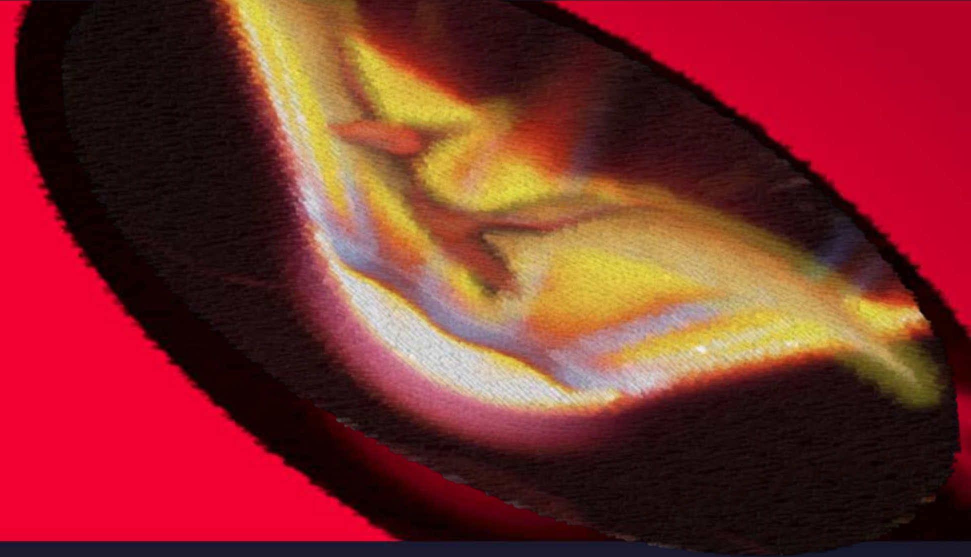


NASA SPACE TECHNOLOGY MISSION DIRECTORATE EARLY CAREER INITIATIVE

PTERODACTYL: THE DEVELOPMENT AND PERFORMANCE OF GUIDANCE ALGORITHMS FOR A MECHANICALLY DEPLOYED ENTRY VEHICLE

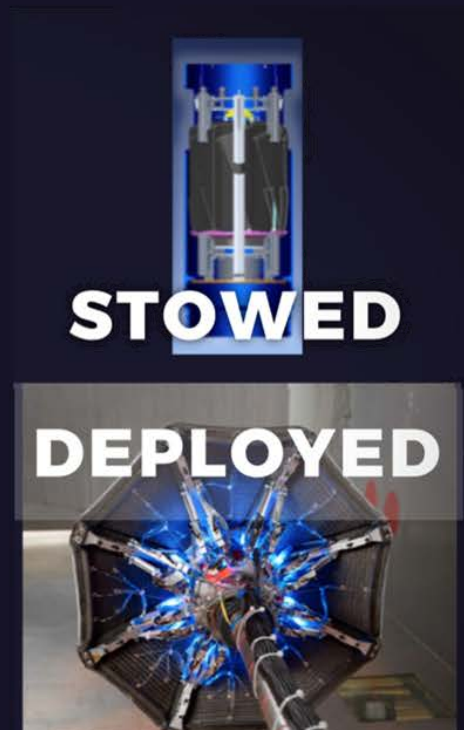
Breanna Johnson

NASA Johnson Space Center

Flight Mechanics and Trajectory Design Branch EG5

MOTIVATION

NASA's Space Technology Mission Directorate is funding Pterodactyl through the **Early Career Initiative (ECI) Award** to address the need for deployable entry vehicles that can land small and large mass payloads precisely



Deployable Entry Vehicles (DEV)

GUIDANCE & CONTROL MAKE DEV APPLICATIONS REALIZABLE!

GOAL

Feasibility study such that the solution closes

- Targeting Performance (G&C)
- Packaging and Structural Analysis

Selected Lunar Return mission parameters to stress design for precision targeting and future scalability

PTERODACTYL BASELINE VEHICLE (PBV)

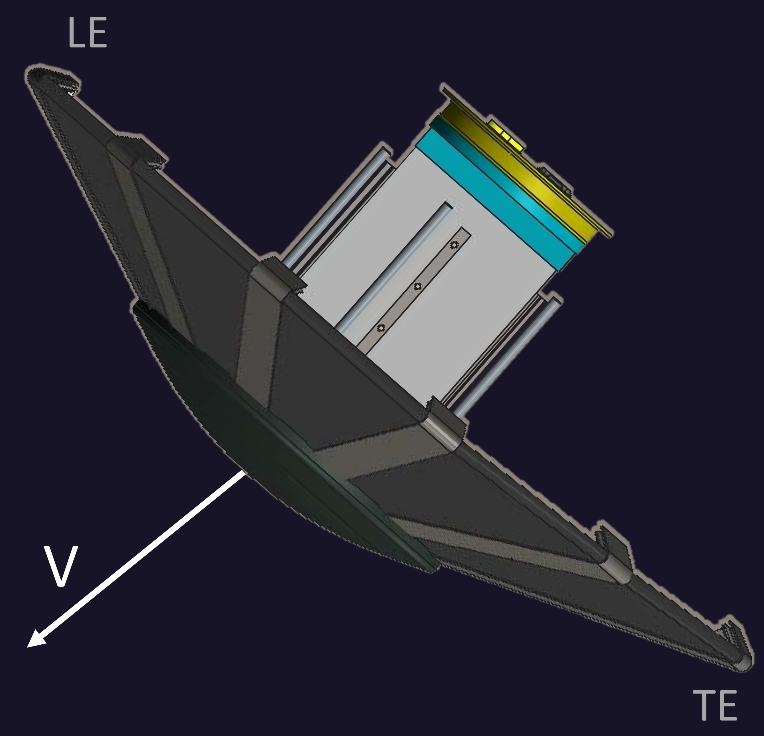
asymmetric

diameter = 1+ m

mass = 59.4 kg

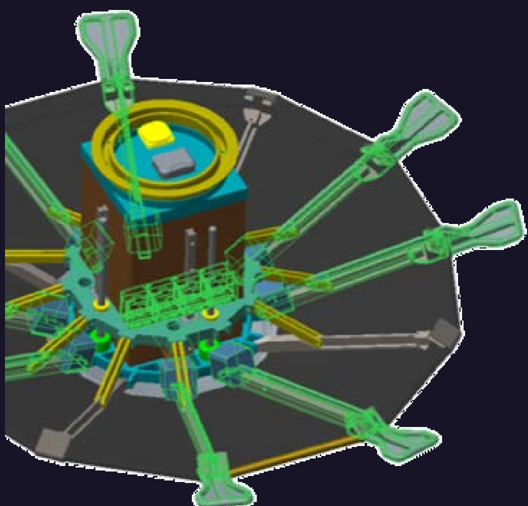
$L/D_{trim} = 0.2$

$\alpha_{trim} = -12^{o}$

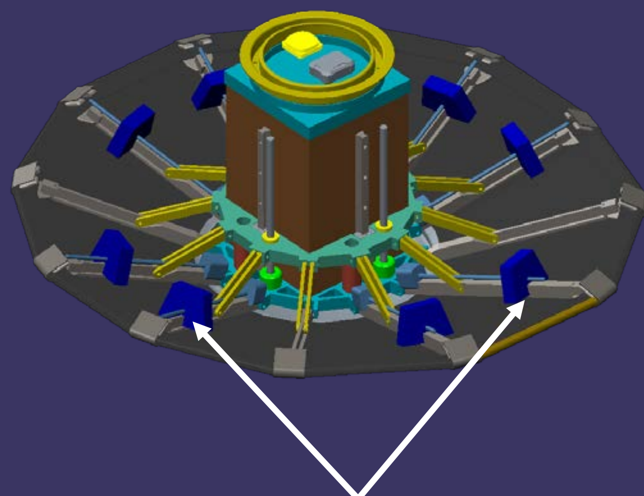


CONTROL SYSTEM OPTIONS

Flaps Control System (FCS)

