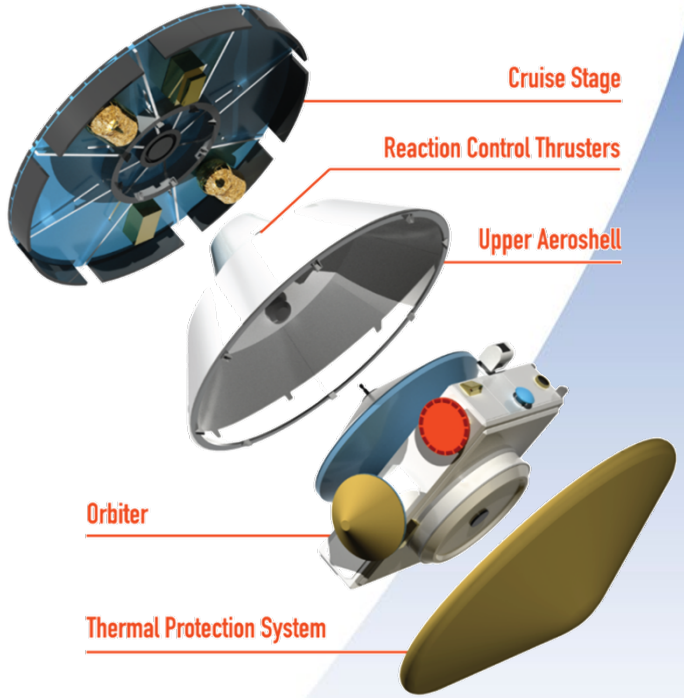
6-DoF Uranus Aerocapture Trajectory Analysis

2025 AIAA SciTech Forum
GNC-21/AFM-15: Entry, Descent, and Landing Technology – Aerocapture for Ice Giants I
Orlando, FL
January 8, 2025

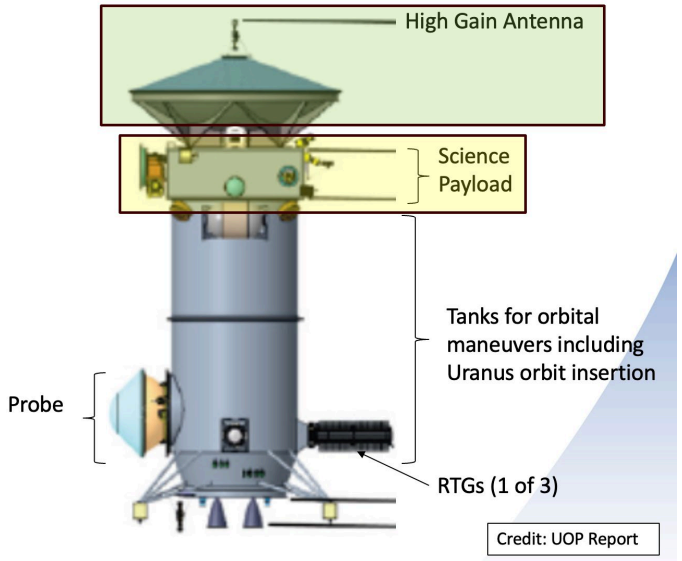
Rohan Deshmukh, PhD
Atmospheric Flight and Entry Systems Branch
NASA Langley Research Center
rohan.g.deshmukh@nasa.gov

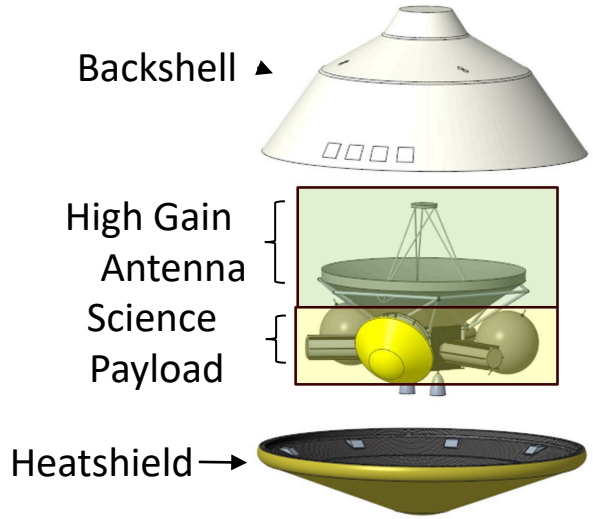
NASA Early Career Initiative



Motivation

- **Aerocapture can potentially enable faster arrival trajectories and reduce orbit insertion propellant mass at Uranus**
- **Question: How well does aerocapture perform at Uranus when the modeling and simulation fidelity is increased from 3-DOF to 6-DOF?**





Uranus Aerocapture Talks SciTech 2025

ECI Overview (Dutta)	Mission Design and Navigation (Mages)	6DoF (Deshmukh)	Aerothermal (Scoggins)	Aerodynamics (Shellabarger)	Thermal Protection System (Morgan)	Mechanical (Gomez-Delrio)	Guidance (Matz)	Navigation (Chadalavada)
AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?	AIAA-2025-?

NASA Space Technology Mission Directorate funded Early Career Initiative (ECI). Project aims to mature the analysis and technology state of Uranus aerocapture

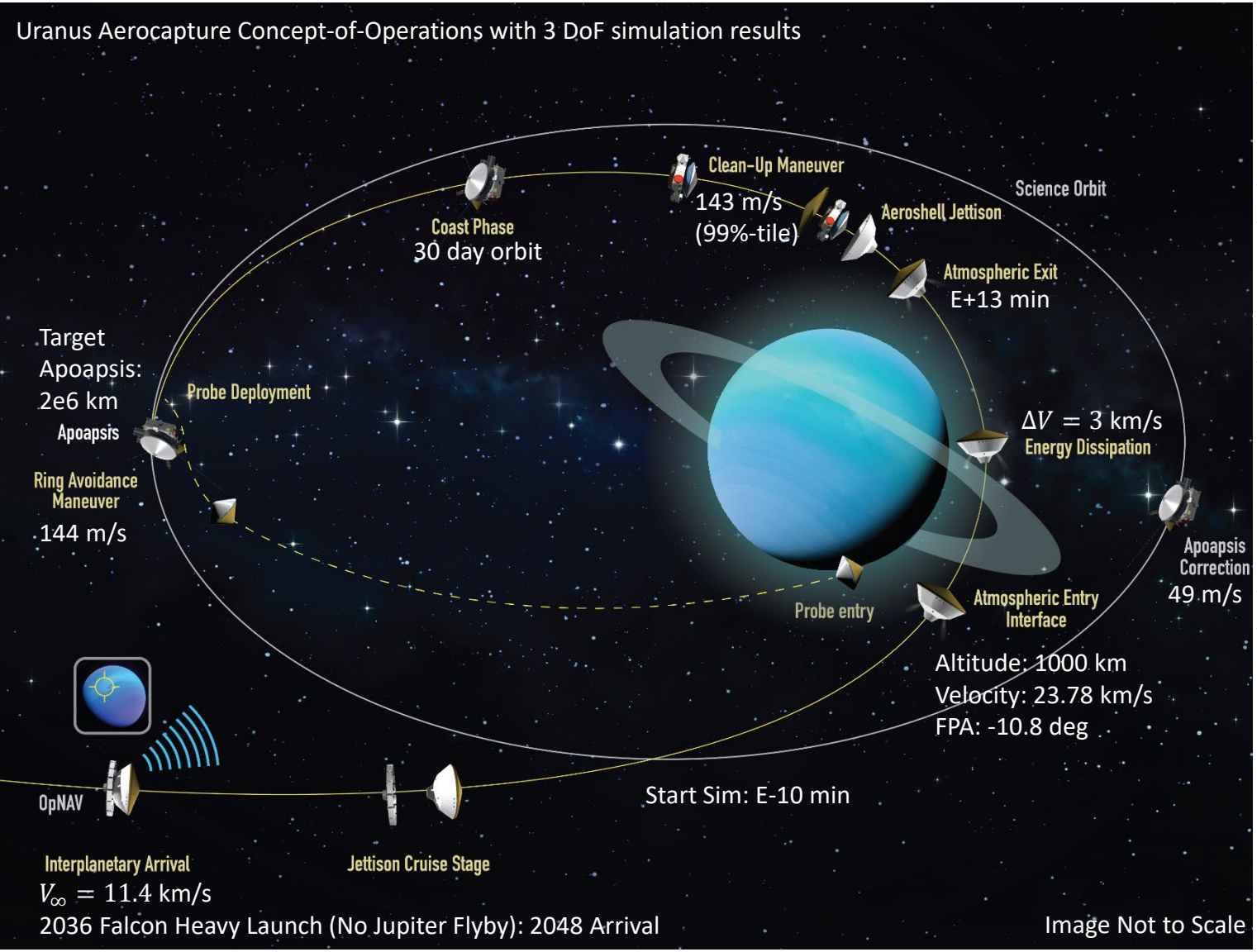
Outline

- **Uranus Aerocapture Overview**
- **6-DOF Modeling and Simulation**
- **Simulation Results**
  - Nominal Trajectory
  - Monte Carlo Results
- **Study Findings**
- **Future Work**

Co-Authors
Soumyo Dutta (LaRC)
Sai Chadalavada (LaRC/AMA)

