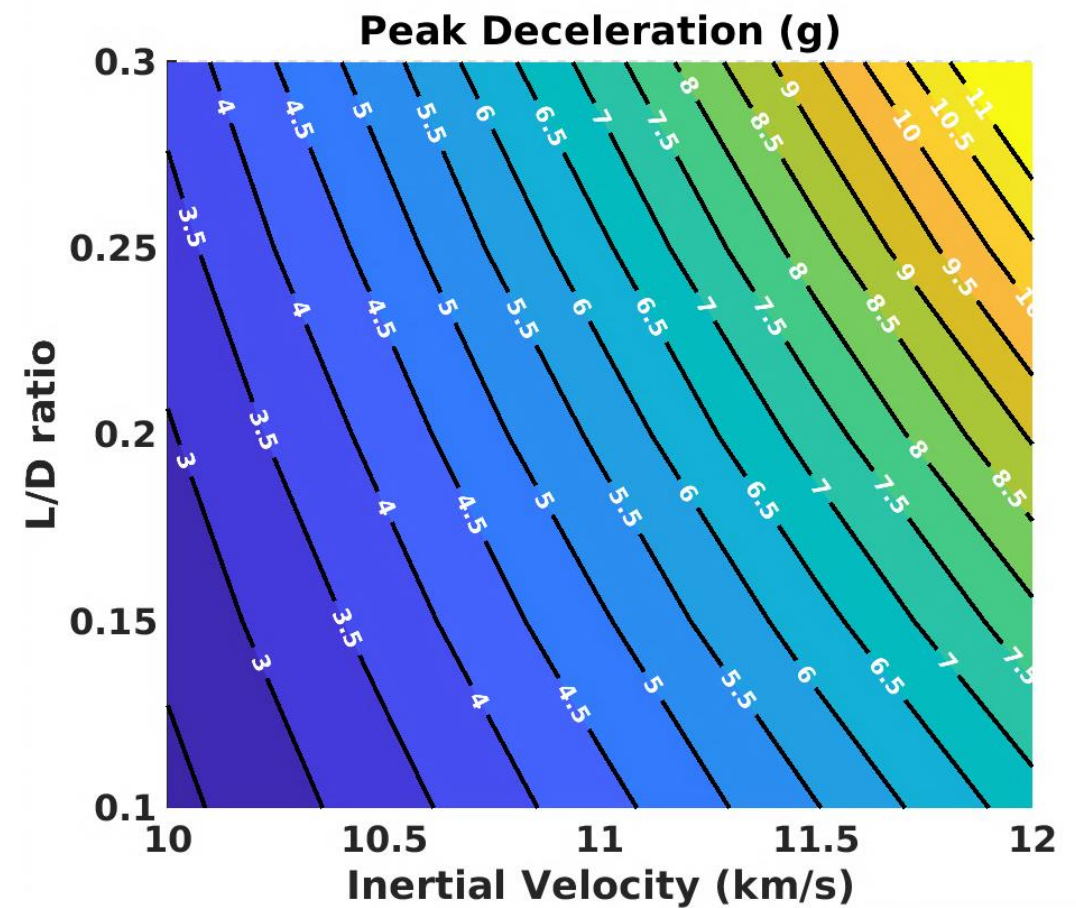
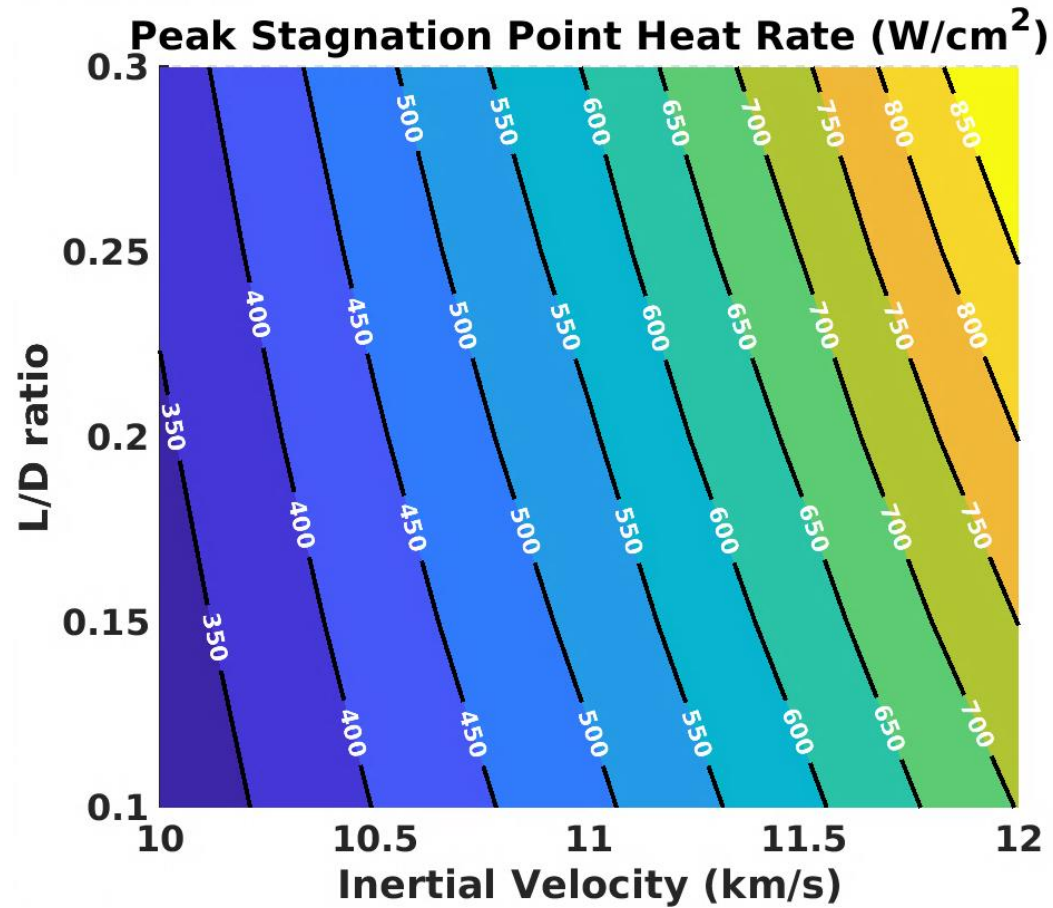


²Kelly Smith, "Predictive Lateral Logic for Numerical Entry Guidance Algorithms," AAS/AIAA Space Flight Mechanics Meeting (2016).

- Genesis and POST2 results line up very well
 - Gives confidence that guidance team trade studies will translate well to POST2 performance



Tradespace Analysis





Monte Carlo Sensitivities Atmospheric Density Error

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- Important to study larger-than-usual atmospheric density uncertainties to demonstrate aerocapture robustness for other planetary bodies
- Larger targeting errors, post-aerocapture burn costs expected, but not prohibitive
- Suggests that the ARRIVAL design is robust to high density environments, answering a high-risk item from the ADRAT report

99 %-tile Values	BLT $\pm 3\sigma$	BLT $\pm 6\sigma$
Surface Impacts	0	0
Apoapsis Error (km)	36.8	140.3
PRM ΔV (m/s)	159.2	181.4