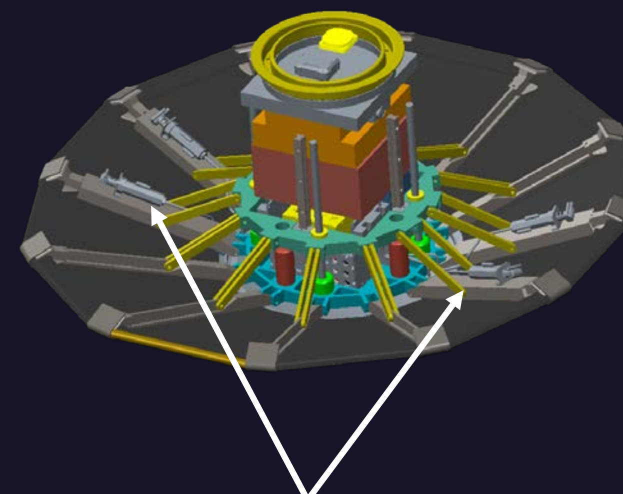


Mass Movement Control System (MMCS)



Independent
Moveable Masses

Reaction Control System (RCS)



4 RCS Jets

* If selected, a control system option would be used independently for entry

GUIDANCE DEVELOPMENT OBJECTIVES

Need a guidance algorithm capable of exploring two different guidance and control techniques to determine targeting accuracy and load constraints :

$\alpha-\beta$	ϕ
Uncoupled down/cross range control	Coupled down/cross range control

Bank control methods are well known, but alpha-beta methods are not

New Development	Purpose
Develop methodology for identifying $\alpha-\beta$ control	Precision targeting by reducing down range and cross range errors, decoupled

GUIDANCE ALGORITHM SELECTION

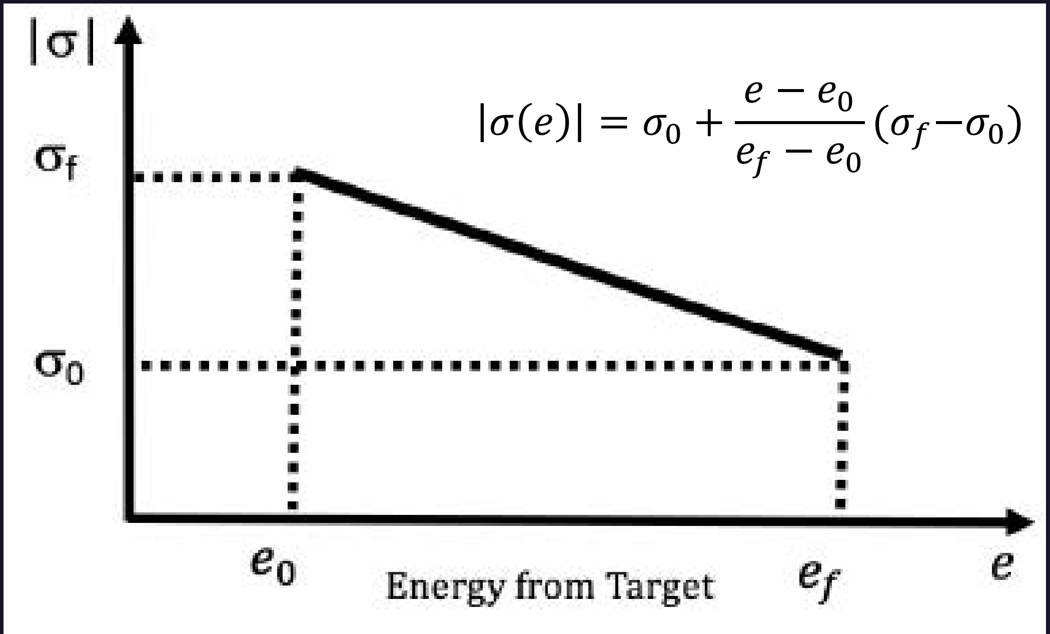
Selected the Fully Numerical Predictor-corrector Entry Guidance (FNPEG) because:

- Unlike other guidance algorithms, FNPEG is a *unified* method based on the same algorithmic principles applicable to a wide range of vehicles (low to high L/D)
- FNPEG can also be applied to skip as well as direct entry for orbital and sub-orbital entry missions
- FNPEG has good convergence rates and can enforce complicated (quadratic) inequality heating and aerodynamic load constraints
- Reliance on fundamental equations of motion makes FNPEG an attractive option to be adapted to produce angle of attack (alpha) and sideslip angle (beta) commands

$$
\begin{aligned}
\dot{Q} &= k_Q\sqrt{\rho}V^{3.15} \leq \dot{Q}_{max} \\
a &= \sqrt{L^2 + D^2} \leq a_{max} \\
\bar{q} &= (g_0 R_0 \rho V^2)/2 \leq \bar{q}_{max}
\end{aligned}
$$

Lu, P. Entry Guidance: A Unified Method. Journal of Guidance, Control, and Dynamics, Vol. 37, No. 3, 2014, pp. 713- 728.

FNPEG BANK ANGLE PROFILE



Bank angle sign changed to correct crossrange error partially incurred from bank angle modulation

** e is the total mechanical energy (kinetic + potential)*

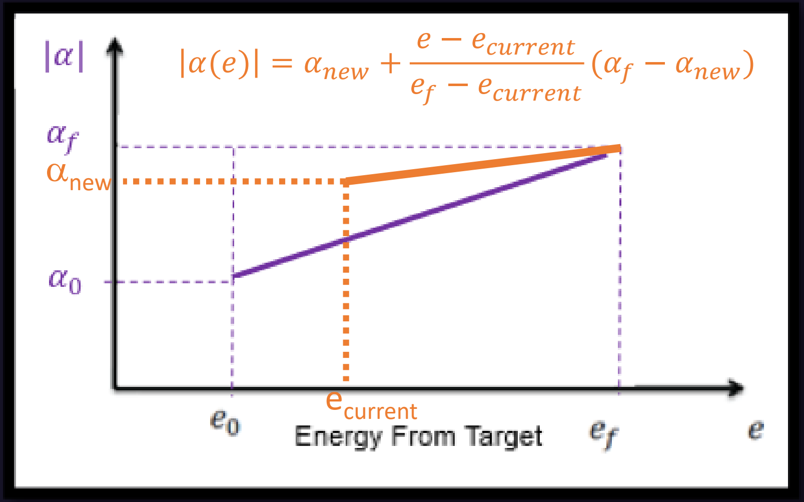
FNPEG UNCOUPLED RANGE CONTROL

Structural and aerodynamic analyses for different control system architectures suggested an additional need for a non-bank angle guidance

FNPEG Uncoupled Range Control (URC) was created to minimize downrange & crossrange error using user-defined alpha and beta ranges to generate commands

Robustness is maintained by reserving lift margin for dispersed cases at the end of trajectory

FNPEG URC Profile



Sideslip angle command is found using a proportional derivative control for tracking azimuth angle

* *e is the total mechanical energy (kinetic + potential)*

EXAMPLE 3DOF SIMULATION SETUP

Flight Analysis and Simulation Tool (FAST)

Earth Global Reference Atmospheric Model (GRAM)