LaRC: NASA Langley Research Center
AMA: Analytical Mechanics Associates

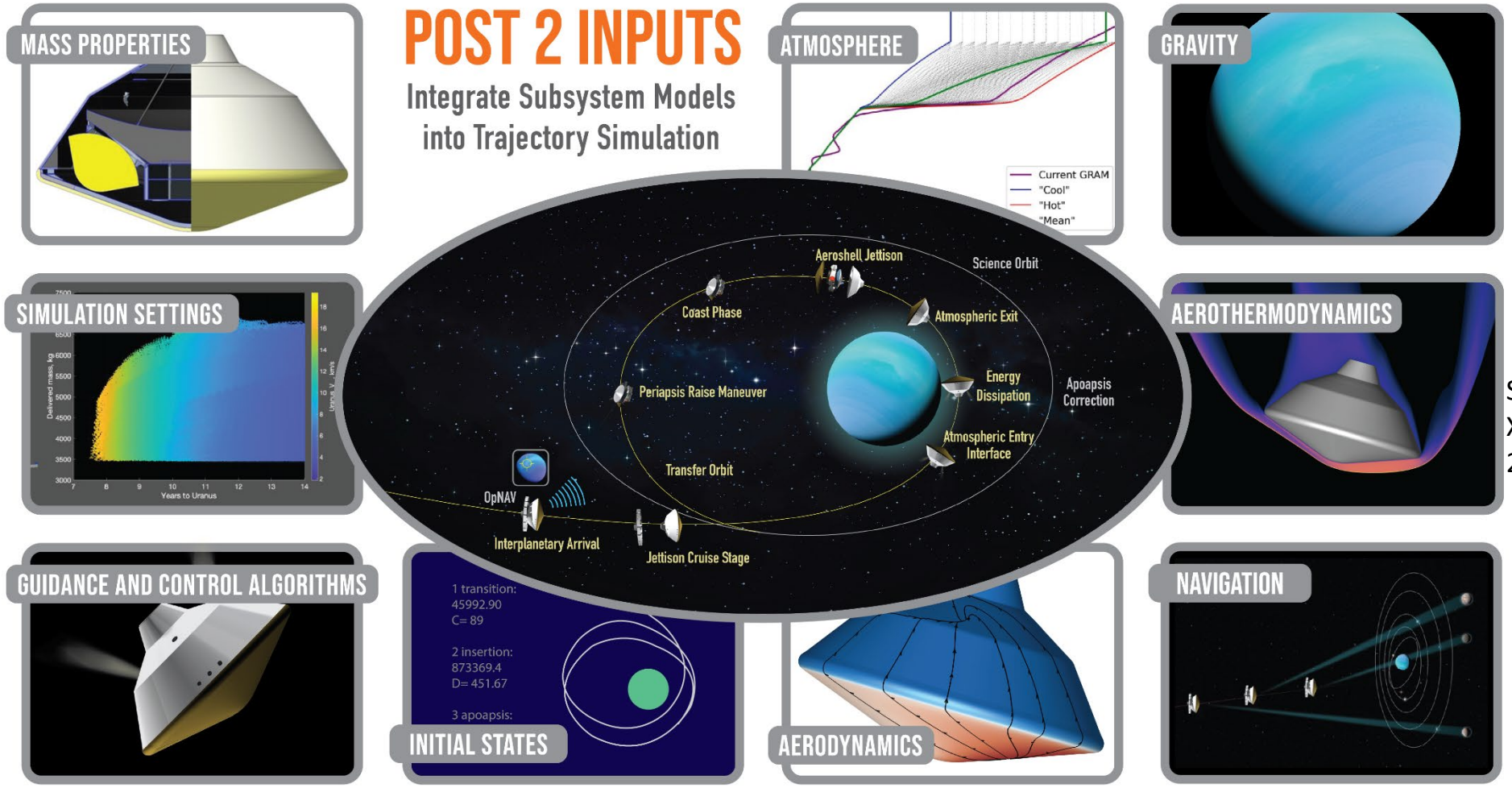
Overview: Uranus Aerocapture



- **Arrive at Uranus on a hyperbolic trajectory (V_∞)**
- **Reach entry interface at 1000 km altitude**
- **Active guidance steers aeroshell during atmospheric flight (ΔV) targeting desired apoapsis altitude at exit**
- $\Delta V_{total} = \Delta V_{CM} + \Delta V_{RAM} + \Delta V_{ACM}$
  - Clean-up Maneuver (CM) to 30 day orbit
  - Ring Avoidance Maneuver (RAM)
  - Apoapsis Correction Maneuver (ACM)

Trajectory Simulation Framework

- **Program to Optimize Simulated Trajectories II (POST2) utilized for trajectory simulations**



See AIAA-2025-XXXX

See AIAA-2025-XXXX and AIAA-2025-XXXX

See AIAA-2025-XXXX

See AIAA-2025-XXXX

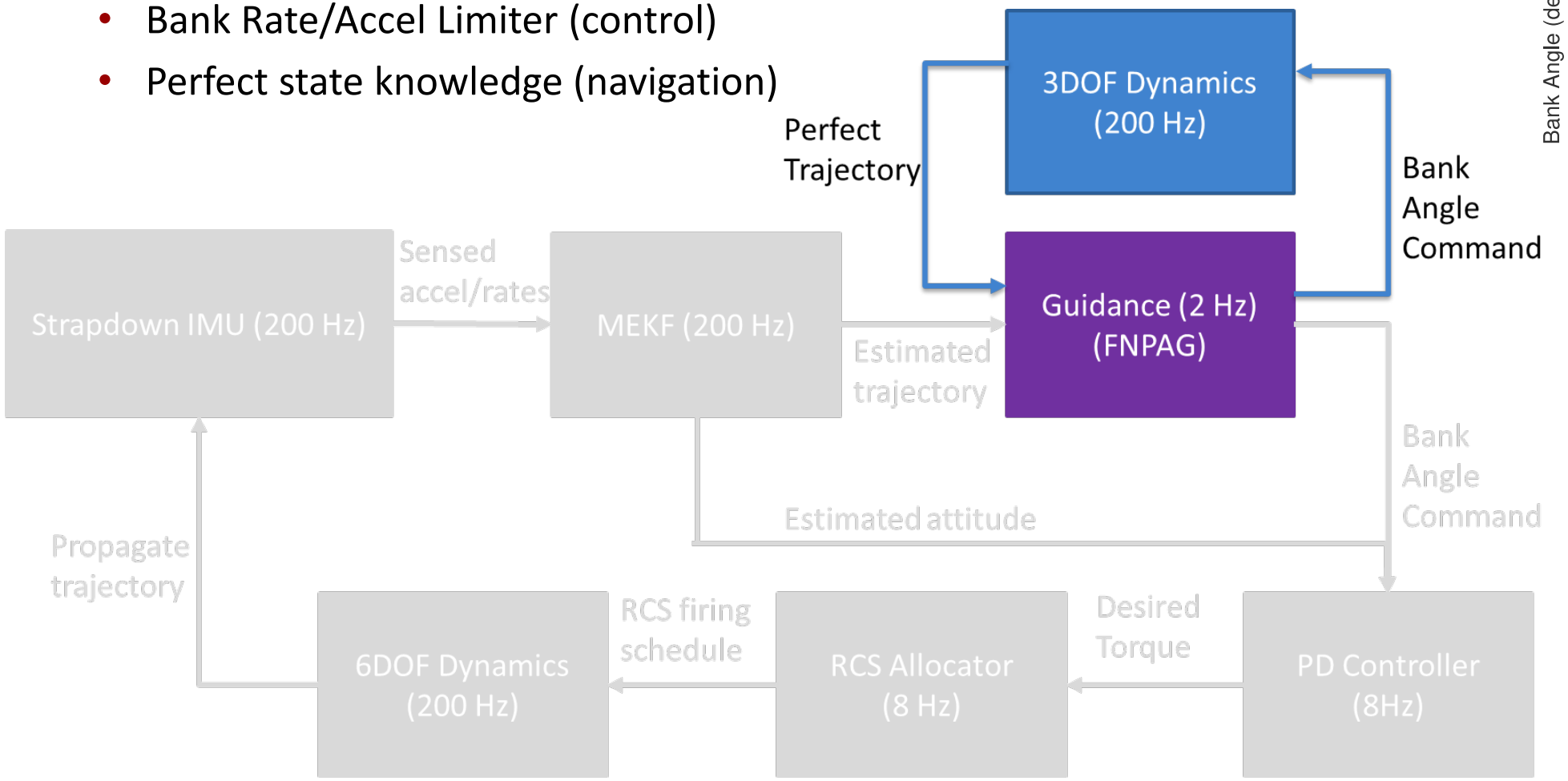
See AIAA-2025-XXXX

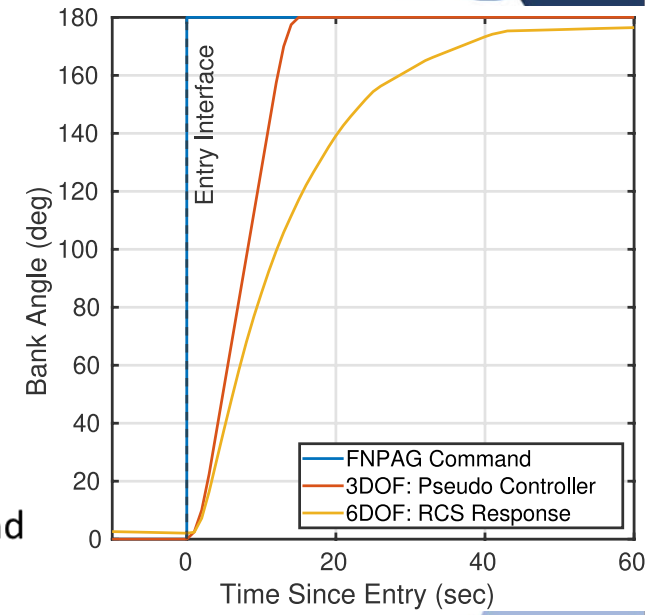
See AIAA-2025-XXXX

Aerocapture Guidance, Navigation, and Control

3 DoF Mode

- Bank commands from FNPAG (guidance)
- Bank Rate/Accel Limiter (control)
- Perfect state knowledge (navigation)





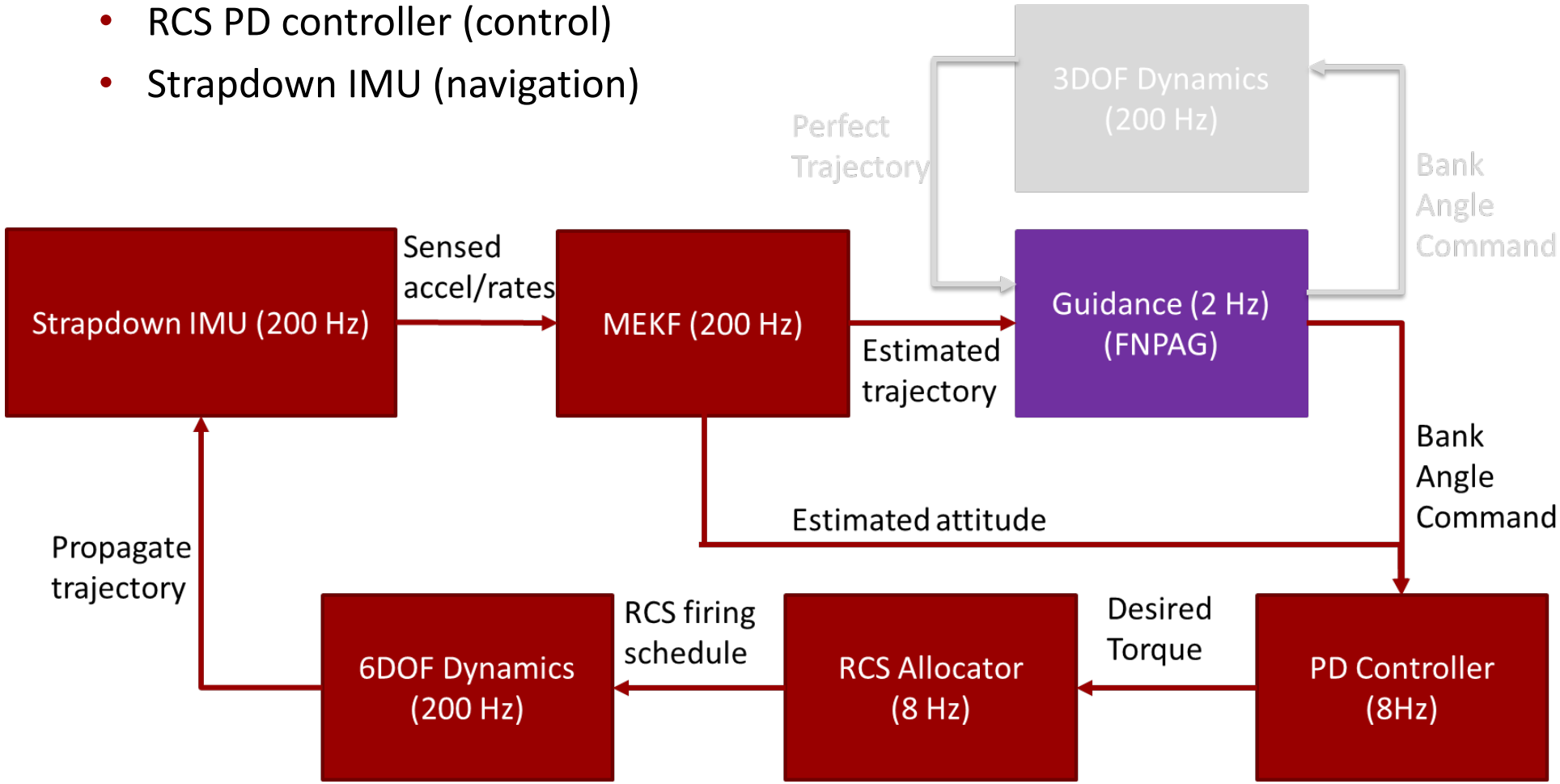
FNPAG: Fully Numerical Predictor Corrector Aerocapture Guidance
RCS: Reaction Control System

