Performance Analysis of Aerocapture Systems for Uranus Orbiters

2024 AIAA SciTech Forum
GNC-13/AFM-04/SFM-11: Entry, Descent, and Landing GN&C Technology IV – Aerocapture for Ice Giants I
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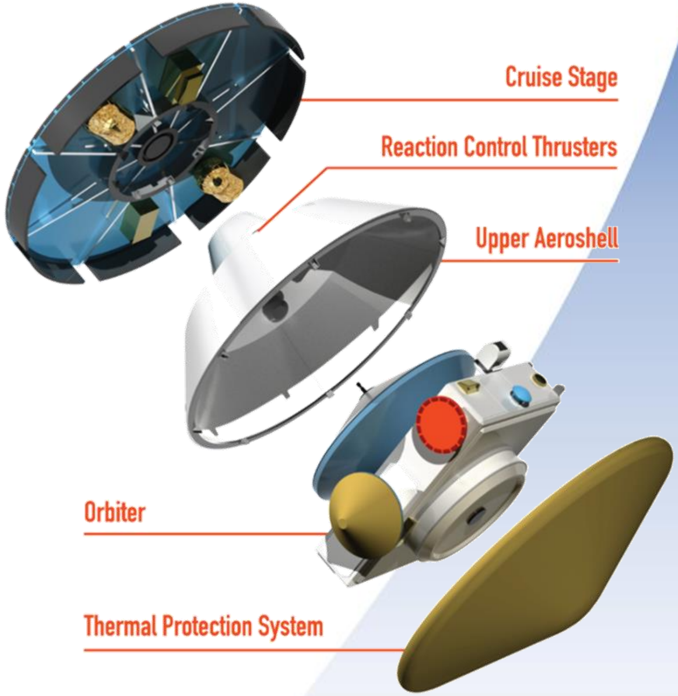
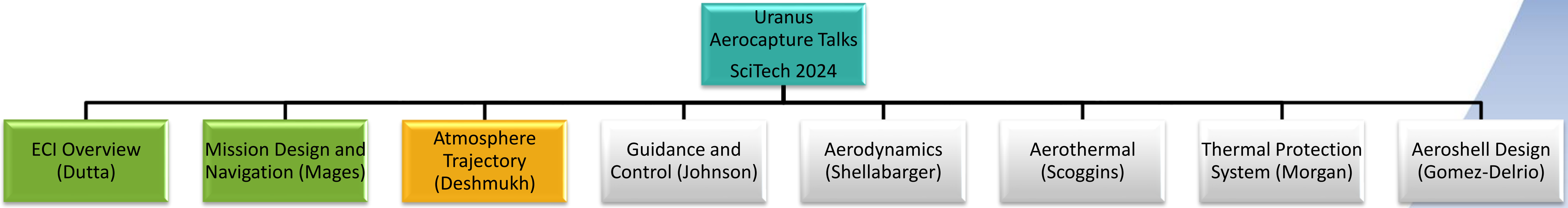
NASA Early Career Initiative



Motivation

- **Aerocapture can potentially enable faster arrival trajectories and reduce orbit insertion propellant mass at Uranus**
  - Improvements to the proposed Uranus Orbiter and Probe Flagship mission concept
- **Question: How well does aerocapture perform at Uranus using a Mars Science Laboratory-derived aeroshell design?**



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

Outline

- **Overview**
- **Trajectory Simulation Framework**
- **Uranus Aerocapture Design Space**
- **Performance Analysis**
  - Baseline Scenario
  - Interplanetary Navigation Sensitivity
  - Arrival Trajectory Sensitivity
  - Atmosphere Sensitivity
- **Study Findings**
- **Future Work**

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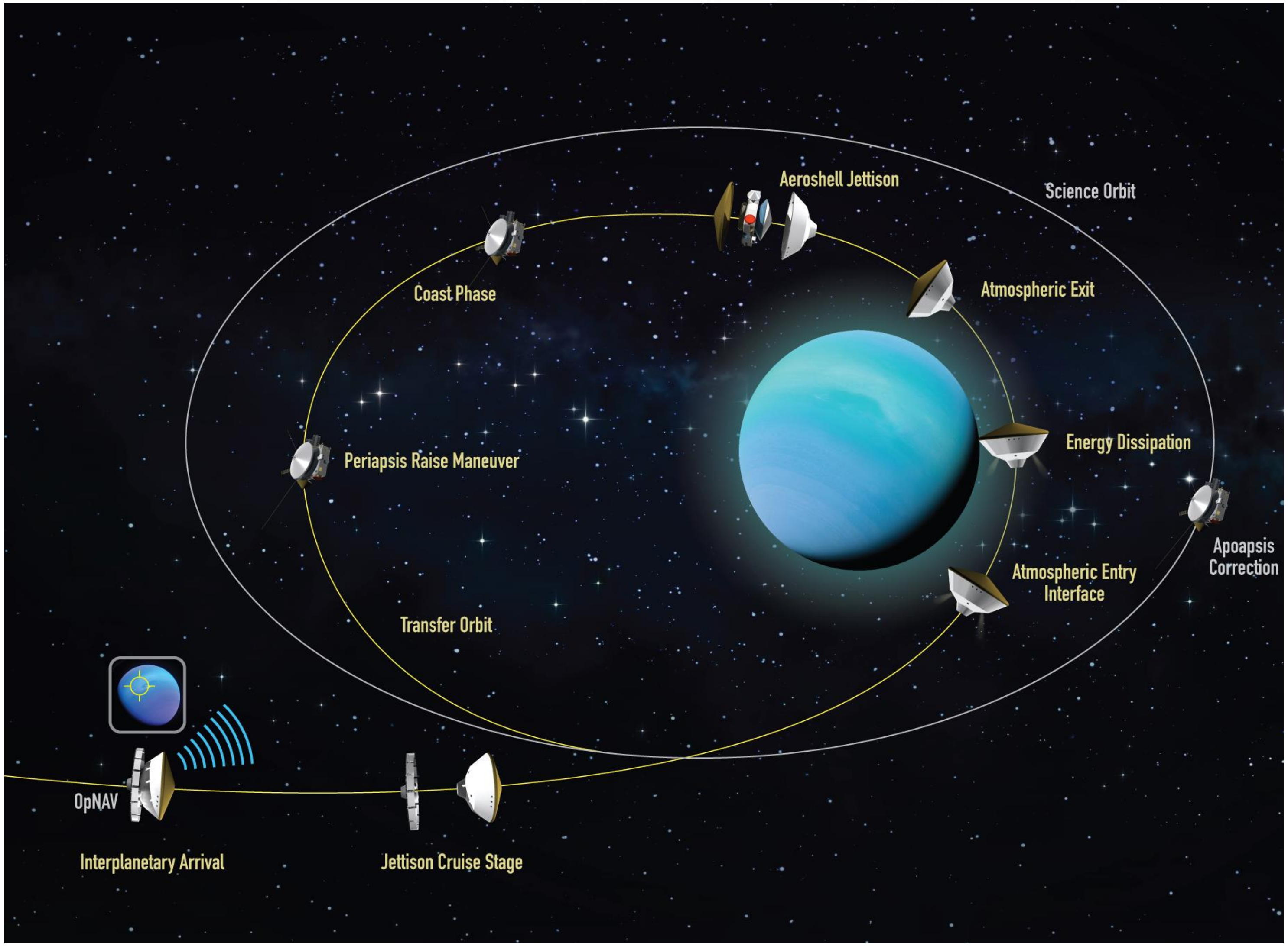
LaRC: NASA Langley Research Center
ARC: NASA Ames Research Center
JSC: NASA Johnson Space Center
JPL: Jet Propulsion Laboratory

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_{UOI}) targeting desired apoapsis altitude at exit
- Exit atmosphere on elliptical orbit. Raise periapsis out of atmosphere and then correct residual apoapsis error ($\Delta V_{total} = \Delta V_{PRM} + \Delta V_{ACM}$)
- Post-aerocapture equatorialization done to correct orbital plane

Trajectory Simulation Framework

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

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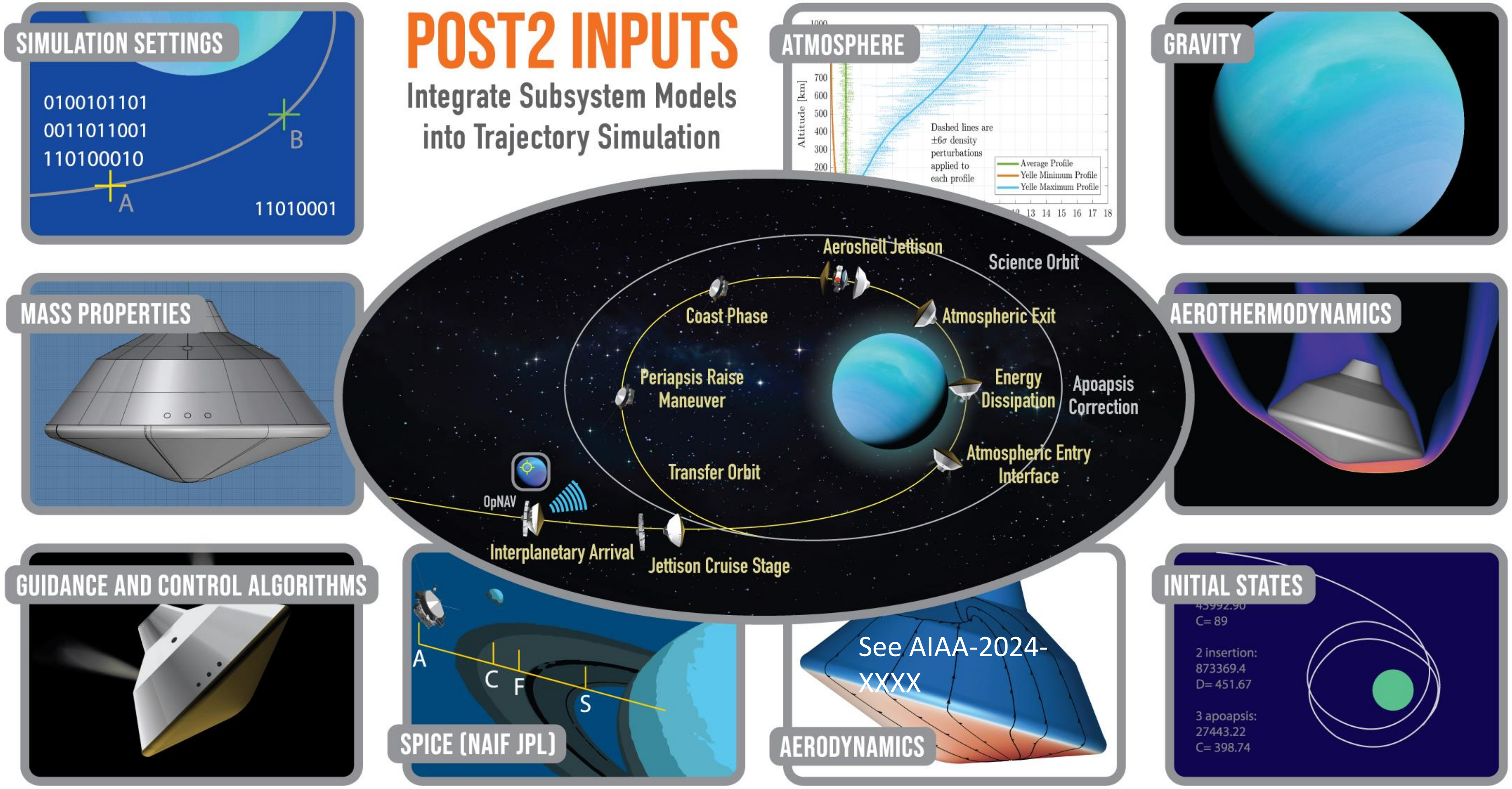

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Trajectory Simulation Model Inputs

