



Aerodynamics of a Uranus Aerocapture System Using a Mars-Heritage Entry Vehicle

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Motivation

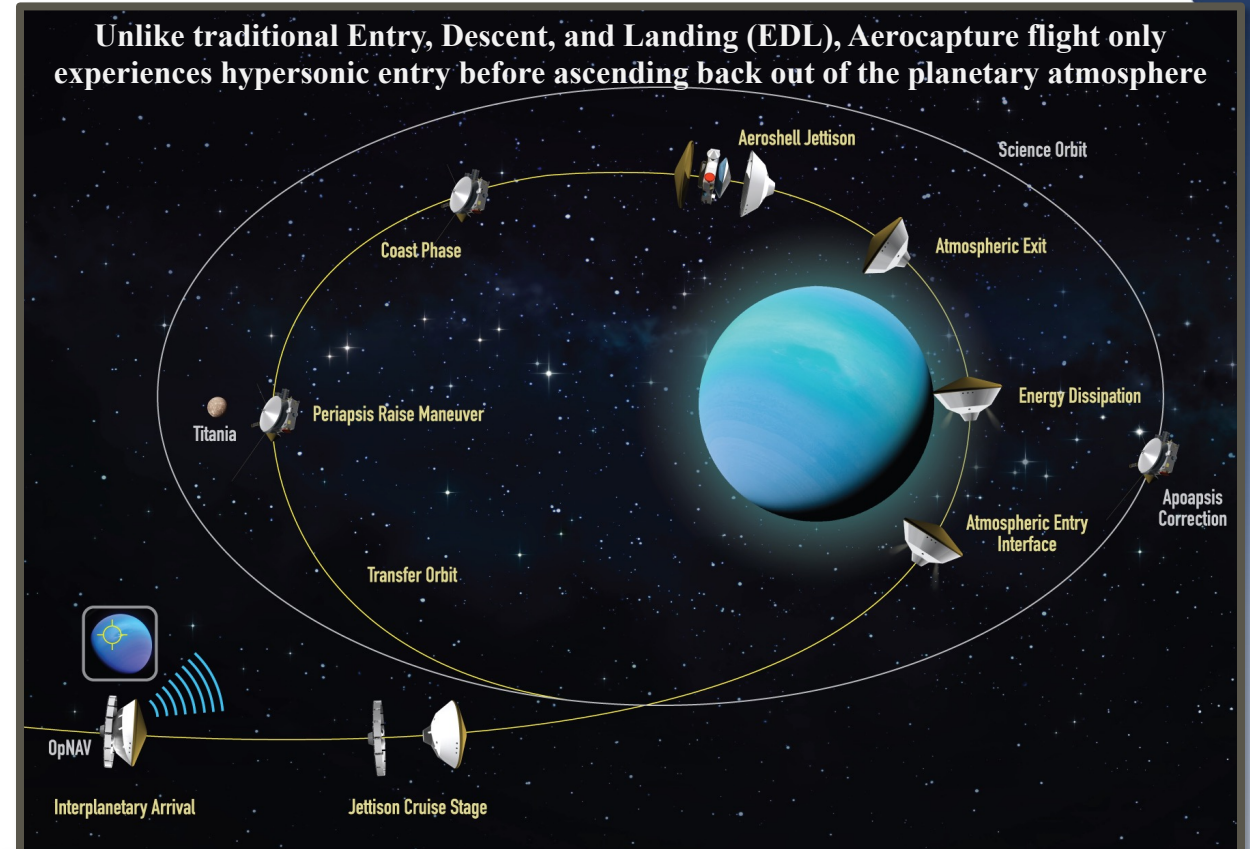


➤ **Uranus:** **The Highest Priority Destination for a New NASA Flagship-Class Planetary Science Mission**

- Propulsive-capture orbiters can expect:
 - 13–15-year travel times
 - Propellant requiring two-thirds of orbiter launch mass budget

➤ **Aerocapture:** **Orbit Insertion via Aerodynamic Forces from Atmospheric Flight**

- **Reduces onboard fuel requirements**
- **Allows for faster interplanetary travel**



Project Objective: Evaluate the advantages of aerocapture for use in delivering a planetary science mission to Uranus using a heritage flight vehicle design

This project is a NASA Science Technology Mission Directorate (STMD) funded Early Career Initiative

Introduction

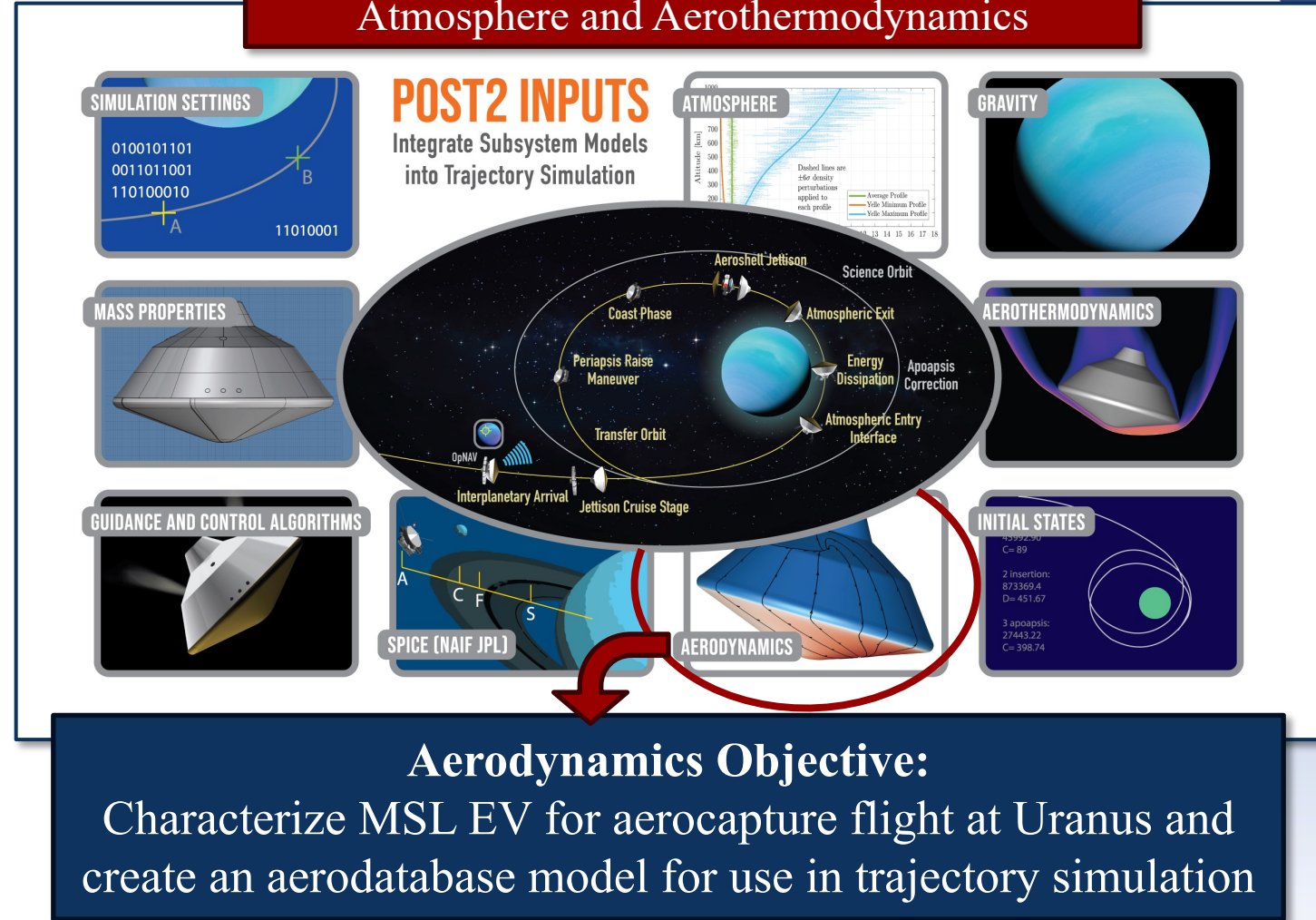
➤ Trajectory Simulation in POST2*

- Heritage framework for NASA Entry, Descent, and Landing (EDL) missions
 - Used for Mars Science Laboratory (MSL) and Mars 2020 missions
- Uranus application requires new aerodynamic database (ADB) for trajectory simulation