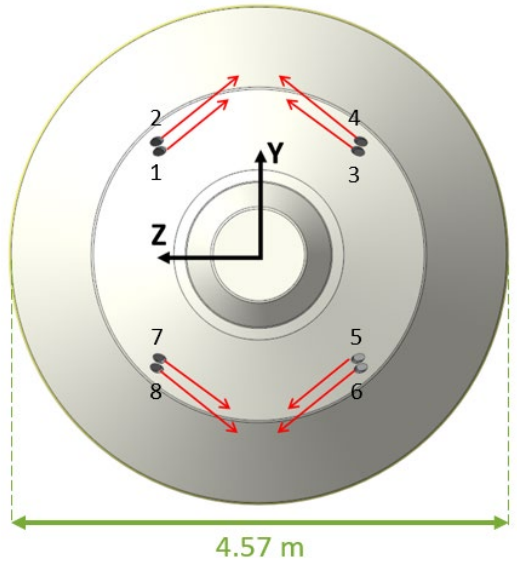
Aerocapture Guidance, Navigation, and Control

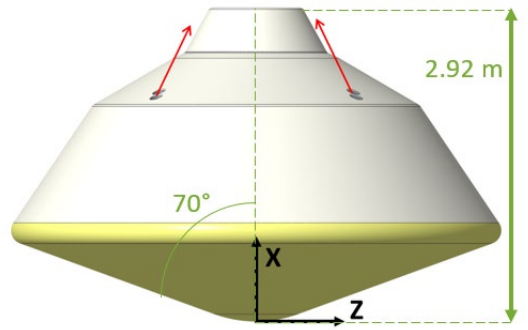
6 DoF Mode

- Bank commands from FNPAG (guidance)
- RCS PD controller (control)
- Strapdown IMU (navigation)

Note: Current work assumes a simple 6DOF simulation framework for preliminary analysis







PD: Proportional Derivative
IMU: Inertial Measurement Unit
MEKF: Multi-Extended Kalman Filter

Trajectory Simulation Model Inputs

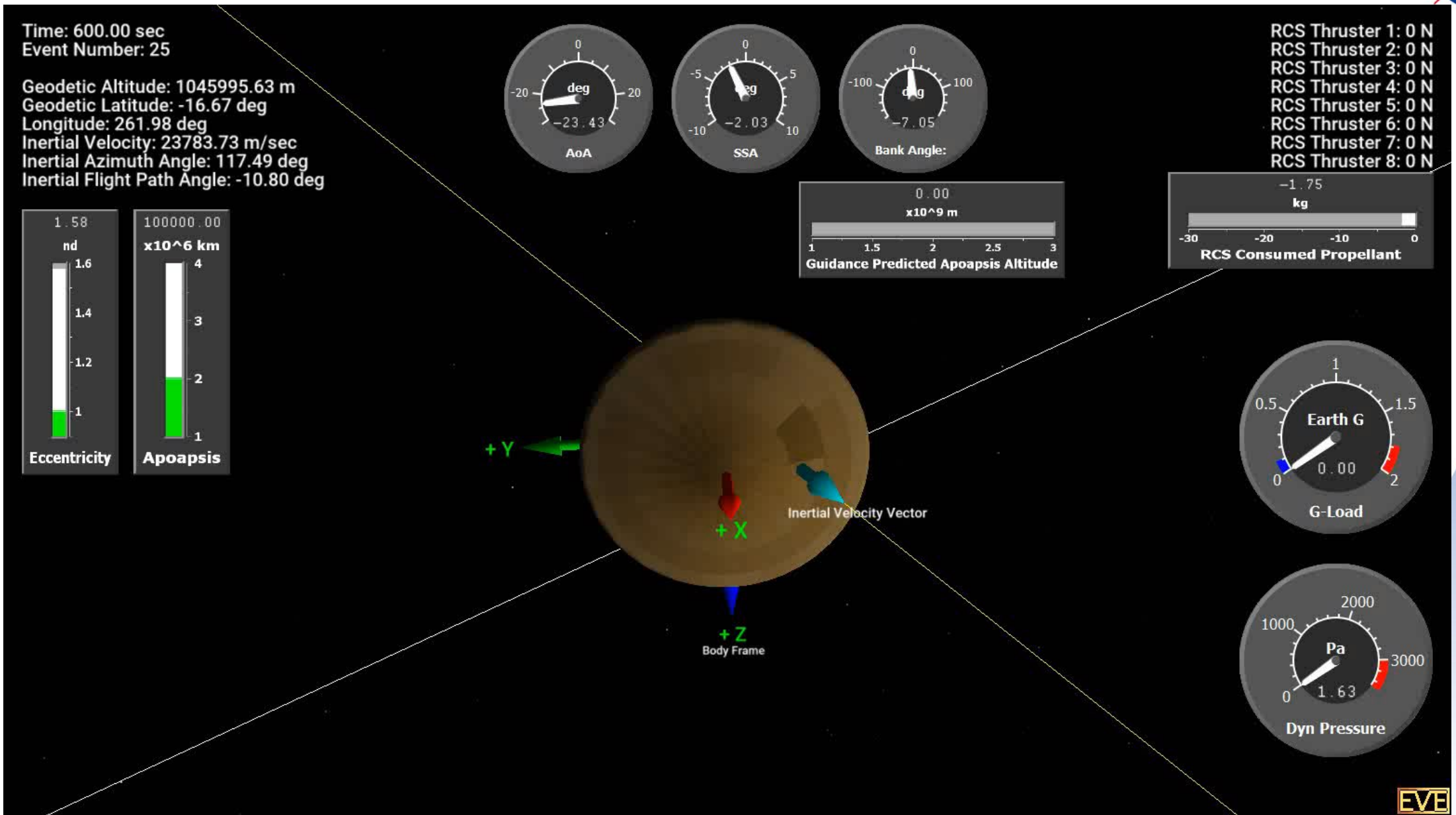
- Delivery State dispersions provided by entry state file (ESF)*
- UranusGRAM provides nominal and dispersed atmosphere
- Disperse on-board navigation via strapdown IMU and MEKF
- Aerodatabase provides nominal and dispersed aerodynamics
- Disperse mass properties by +-10%

Category	Variable	Nominal	$\pm 3\sigma$
Delivery State	Inertial Entry Flight Path Angle	-10.80 deg	0.150 deg
	Inertial Entry Velocity	23783.72 km/s	9.215 m/s
	Entry Altitude	1000 km	26.281 km
	Entry Latitude	-16.02 deg	0.116 deg
	Entry Longitude	262.12 deg	0.227 deg
	Inertial Entry Azimuth Angle	117.45 deg	0.063 deg
	Attitude Rates	0 deg/s	0.75 deg/s
	Attitude Angles	0 deg	0.15 deg
	Entry - 10 min Epoch	2048-10-29 13:47:36.00 ET	Fixed
Atmosphere	Random Error Seed	1	29999
	Density Perturbation Scale Factor	1	
Navigation	Accel/Gyro Random Error Seed	0 / 0	3000 /3000
	MEKF Quaternion 1	-0.59	Magnitude
	MEKF Quaternion 2	0.19	0.15 deg
	MEKF Quaternion 3	0.08	0.15 deg
	MEKF Quaternion 4	0.78	0.15 deg
Aerodynamics (Continuum)	Axial Force Adder/Multiplier	0 / 0	0 / 5.38%
	Normal Force Adder/Multiplier	0 / 0	0.0185 / 10%
	Side Force Adder/Multiplier	0 / 0	0.0185 / 10%
	Pitch Moment Adder/Multiplier	0 / 0	0.00948 / 20%
	Yaw Moment Adder/Multiplier	0 / 0	0.0693 / 20%
	Roll Moment Adder/Multiplier	0 / 0	0.000219 / 0%
Mass Properties	C.G Multiplier	1	0.1
	Inertia Multiplier	1	0.1

Unless otherwise noted, each category assumes a normal distribution

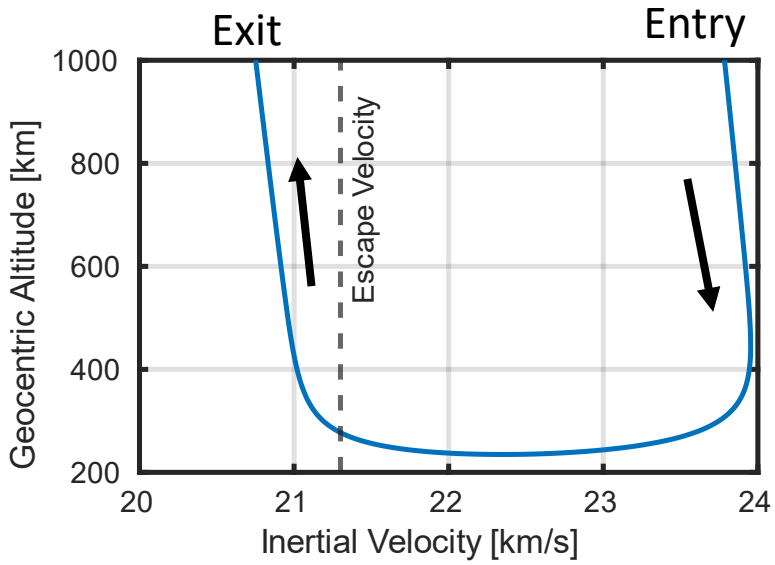
*ESF provides dispersed state in each row; values in table are resulting ±3σ value from each variable distribution