- **Oblate Ellipsoidal Gravity Model**
- **Uranus Global Reference Atmosphere Model 2021**
- **Uranus-Based CFD Aerodatabase**
- **Sutton-Graves aerothermal model used in trajectory sim**
  - AIAA-2024-XXXX used CFD based runs for higher-fidelity aerothermal characterization
- **Fully Numerical Predictor-Corrector Aerocapture Guidance (FNPAG)**
  - Bank angle control
- **MSL-derived aeroshell design housing UOP payload**

Category	Variable	Value	Units
Gravity	Equatorial Radius	25559	km
	Polar Radius	24973	km
	J2	0.003343	
	Rotational Rate	-1.012371E-4	rad/s
	Gravitational Constant	5.793951E6	km^3/s^2
SPICE	Binary Files	de430, ura111	
	Leap Second Kernel	naif0012	
	Planetary Constant Kernel	pck00010	
Atmosphere	Atmosphere Entry/Exit Altitude	4000	km
	Guidance Entry/Exit Altitude	1000	km
	Model	UranusGRAM 2021	
Aerodynamics	Hypersonic L/D	0.25	
	Hypersonic Ballistic Coefficient	140	kg/m^3
	Hypersonic Trim Angle of Attack	-17	deg
GNC	Guidance Algorithm	FNPAG	
	Guidance Trigger	0.1	G’s
	Guidance Rate	2	Hz
	Onboard Navigation	Perfect State Knowledge	
	Control Method	Bank Angle	
	Control Rate Limit	15	deg/s
	Control Acceleration Limit	5	deg/s
Aerothermal*	Sutton-Graves Constant	8.645E-5	kg^0.5/m
Aeroshell	Mass	4064.25	kg
	Diameter	5	m
	Nose Radius	1.25	m

Uranus Aerocapture Design Space

- **Objective: Understand how aeroshell design (L/D, BC) and interplanetary trajectories (V_∞) influence aerocapture performance metrics. Identify candidate solutions for performance assessment.**
- **Methodology: Corridor Width assessment**
  - Parametric design-space → L/D, BC, V_∞
    - L/D from 0 to 0.5 → assess blunt-body aeroshells
    - BC from 120 to 160 kg/m^2 → assess MSL-derived aeroshell housing UOP payload mass
    - V_∞ from 10 to 20 km/s → assess range of solutions from interplanetary trajectory-space
  - Solve for max/min control trajectories that achieve the target orbit → corridor width bounds
  - Calculate key aerocapture performance metrics → peak heating, peak deceleration, corridor width
  - Calculate corridor over individual 3σ trajectory dispersions (atmosphere, aerodynamics) → flight envelope

L/D: Lift-to-Drag Ratio
BC: Ballistic Coefficient

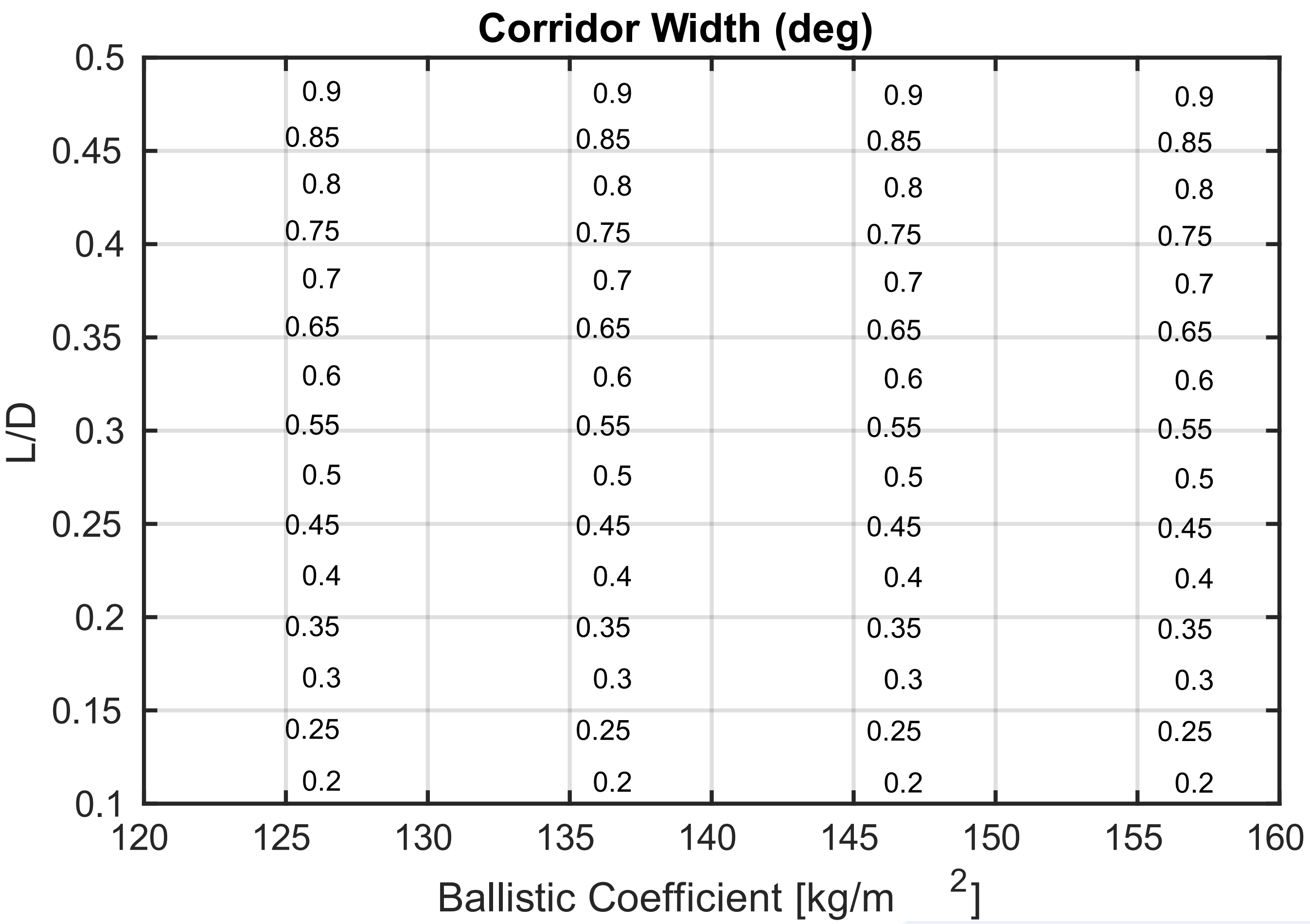
Uranus Aerocapture Design Space

Corridor Width

- Metric that defines how wide the guidable trajectory-space is
- Increases with L/D
- Not affected by BC

Implications

- Lifting control is the best control option for Uranus aerocapture
  - Drag control (modulate BC) has little influence on the width
- Obtain similar width for same L/D if aeroshell diameter or entry wet mass is changed (e.g. changes to BC)
  - $BC = \frac{m}{C_D S_{ref}}$



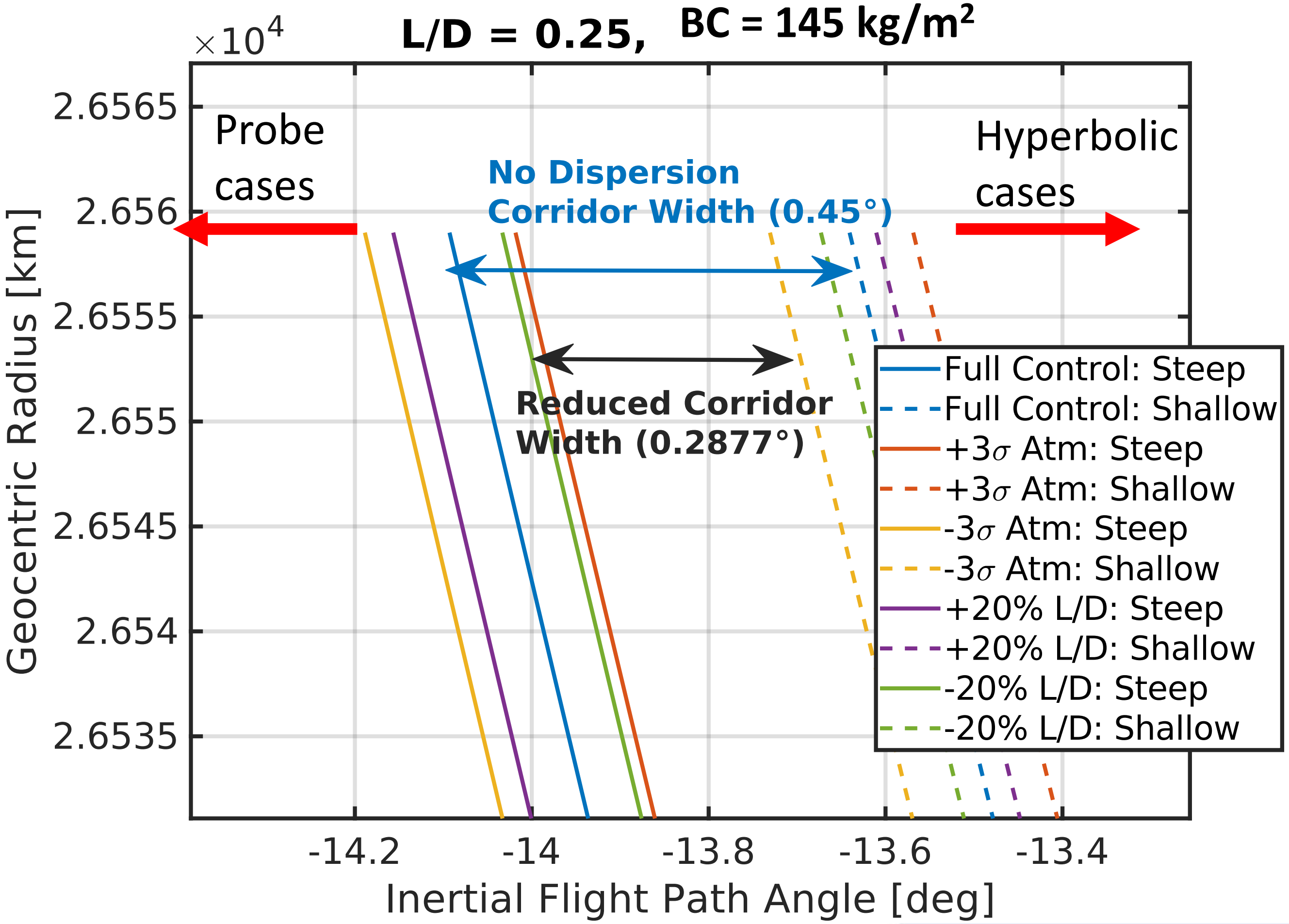
Uranus Aerocapture Design Space

Flight Envelope

- Metric that defines how much guidable trajectory-space remains after applying trajectory dispersions
- Apply statistical dispersion limits one variable at a time
- Analyze baseline aeroshell design