➤ Current work is culmination of two year effort

- Year 1: Implications of flight for aerocapture and H₂/He atmosphere, heavily rooted in MSL work
- Year 2: Update MSL ADB for Uranus aerocapture

Aerodynamics inputs are closely coupled to Atmosphere and Aerothermodynamics



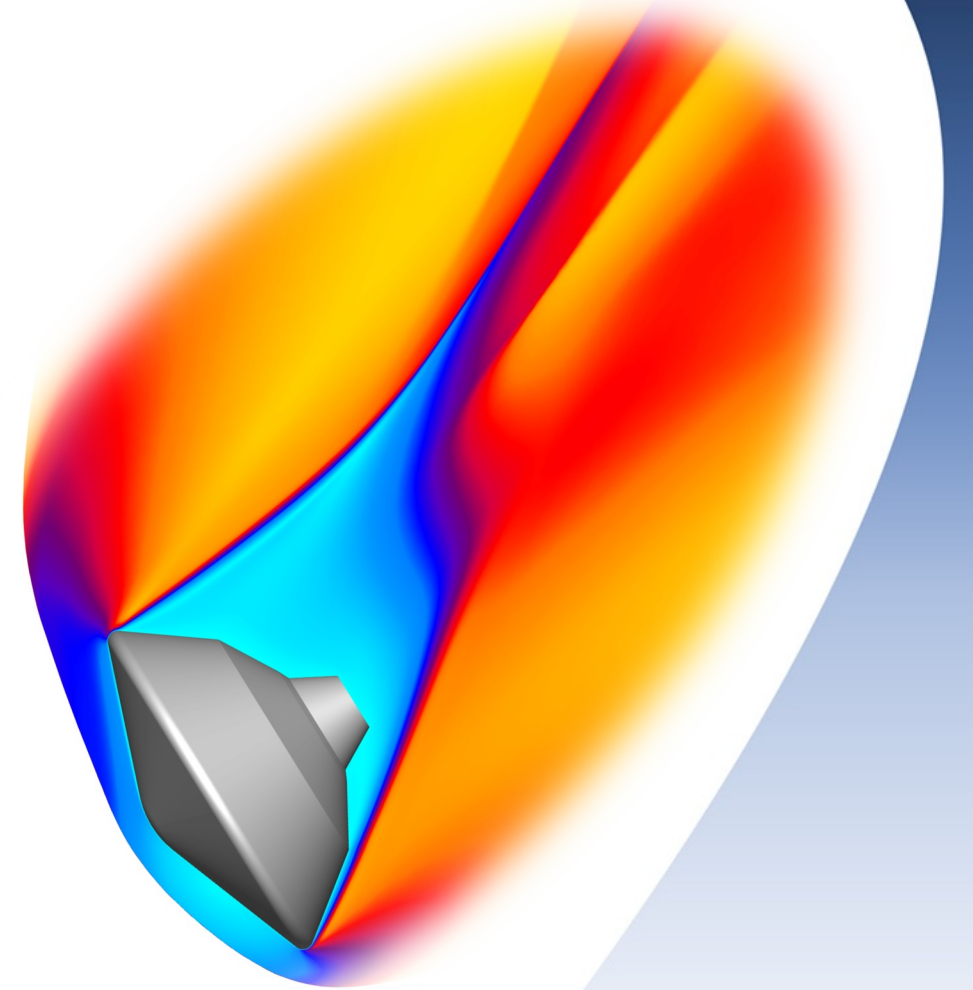
*Program to Optimize Simulated Trajectories II



Overview



- Motivation
- Introduction
- **Vehicle Geometry**
- **Methods**
- **Overview of Computations**
- **Aerodynamic Characterization**
- **Comparison to Mars Heritage Data**
- **Aerodatabase Formulation**
- **Sensitivity to Shape**
- **Uncertainty Modeling**
- **Impacts on Flight Trajectory**
- **Summary and Considerations**

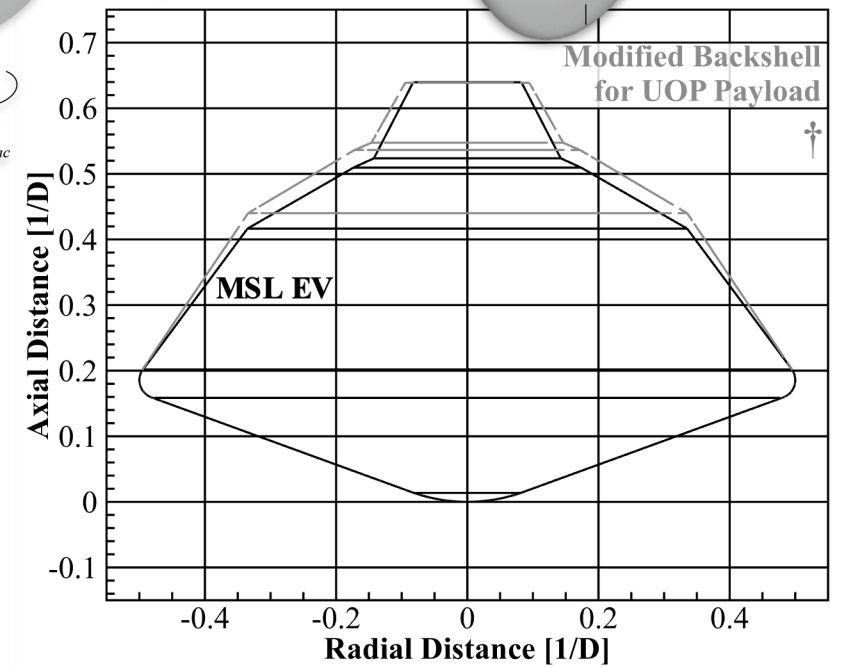
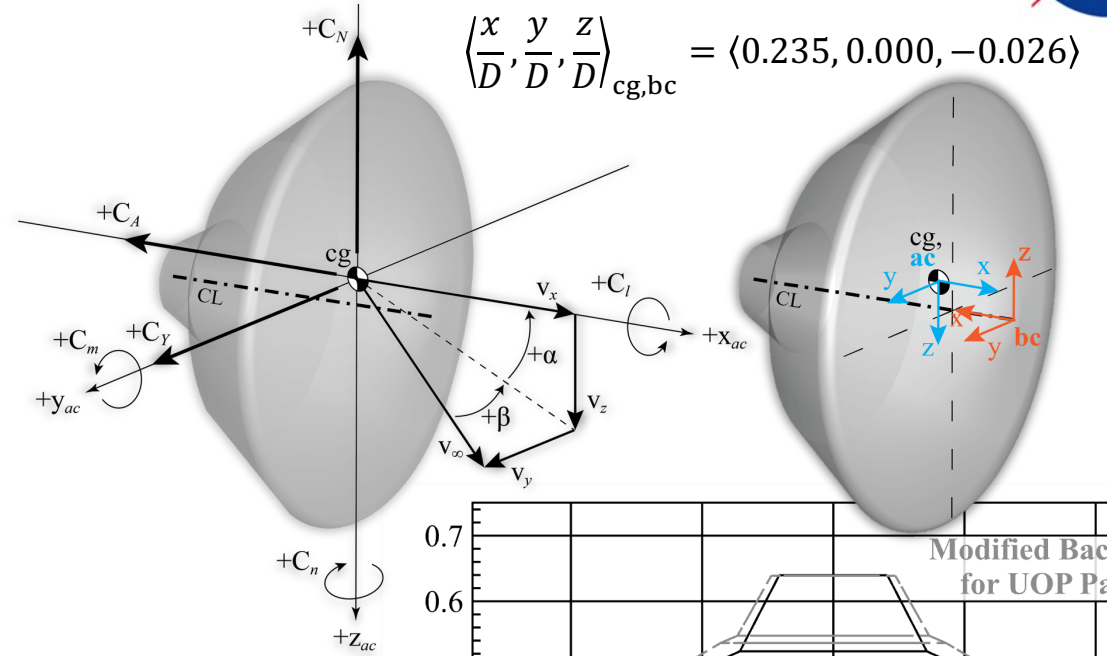