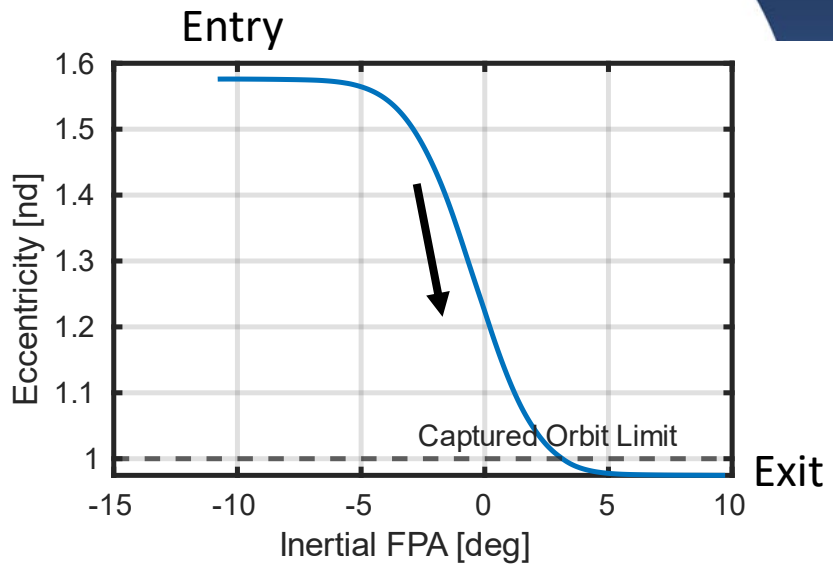
6DOF Nominal Trajectory

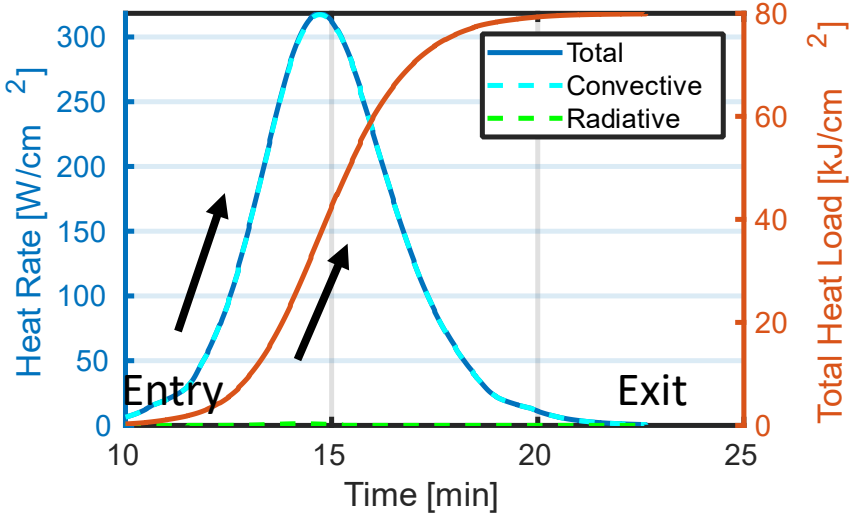


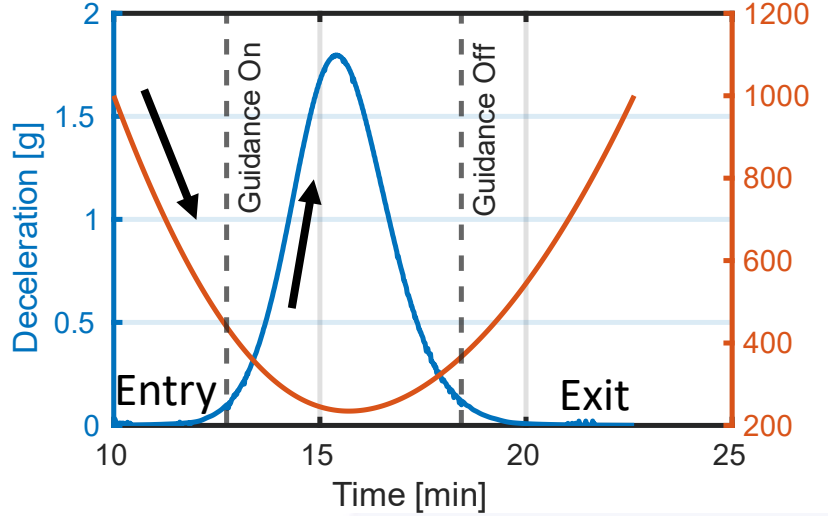
6DOF Nominal Trajectory

- 3 km/s of velocity dissipation
- 13 min flight time from entry to exit
- Total peak heat rate of 318 W/cm^2 at ~5 min after entry
- Peak deceleration of 1.75 Earth G at ~5 min after entry
- Integrated total heat load of 80 kJ/cm^2