Implications

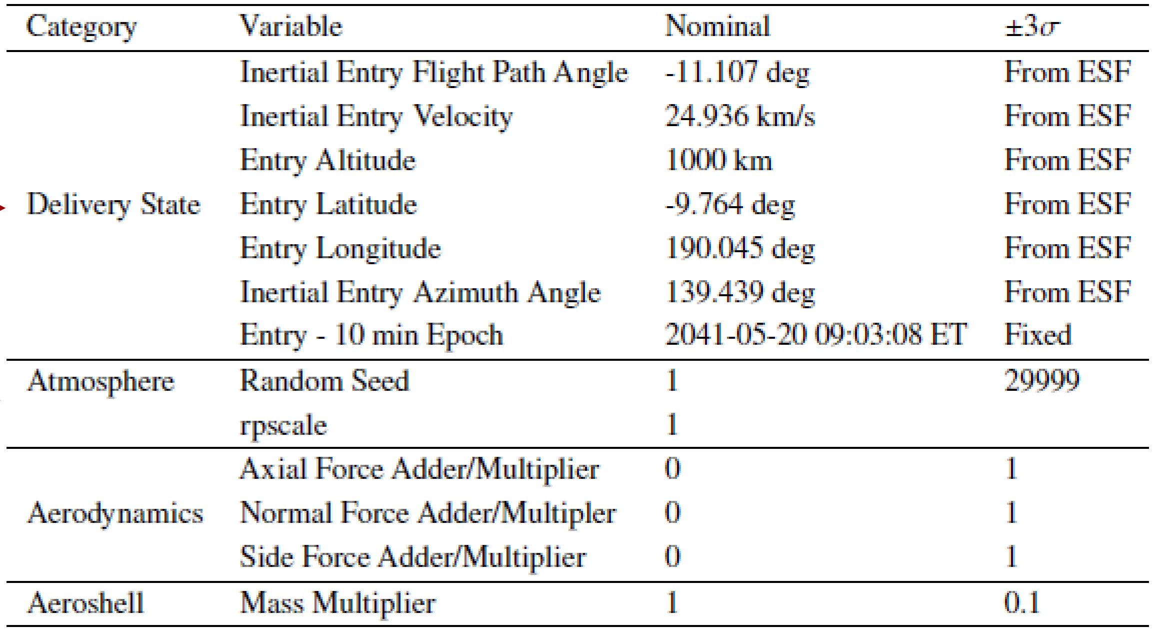
- Atmosphere significantly reduces width
  - Indicates biggest variable sensitivity to Uranus aerocapture
- Reduced width can be compared against delivery state uncertainty
  - If larger than width, have zero remaining control margin. Lead to uncaptured cases



Performance Analysis

- **Four Monte Carlo scenarios conducted to assess performance sensitivity**
  1. Baseline → control
  2. Navigation → assess sensitivity to navigation solutions
  3. Arrival Trajectory → assess sensitivity to faster and slower arrival trajectories (V_∞)
  4. Atmosphere → assess sensitivity to different atmosphere model
- **Objective: Understand how each scenario influences aerocapture performance metrics and robustness**
  - What are the key drivers?
  - Where does aerocapture break?
  - What methods can we develop to reduce risk?

Baseline Scenario Monte Carlo Dispersion Settings

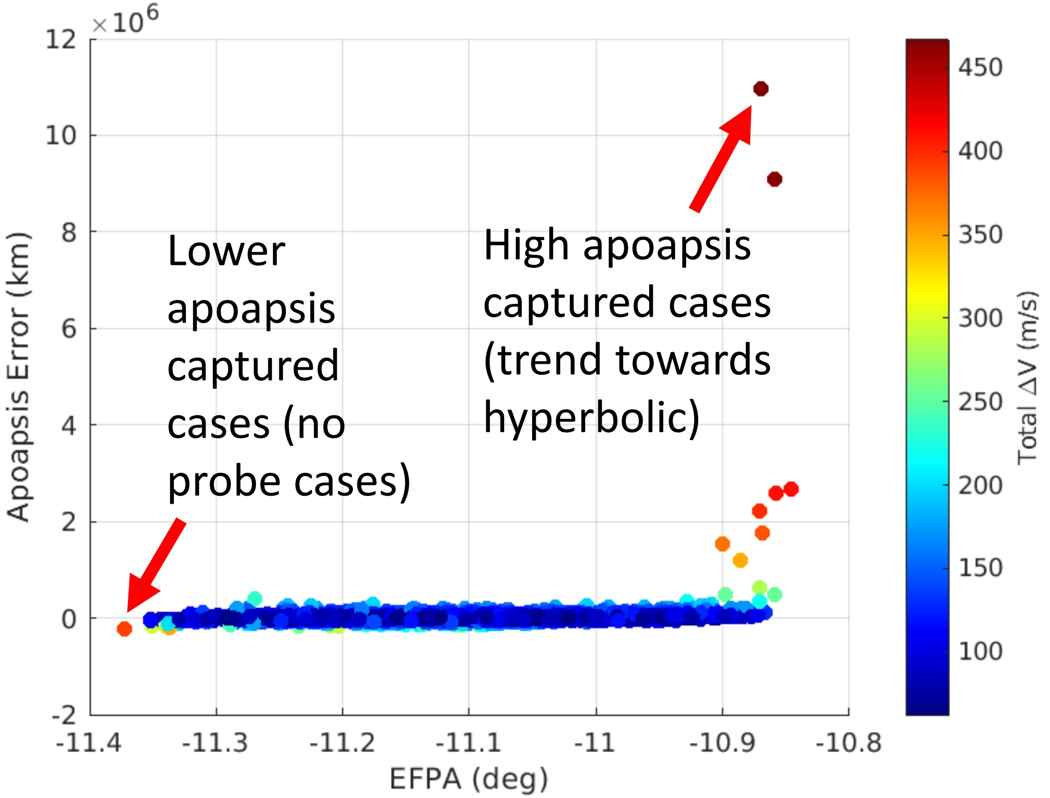


Category	Variable	Nominal	$\pm 3\sigma$
Delivery State	Inertial Entry Flight Path Angle	-11.107 deg	From ESF
	Inertial Entry Velocity	24.936 km/s	From ESF
	Entry Altitude	1000 km	From ESF
	Entry Latitude	-9.764 deg	From ESF
	Entry Longitude	190.045 deg	From ESF
	Inertial Entry Azimuth Angle	139.439 deg	From ESF
	Entry - 10 min Epoch	2041-05-20 09:03:08 ET	Fixed
Atmosphere	Random Seed	1	29999
	rpscale	1	
Aerodynamics	Axial Force Adder/Multiplier	0	1
	Normal Force Adder/Multipler	0	1
	Side Force Adder/Multiplier	0	1
Aeroshell	Mass Multiplier	1	0.1

Baseline Scenario

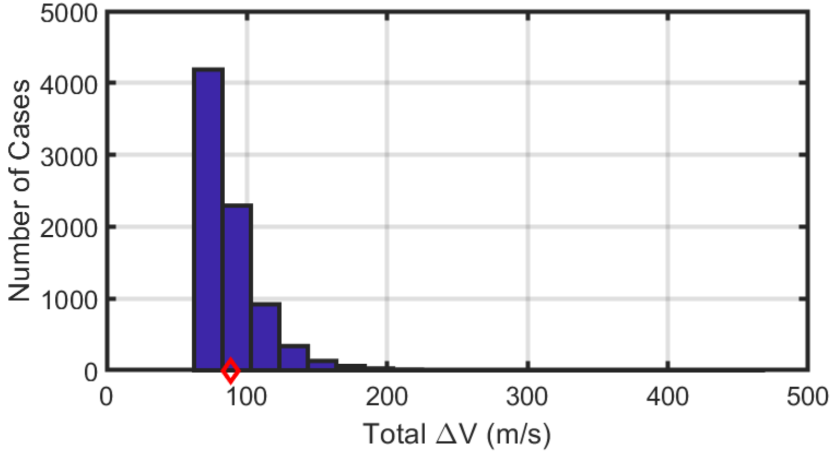
Guidance shows promising results

- Few high ΔV cases correlate to extreme bounds of EFPA



Lower apoapsis captured cases (no probe cases)

High apoapsis captured cases (trend towards hyperbolic)

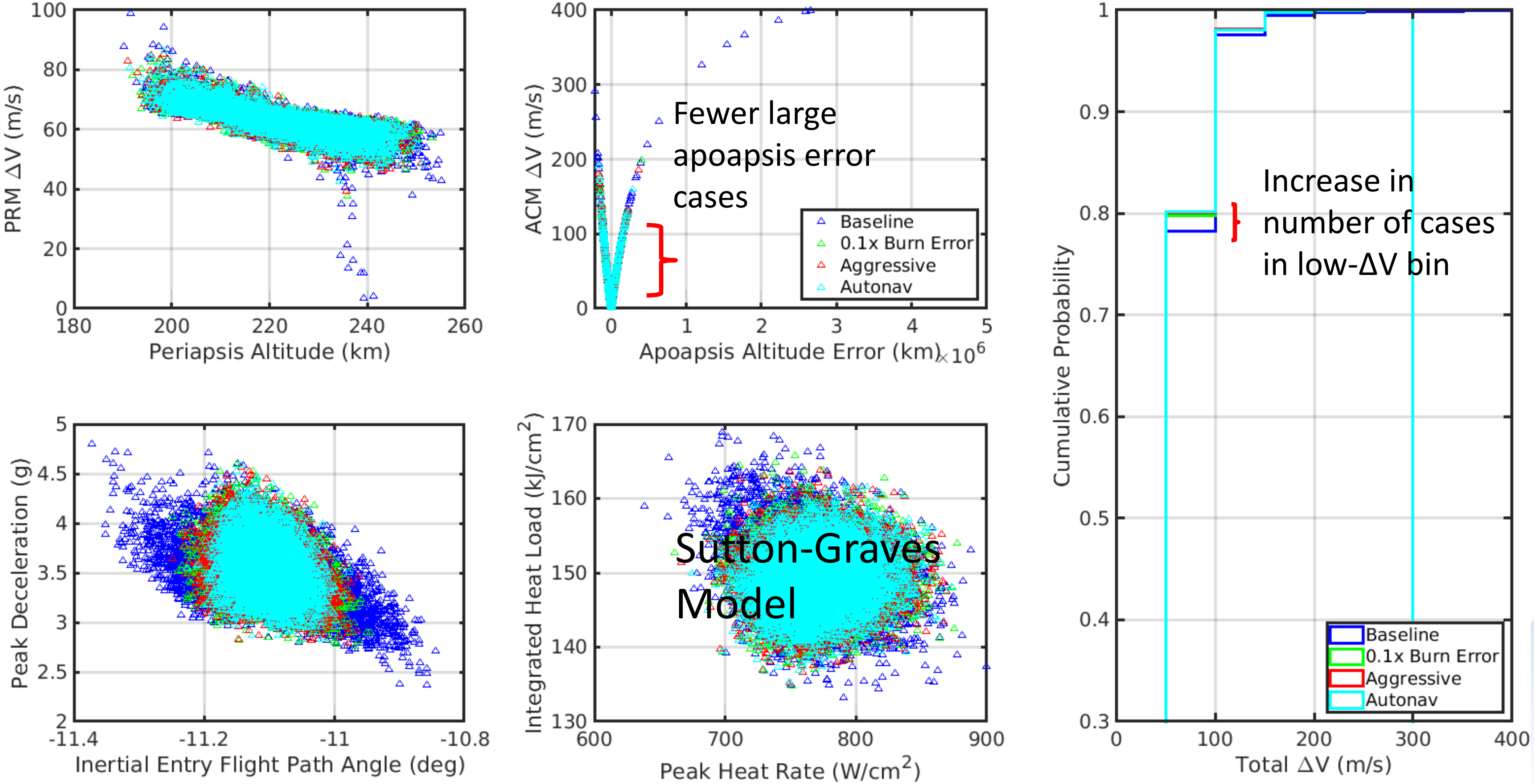


```
Statistics for Total ΔV (m/s):
----------------------------
Capture Success    =    99.9
Nominal      =    71.0669
Mean        =    88.0269
1-Sigma      =    25.8892
3-Sigma      =    77.6676
 0.13 %-tile  =    62.5355
 1.00 %-tile  =    62.9181
50.00 %-tile  =    81.4132
99.00 %-tile  =    174.7263
99.87 %-tile  =    301.9475
Minimum      =    62.2836
Maximum      =    467.6477
```

250 kg propellant estimate (reduction of 88% as compared to UOP)

Navigation Sensitivity

- **Reduction in arrival navigation error leads to improvements in aerocapture performance**