➤ Heritage Entry Vehicle (EV) Aeroshell

- MSL / Mars 2020 Outer Mold Line (OML)
- 70° Sphere-Cone Forebody
- Low Lift-to-Drag ($L/D \leq 0.3$)

➤ Two configurations considered, driven by payload packaging and launch constraints

- Payload is Uranus Orbiter & Probe (UOP) mission
- Backshell modification allows reduction of max diameter to fit currently available launch vehicles
- Effects of backshell expansion are evaluated



Configuration	Aeroshell Diameter [m]	Modified MSL Backshell
MSL / Mars2020 EV	4.5	-
Aerodatabase	5.0	No
Final	4.57*	Yes

*Sized to fit presently available launch vehicles (e.g. Falcon Heavy)

†Modified backshell has 3° expansion aft of shoulder 5

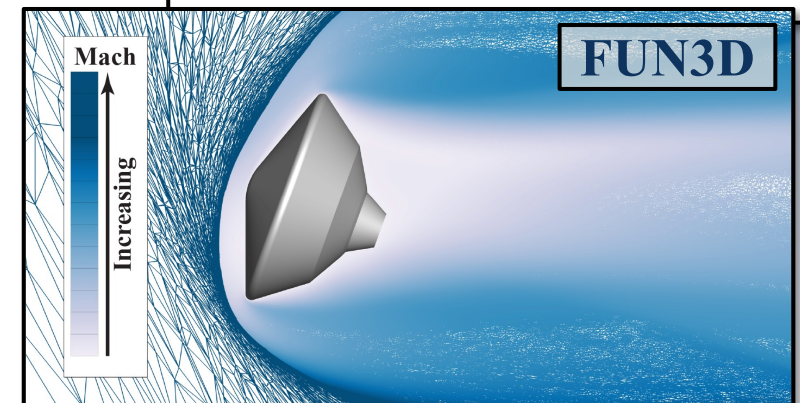
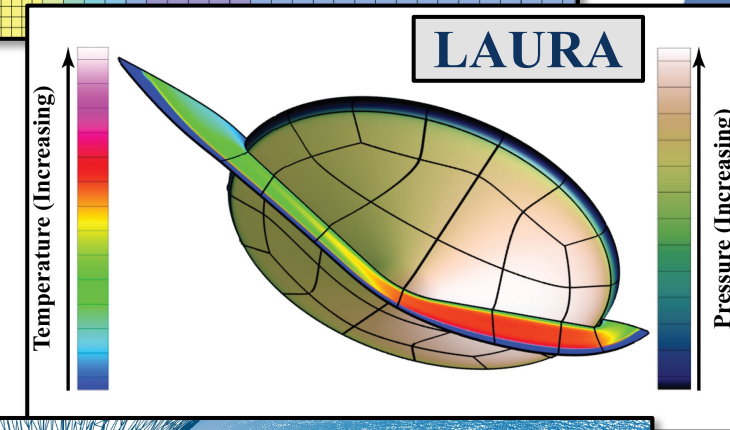
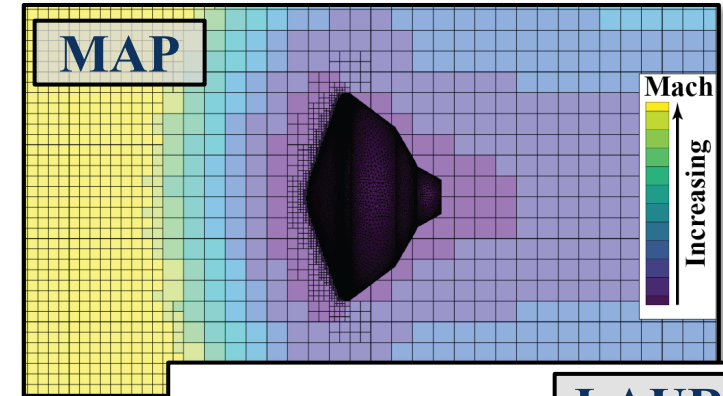


Methods



Knudsen number = Mean Free Path / Max Diameter ($Kn = \lambda/D$)

	Navier-Stokes (NS) Computational Fluid Dynamics (CFD)		Direct Simulation Monte Carlo (DSMC)
Regime	$Kn \leq 10^{-3}$		$10^{-1} < Kn < 10^4$
Solver	FUN3D*	LAURA†	MAP§
Geometry	5.00m and 4.57m	5.00m Forebody-Only	5.00m
Chemistry	H2/He Calorically Perfect Gas	H2/He Reacting Gas (with Ionization)	1) Pure-Hydrogen 2) Hydrogen-Helium 3) Hydrogen-Helium, with Ionization
Use	Configuration effects studies	Populating continuum portion of ADB	Populating rarefied portion of ADB



*Fully Unstructured Navier-Stokes in Three Dimensions

†Langley Aerothermodynamic Upwind Relaxation Algorithm

§Multiphysics Algorithm with Particles

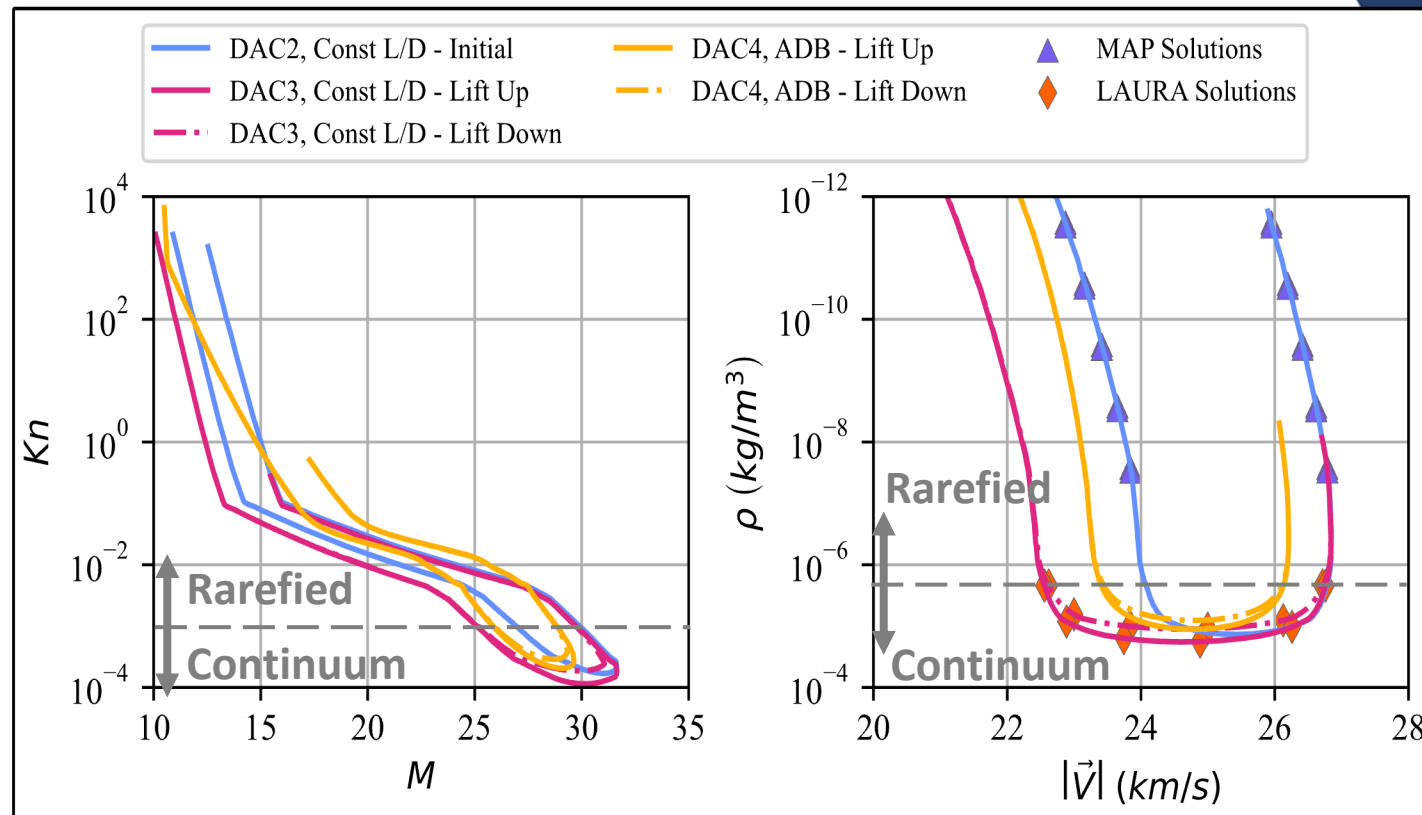
➤ **Due to nature of work, trajectories were constantly evolving**