CBAERO -> CART3D aerodynamic model

FNPEG URC (FNPEG used for bank-driven G&C configurations)

Initial conditions :

- Guidance call rate: 1 Hz
- Angle of attack & sideslip angle accelerations: 5 °/s/s
- Angle of attack & sideslip angle rate limits: 5 °/s

FCS Configuration

Pterodactyl Baseline Vehicle (PBV)

1 m diameter

Mass = 72 kg

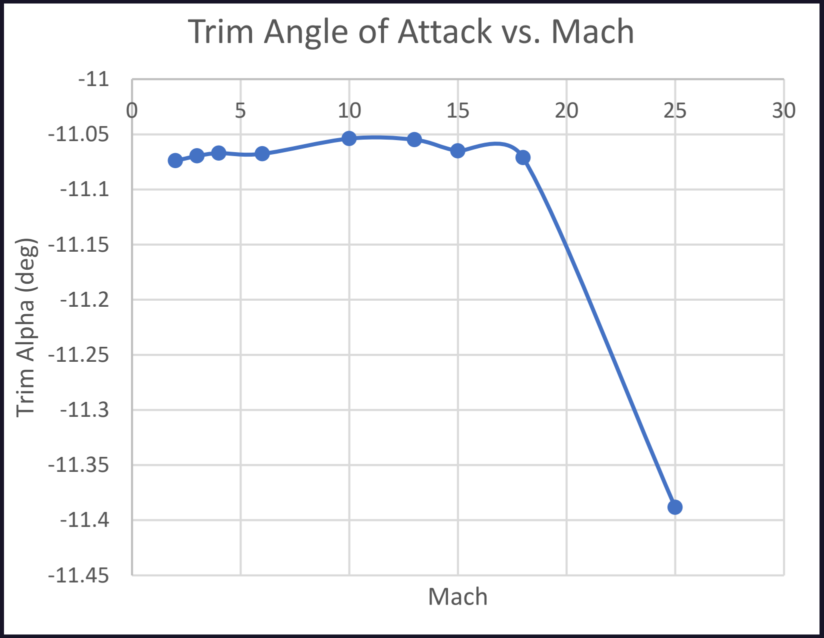
Loading Constraints

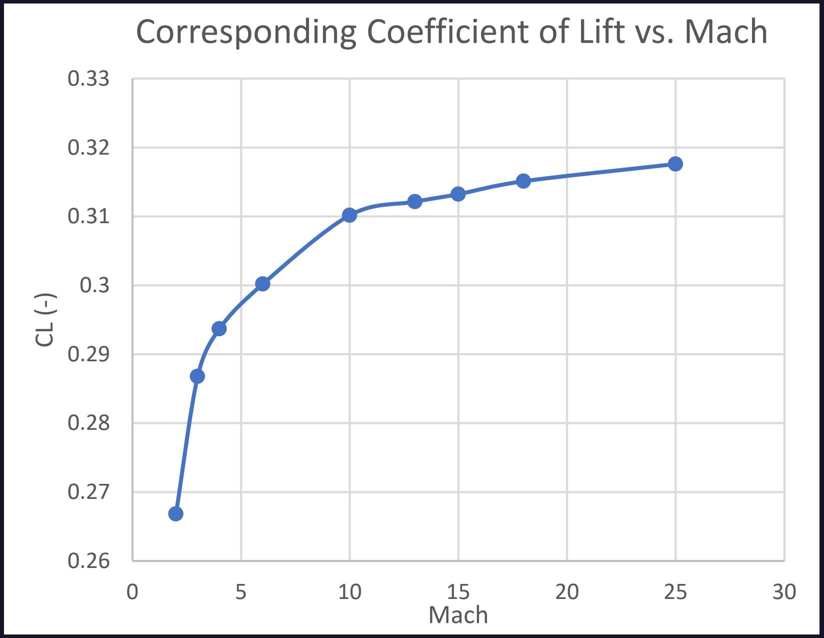
Heating Rate $\leq$ 250 W/cm^2

G-load $\leq$ 15g's

FNPEG AERODYNAMICS LOOKUP METHOD

Bank angle guidances may use current trim angle of attack to estimate aerodynamic lift and drag with simple table lookup or equation



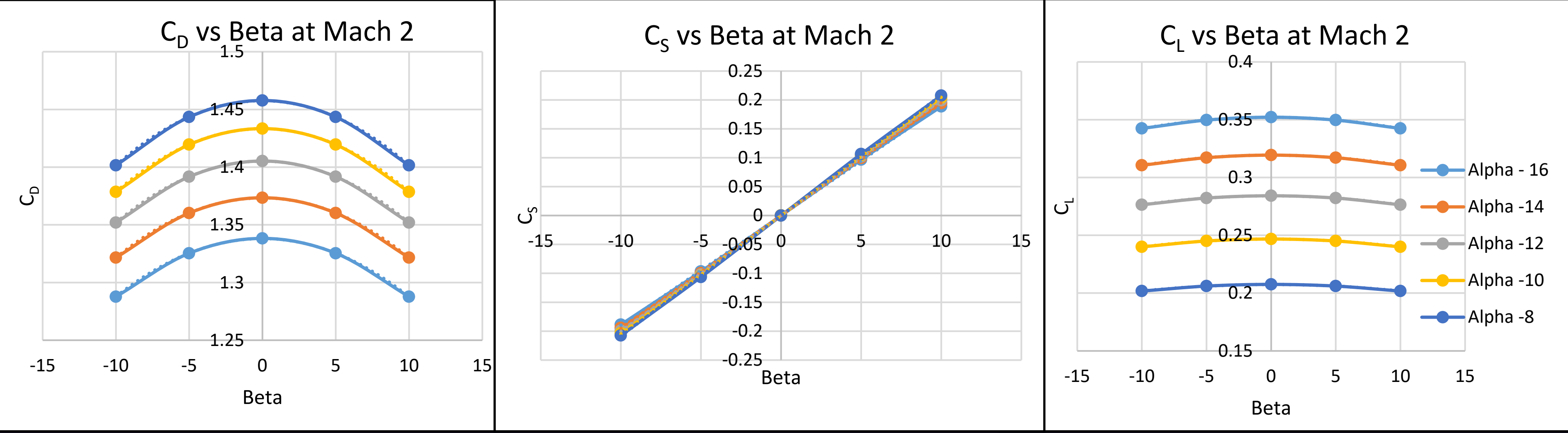


CHALLENGE IN URC IMPLEMENTATION

Challenge: update FNPEG lookup method to include side force, C_S, in addition to C_L, C_D with three independent variables α, β, M

Solution: Polynomial fits about beta was a discovered solution

- Distance between CD vs. Beta curves of Alpha for each Mach number were not equal (increased polynomial fit difficulty)
- To reduce computational load, a polynomial fit 2-step interpolation was used
- Coefficients used to define equations useful for automatic lateral logic gain updates based on dynamic pressure
- Updated aerodynamic fading filters (estimate density/aero uncertainties) to include side force