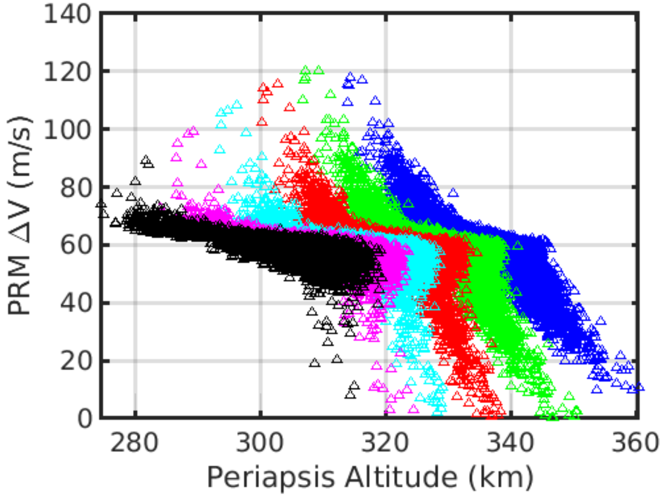
Fewer large apoapsis error cases

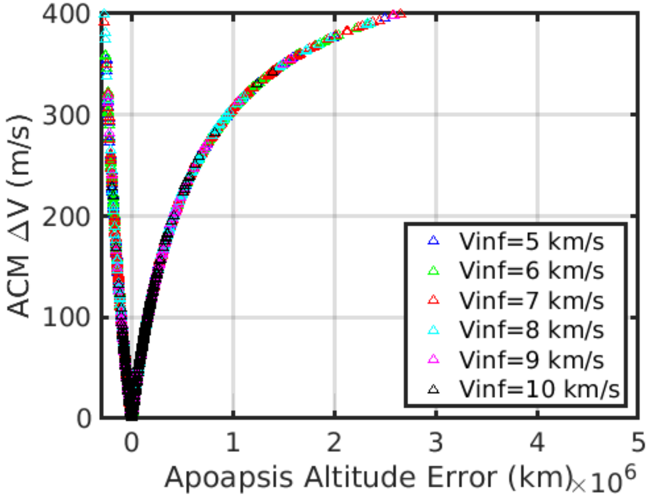
Sutton-Graves Model

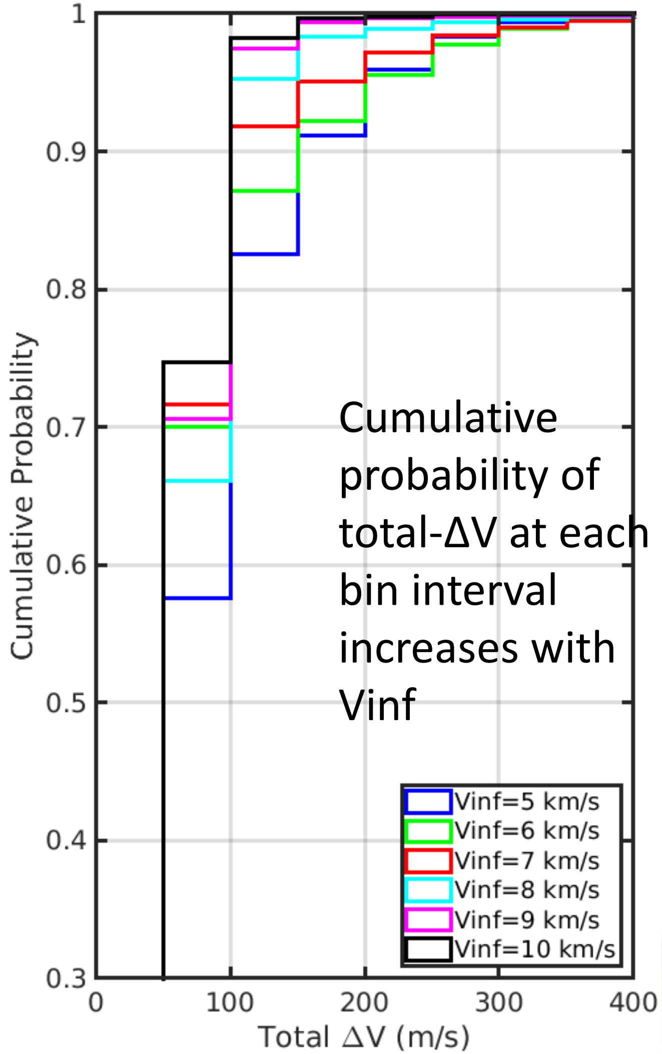
Increase in number of cases in low-ΔV bin

Arrival Trajectory Sensitivity

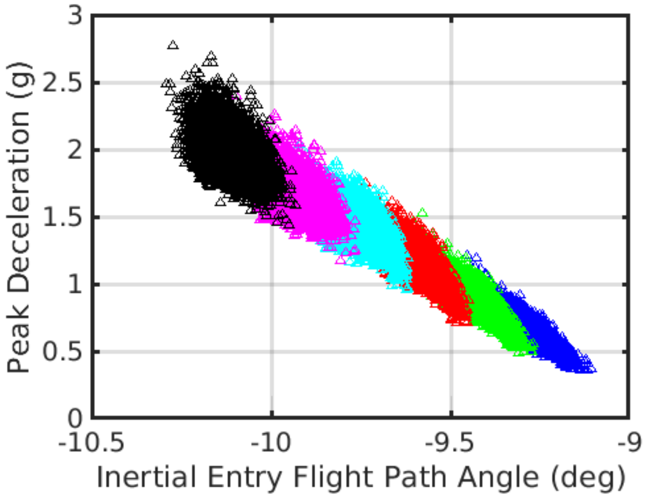
- **Slower arrival trajectories produce similar orbit insertion performance with lower heating and deceleration environment**

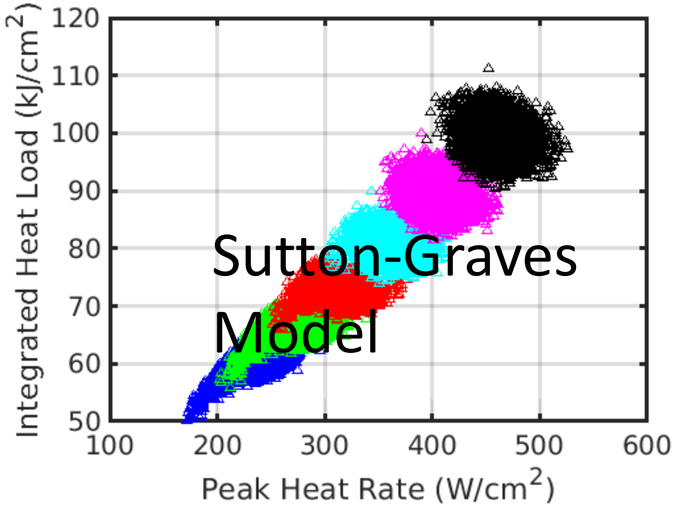






Cumulative probability of total-ΔV at each bin interval increases with Vinf

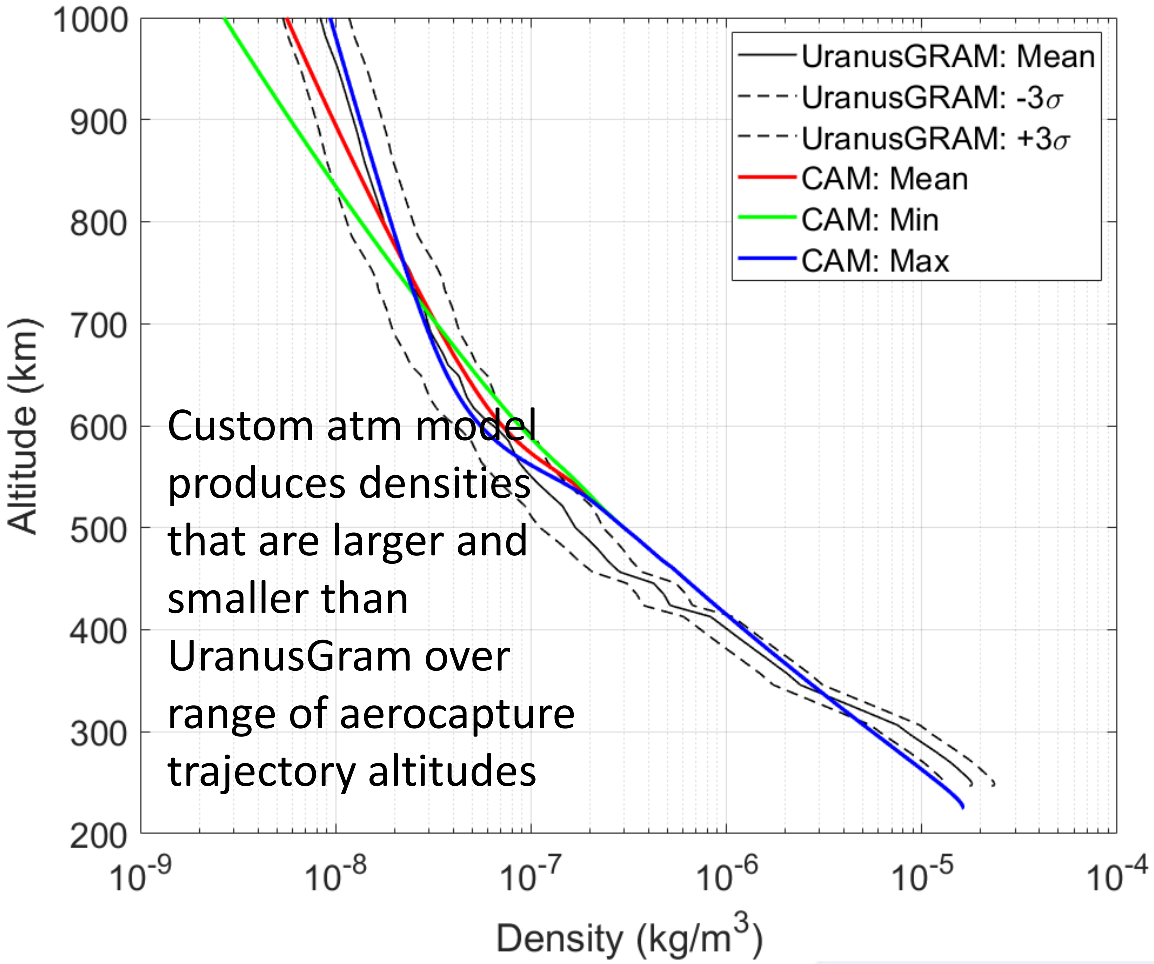




Sutton-Graves Model

Atmosphere Sensitivity

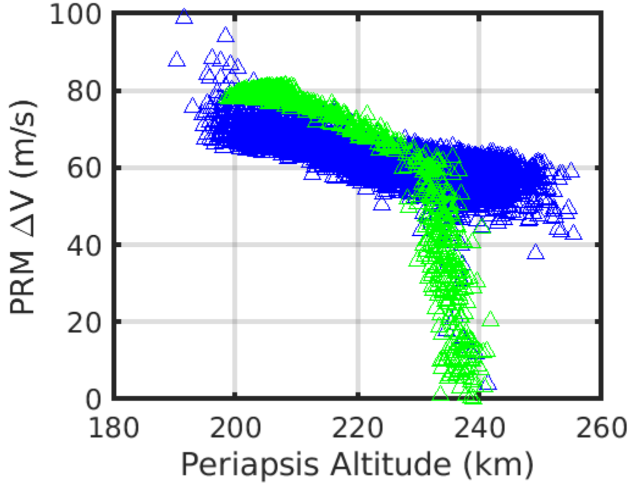
- **Biggest uncertainty for Uranus aerocapture is atmosphere knowledge**
  - If atmosphere profile is different than current knowledge, then how will it affect aerocapture performance?
- **Test sensitivity by utilizing a different atmosphere model than guidance assumes**
  - Custom atmosphere model developed by J. Garland and K. Sayanagi (see mean, min, and max profiles); utilize as truth model in POST2
  - FNPAG utilizes UranusGRAM mean; see how well guidance can adjust to different density profiles

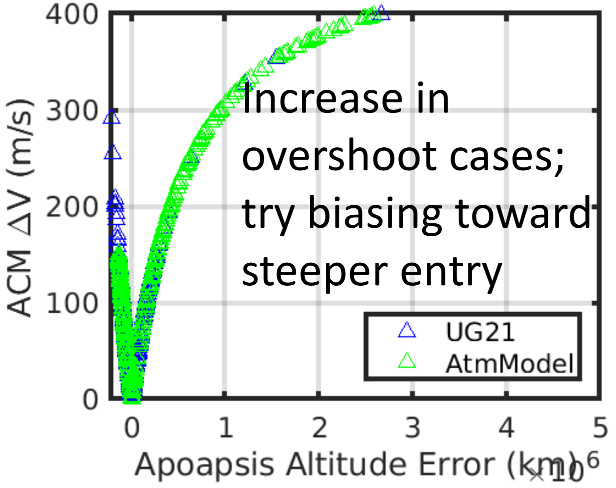


Custom atm model produces densities that are larger and smaller than UranusGram over range of aerocapture trajectory altitudes