- Each data source used latest trajectory cases at start of computations
- Latest trajectories fall in the space between

➤ **Reference trajectories used to obtain conditions for CFD cases to be run**

➤ **Computations used to...**

- Build aerodatabase for trajectory simulation
- Assess OML changes in final configuration
- Update MSL Uncertainty Model



FUN3D comparison cases were run at the peak dynamic pressure condition

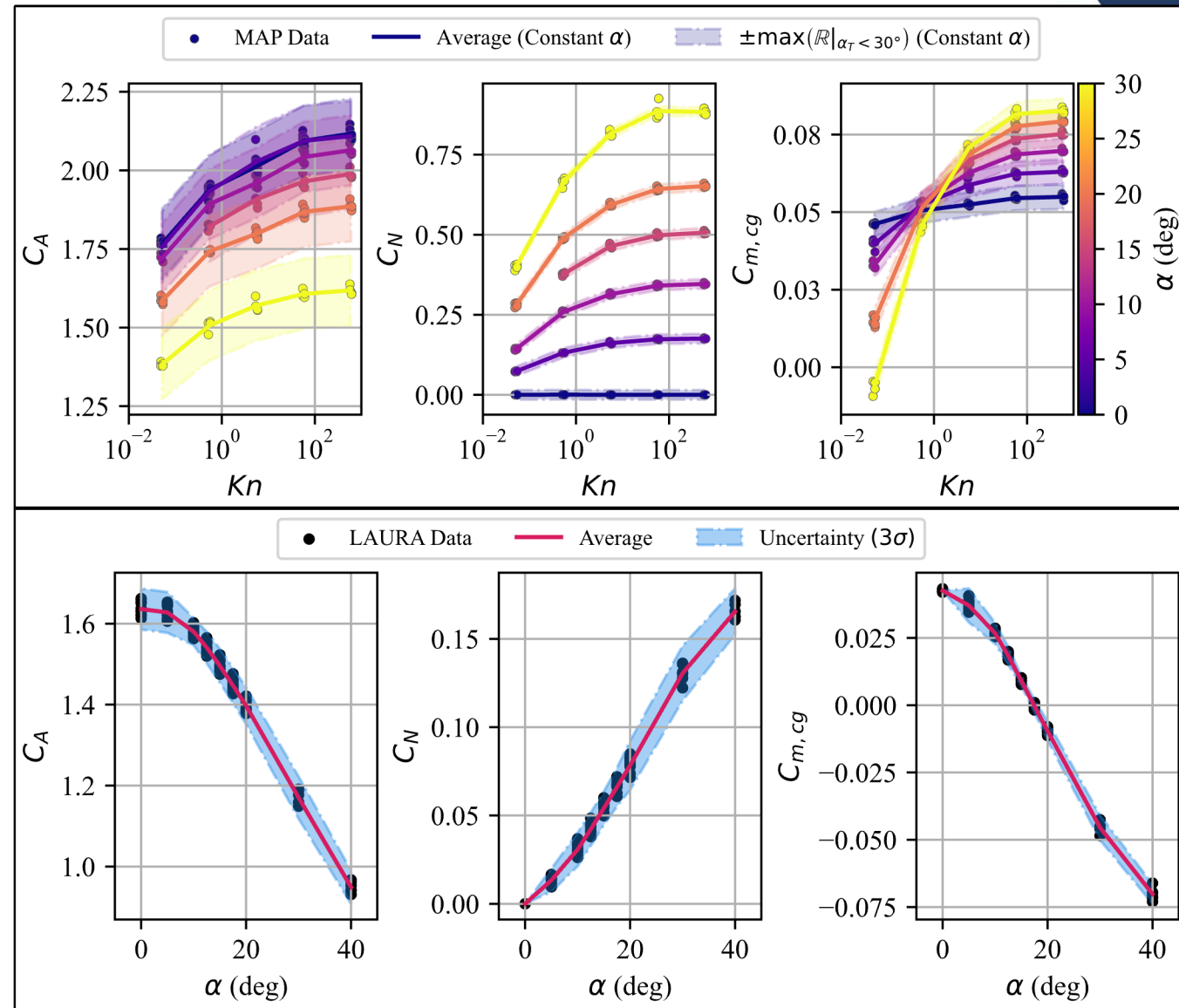
Handoff between rarefied and continuum regimes occurs at $Kn \approx 10^{-3}$

➤ Rarefied

- For current work, shows functional independence of chemistry model
- Data averaged to approximate for anticipated changes in atmospheric composition during flight ($H_2 \rightarrow H_2, He \rightarrow H_2$)
- Uncertainty approximated by data range due to low number of data points per condition