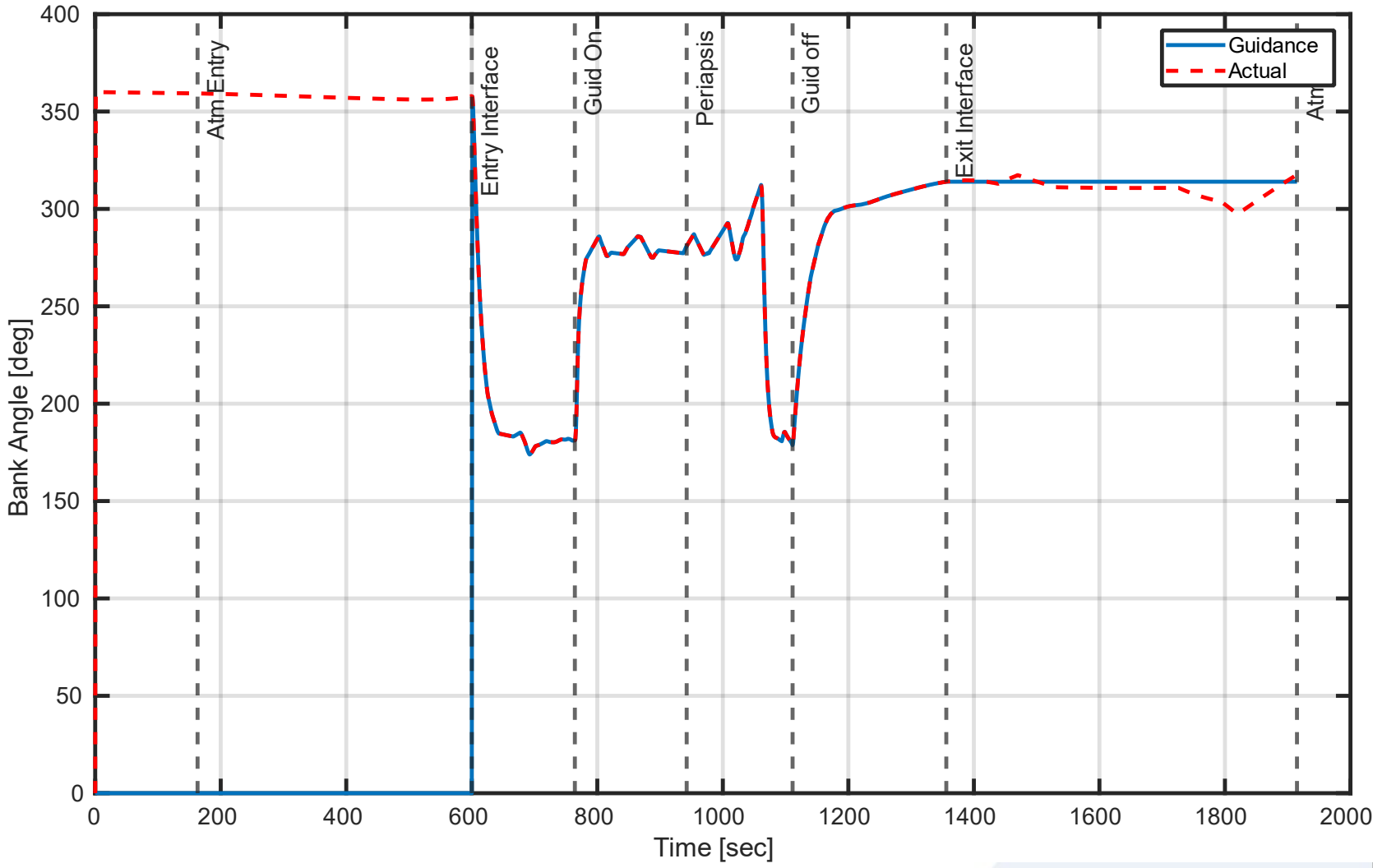






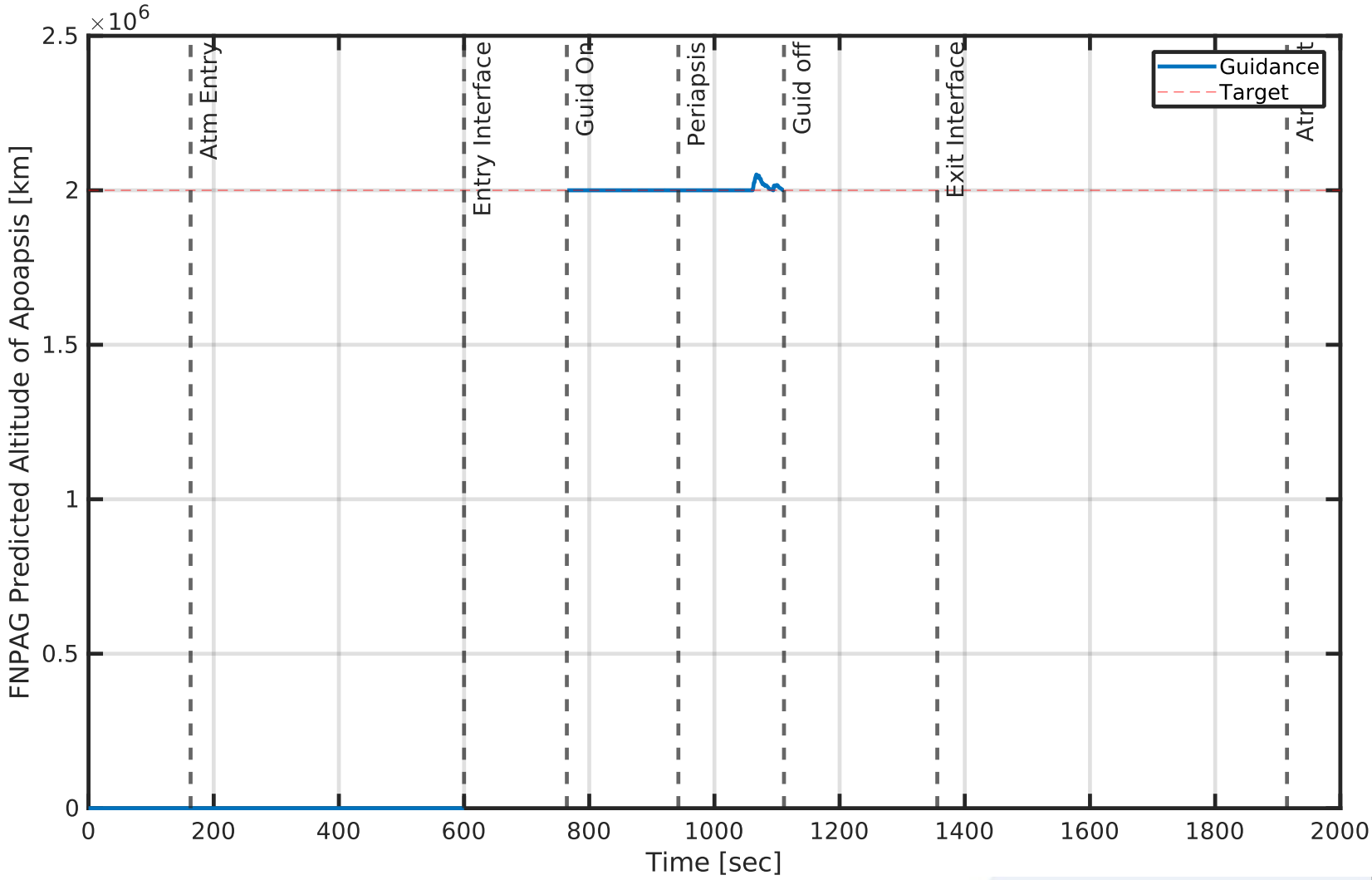
6DOF Nominal Trajectory

- **RCS able to achieve guidance bank commands**
- Closed-loop guidance able to optimize to target apoapsis
- Control system able to trim AoA at -17 deg
- Trim AoA produces desired 0.25 L/D
- RCS propellant useage of 22 kg



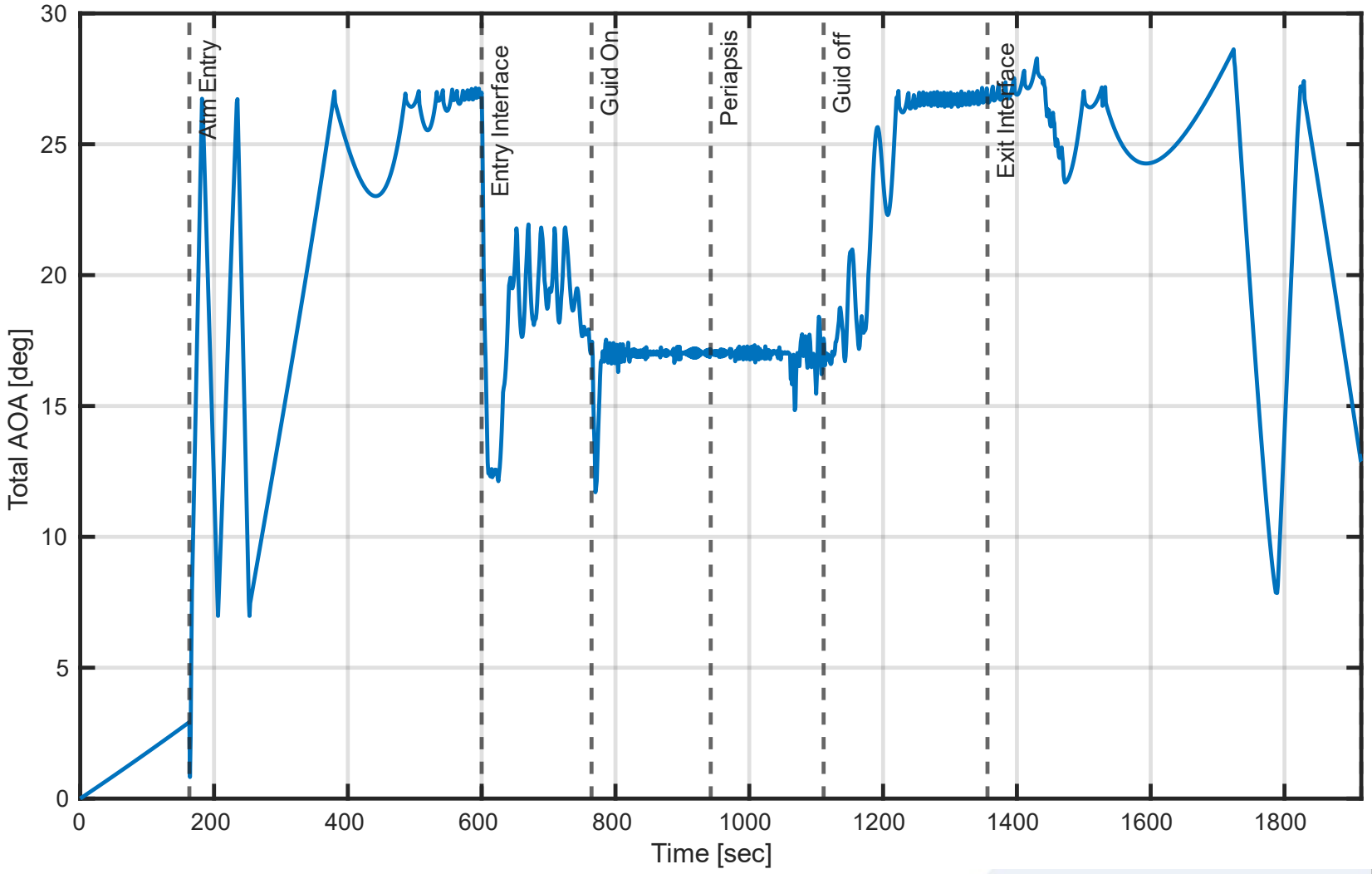
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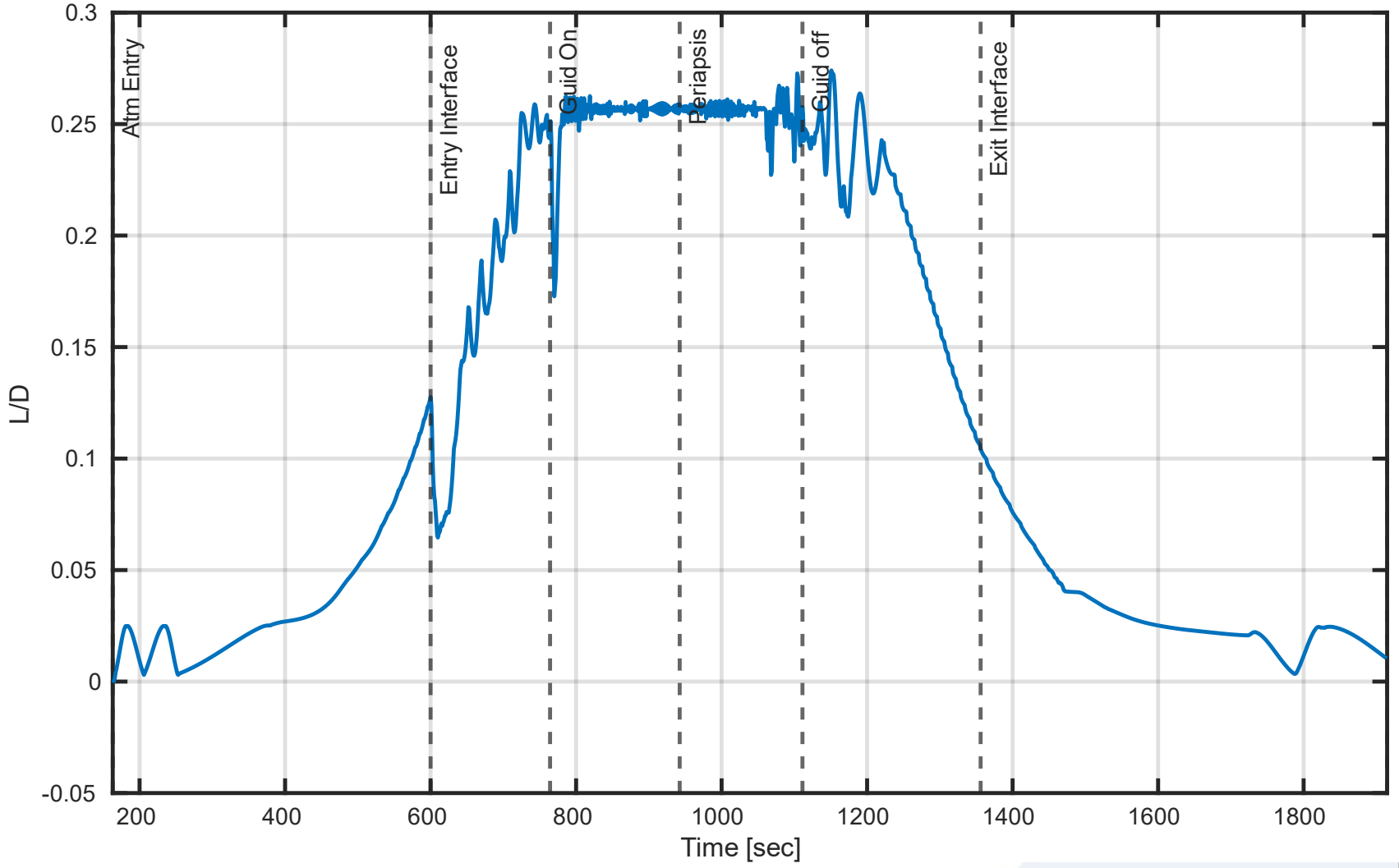
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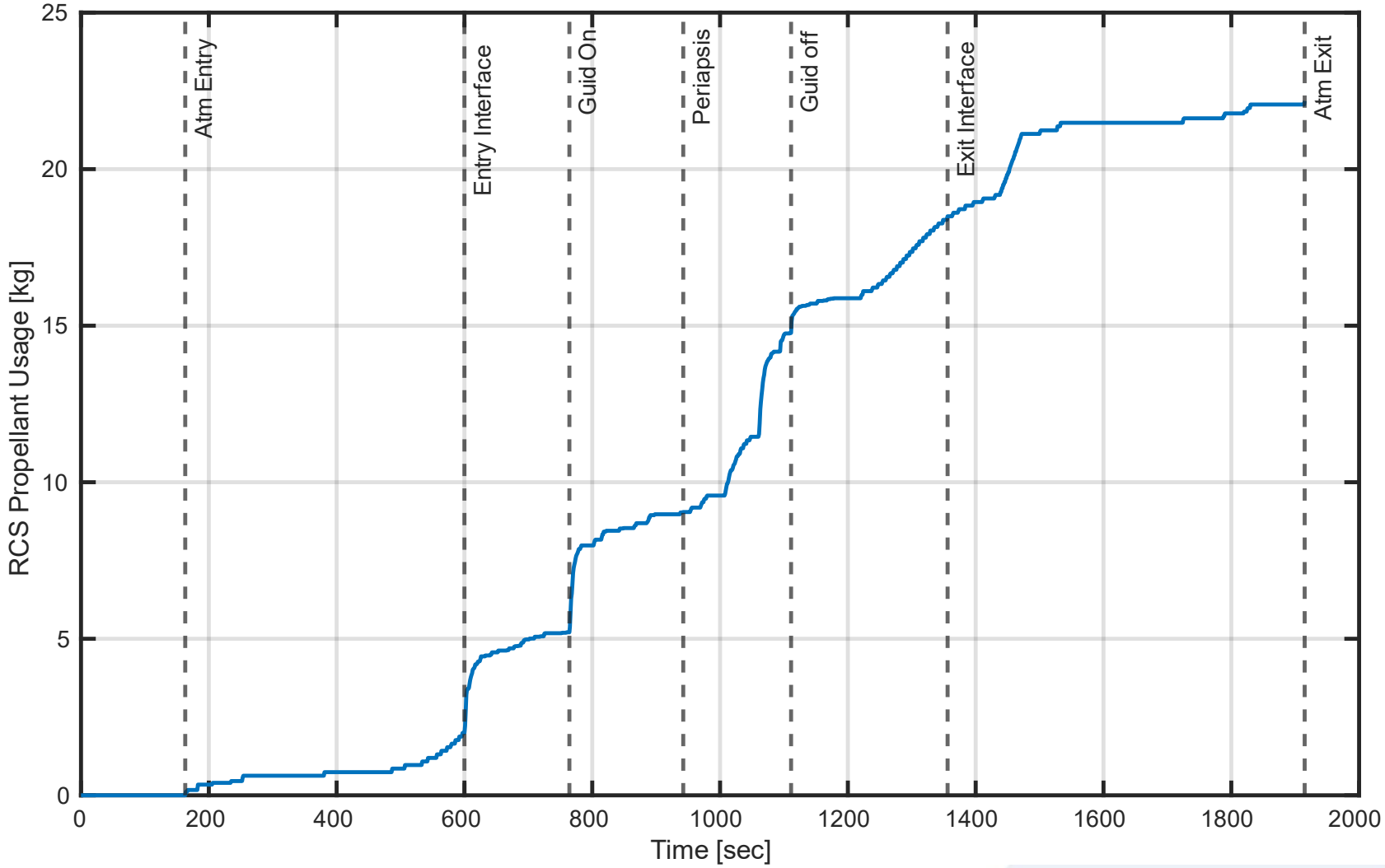
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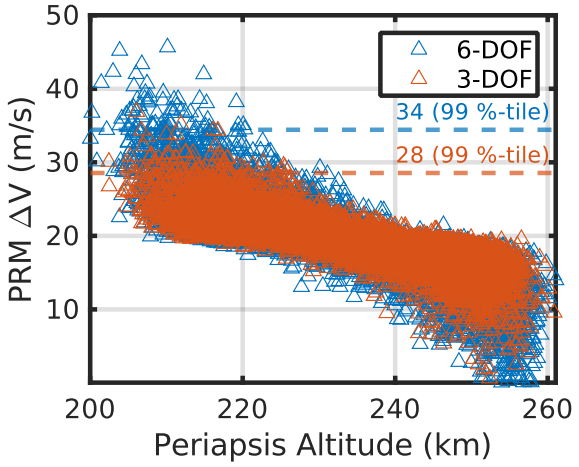
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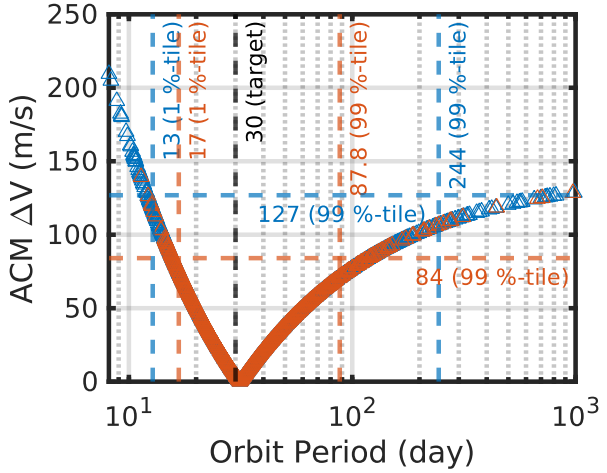
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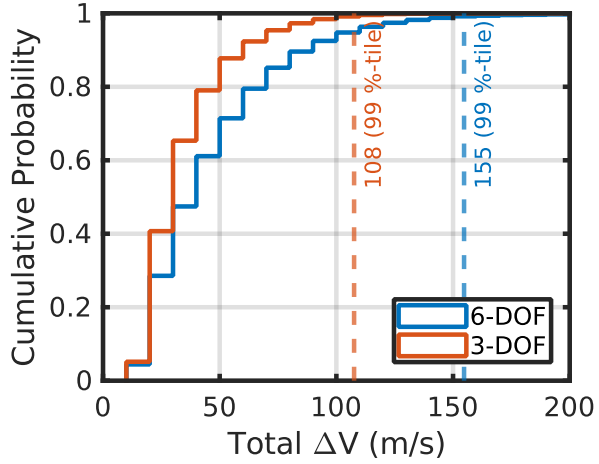