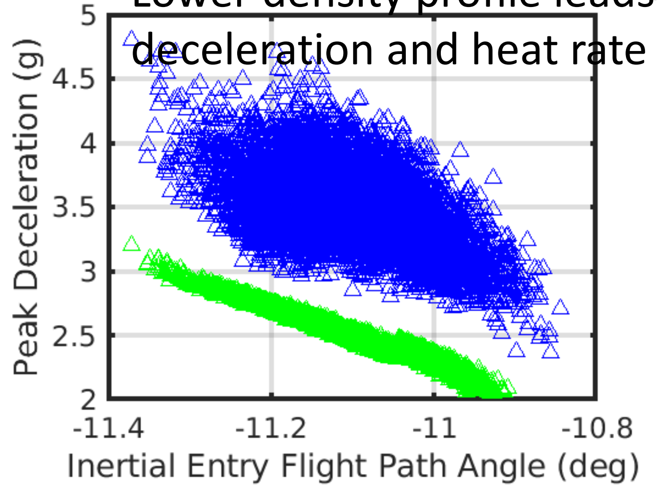
Atmosphere Sensitivity

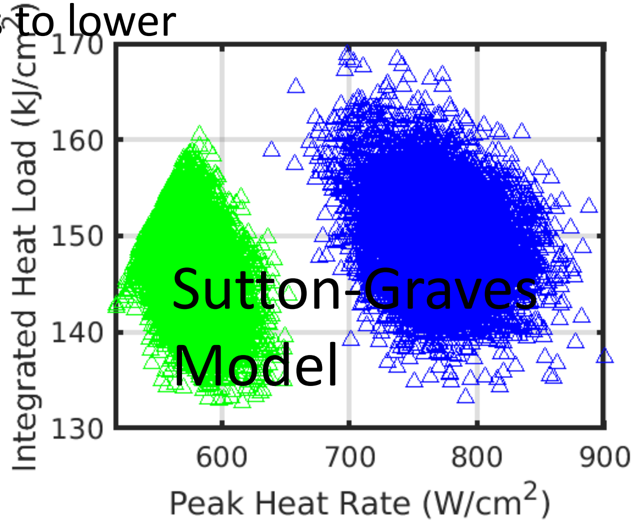
- **Guidance is able to correct for difference in atmosphere model**

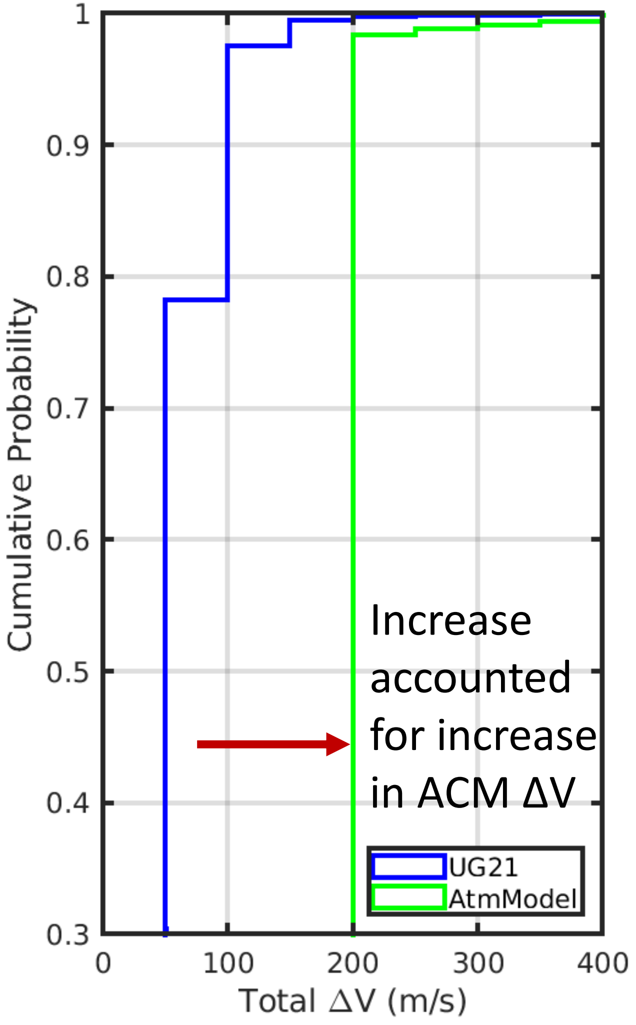



Increase in overshoot cases; try biasing toward steeper entry

Lower density profile leads to lower deceleration and heat rate




Sutton-Graves Model


Increase accounted for increase in ACM ΔV

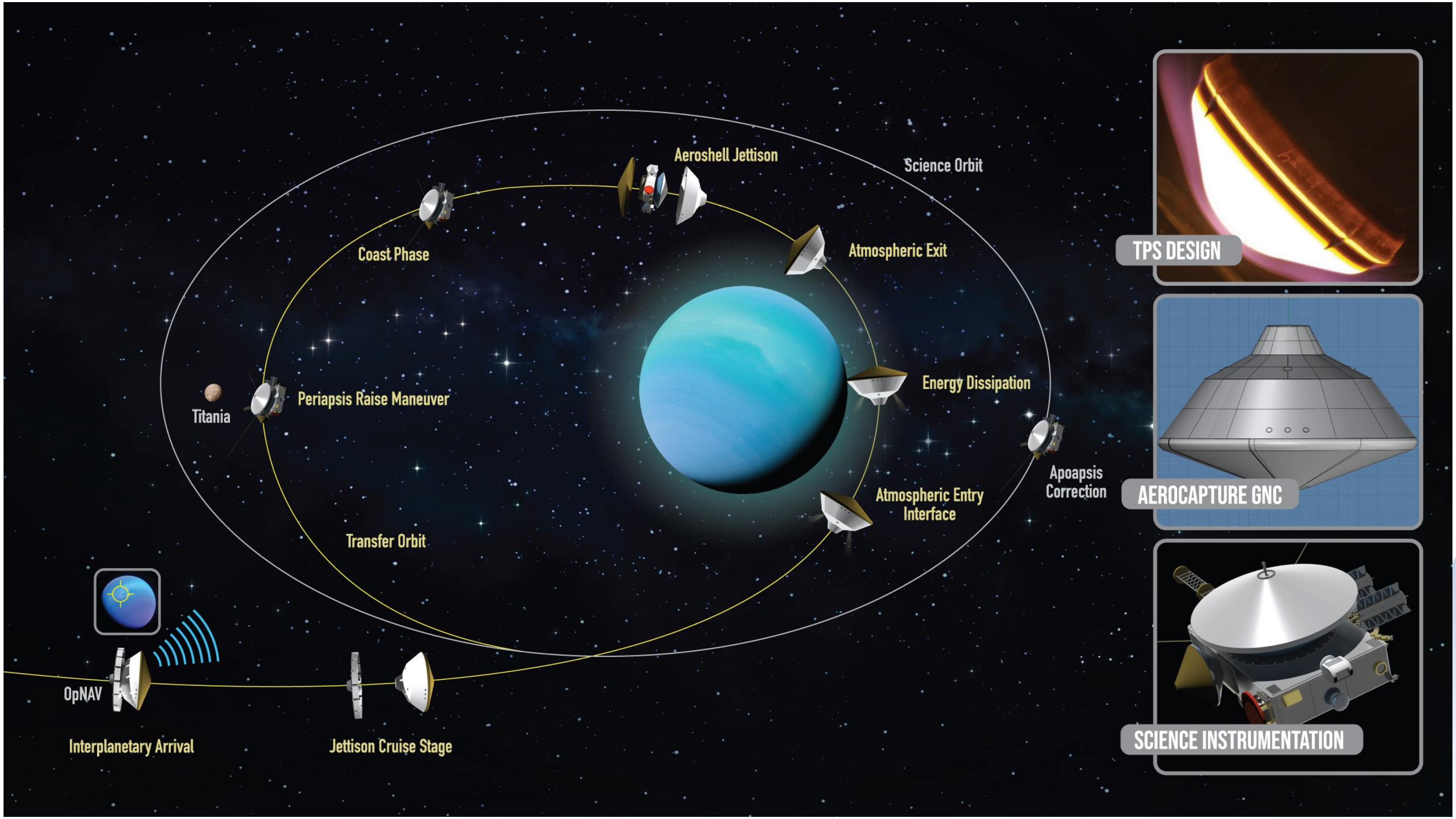
Study Findings

- **Feasible aerocapture design for Uranus Orbiter and Probe mission concept**
- **Conducted Monte Carlo sensitivity studies**
  - Navigation Sensitivity: Reduced EFPA uncertainty can improve aerocapture performance.
  - Arrival Trajectory Sensitivity: Uranus aerocapture is feasible for range of arrival Vinf from 5 to 20 km/s. TPS may limit upper bounds on V_∞. Guidance tuning can be done to improve results for each condition analyzed.
  - Target Orbit Sensitivity: Uranus aerocapture is feasible for larger apoapsis target orbits. Reduces periapsis-raise maneuver cost.
  - Atmosphere Model Sensitivity: Guidance shows promising resilience to overcoming differences in atmosphere knowledge.

Future Work

- **Additional guidance tuning and entry biasing**
- **Conduct further Monte Carlo sensitivity studies**
  - Alternative control methods (Direct Force Control and Drag Modulation)
  - Knowledge Navigation Sensitivity
- **6DOF Simulation Development and Analysis**
  - Develop POST2 simulation from 3DOF to 6DOF
  - Assess guidance performance in 6DOF environment

Questions


Aeroshell Jettison
Science Orbit
Coast Phase
Atmospheric Exit
TPS DESIGN
Energy Dissipation
Periapsis Raise Maneuver
Titania
Apoapsis Correction
AEROCAPTURE GNC
Atmospheric Entry Interface
Transfer Orbit
OpNAV
Interplanetary Arrival
Jettison Cruise Stage
SCIENCE INSTRUMENTATION