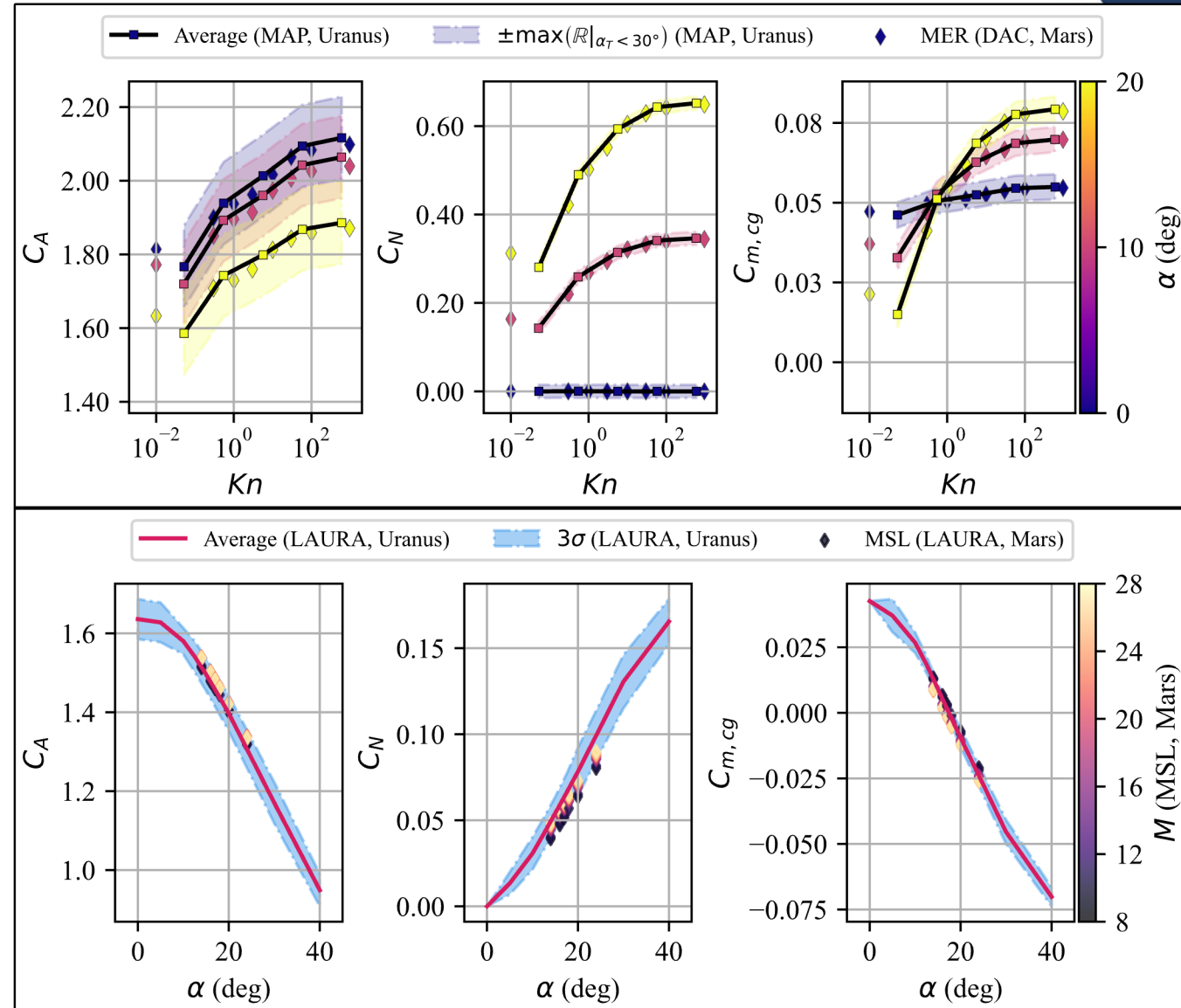
➤ Continuum

- Cases show little sensitivity to velocity, anticipated given asymptotic behavior with respect to Mach number
- Cases averaged to be function of EV total angle of attack only for current work

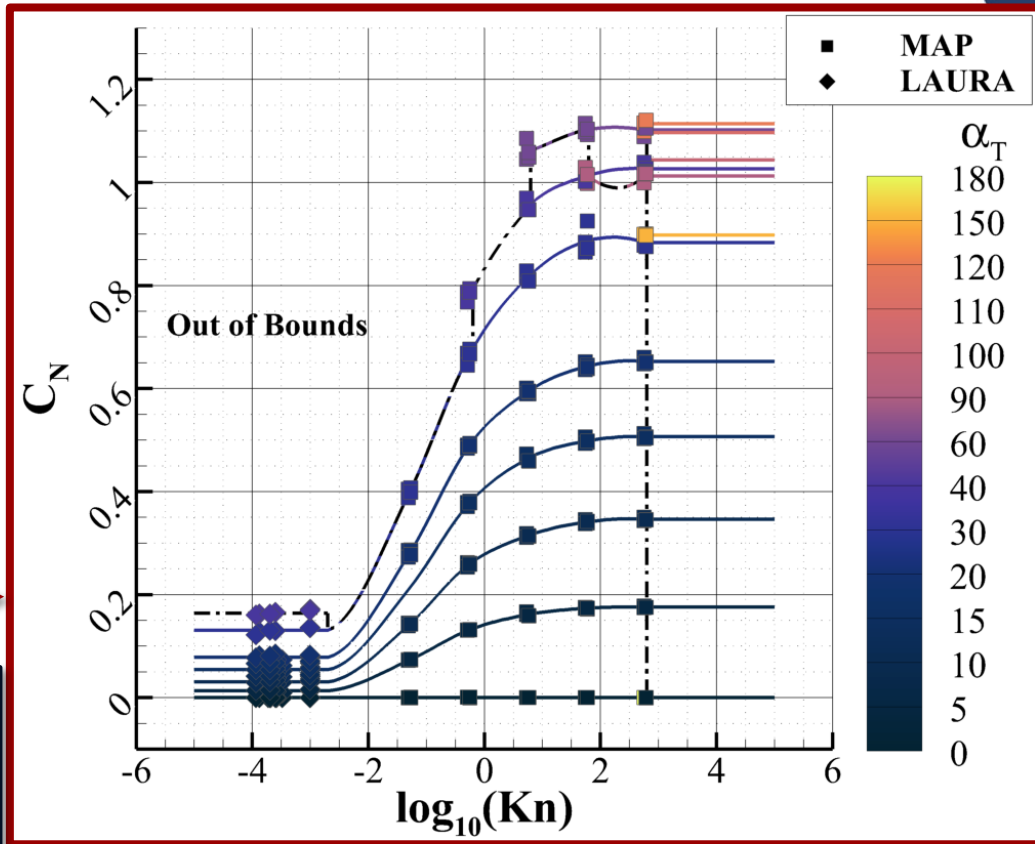


Comparison to Mars Heritage Data

- **Comparisons made to investigate claim to heritage design**
 - Sufficient agreement indicates expected savings (time and effort) hold true
- **Rarefied**
 - Comparison to MER (used by MSL)
 - Good agreement at all but lowest Kn
 - Exact cause is undetermined, large number of potential causes (geometry, chemistry, etc)
 - Appears to be localized difference
- **Continuum**
 - Comparison to MSL
 - Also used LAURA Forebody-Only
 - Shows good agreement, especially at similar Mach number to current work ($M \sim 30$)

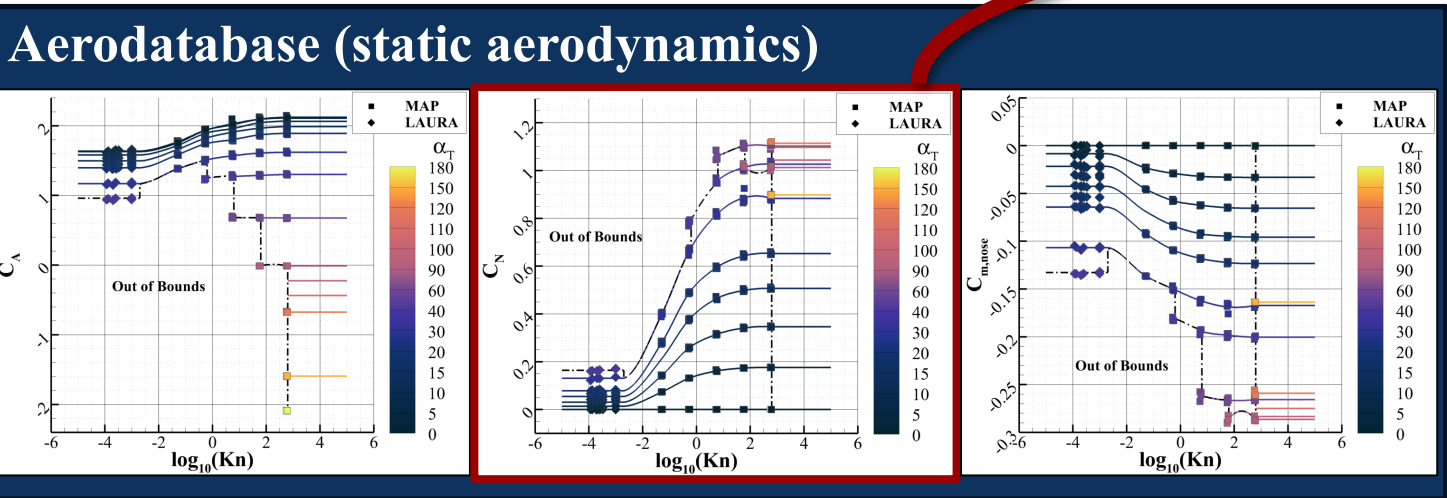


- **ADB created to provide continuous aerodynamic characterization**
 - Formulates aerodynamics as $f(Kn, \alpha_T)$
 - Dynamic damping terms not modeled
 - Conservative assumption (see paper)
- **Out-of-Bounds reporting alerts when extrapolation of data occurs**