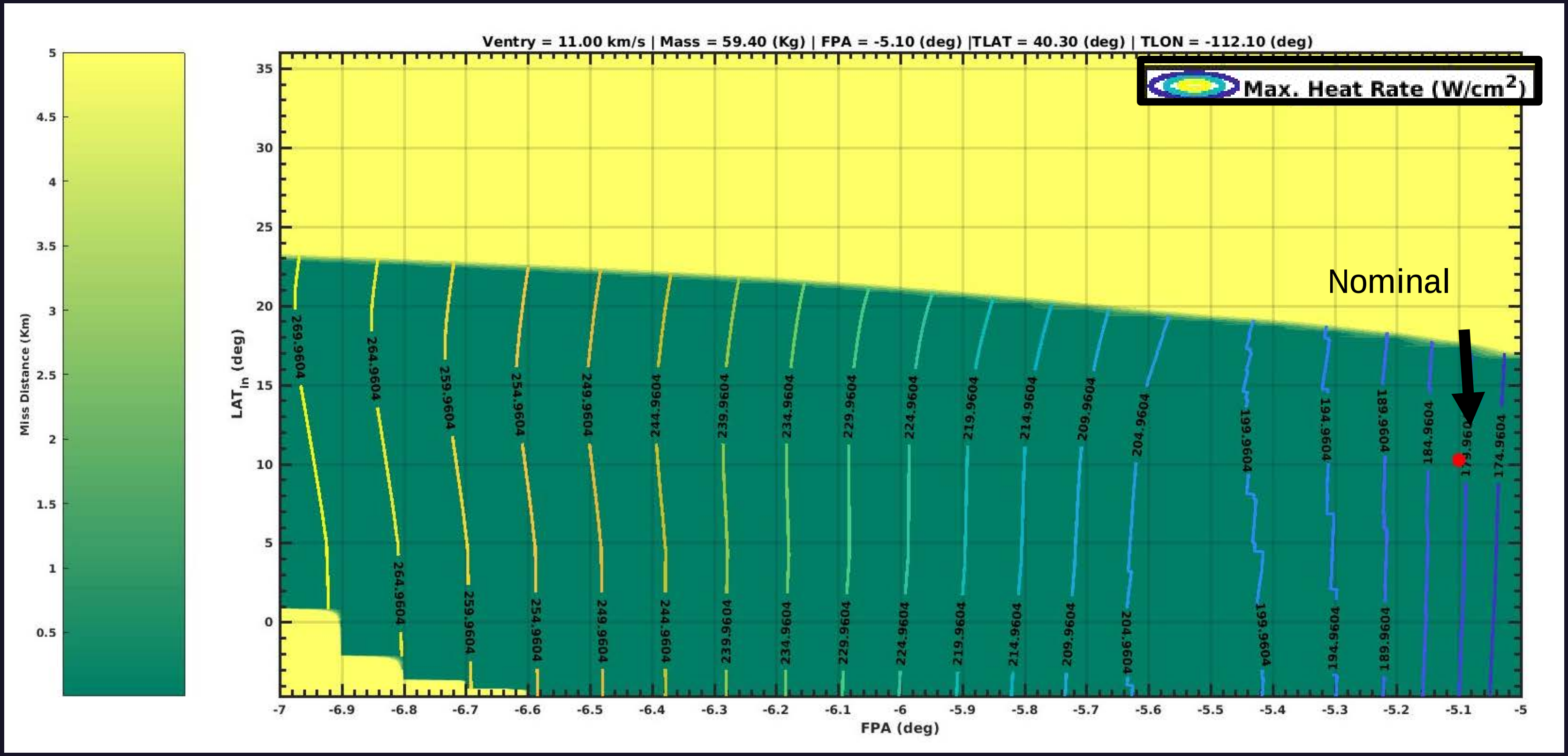
for example $C_D = X_{C_D}\beta^2 + Y_{C_D}\beta + Z_{C_D}$

CHALLENGES IN URC IMPLEMENTATION
(CONT'D)

Finding the correct EI FPA and EI Latitude for good performance

- Latitude Cases: [-4.7, 36.0] (deg)
- FPA Cases: [-7, -5] (deg)
- Latitude increment = 0.05 (deg)
- FPA increment = 0.10 (deg)

Contour Graph: Miss Distance (km) and Max. Heat Rate ($\frac{\mathrm{W}}{\mathrm{cm}^2}$)



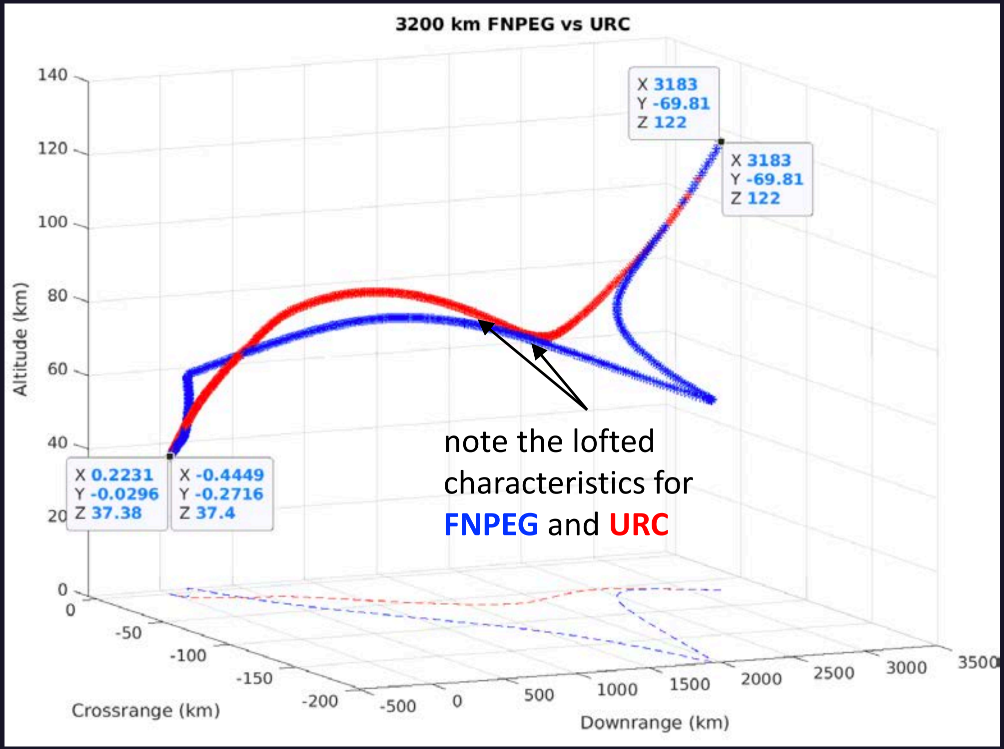
EI Latitude (deg)	10.263
EI Longitude (deg)	-114.3

FNPEG URC PROFILE

This is an example trajectory path for an FNPEG-URC flaps controlled PBV, beginning 3200 km away from the target

Entry Interface (EI) Parameters	Value	Units
Altitude	122	km
Latitude	-4.7	deg
Longitude	-112	deg
Relative Velocity	11	km/s
Relative Azimuth	0	deg
Relative Flight Path Angle	-5.1	deg

Guidance Target Parameters	Value	Units
Altitude Target	31	km
Latitude Target	40	deg
Longitude Target	-112	deg
Relative Velocity Target	0.69	km/s