Backup

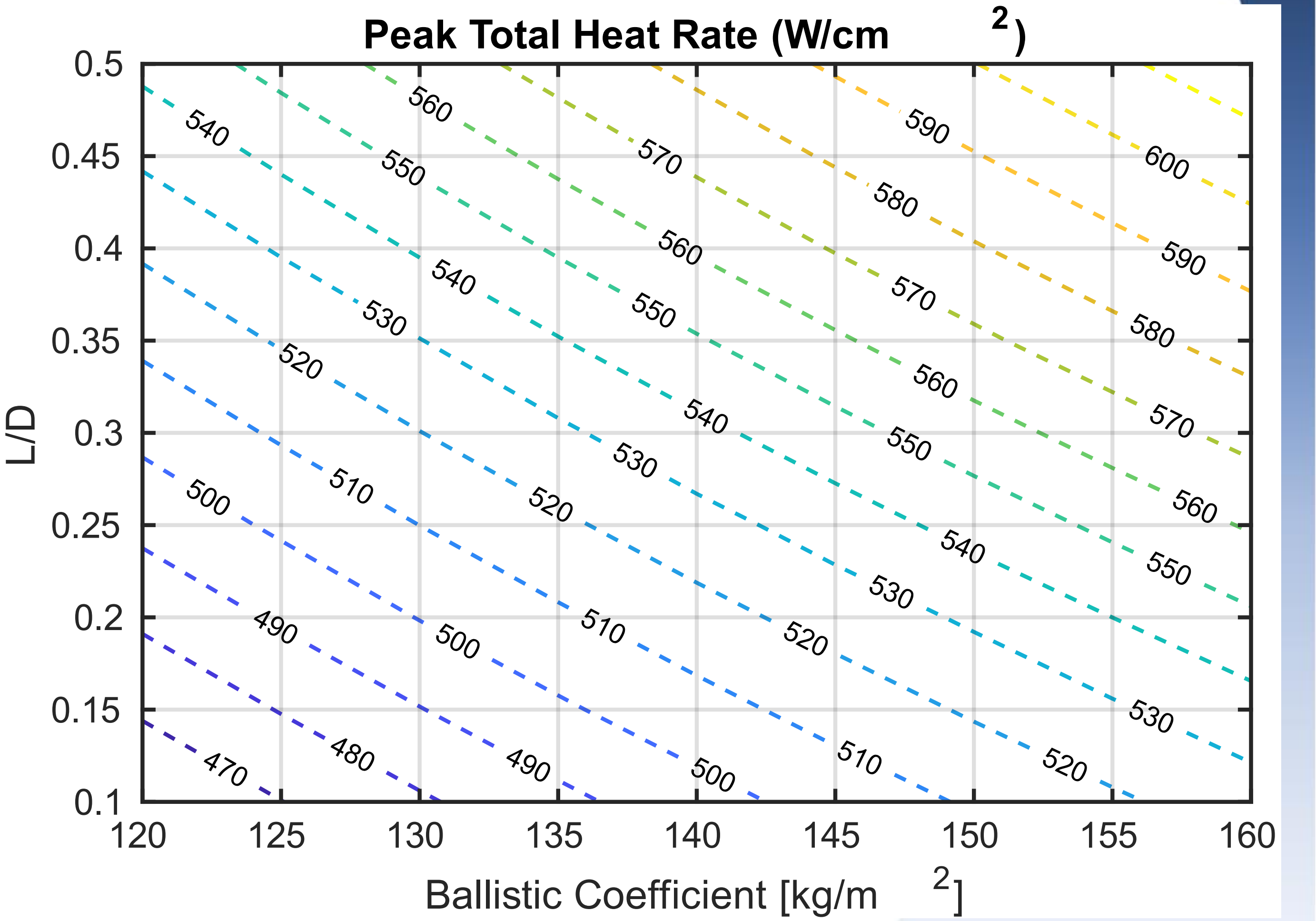
Uranus Aerocapture Design Space

Peak Heat Rate/Heat Load

- Sutton-Graves model to estimate peak stagnation point convective heat rate
- Integrate heat rate over time to get heat loac
- Increases with L/D and BC

Implications

- Range of heat rates/load are within performance capabilities of C-PICA
    - Don’t need higher-performing TPS material
- Low L/D and low BC are good aeroshell design consideration to reduce heating
    - Drag control (modulate BC) has little influence on the width



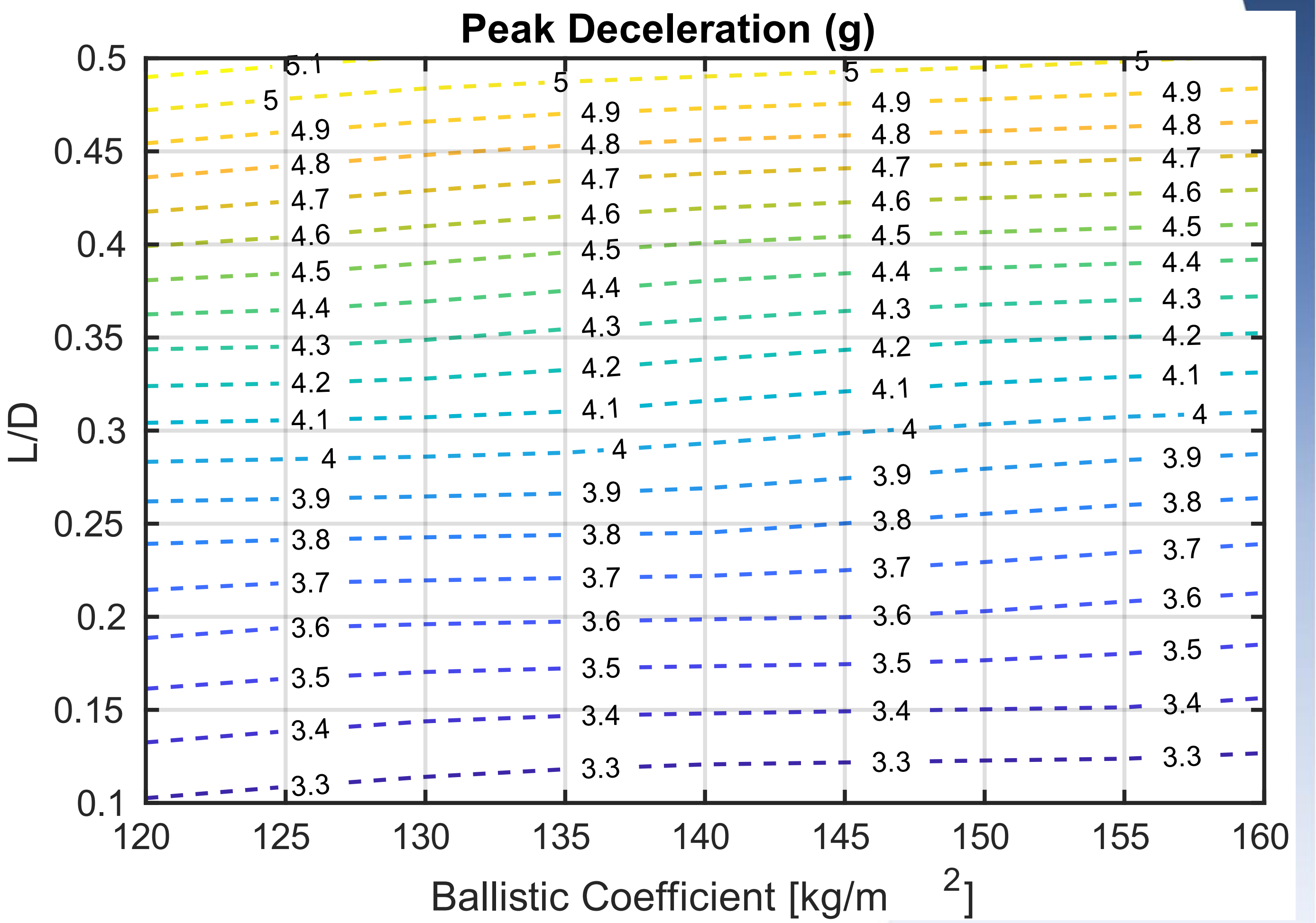
Uranus Aerocapture Design Space

Peak Deceleration

- Metric that defines how much aerodynamic loading is imparted on aeroshell structure
- Increases with L/D
- Small increase with BC

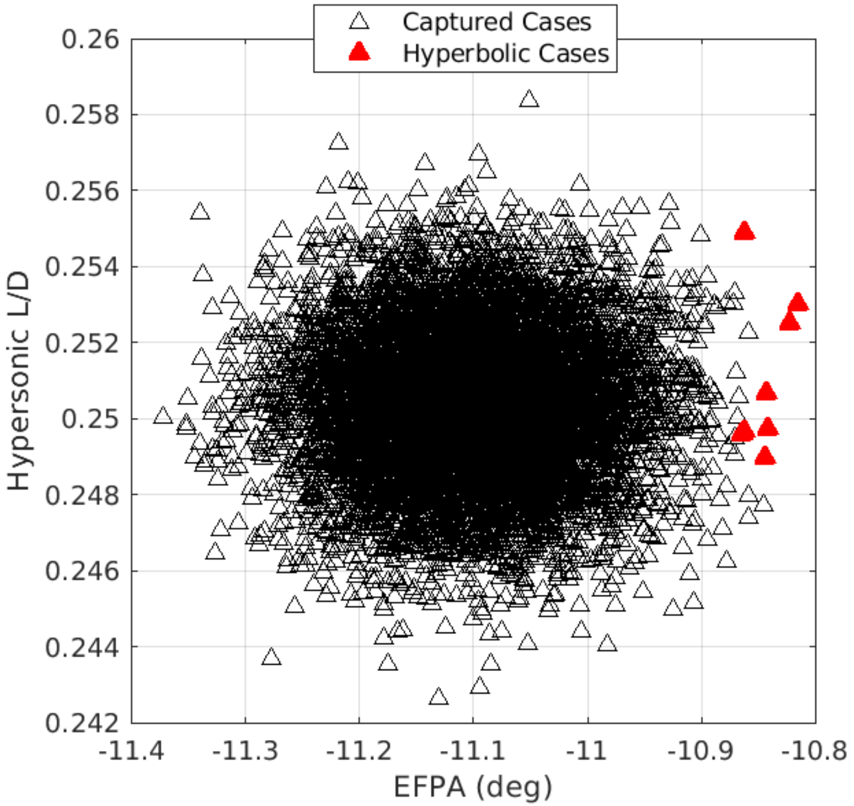
Implications

- Deceleration loads during aerocapture are benign
  - MSL aeroshell sustained 13 g during Mars EDL