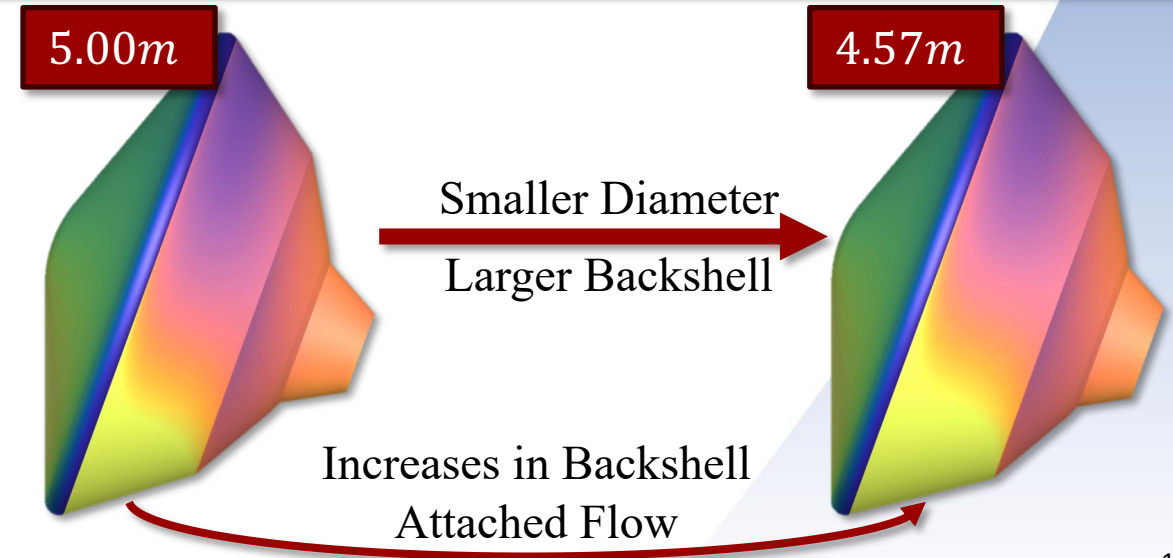
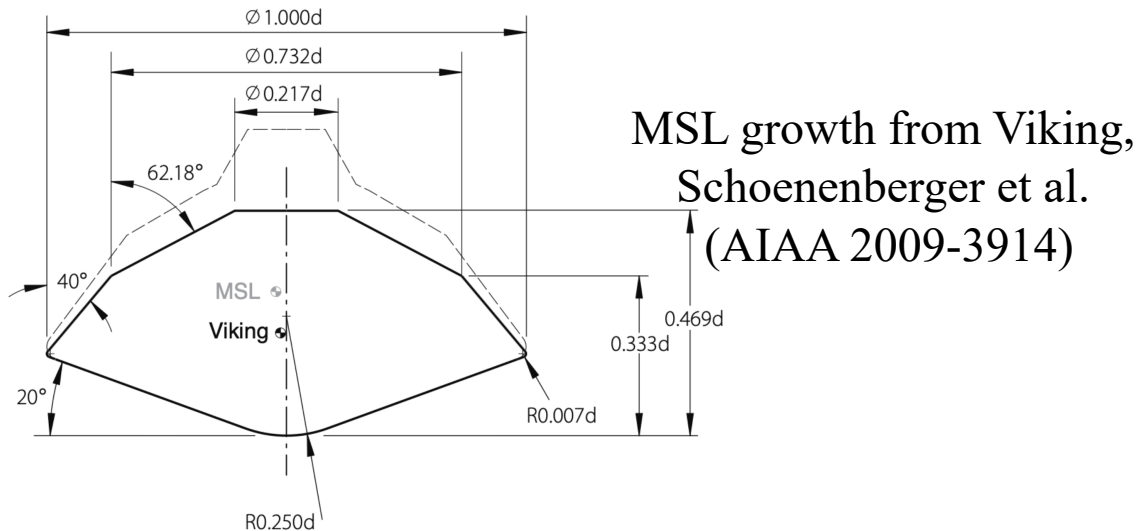
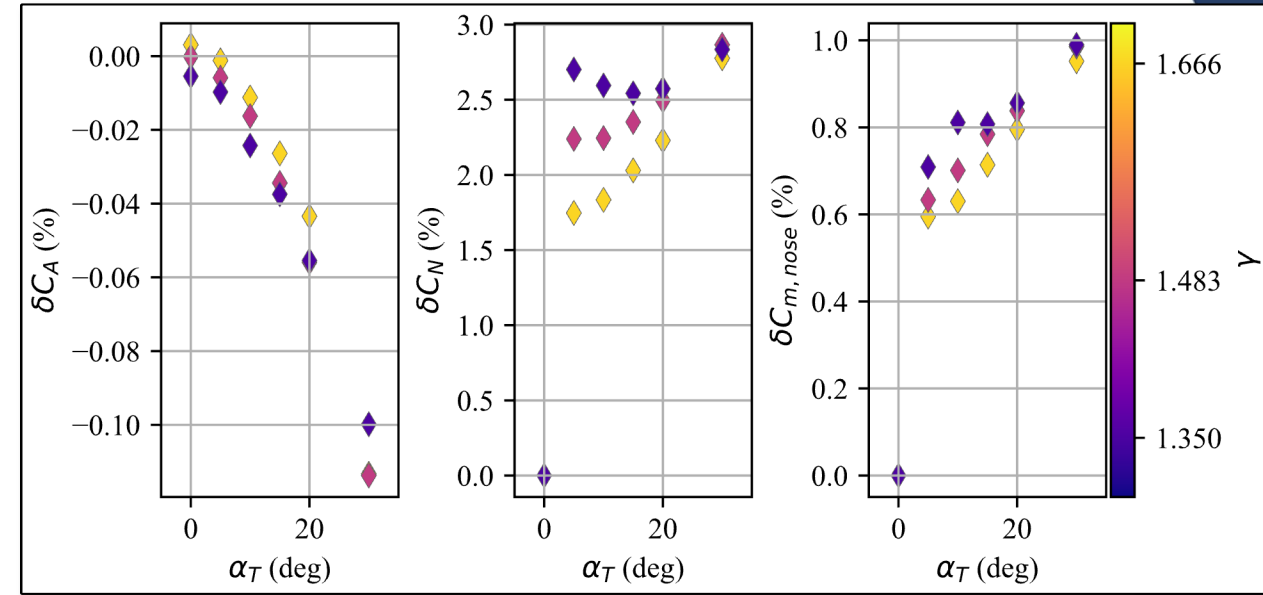


ADB output (curves), CFD data (symbols)

Normal force highlighted as example, see paper for axial force and pitching moment



- **Final study configuration (4.57m) has different OML from that used to populate ADB (5.00m)**
 - Similar variation / evolution was seen on MSL, originally based on Viking OML
- **FUN3D study to evaluate changes**
 - Forces and moments
 - Surface properties (see paper)