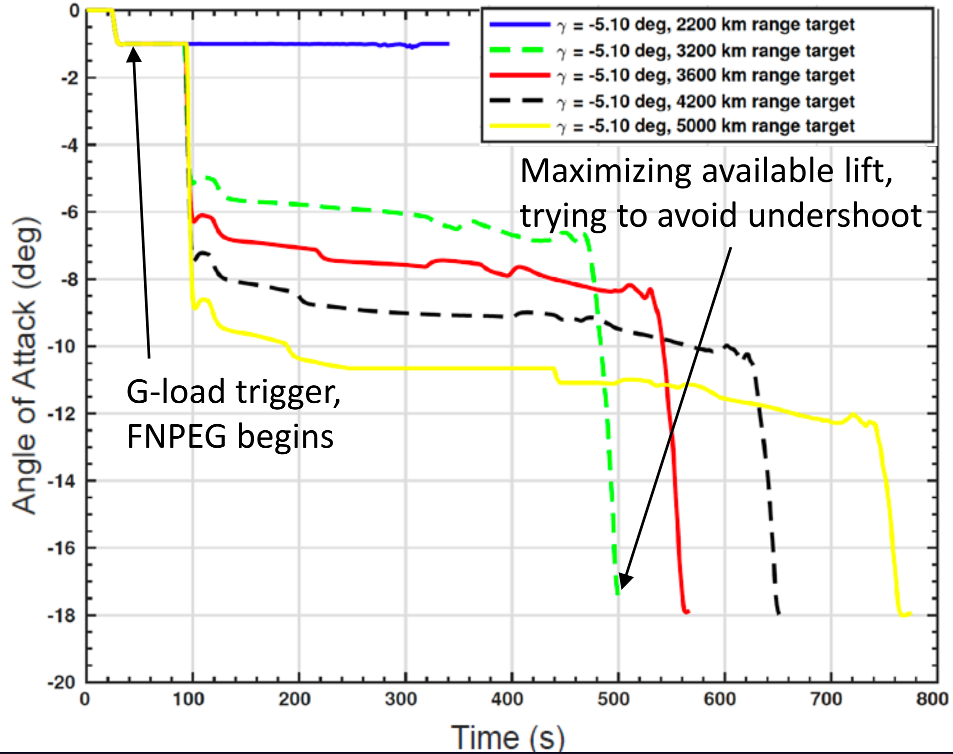


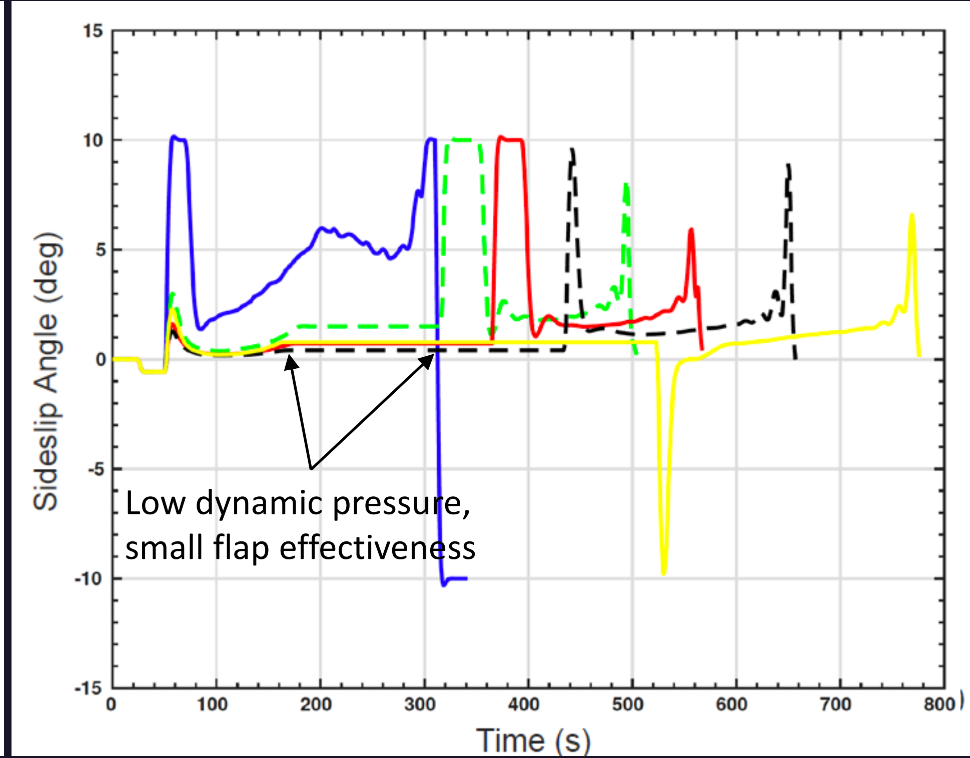
*Comparable profiles between the two algorithms are observed, ≤3km miss distance is desired

URC TARGETING PERFORMANCE

These guidance profiles resulted in:

- Trajectories that did not exceed the heating rate and g-load constraints
- Guidance solutions that typically become more lift up to protect for trajectory dispersions near the end of entry
- Miss distance is less than 0.5 km for four of the five cases shown





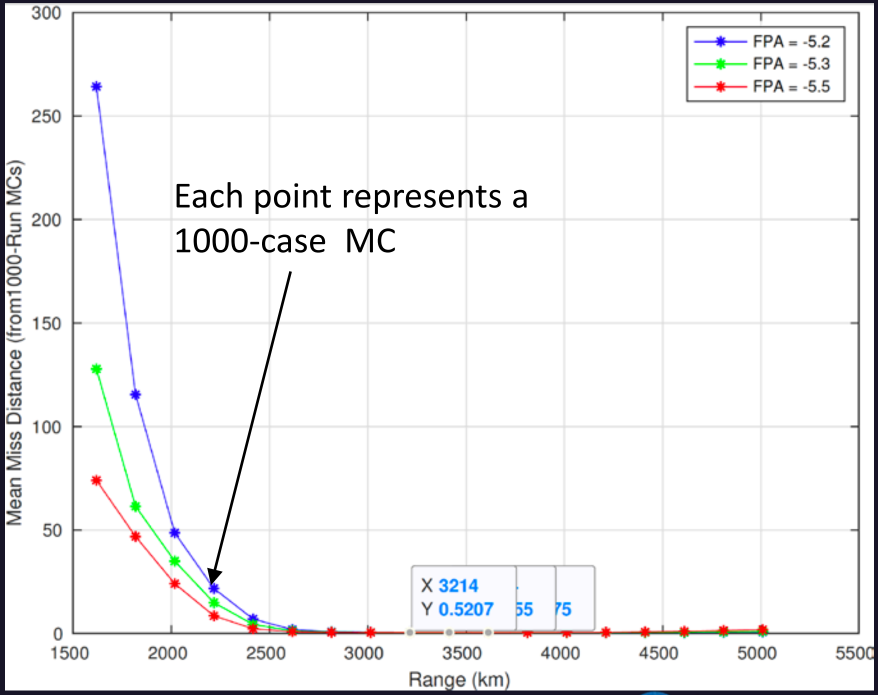
URC TARGETING PERFORMANCE

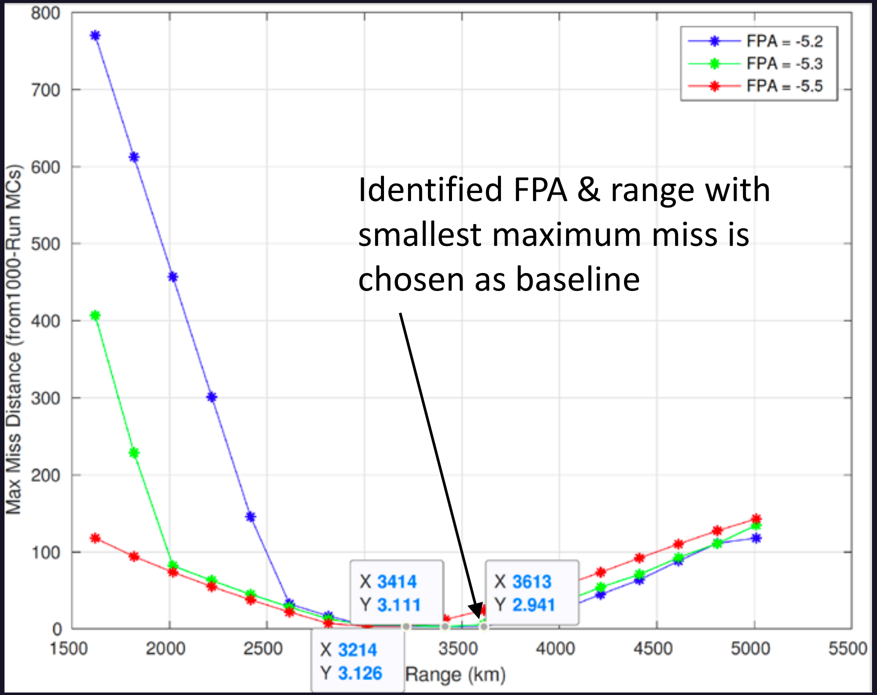
Monte Carlos (MCs) were run with typical dispersions for a lunar entry mission