6DOF Monte Carlo Trajectory

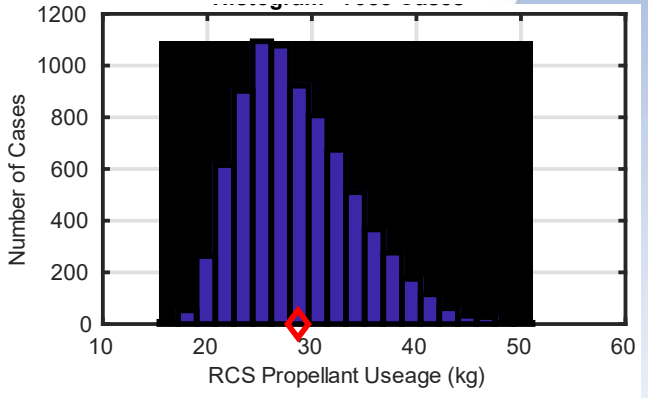
Compare 6DOF Monte Carlo simulation to 3DOF Monte Carlo simulation







- **Increased orbit insertion cost**
- Similar aeroheating and deceleration
- More hyperbolic cases*

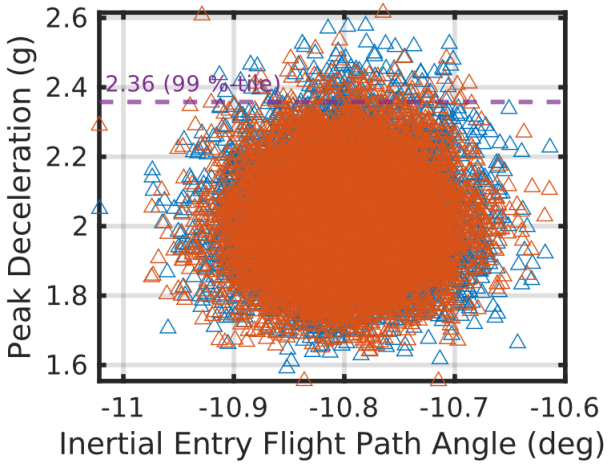


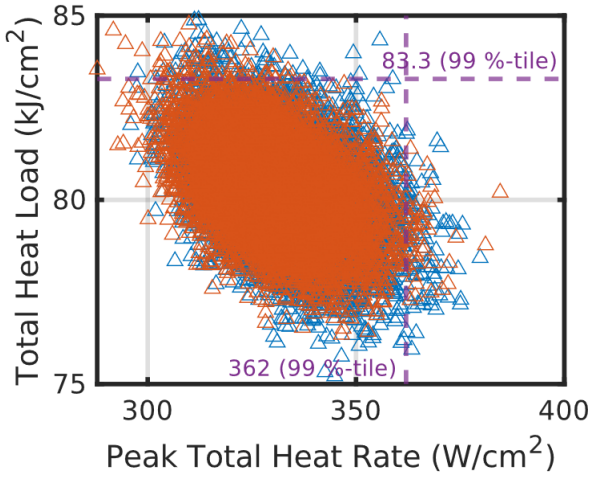
*Recovery ΔV introduced as mitigation strategy to capture remaining hyperbolic cases

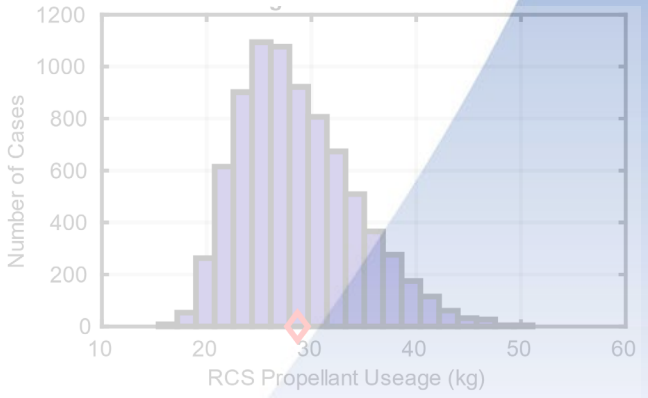
6DOF Monte Carlo Trajectory

Compare 6DOF Monte Carlo simulation to 3DOF Monte Carlo simulation

- Increased orbit insertion cost
- **Similar aeroheating and deceleration**
- More hyperbolic cases*





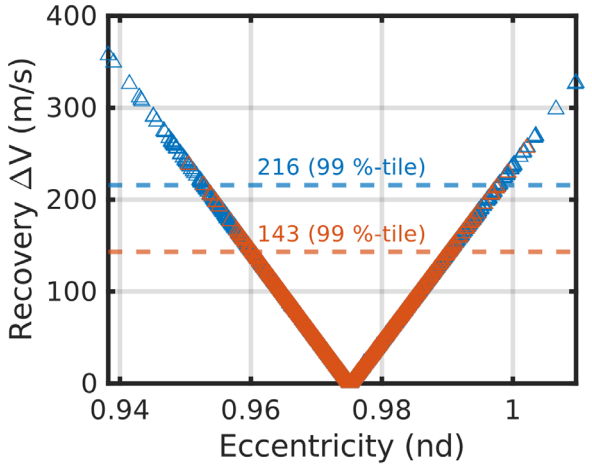


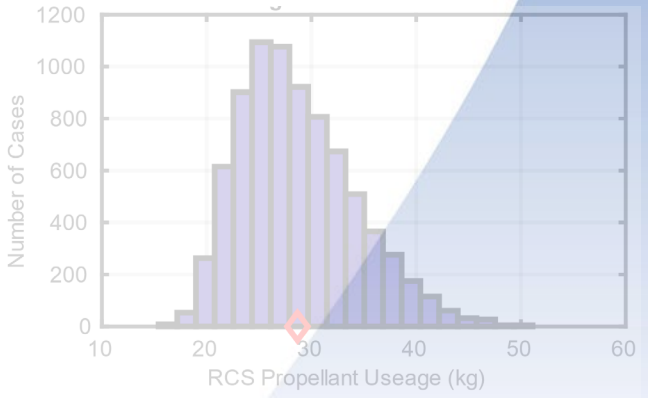
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6DOF Monte Carlo Trajectory