Uncertainty Modeling



➤ Prior work used MSL uncertainty model directly

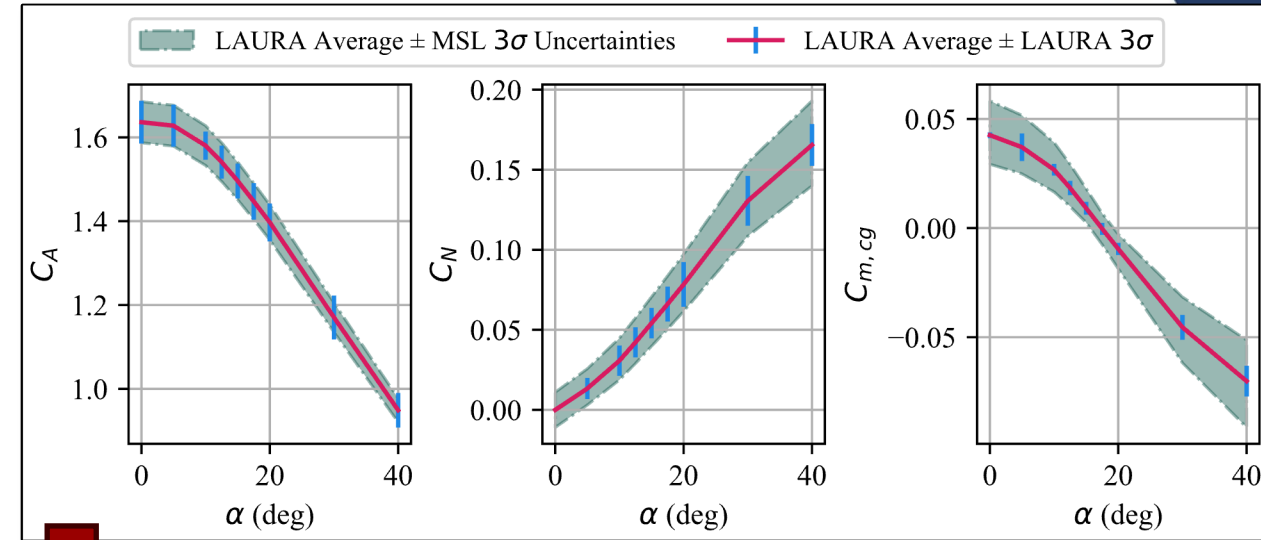
- Model was developed for Mars
- Insufficient data at time to inform updates

➤ Current work provides first-order update to MSL model for application

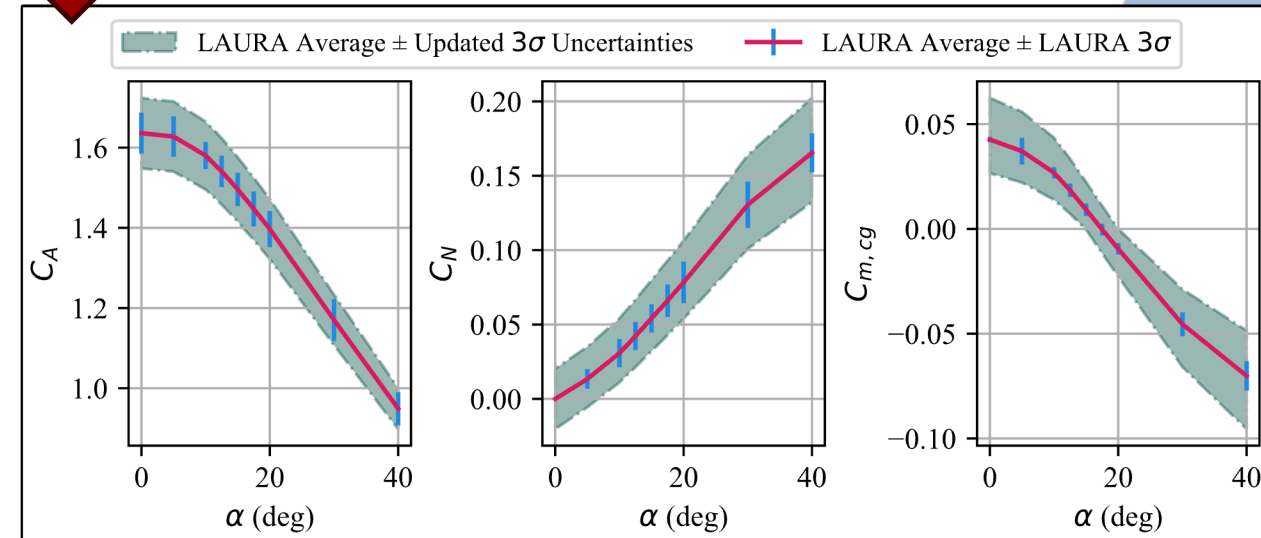
- RSS-update, MSL model and new Uranus CFD
 - Add potentially unaccounted uncertainties
 - Reduce double-counting known sources
- Addresses apparent non-conservatism in application to new planet / atmosphere
- Should be further updated in future work

Updated MSL Uncertainty Model for Uranus Aerocapture

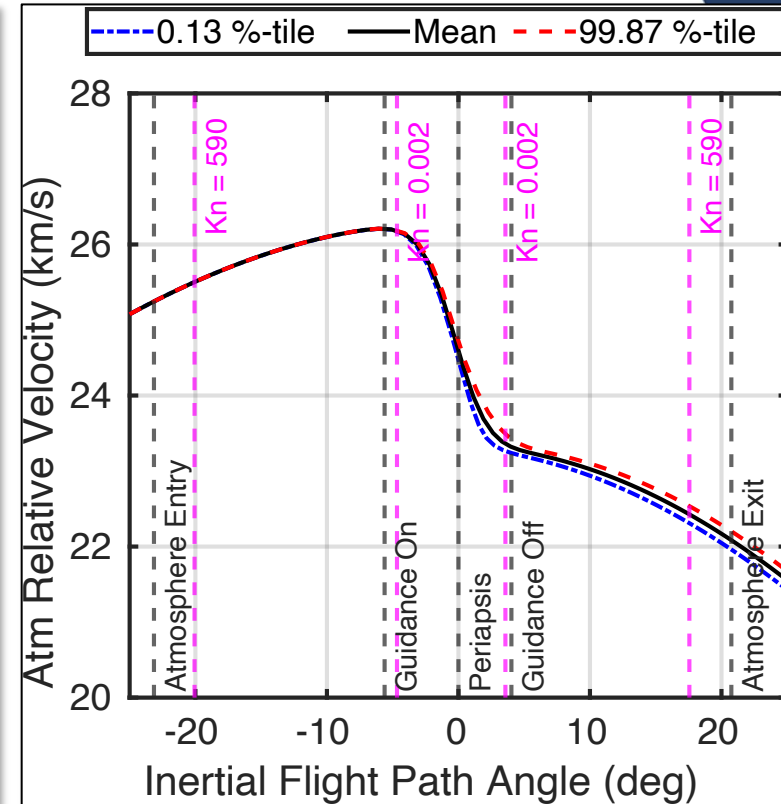
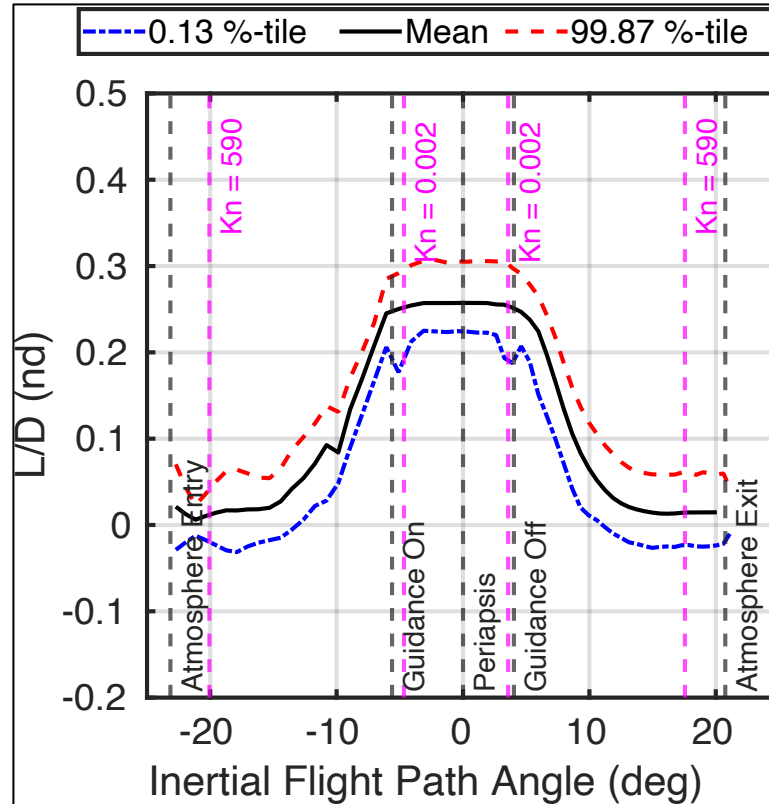
	C_A	C_Y, C_N	C_m	C_n	C_l
$Kn > 0.1$	$\pm 7.45\%$	$\pm 0.0179, \pm 10\%$	$\pm 0.00652, \pm 20\%$	$\pm 0.00596, \pm 20\%$	0.0005
$M > 10$	$\pm 5.38\%$	$\pm 0.0185, \pm 10\%$	$\pm 0.00948, \pm 20\%$	$\pm 0.00693, \pm 20\%$	0.000219