All runs for example FNPEG-URC case satisfy heating (<250 W/cm^2), g-load (<15 g's), and miss distance (<3 km) desired limits

Monte Carlo Variables	Standard Deviation σ
Initial Velocity	$\pm$3.33 m/s
Initial FPA	$\pm$0.03 °
Initial Azimuth	$\pm$0.1°
Initial Lat	$\pm$0.1°
Initial Lon	$\pm$0.1°
Initial Altitude	$\pm$100 m
Initial Mass	$\pm$1% kg

Monte Carlo Variables	Multiplier
EARTH GRAM	N/A
CD, CL, CS	0.9-1.1





GUIDANCE AND CONTROL CONFIGURATION COMPARISON

CONTROL SYSTEM PERFORMANCE

Dedicated aerodynamic, aerothermal, structural, and packaging analyses defined operational control regimes to reach the UTTR target [Lat = 40°, Lon = -112.1°]

- RCS Performance Statistics (**FNPEG**):
  - α_{trim} = -16.6°
  - L/D_{trim} = 0.27
  - $\beta_{ball\ coef}$ = 54 kg/m^2

1000-case MC	Mean	Max
Miss Distance	0.42 km	1.30 km
Peak Heat Rate	196 W/cm^2	211 W/cm^2
Peak G-load	5.8 g	6.5 g

γ_{EI}=-5.2°, Range to target = 3400 km

- FCS Performance Statistics (**URC**):
  - $[\alpha_{range}]$, $[\beta_{range}]$ = [- 1 °,-18°] , [±10 °]
  - L/D_{range} = [0.04, 0.30]
  - $[\beta_{ball\ coef}]$ = 58 kg/m^2

1000-case MC	Mean	Max
Miss Distance	0.42 km	0.87 km
Peak Heat Rate	202 W/cm^2	217 W/cm^2
Peak G-load	6.6 g	7.49 g

γ_{EI}=-5.2°, Range to target = 3400 km

- MMCS Performance Statistics (**URC**):
  - $[\alpha_{range}]$, $[\beta_{range}]$ = [- 9 °,-17°] , [±10 °]
  - L/D_{range} = [0.15, 0.29]
  - $[\beta_{ball\ coef}]$ = 64 kg/m^2

1000-case MC	Mean	Max
Miss Distance	0.26 km	0. 72 km
Peak Heat Rate	243 W/cm^2	260 W/cm^2
Peak G-load	8.2 g	8.9 g

γ_{EI}=-5.8°, Range to target = 4800 km

CONTROL SYSTEMS PERFORMANCE
(CONT'D)

Dedicated aerodynamic, aerothermal, structural, and packaging analyses defined operational control regimes to reach the UTTR target [Lat = 40°, Lon = -112.1°]

- RCS Performance Statistics (**FNPEG**):
  - α_{trim} = -14°
  - L/D_{trim} = 0.23
  - $\beta_{ball\ coef}$ = 58 kg/m²

1000-case MC	Mean	Max
Miss Distance	0.44 km	1.2 km
Peak Heat Rate	198 W/cm²	212 W/cm²
Peak G-load	5.8 g	6.4 g

γ_{EI}=-5.2°, Range to target = 3400 km

- **Altered** RCS Performance Statistics (**FNPEG**):
  - α_{trim} = -10°
  - L/D_{trim} = 0.17
  - $\beta_{ball\ coef}$ = 58 kg/m²

1000-case MC	Mean	Max
Miss Distance	0.65 km	26.37 km
Peak Heat Rate	193 W/cm²	207 W/cm²
Peak G-load	5.6 g	6.2 g

Cases that undershoot target due to low L/D

γ_{EI}=-5.2°, Range to target = 3400 km

- MMCS Performance Statistics (**URC**):
  - [α_{range}], [β_{range}] = [- 9 °,-17°] , [±10 °]
  - L/D_{range} = [0.15, 0.29]
  - [$\beta_{ball\ coef}$] = 64 kg/m²

1000-case MC	Mean	Max
Miss Distance	0.26 km	0. 72 km
Peak Heat Rate	243 W/cm²	260 W/cm²
Peak G-load	8.2 g	8.9 g

γ_{EI}=-5.8°, Range to target = 4800 km

- **Altered** MMCS Performance Statistics (**URC**):
  - [α_{range}], [β_{range}] = [- 9 °,-17°] , [±4.5 °]
  - L/D_{range} = [0.15, 0.29]
  - [$\beta_{ball\ coef}$] = 64 kg/m²

1000-case MC	Mean	Max
Miss Distance	0.76 km	3.58 km
Peak Heat Rate	243 W/cm²	260 W/cm²
Peak G-load	8.12 g	8.81 g

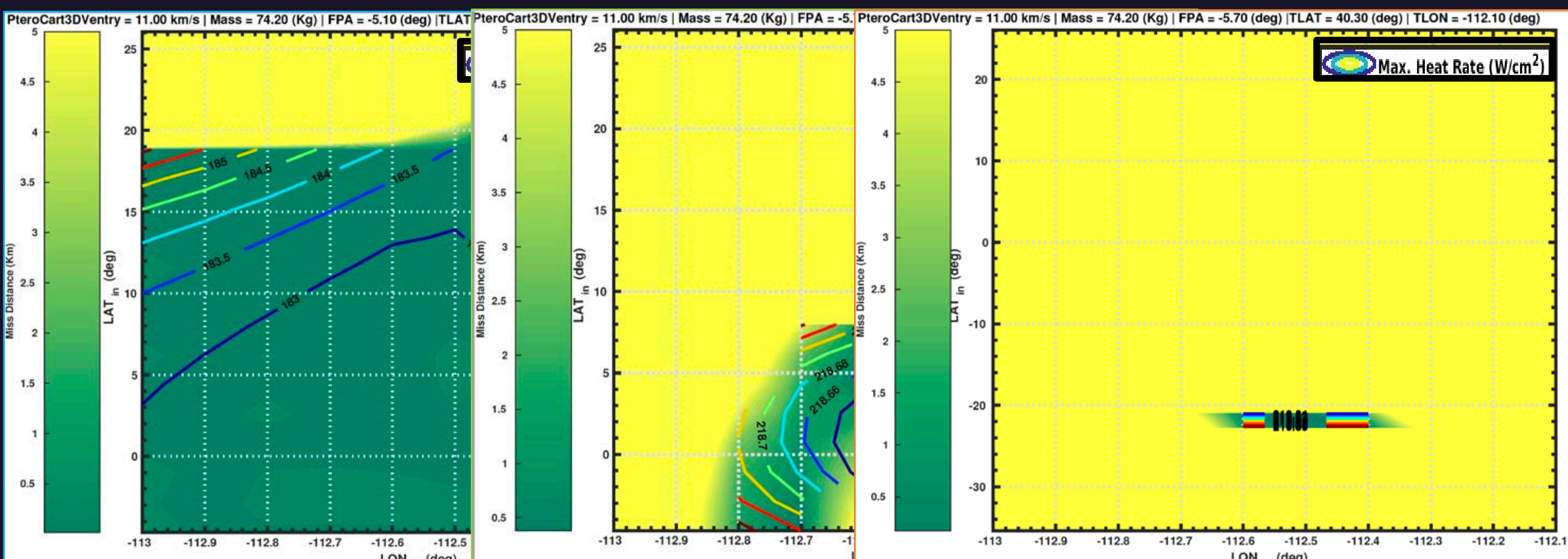
Max miss distances increase with decreased authority