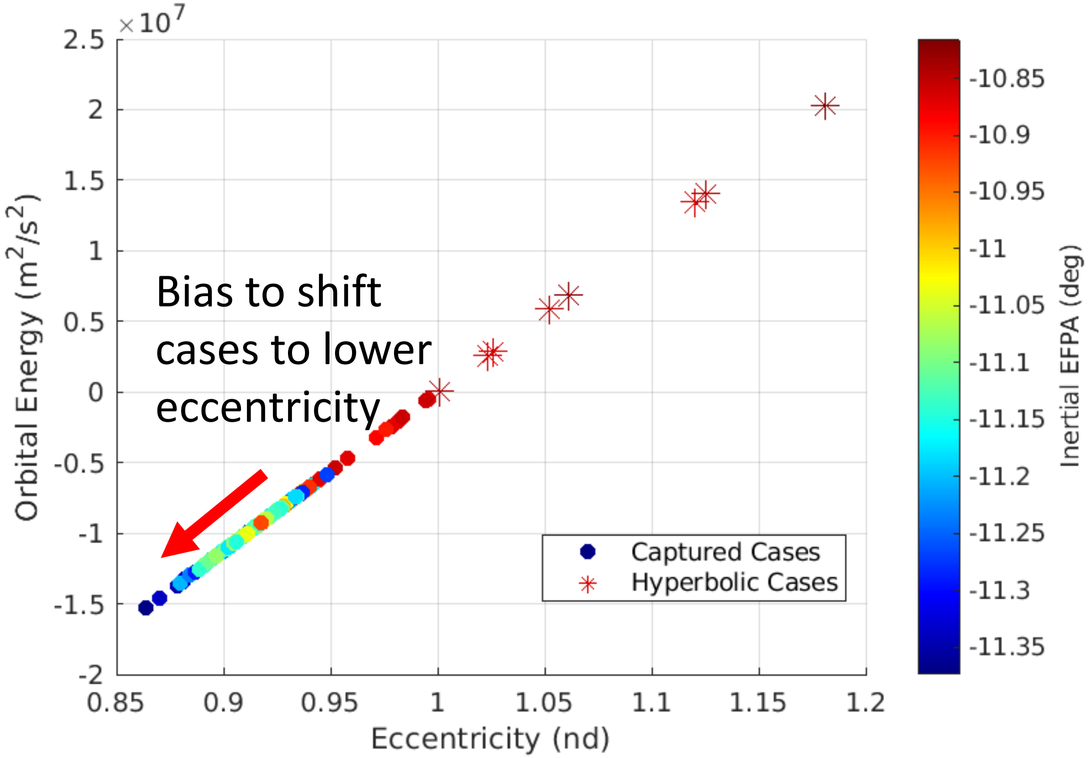


Baseline Scenario

- **Understanding uncaptured cases**



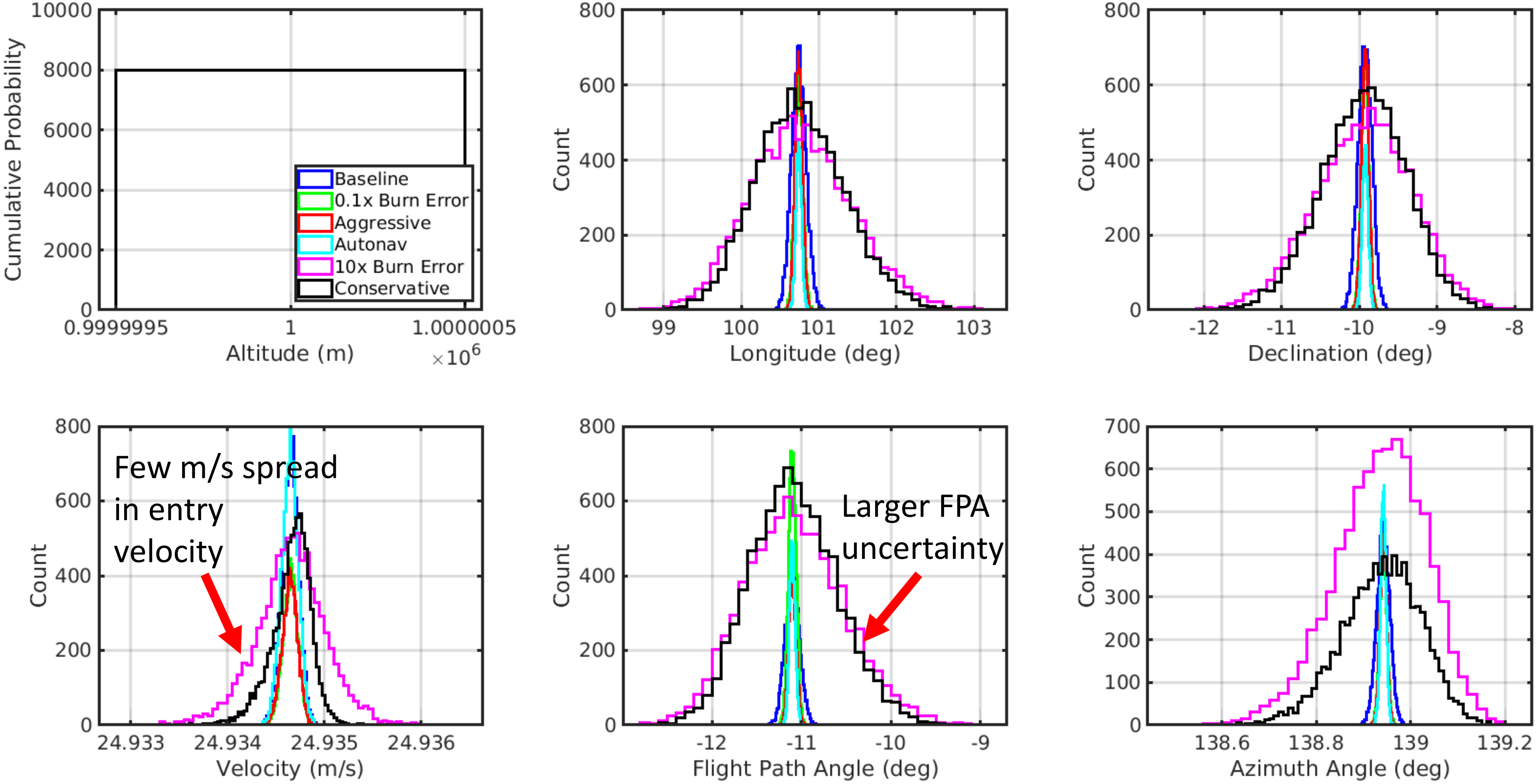
Hyperbolic cases have strong correlation to shallow EFPA



Shallower EFPA lead to higher post-aerocapture trajectory eccentricity. Potential mitigation for hyperbolic cases is to bias nominal EFPA steeper (future work)

Navigation Sensitivity

- **Entry Interface Dispersed States**

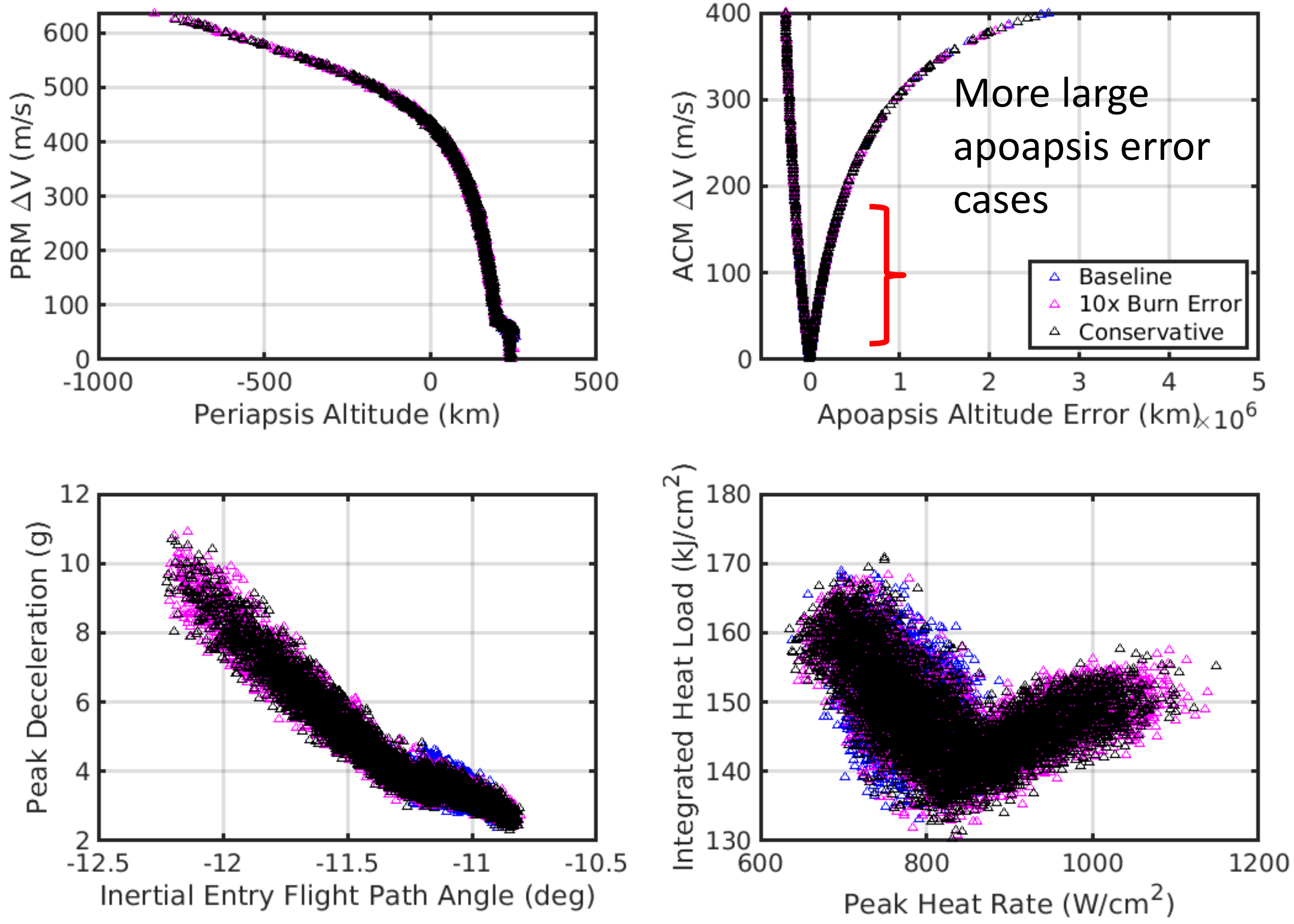


Few m/s spread in entry velocity

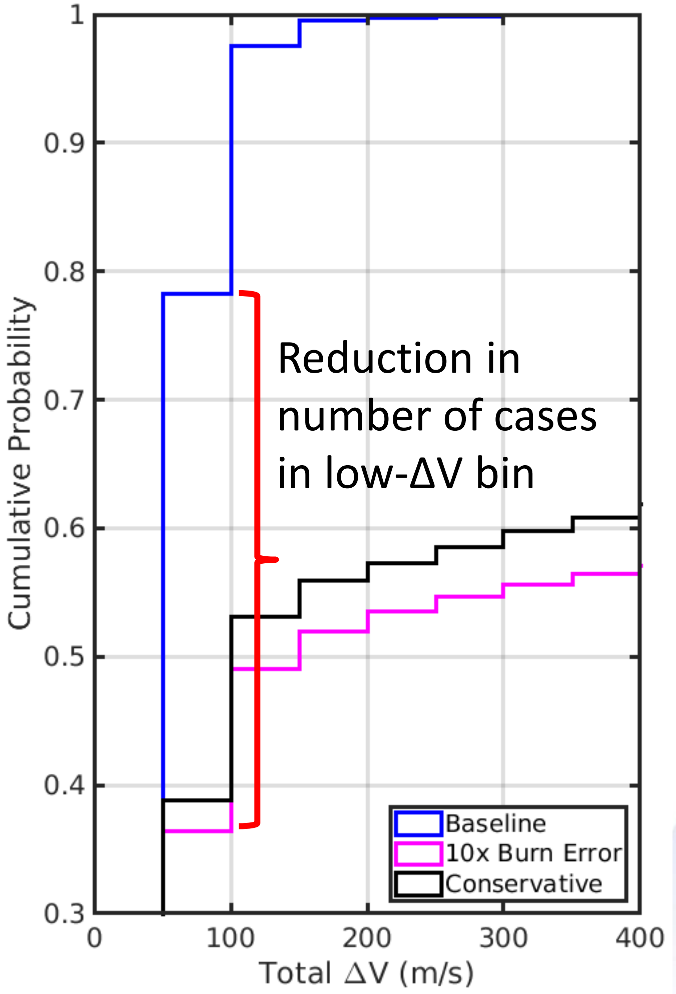
Larger FPA uncertainty

Navigation Sensitivity

- **Increase in arrival navigation error leads to reduction in aerocapture performance**



More large apoapsis error cases

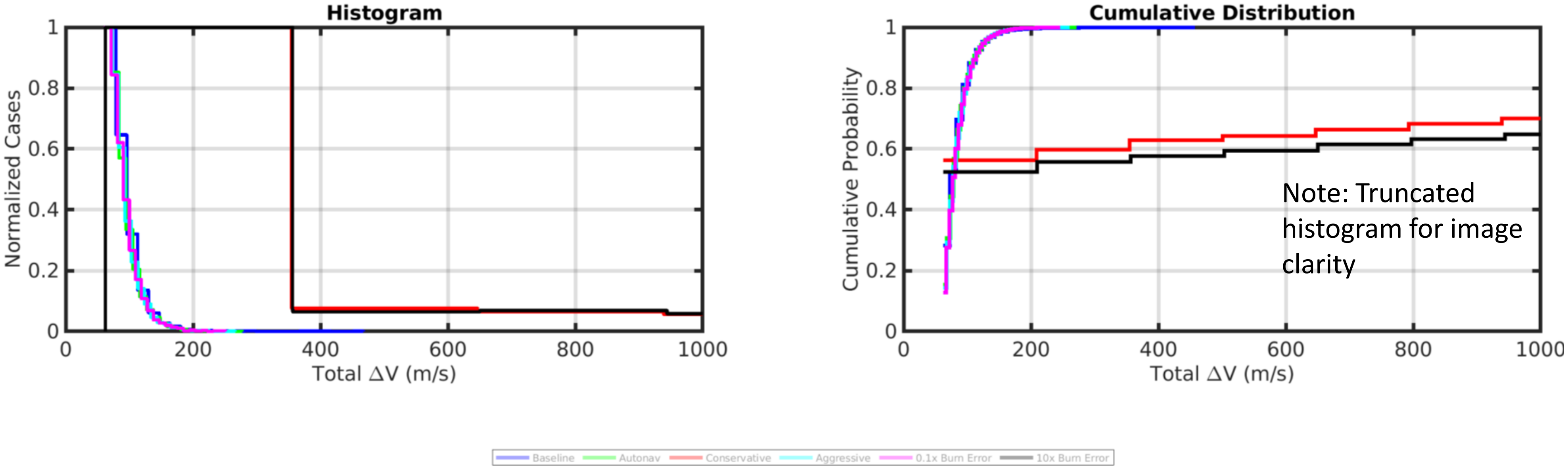


Reduction in number of cases in low-ΔV bin

Note: Truncated histogram for image clarity

Navigation Sensitivity

- **Sensitivity of arrival navigation can be seen in the capture success rate and post-aerocapture total DV**