Root-Sum-Square Update of Uncertainty Model



- **Impacts to L/D used to assess aerodynamic performance**
 - Direct analog to control authority during deceleration
- **Assessed in POST2 using new aerodatabase and uncertainty model**
 - With uncertainty updates, vehicle manages to successfully command $L/D = 0.25 \pm 0.05$ in continuum flight
 - Trajectory simulation shows this provides sufficient control authority to insert science payload into desired orbit via aerocapture at Uranus



Despite uncertainty updates leading to a $\pm 20\%$ variation in nominal L/D, the aerocapture vehicle retains sufficient control margin to statistically achieve orbital capture



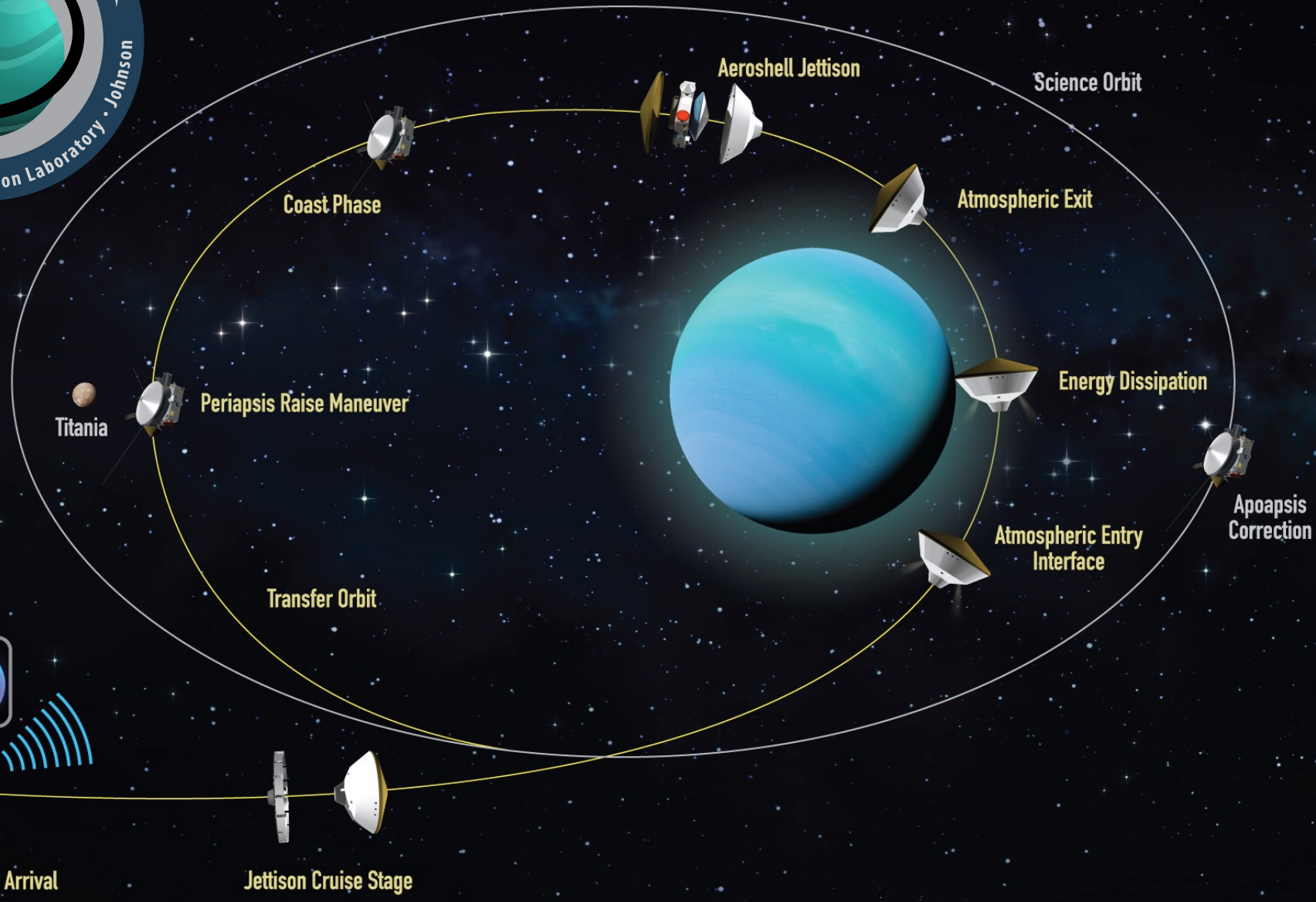
Summary



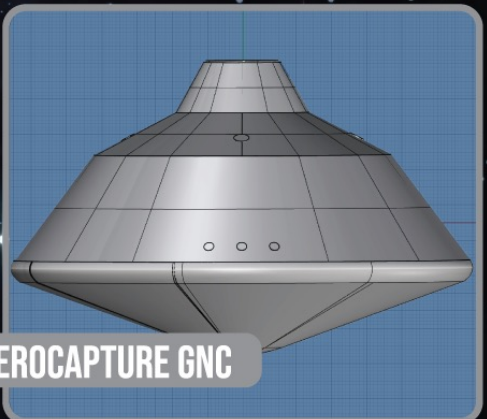
- **Analysis has been performed to characterize the aerodynamics of a Mars-heritage low-L/D entry vehicle for aerocapture use at Uranus**
- **An aerodatabase has been formulated using this data for use in Monte Carlo six-degree-of-freedom flight trajectory simulations**
- **First-order effects of geometry changes have quantified**
- **An updated uncertainty model has been developed to capture Uranus-specific aerodynamics, adding conservatism to the analysis**
- **Flight trajectory simulation with this aerodatabase and uncertainty model shows statistically successful ability to use aerocapture to place flagship science payload at Uranus**



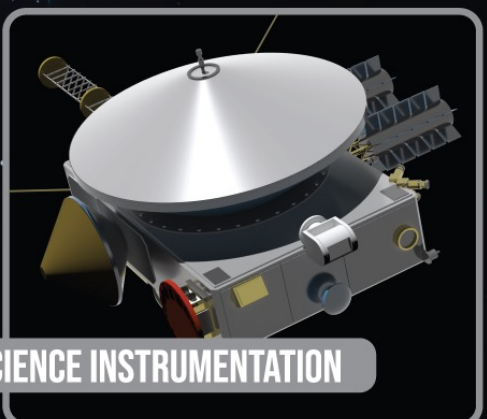
Questions?



TPS DESIGN



AEROCAPTURE GNC



SCIENCE INSTRUMENTATION