γ_{EI}=-5.8°, Range to target = 4800 km

FCS OPERABLE REGIMES DECREASES

Further controls and aerodynamic analysis led to multiple iterations of alpha-beta operational regimes for guidance

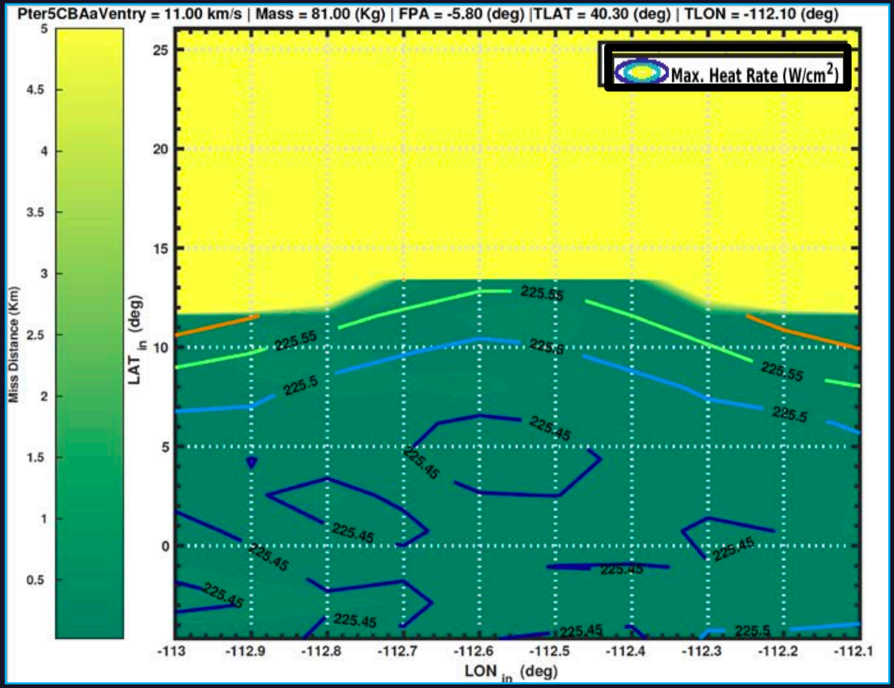
- **Iteration 1:** $[\alpha_{range}], [\beta_{range}]$ = [+ 1 °,-20°] , [±10 °]
- **Iteration 2:** $[\alpha_{range}], [\beta_{range}]$ = [- 1 °,-18°] , [±10 °]
- **Iteration 3a:** $[\alpha_{range}], [\beta_{range}]$ = [- 9.5 °,-20.5 °] , [±0.6 °]
- **Iteration 3b:** $[\alpha_{range}], [\beta_{range}]$ = [- 12.0 °,-17.0°] , [±1.0 °]
- **Iteration 3c:** $[\alpha_{range}], [\beta_{range}]$ = [- 13.5 °,-15.4°] , [±1.6 °] (not shown due to poor convergence)

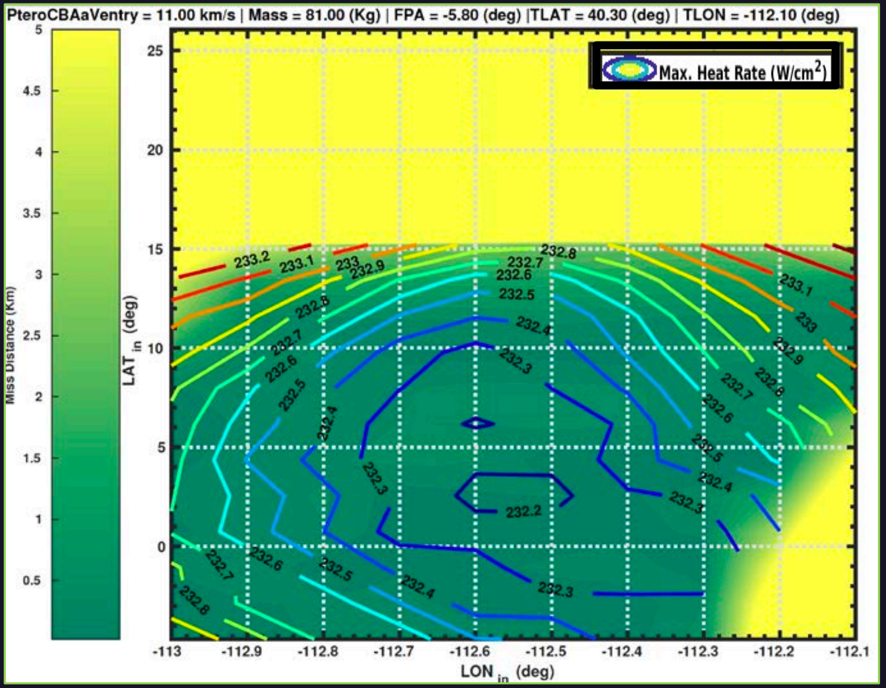


MMCS OPERABLE REGIMES DECREASES

Further controls and aerodynamic analysis led to multiple iterations of alpha-beta operational regimes for guidance

- **Iteration 1:** $[\alpha_{range}], [\beta_{range}]$ = [- 1 °,-18°] , [±10 °]
- **Iteration 2:** $[\alpha_{range}], [\beta_{range}]$ = [- 9 °,-17°] , [±10 °]
- **Iteration 3:** $[\alpha_{range}], [\beta_{range}]$ = [- 9 °,-17 °] , [±4.5 °]





CONCLUSION

Due to the shrinking operable alpha-beta ranges, and thus control authority, provided from integrated structural, aerodynamic, and controls analysis, alpha-beta performance is degraded.

bank=0	**FNPEG-URC** Guidance Command Limits						99.9% Miss Distance (km)	99.9% Max Heat Rate (W/cm^2)	99.9% Max G-load (g)
	alpha bounds (d)	beta bounds (d)	alpha rate limit (d/s)	beta rate limit (d/s)	alpha accel limit (d/s/s)	beta accel limit (d/s/s)			
FLAPS DCM 10 (EI : ilon=-112.8, fpa = -5.8, irange=5400km)	[-9.5, -20.5]	[-0.6, +0.6]	5	5	5	5	32.72	244.18	9.07
MASS MVT DCM 13 (EI : ilon=-112.8, fpa = -5.8, irange=4800km)	[-9, -17]	[-4.5, +4.5]	5	5	5	5	3.39	255.57	8.64

CONCLUSION
(CONT'D)