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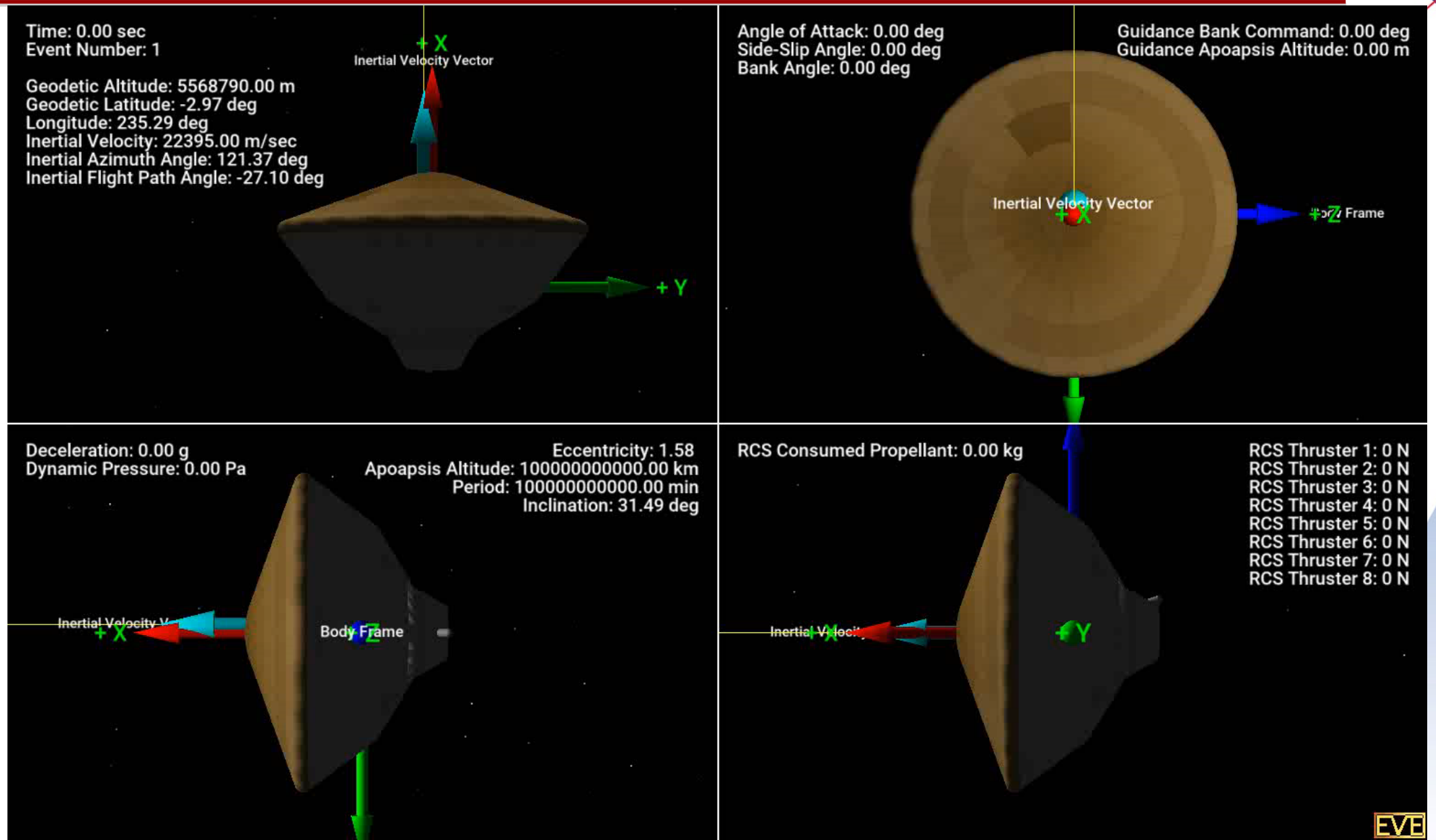


***Recovery ΔV introduced as mitigation strategy to capture remaining hyperbolic cases**

Study Findings

- **Developed 6DOF modeling and simulation framework**
  - One of the first developed for aerocapture
  - Applied it to the Uranus Orbiter and Probe
- **Conducted trajectory analysis**
  - Demonstrated viability of using a PD RCS control system for achieving bank angle commands during aerocapture
  - 6DOF Monte Carlo simulations produce results that are generally comparable to 3DOF simulation results
    - Slightly worsened orbit insertion performance but can be accounted for using recovery ΔV
    - RCS propellant mass allocation less than 50 kg
- **Future Work**
  - Analysis of dispersions sources to understand key drivers to 6DOF Monte Carlo results
  - Improve fidelity of GNC modeling
  - Assessment of alternative RCS control algorithms

Questions

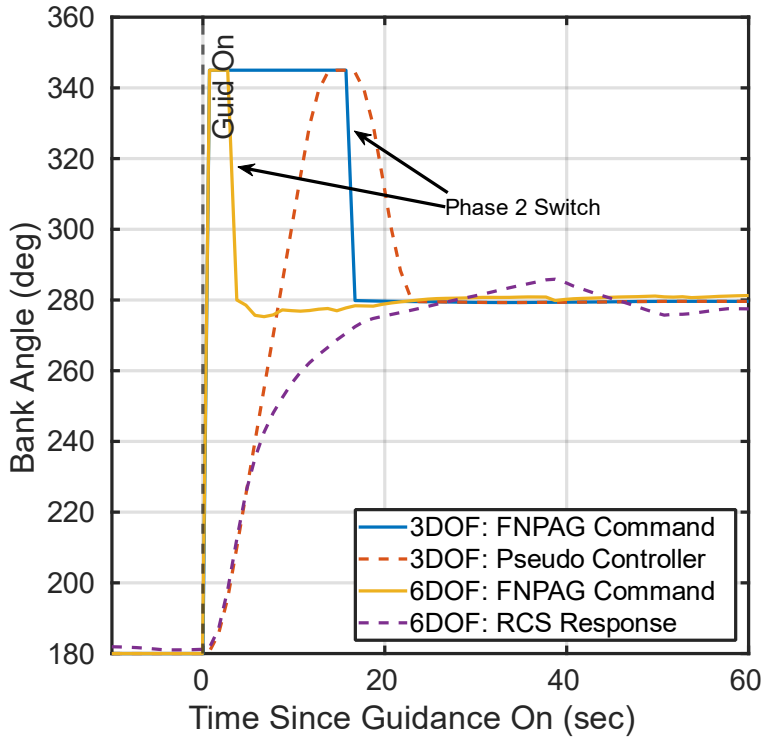

Time: 0.00 sec
Event Number: 1
Geodetic Altitude: 5568790.00 m
Geodetic Latitude: -2.97 deg
Longitude: 235.29 deg
Inertial Velocity: 22395.00 m/sec
Inertial Azimuth Angle: 121.37 deg
Inertial Flight Path Angle: -27.10 deg
+ X
Inertial Velocity Vector
+ Y
Angle of Attack: 0.00 deg
Side-Slip Angle: 0.00 deg
Bank Angle: 0.00 deg
Guidance Bank Command: 0.00 deg
Guidance Apoapsis Altitude: 0.00 m
Inertial Velocity Vector
Deceleration: 0.00 g
Dynamic Pressure: 0.00 Pa
Eccentricity: 1.58
Apoapsis Altitude: 100000000000.00 km
Period: 100000000000.00 min
Inclination: 31.49 deg
Body Frame
RCS Consumed Propellant: 0.00 kg
RCS Thruster 1: 0 N
RCS Thruster 2: 0 N
RCS Thruster 3: 0 N
RCS Thruster 4: 0 N
RCS Thruster 5: 0 N
RCS Thruster 6: 0 N
RCS Thruster 7: 0 N
RCS Thruster 8: 0 N
EVE

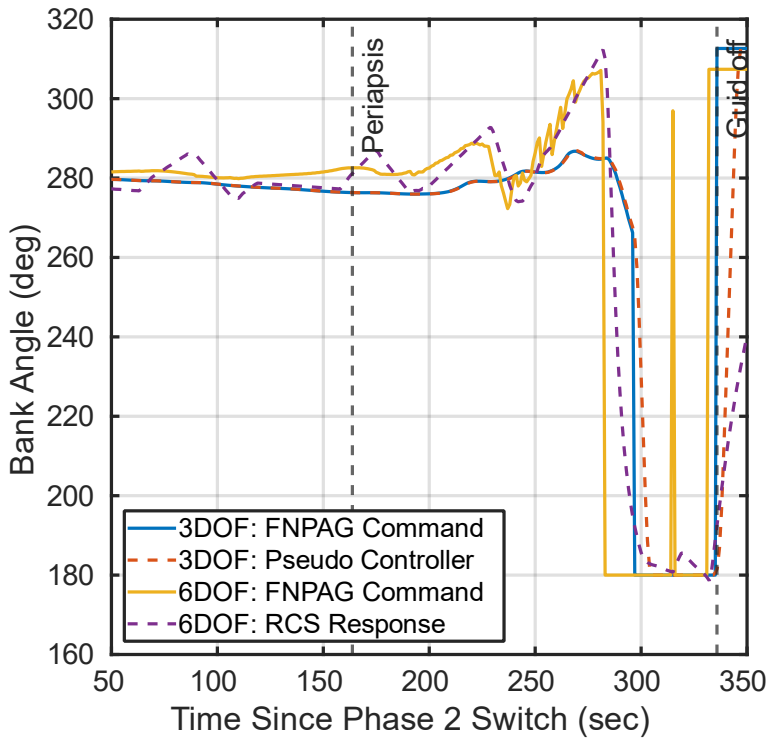
Backup

Aerocapture Guidance, Navigation, and Control

RCS PD Controller

- Inspired from MSL attitude Entry Controller [1]
- Utilizing PD with saturation logic [2]
- Gain schedule based on region of flight





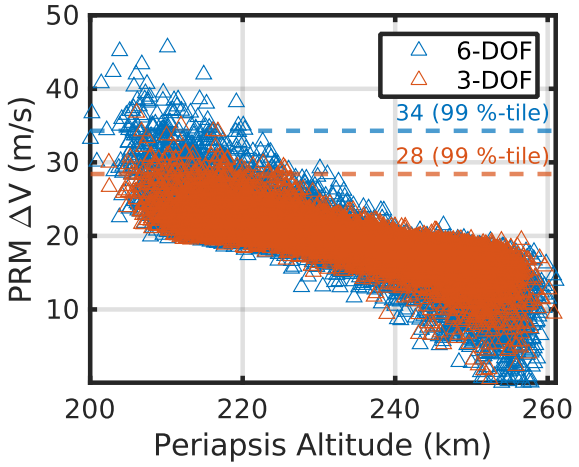
	Entry	Active Guidance	Exit
Pitch	Kp = 0.5 Kd = 2.5 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.5 Kd = 2.5 Prop Err Deadband = 5 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.5 Kd = 2.5 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s
Roll	Kp = 0.1 Kd = 1.5 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.3 Kd = 2.0 Prop Err Deadband = 5 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.1 Kd = 3.0 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s
Yaw	Kp = 0.1 Kd = 1.5 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.3 Kd = 2.0 Prop Err Deadband = 5 deg Deriv Err Deadband = 0.1 deg/s	Kp = 0.1 Kd = 3.0 Prop Err Deadband = 10 deg Deriv Err Deadband = 0.1 deg/s