Note: Truncated histogram for image clarity

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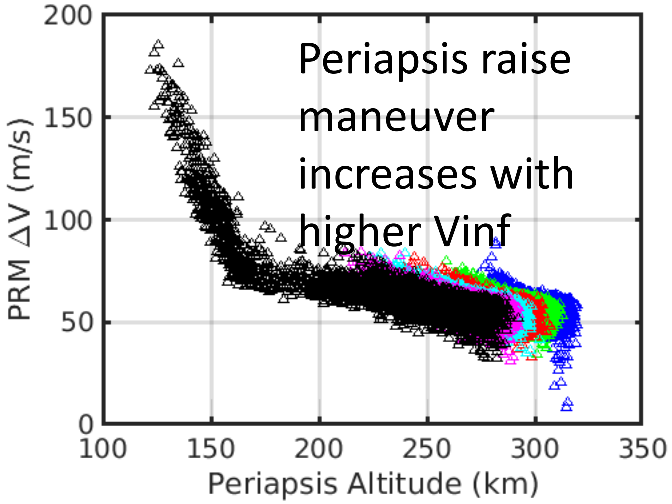
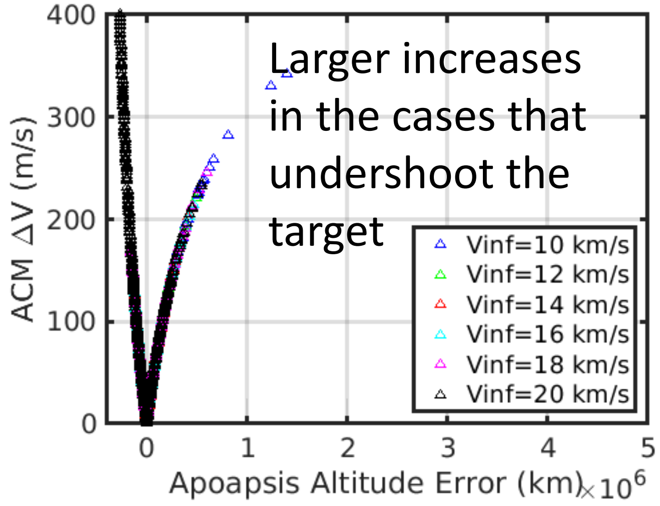
Statistics for:                  Baseline      Autonav      Conservative    Aggressive    0.1x Burn Error    10x Burn Error
-----------                     -----------   -----------   -----------    -----------    -----------        -----------
Capture Success       =          99.9000      100.0000       69.3163       100.0000       100.0000           65.5293
Mean        =                    88.0269       86.6239      960.3044        86.6911        86.7125         1159.2712
1-Sigma       =                  25.8892       21.9918     1359.8862        21.9102        21.9857         1526.6458
3-Sigma       =                  77.6676       65.9753     4079.6585        65.7307        65.9571         4579.9375
00.13 %-tile =                   62.5355       62.6071       62.6863        62.5753        62.6062           62.6377
 1.00 %-tile =                   62.9181       62.9085       63.4600        62.9553        62.9883           63.2840
50.00 %-tile =                   81.4132       80.8069      131.2592        80.8830        80.8232          160.5433
99.00 %-tile =                  174.7263      165.8330     5349.2944       165.2276       166.1538         5535.3510
99.87 %-tile =                  301.9475      214.3575     5856.8037       216.1771       217.4369         5914.9703
Min =                            62.2836       62.3369       62.5298        62.4082        62.2854           62.5116
Max =                           467.6477      277.1767     5904.5570       266.3660       250.8374         5938.9332
```

Arrival Trajectory Sensitivity

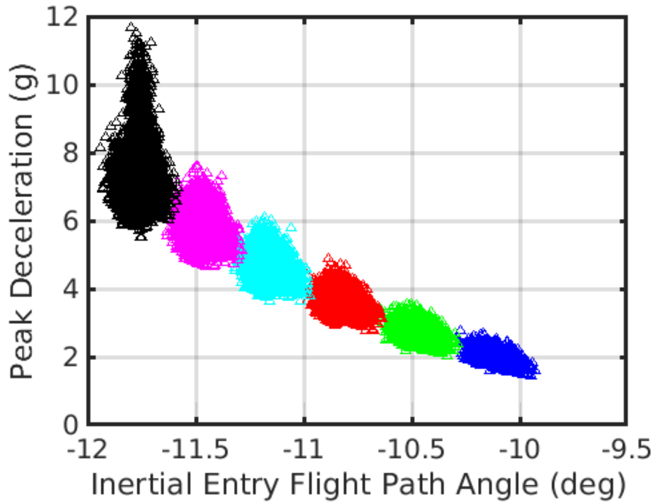
- See converse trends for faster arrival trajectories

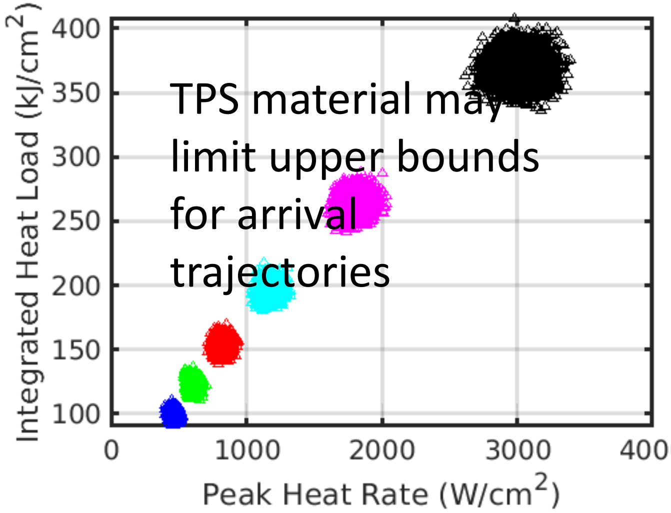


Periapsis raise maneuver increases with higher Vinf

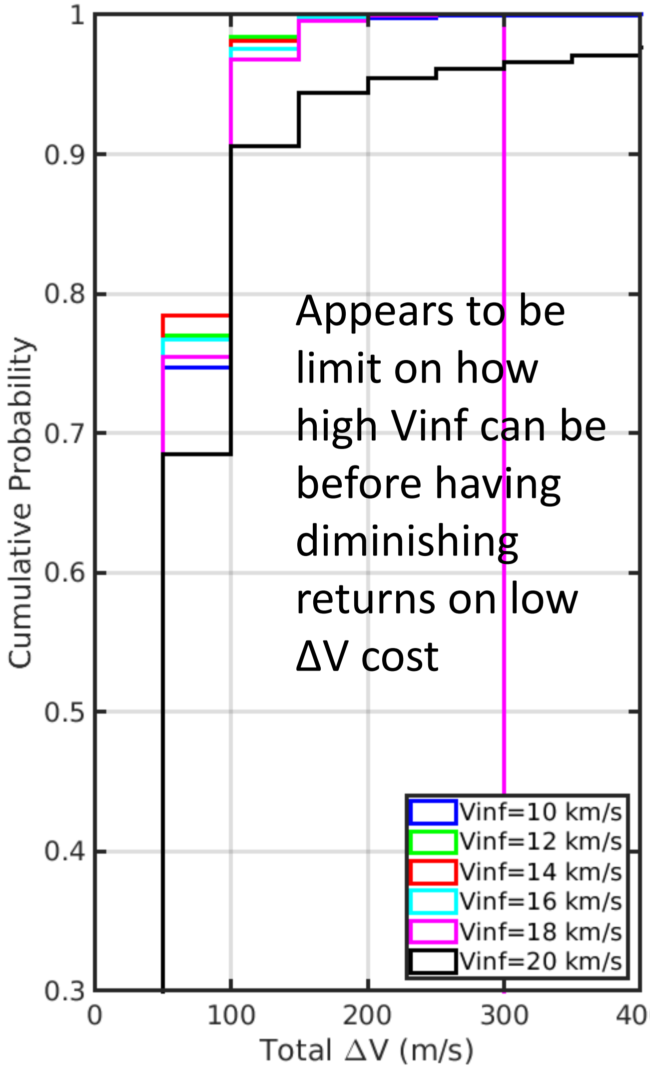


Larger increases in the cases that undershoot the target





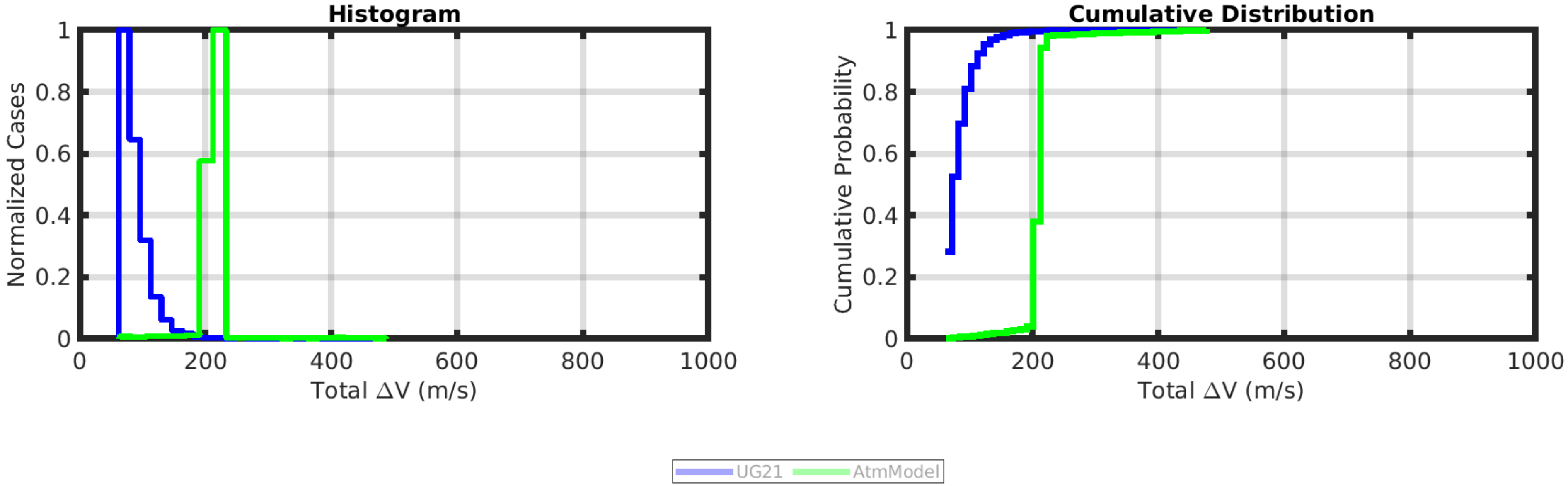
TPS material may limit upper bounds for arrival trajectories



Appears to be limit on how high Vinf can be before having diminishing returns on low ΔV cost

Atmosphere Sensitivity

- **Guidance is able to correct for difference in atmosphere model**



```
Statistics for:              UG21                      AtmModel
-----------                   -----------               -----------
Capture Success        =  99.9000                   98.0877
Mean           =          88.0269                   213.5531
1-Sigma        =          25.8892                   26.4150
3-Sigma        =          77.6676                   79.2449
00.13 %-tile =            62.5355                   68.8882
 1.00 %-tile =            62.9181                   113.6331
50.00 %-tile =            81.4132                   213.5316
99.00 %-tile =            174.7263                  320.6207
99.87 %-tile =            301.9475                  454.0193
Min =                     62.2836                   63.3246
Max =                     467.6477                  487.8313
```

Slight reduction in the capture success rate. But result does show promise.

Varying density profiles in Atm Model lead increased total ΔV costs