Therefore, bank trajectories are recommended for the PBV

beta=0	**FNPEG-Bank** Guidance Command Limits					99.9% Miss Distance (km)	99.9% Max Heat Rate (W/cm^2)	99.9% Max G-load (g)
	alpha trim constant (d)	bank bounds (d)	bank rate limit (d/s)	bank accel limit (d/s/s)	Mass (kg)			
FLAPS DCM 10 (EI : ilon=-112.8, fpa = -5.2, irange=3400km)	-14	[-180, +180]	15	5	74.2	0.64	210.89	6.15
MASS MVT DCM 13 (EI : ilon=-112.8, fpa= -5.2, irange=3400km)	-13.5	[-180, +180]	15	5	81.0	1.10	215.85	6.19
RCS DCM 14 (EI: ilon=-112.8, fpa= -5.2, irange=3400 km)	-16.6	[-180, +180]	15	5	69.1	0.93	208.87	6.34

LESSONS LEARNED

Feasible guidance solutions exist for DEVs

FNPEG's *unified* algorithmic principles allow for high flexibility with little/no tuning for various regimes

A new guidance method FNPEG-URC was successfully created to decouple downrange and crossrange control

Regions of viable EI states are identified such that each control system may robustly reach the target precisely (<3 km)

Success of FNPEG-URC designs (Mass Movement, Flaps) is strongly dependent on operational sideslip range

REFERENCES – SPECIAL SESSION

Yount, B. C., Cassell, A. M., and D'Souza, S. N., "Pterodactyl: Mechanical Designs for Integrated Control Design of a Mechanically Deployable Entry Vehicle (DEV)," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Nikaido, B. E., D'Souza, S. N., Hays, Z. B., and Reddish, B. J., "Pterodactyl: Aerodynamic and Aeroheating Database Development for Integrated Control Design of a Mechanically Deployable Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Okolo, W. A., Margolis, B. W., D'Souza, S. N., and Barton, J. D., "Pterodactyl: Development and Comparison of Control Architectures for a Mechanically Deployable Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Hays, Z. B., Yount, B. C., Nikaido, B. E., Tran, J., D'Souza, S. N., Kinney, D. J., and McGuire, M. K., "Pterodactyl: Thermal Protection System for Integrated Control Design of a Mechanically Deployable Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

Alunni, A.I., D'Souza, S.N., Yount, B.C., Okolo, W.A., Nikaido, B.E., Margolis, B.W., Johnson, B.J., Barton, J.D., Lopez, G., Wolfarth, L. S., and Hays, Z. B., "Pterodactyl: Trade Study for an Integrated Control System Design of a Mechanically Deployable Entry Vehicle," AIAA SciTech 2020 Forum, AIAA, Orlando, FL, 2020.

ACKNOWLEDGEMENTS

NASA Core Team

Dr. Sarah D'Souza (Principal Investigator)
Antonella Alunni (Lead Systems Engineer)
Breanna Johnson (Guidance and Trajectory Design Lead)
Dr. Wendy Okolo (Control System Design Lead)
Ben Nikaido (Aerodynamics and Aeroheating Lead)
Bryan Yount (Mechanical Design and Structures Lead)
Benjamin Margolis (Controls Engineer)
Zane Hays (TPS System Modeling)

Advisors

Ricky Howard
STMD ECI Program Executive

Michelle Munk
NASA STMD Mentor and
EDL Principal Technologist

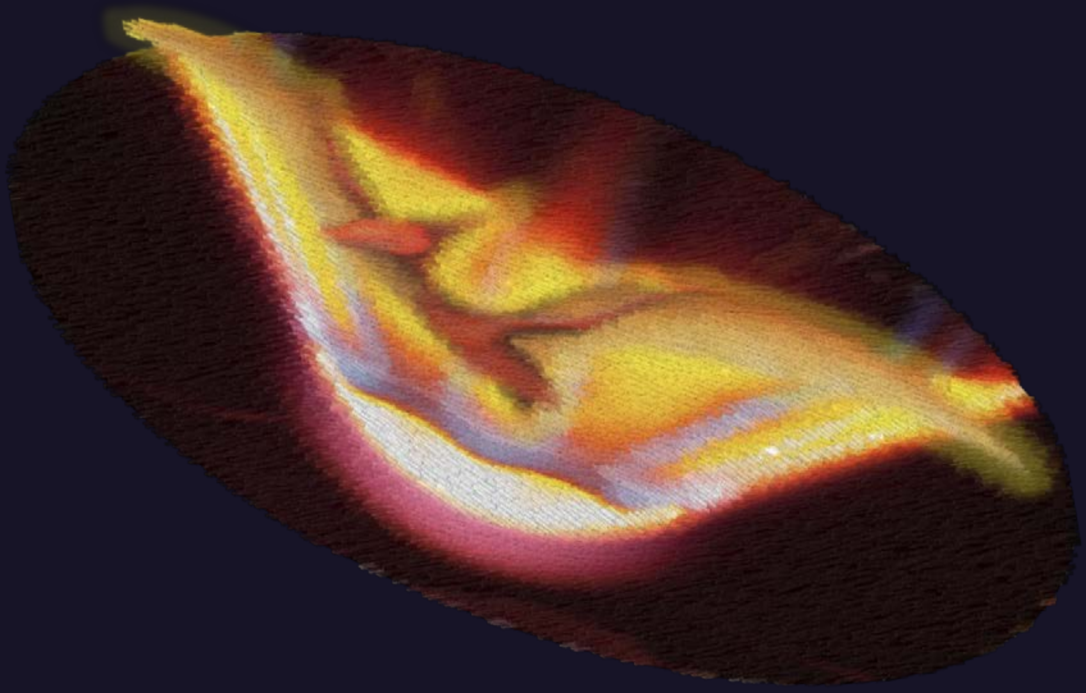
Dr. Dave Kinney, Dr. Alan Cassell, and Ron Sostaric
NASA Mentors

Industry Partners

Kenneth Hibbard, Jeffrey Barton, Dr. Gabriel Lopez, Jeremy John, and Larry Wolfarth

Dr. Stephen Robinson
Brandon Reddish

QUESTIONS?



HERITAGE

- First Generation – Designed for low-lifting capsule vehicles in the Apollo program
  - Skip entry and final-direct entry ("Apollo entry guidance") phase
  - Flies trim alpha w/o modulation
  - Relies on sensitivity coefficients from linearized reference trajectory for predicted downrange error
  - Crossrange controlled with bank reversal logic that changes the sign when crossrange to landing exceeds a velocity-dependent deadband
- Second Generation – Designed for the high L/D Space Shuttle
  - Compared to Apollo (low L/D) flight time and downrange traveled are much longer
  - Linearized gain scheduled tracking law for bank angle modulation is employed to follow the reference profile (similar bank reversal logic)
- Third Generation – Depart from Apollo or Shuttle and rely more on predictor-corrector algorithms for real-time trajectory design and guidance solution
  - No reliance on pre-planned reference trajectory or tracking law
  - Primarily proposed for low lifting vehicles since satisfaction of the constraints is mainly through carefully chosen initial condition

SIDE FORCE CHANNEL IN URC

Two Sideslip Channel Approaches Explored to Extract Commanded Side Force:

- Azimuth (error between current and target/commanded)
- Crossrange (error between current and zero)

$$S_{CMD} = K_{\psi}(\psi_{err} \pm \psi_{db}) + K_{\dot{\psi}}(\dot{\psi}_c - \dot{\psi})$$, where gains are dynamic pressure dependent

- Once the commanded side force is found, β_{CMD} is found

$$\beta_{CMD} = \frac{(S_{CMD} \cdot StoCS) - CSmax_{C0}}{CSmax_{B0}}$$, where $CSmax = CSmax_{B0} \cdot \beta + CSmax_{C0}$