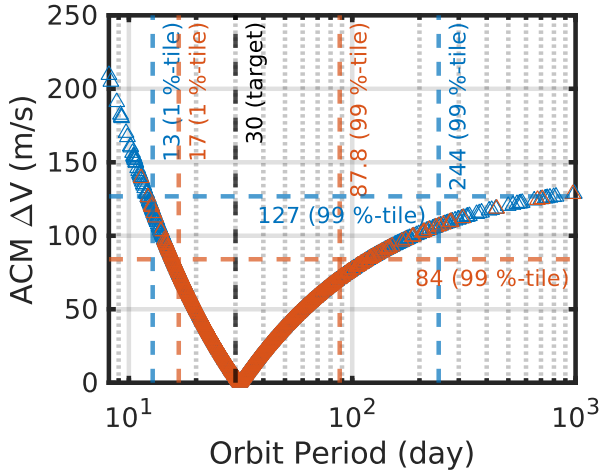
[1] Brugarolas, P.B and San Martin, A.M., and Wong, E.C., "Attitude Controller for the Atmospheric Entry of the Mars Science Laboratory", *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Honolulu, HI, August 2008.

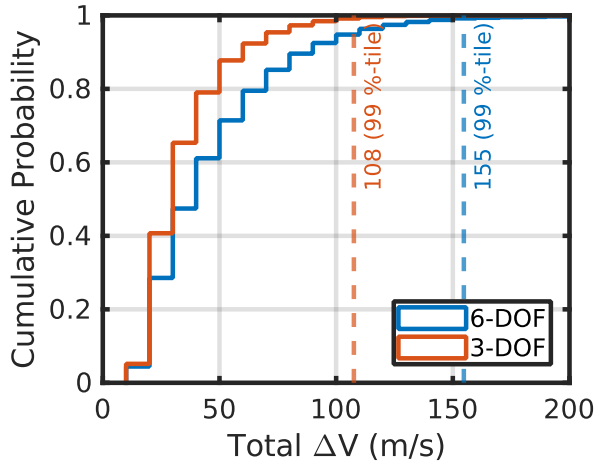
[2] Wie, B., "Space Vehicle Guidance, Control, and Astrodynamics", *AIAA Educational Series*, 2015

6DOF Monte Carlo Trajectory

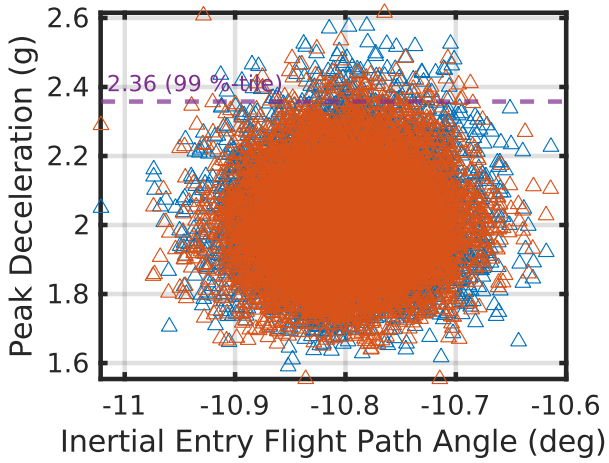
Compare 6DOF Monte Carlo simulation to 3DOF Monte Carlo simulation

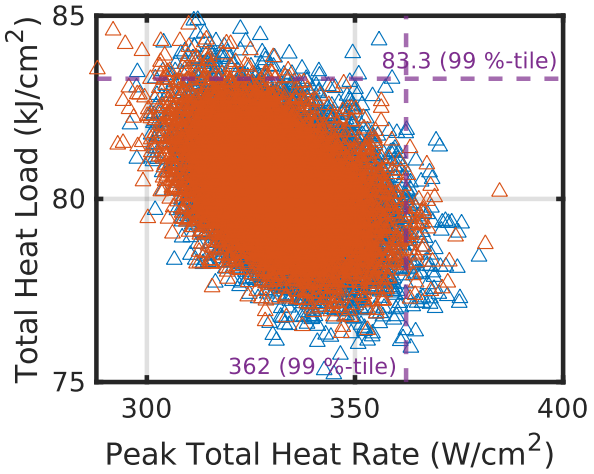


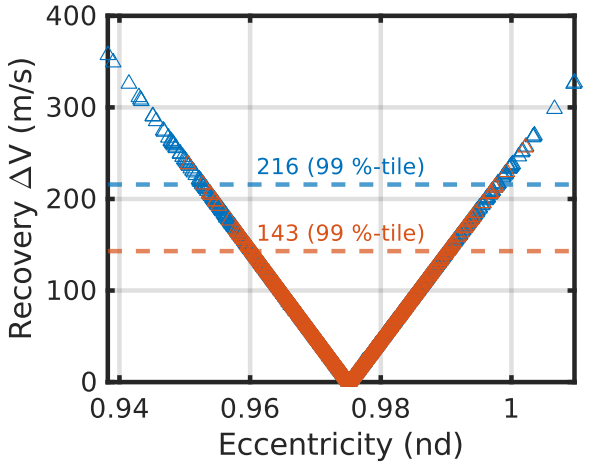


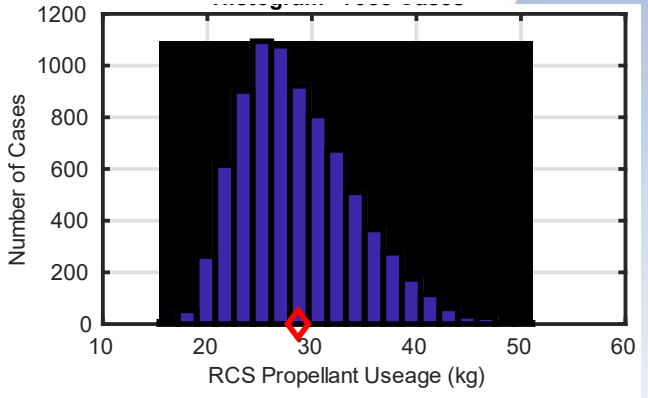


- **Slightly worse orbit insertion performance**
- **More hyperbolic cases***
- **Similar aeroheating and deceleration**





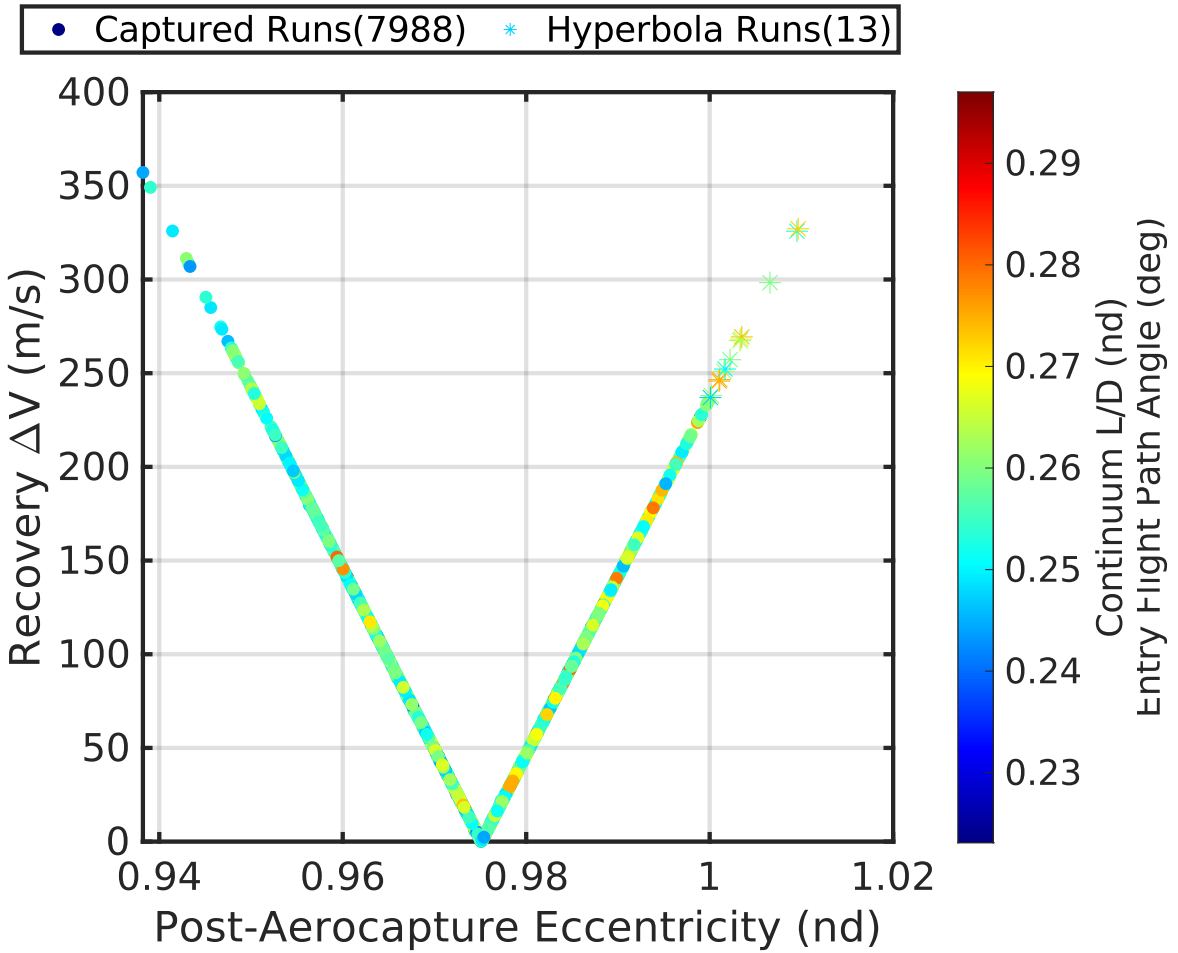




***Recovery ΔV introduced as mitigation strategy to capture remaining hyperbolic cases**

6DOF Monte Carlo Trajectory

Assess key dispersions sources to understand if any correlations to aerocapture performance exist



- **Aerodynamic dispersions don't drive orbit insertion performance**
- **Delivery state dispersions don't drive orbit insertion performance**
- **Atmospheric dispersions can influence orbit insertion performance**